The physiology of water use efficiency of crops subjected to subsurface drip irrigation, oxygation and salinity in a heavy clay soil

Surya Prasad BHATTARAI
BSc *Agr*.TU, Nepal and MSc *Agr.*University of Essex, UK

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School of Biological and Environmental Sciences
Faculty of Arts, Health and Sciences
Central Queensland University
Rockhampton, QLD 4702, Australia
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EXECUTIVE SUMMARY

Furrow is the dominant irrigation method for agriculture throughout the world. However, due to water use inefficiencies, only about 50% of the water that reaches the field is used by the crop, the remainder at times negatively impacting the environment. This research explored the potential of subsurface drip irrigation (SDI) to raise water use efficiency (WUE) of cotton produced on a heavy clay soil, and to minimize the negative environmental impact of irrigation water. SDI cotton irrigated at the rate of 75 % daily crop evapo-transpirational demand (ETc) produced yield equivalent to, or greater than, that with SDI at 120/105 ETc in both seasons in Emerald, Queensland. Lint yield of SDI 75% ETc was comparable to the conventional furrow method in 2001/02 season and less by 18% in 2002/03 season, but used only approximately half of the water input (52%). The SDI crop irrigated at 50% ETc showed enhanced crop earliness and WUE, but had lower lint yield, whereas higher SDI irrigation levels (> 90% ETc) delayed crop maturity without benefits for yield or WUE. Furrow registered the highest drainage and runoff over the two seasons (114 mm and 224 mm) compared with the SDI at 105/120 ETc (65 mm and 32 mm) whereas SDI 90% ETc had no runoff but leakage of 17 mm and neither drainage nor runoff were observed at SDI at 50 and 75% ETc. It was hypothesized that at higher irrigation rates, SDI crops experience lack of oxygen in the root zone, which becomes a limiting factor for improving WUE at higher irrigation rates at and above 90% ETc for cotton in heavy clay soil.

The potential of subsurface oxygation (irrigating oxygen-rich water to plants through drip tape- the details about oxygation approach, mechanism and terminology are presented in Bhattarai *et al.,* 2005c) using aerated irrigation water (mixing 12% air by volume of water using Mazzei model venturi for in-line air injection) or hydrogen peroxide solution (at 0.5 ml H_2O_2 L^{-1} of irrigation water throughout the irrigation cycle)

was therefore investigated at a range of soil moisture levels in the glasshouse, screenhouse and outside at Rockhampton, Queensland. Following irrigation events soil O_2 declined by 45% in non-aerated plots while in aerated plots soil O_2 decreased by only 25%. Oxygen measurements in the rhizosphere over a 72-hour period during the flowering stage revealed greater oxygen concentration with aerated treatments compared with the control at both field capacity (8.1 vs 7.1 mg L^{-1}) and deficit (9.2 vs 8.1 mg L^{-1}) soil moisture conditions. Yield was increased on average by 86, 20 and 21% for soybean, cotton and tomato, respectively, due to aeration across soil moisture levels and types of aeration. Such increase in yield was associated with greater number of pods for soybean, bolls and their individual weight for cotton and fruit size in tomato. Aeration treatments also increased water use by plants and were associated with greater WUE in all experiments. The effect of aeration was significant on the rate of net photosynthesis per unit leaf area when pots were aerated, but instantaneous leaf stomatal conductance and unit leaf transpiration rates were not affected. However, higher stem sap flow rates indicated greater canopy transpiration over longer time intervals in aerated treatments. Higher root weight and soil respiration were observed in aerated treatments compared with the control. Hence, aeration-induced root functioning was arguably responsible for greater fruit set and yield in all three crops, while in vegetable soybean greater canopy interception of radiation and greater total vegetative biomass were also responsible for additional yield benefits, and in tomato the effect was due to higher leaf area, chlorophyll content, and bigger fruit.

Salinity is a major environmental threat in many parts of the world. Salinity in clay soils is often associated with sodicity, which reduces the porosity in the soil thereby reducing soil oxygen concentration. The effect of oxygation (with aerated water) for SDI crops in a range of salinities (tomato: 2.0, 4.0, 8.6,10.0; cotton and soybean: 2.0, 8.0, 14.0, 20.0 dS m^{-1} ECe) in heavy clay soils was evaluated. Oxygation on average increased yield of tomato, vegetable soybean and cotton by 38, 12 and 18 percent respectively, but yields decreased significantly with increasing salinity levels. Aeration of saline soil increased WUE for fruit and biomass in all three species but not the instantaneous WUE, measured as µmol CO_2 fixed per mmol H_2O transpired, with the exception of cotton. Aeration increased, and salinity decreased, cumulative transpiration as determined by stem sap flow over a two week period during flowering in vegetable soybean. Plants in aerated treatments showed increased stem diameter, improved membrane permeability expressed by reduced relative leakage ratio and possibly enhanced ion regulation as revealed by greater sodium exclusion and intact root membrane as revealed in the TS of aerated roots in the saline soils. The increase in yield in tomato and cotton was also accompanied by increased harvest index, greater fruit size, higher fruit number, shoot: root ratio, and lower water stress index. The rate of net leaf photosynthesis increased with aeration and decreased with salinity in cotton and soybean; however, in tomato the aeration effect on photosynthesis was not significant although salinity did significantly reduce net leaf photosynthesis. Aeration improved selective membrane permeability as evidenced by reduced electrolyte leakage.

Hence it is suggested that aeration helps exclude the ingress of salts into the plants and increases uptake of water and nutrients for growth in saline environments. Evidence from these controlled environment experiments warrants the commercial-scale testing of the oxygation technology for application to the agricultural and horticultural industries especially to add value to growers' investments in SDI and to diminish potential negative impacts of over-use of irrigation water.

PUBLICATIONS/ PRESENTATIONS

PUBLISHED

1. *Indian Journal of Plant Physiology,* Special Issue, Part 1(8): 55-62 (2003)

Studying the economic and physiological basis for cotton production on subsurface drip irrigation in heavy clay soils of central Queensland, Australia: An analysis of water-lint production function.

2. *Annals of Applied Biology,* 144:285-298 (2004).

Aerated subsurface irrigation water gives growth and yield benefits to zucchini, vegetable soybean and cotton in flooded and heavy clay soils.

3. *Proceedings of the 11th Australian Agronomy Conference held on 6-8 February 2003 at Geelong, Victoria, Australia* (2003).

Physiological response of the cotton crop subjected to different water regimes in subsurface drip irrigation system on heavy clay soil at Emerald, central Queensland, Australia.

http://www.regional.org.com/au/asa/2003/p/4/bhattarai.htm

4. *Proceedings of the 4th International Crop Science Congress held on 26 September - 2 October 2004, Brisbane, Australia.*

Oxygation of rhizosphere with subsurface aerated irrigation water improves lint yield and performance of cotton on saline heavy clay soil.

http://www.regional.org.au/asa/cs/docs/665/cropscience2004_bhattarai+rev.doc

SUBMITTED

5. *Experimental Agriculture,* (In press): (2005)

Response of cotton to subsurface drip and furrow irrigation in a vertosol.

6. *International Society of Horticulture Science 656: Proceedings of Joint Regional Horticultural Conference: Harnessing the Potential of Horticulture in the Asia-Pacific Region. Held at Sunshine coast, QLD, Australia, 1-3 September 2004 .Pp6* (2004).

Influence of soil moisture stress on yield, quality and blossom end rot of tomato in a heavy clay soil.

7. *Plant and Soil* (July 2005)

Carbon isotope discrimination and related water use efficiencies by tomato (*Lycopersicon esculentum* L.) at different soil moisture regimes.

8. *Scientia Horticulturae* (December 2004)

Root aeration improves yield and water use efficiency of tomato in heavy clay and saline soils.

9. *Advances in Agronomy* (March 2005) - invited publication

Oxygation unlocks yield potentials of crops in oxygen limited soil environments. Chapter in Advances in Agronomy, USA.

MANUSCRIPTS UNDER PREPARATION

10. *Crop Science* (August 2005)

Vegetable soybean and salinity: I. Response in growth, development, water relations and ion accumulations to subsurface aeration.

11. *Crop Science* (August 2005)

Vegetable soybean and salinity: II. Gas exchange, changes in membrane permeability, and resources use efficiency with subsurface aeration.

12. *Plant and Soil* (August 2005)

Growth, development, physiological performance and yield of vegetable soybean at various soil moisture levels.

13. Plant and Soil (August 2005)

Growth, development, physiological performance and yield of cotton at various soil moisture levels.

CONFERENCE PRESENTATIONS

14. *Second International Congress of Plant Physiology (Sustainable Plant Productivity Under Changing Environment). Delhi India, 8-12 January 2003, (Oral presentation).*

Studying the economic and physiological basis for cotton production on subsurface drip irrigation in heavy clay soils of central Queensland, Australia: An analysis of water-lint production function.

15. *11th Australian Agronomy Conference*. Geelong, Victoria, Australia, 6-8 February 2003, (Poster presentation).

Physiological response of cotton subjected to different water regimes in subsurface drip irrigation system on heavy clay soil at Emerald, central Queensland, Australia.

16. *Ninth Productive Use and Rehabilitation of Saline Land (PUR$L) Conference* Yeppoon, QLD, Australia, 29 September - 2 October 2003, (Poster presented jointly with Lance Prendergast, Honours student).

Root Zone Oxygation: Enhanced Salinity Tolerance on Tomato in a Heavy Clay Soil.

17. 4th *International Conference on Applications of Stable Isotope Techniques to Ecological Studies*. Wellington, New Zealand, 19-23 April 2004. (Poster presentation)

Carbon isotope discrimination and related water use efficiencies by tomato (*Lycopersicon esculentum* L.) at different soil moisture regimes.

18. *AuSHS and NZSHS Joint Regional Horticultural Conference: Harnessing the Potential of Horticulture in the Asian-Pacific Region*. Coolum, Sunshine Coast, QLD, Australia, 1-3 September 2004, (Poster presentation).

Soil moisture stress influence on quality, yield and blossom end rot of tomato (*Lycopersicon esculentum* L.) in heavy clay soil.

19. *4th International Crop Science Congress,* Brisbane, QLD, Australia, 26 September – 1 October 2004.

Oxygation of rhizosphere with subsurface aerated irrigation water improves lint yield and performance of cotton on saline heavy clay soil.

20. *Cotton research and development conference, Brisbane, QLD, Australia, 2002.*

Subsurface drip irrigation (SDI) on heavy clay soils- an opportunity to increase WUE and reduce off-farm environmental impacts of cotton production.

Image 1. Different types of publications during the study.

ABBREVIATIONS

ABA	Abscisic acid
ACC	1-aminocyclopropane 1-carboxylic acid.
ATP	Adenosine triphosphate
AVRDC	Asian Vegetable Research and Development Centre
CDE	Convection, dispersion equation
CFU	Colony forming units
CQU	Central Queensland University
CSIRO	Commonwealth Scientific and Industrial Research Organization
CU	Consumptive use
CWSI	Crop water stress index
CWU	Crop water use
DNRM&E	Department of Natural Resources Mines and Environment
DO	Dissolved oxygen
DPI	Department of Primary Industries
DW	Dry weight
EC (e)	Electrical conductivity of saturated paste
EGM	Environmental gas monitoring
ESP	Exchangeable sodium percentage
ET	Evapotranspiration
ETc	Crop evapotranspiration
ETo	Reference crop evapotranspiration
FC	Field capacity
FW	Fresh weight
GA	Gibberellic acid

GABA	Gamma amino butyrate
HP	Hydrogen peroxide
IAA	Indole acetic acid
IE	Irrigation efficiency
IRGA	Infra red gas analyser
LAI	Leaf area index
LEPA	Low energy precision application
LI	Light interception
LSD	Least significant difference
LWP	Leaf water potential
LWR	Leaf weight ratio
ML	Mega litre
MPN	Most probable number
MRR	Marginal rate of return
NADP	Nicotinamide adenosine dinucleotide phosphate
NAWF	Nodes above white flower
ODR	Oxygen diffusion rate
PAR	Photosynthetically active radiation
PCA	Plate count agar
PSG	Plant Sciences Group
RLD	Root length density
ROS	Reactive oxygen species
RUE	Radiation use efficiency
RWC	Relative water content
SAR	Sodium absorption ratio

SC	Stomatal conductance
SDI	Subsurface drip irrigation
SE	Standard error
SED	Standard error of deviation
SLA	Specific leaf area
SLR	Specific leaf ratio
SPAD	Soil-Plant Analyses Development (SPAD) unit of Minolta Camera
SPSS	Statistical package for social sciences
TE	Transpiration efficiency
VC	Variable cost
WP	Wettable powder
WUE	Water use efficiency
WUE_i	Instantaneous water use efficiency
WUE_{sl}	Season long water use efficiency

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1
General Introduction

The contribution of irrigation to agricultural production is very significant to the world food supply. However, current irrigation practices such as furrow are inefficient causing environmental hazards such as salinity, run-off and contamination of water bodies. SDI overcomes most of these shortcomings of the conventional irrigation methods, but the gain in terms of the yield is not consistent. This chapter provides the background information on the issues pertinent to SDI and sets the framework for the research agenda as reported in chapters 3-5. Also included are the aims and objectives, hypotheses, limitations of the studies and finally overall overview of the thesis is presented in this chapter.

1.1 SIGNIFICANCE OF IRRIGATED AGRICULTURE

Irrigated agriculture has played a vital role in supporting a dramatic increase in global food production over recent decades. While only 20% of the world's agricultural land is irrigated, it produces 40% of world's food supply (Howell, 2001). Irrigation also improves the efficiency of other production inputs such as fertilizers, improved seeds and agrichemical. Hence, often the low-input irrigated farming is more productive than high-input rainfed farming (Rosegrant *et al.*, 2002). Therefore, irrigated agriculture will be a dominating feature of future farming in order to be able to produce sufficient food for an ever-growing world population.

1.2 IRRIGATION TYPES

Different methods are used for irrigation around the world. Flood, furrow, sprinkler, central pivot, drip/subsurface drip and other micro-irrigation technologies are common irrigation types. However, most of the world's agricultural lands are irrigated with furrow, which involves surface flow under gravity. The irrigation efficiency (expressed as the ratio of crop water use to applied irrigation water) of furrow is only about 50-60% (Jensen *et al.*, 1990). Loss of irrigation water in furrow emanates from run-off, deep drainage and evaporation of water from the wet soil surface and exposed furrows. The negative environmental impacts associated with conventional furrow irrigation are due to run-off and deep drainage causing erosion and contamination of water bodies by pollutants that have high environmental costs (Milroy and Tennakoon, 2002). High intensity furrow irrigation schemes are also often blamed for waterlogging and soil salinization, the latter which now affects 30% of irrigated land (Eldeiry *et al.*, 2004). Salinization is reducing the existing area under irrigation by up to 2% a year. To increase irrigation's contribution to food production, FAO (2002) states that what is needed is for improved efficiency in the use of irrigation water. As the possibility of sourcing more water for irrigation is an unlikely scenario, there is an urgent need to improve irrigation and water use efficiency of conventional irrigation practices of agriculture in order to sustain agriculture and food production.

1.3 SUBSURFACE DRIP IRRIGATION IN HEAVY CLAY SOIL FOR COTTON

Subsurface Drip Irrigation (SDI) offers maximum irrigation efficiency (IE) and also allows flexibility for control of run-off and deep drainage. Many earlier studies on SDI focused on light textured soils (Ayars *et al.*, 1999; Camp, 1998), where loss of irrigation water through drainage and run-off with furrow irrigation was overwhelmingly high. However, there are also vast acreages of land under heavy soils, such as the cracking clays of Central Queensland, Australia, where loss of irrigation water with furrow is reported as significant (Milroy and Tennakoon, 2002)**.** Therefore, the potential of SDI for improving WUE needs to be harnessed for such soils in order to reduce the large losses of irrigation water characteristically associated with conventional furrow irrigation in heavy clay soils. It is not known exactly how efficient SDI is in the heavy cracking clay soils, in comparison to furrow, in relation to reducing the loss of irrigation water. Additionally, it is also not known how plant performance would change in response to different rates of irrigation with SDI on such cracking clays in comparison to conventional furrow irrigation. There is a knowledge gap warranting research focus. Part of the thesis research addresses this issue and attempts to determine the interrelationships between cotton physiological responses and an optimum irrigation rate of SDI cotton for heavy clay soils.

1.4 CROPS IRRIGATED WITH SUBSURFACE DRIP EXPERIENCE HYPOXIA

In spite of its greater IE, substantial reduction of run off and drainage, and other associated benefits, there is negligible crop yield gain with SDI at non-limiting canopy transpiration rates in comparison to conventional furrow irrigation. Without such yield advantage, given the large costs involved at the establishment phase, SDI has not been a favoured irrigation method for the majority of growers. Therefore, the optimization of SDI to increase yield has become a focus of research.

System capacity of SDI is generally designed to meet 110 to 120% of the highest expected seven day evapotranspiration (ET) rate (ASAE, 1991; Conrad, 1992). This allows for unreasonably hot weather, or make-up capacity if irrigators got behind in meeting crops' irrigation needs. In light textured soils, SDI crops are generally irrigated at or above the 100% of daily ETc. However, the behaviour of soil water is very different in heavy clay soil, therefore, the recommendation made for light textured soils does not hold true for heavy clay soil (Raine and Foley, 2002a). SDI as a point source delivery directly in the root zone develops a saturated wetting front for the rhizosphere especially when irrigation rates are close to 100% ETc and even if lower (Machado *et al.*, 2003). Long hours of irrigation, which is required in the tropics, concentrated root development around the emitters and relatively low hydraulic conductivity in the heavy clay lead to sustained saturation of the root zone in heavy clay soil inducing hypoxia, which is detrimental for root functioning and immediately affects growth. Meek *et al.* (1983) reported that daily trickle-irrigated tomato crops at 100-120% ETc in clay soil decreased O_2 concentration to 0.03-0.06 L L^{-1} at 20 cm, which is less than the minimum threshold value (Glinski and Stepniewski, 1985) and concluded that continuous severe interference in the aeration status of the soil at and below 20 cm had significant impact on performance. Goorahoo *et al.* (2002) confirmed that SDI crops in the field suffer from lack of oxygen (O_2) in the root zone and proposed alternative forced aeration of rhizosphere in the bell pepper.

Cotton experiments conducted in heavy clay soil in 2001/02 and 2002/03 seasons at Central Queensland, Australia consistently showed depression of plant performance at SDI ≥ 90% ETc with a plateau at 75% ETc suggesting that rhizosphere O_2 becomes limiting for the greater root activity in such soils at higher SDI rates. Thus it is hypothesized that the oxygen limitation in the rhizosphere of the SDI crop in heavy clay is a limitation to yield, the evidence of which is presented in chapter 3 and becomes the basis for aeration research as reported in Chapter 4. Chapters 4 and 5 of the thesis research are focused to unravel the phenomenon of O_2 deficiency in the root zone of different crops and suggest mechanisms to ameliorate such hypoxic rhizosphere.

1.5 AERATED WATER IRRIGATION OVERCOMES HYPOXIA

Respiring plant roots consume large amounts of O_2 (~5 ml O_2 h^{-1} g^{-1} of dry weight at 25°C). Plant performance is severely impeded when O_2 is limiting in the root zone. As O_2 diffuses 10,000 times slower in water than in other gases, a saturated soil presents limitation for the diffusion of O_2 to the roots. Theoretical and experimental approaches (Letey, 1961; Grable, 1966; Herr and Jarrel, 1980; Everard, 1985), and modelling (Armstrong, 1979; Biernbaum, 1992; Meek *et al.*, 1981) suggested that forced aeration of the root zone improves plant performance in solution culture as well as in the soil. However, injection of air alone in the soil for field crops is not practically feasible as forced injected air escapes from the soil through the chimney effect from the point of injection. The basic infrastructure of SDI allows for easy coupling of air injection systems to aerate the irrigation water (air injection with mazzei air injector or hydrogen peroxide-soil catalases breaks down hydrogen peroxide (HP) into O_2 and water) in line and it allows delivery of oxygenated water directly into the root zone. It is hypothesized that the oxygation of the rhizosphere with aerated irrigation water improves plant performance mediated through improved root functioning and growth in heavy clay soil. Recent studies showed that aeration of the rhizosphere of SDI crop increased growth and yield (Goorhaoo, *et al.,* 2002; Heuberger *et al*., 2001), exhibiting a distinct promise for rhizosphere aeration for SDI crops. Unveiling the physiological process governing the positive effect of forced aeration for SDI crops would help commercialise application of oxygation in a range of soil and crop types.

1.6 OXYGATION IMPROVES PLANT PERFORMANCE IN SALINIE SOILS

Salinization of agricultural land is progressively increasing throughout the world. Salinity in clay soil is often associated with sodicity, which reduces porosity in the soil, thereby, reducing the space for soil O_2 (Colmer, 2000). Salinity limits the uptake of nutrients and water by plants and increased the loss of soil water by drainage, runoff and evaporation, as the relative water uptake by plant is reduced (Munns, 2002). Therefore, the efficiency of water and nutrients use is reduced**.** Shoot salt concentration is largely determined by root exclusion efficiency (Tester and Davenport, 2003; Zhang and Blumwald, 2001). Where roots act as highly effective filters as much as 95% of salt can be excluded, and cell sap concentrations in leaves are about twice that of the external solution (Atwell *et al.*, 1999). But salinity and waterlogging, which impair the diffusion of O_2 to roots, affect root membrane stability. This leads to increased Na^+ and Cl^- accumulation in shoot tissues and decreasing the stability of leaf membranes to either dehydration or heat stress (Letey and Stolzy, 1967). The ratio of K^+/Na^+ transported to the shoot under anaerobic conditions decreases progressively on salinization.

It is hypothesized that forced aeration of a saline/sodic rhizosphere confers greater root membrane permeability, which reduces the sodium ingress into the plant, through enhanced salt exclusion by the root**.** Experiments on species susceptible (tomato), moderately tolerant (vegetable soybean) and tolerant (cotton) to salinity at a range of salinities with and without aeration confirmed that the ability of the plant to exclude salt in response to aeration increased significantly (Bhattarai, *et al.,* 2005c submitted). Such increased exclusion conferred greater WUE, and increased leaf water content which contributed to reduced membrane leakage of the leaf tissue, increased leaf area, greater biomass accumulation and overall increased performance of plants in saline soil due to oxygation. Hence, the third part of the research of this thesis considers the opportunities for ameliorating an anaerobic rhizosphere in saline soils by air injection and showed that crop performance on saline soils improved with aeration in susceptible, moderately tolerant and tolerant crop species (Chapter 5).

1.7 AIMS

This thesis encompasses three main aims:

i) To evaluate the physiology of WUE of SDI rates on cotton in comparison to furrow in a heavy clay soil

ii) To examine the circumstances of a developing root zone hypoxia on SDI crops and to evaluate the effect of oxygation on the physiology of WUE and plant performance in a heavy clay soil

iii) To elucidate the influence of salinity/sodicity on soil aeration in a heavy clay soil and examine the effect of oxygation on plant ability to tolerate salinity and uncover the mechanism for increased tolerance due to aeration for different crop species.

1.8 OBJECTIVES

The specific objectives of the study were:

- Compare the conventional furrow with various SDI rates in a heavy clay soil to determine if SDI can improve the WUE of cotton production
- Determine the optimum irrigation levels for the SDI cotton in a heavy clay soil
- Elucidate the physiological response of the cotton crop at different irrigation rates with SDI in a heavy clay soil in comparison to furrow
- Understand the causes and mechanisms for the diminished yield response at higher rates of irrigation in SDI crops in a heavy clay soil, and analyse whether oxygen is limiting at higher irrigation rates
- Develop methods for using aerated water irrigation (oxygation) and evaluate the performance of aeration across a range of soil moisture levels and crops in heavy clay soil

- Evaluate the effect of oxygation for plant tolerance to salinity in heavy clay soil
- Analyse the underlying plant physiological responses and mechanisms in response to oxygation in hypoxic and saline rhizosphere.

1.9 HYPOTHESES

Null hypothesis (Ho)

(Ho) 1: Water use efficiency (WUE) and overall performance of cotton do not vary with different irrigation rates in SDI and in comparison to conventional furrow in a heavy clay soil.

(Ho) 2: Subsurface oxygenation of cotton, vegetable soybean and tomato on the SDI does not influence the WUE and plant performance in a heavy clay soil.

(Ho) 3: Rhizosphere aeration does not affect the ability of SDI tomato, vegetable soybean and cotton to exclude salt and enhance their performance.

Alternative hypothesis (Ha)

(Ha) 1: Water use efficiency (WUE) and overall performance of cotton improves significantly with increasing rate of SDI compared to furrow in a heavy clay soil.

(Ha) 2: Subsurface oxygenation of SDI cotton, vegetable soybean and tomato significantly improves the WUE and plant performance in a heavy clay soil.

(Ha) 3: Rhizosphere aeration significantly improves the ability of root to exclude salts for SDI tomato, vegetable soybean and cotton in a heavy clay soil.

1.10 LIMITATIONS OF THE STUDIES

i. Oxygation in pot environments limits lateral oxygen diffusion from the sides; this is unlikely in the field environment.

ii. Controlled environment of screen house and glasshouse offer little scope for interactions between soil treatments and other environmental and climatic parameters, most particularly rainfall as experienced by the field crops.

1.11 OVERVIEW OF THE THESIS

The thesis consolidates the research findings on three broad fronts: i. cotton performance with SDI in a heavy clay soil, ii. oxygation of SDI crops in heavy clay soil, and iii. benefits of oxygation in saline heavy clay soil environments focusing towards above mentioned aims and objectives. The various studies that address these themes are presented in chapters 2-5.

The following chapter (chapter 2) presents a comprehensive literature review pertinent to the research reported in this thesis. The detailed information related to irrigation systems, the plusses and minuses of SDI irrigation systems, the basis for induced hypoxia of SDI irrigated crops in heavy clay soils especially at higher irrigation rates, and the effect of hypoxia on uptake of water and nutrients are presented. The adverse physiological responses to lack of soil O_2 arising from soil saturation and salinity, and their consequences on plant production are discussed and reviewed in this chapter.

Chapter 3 deals with subsurface drip irrigation in comparison to conventional furrow irrigation and examines the effect of various irrigation rates in SDI and compares these with the conventional furrows more specifically in terms of water use efficiency, plant performance and irrigation associated environmental impact namely runoff and drainage.

By virtue of the very unique delivery of water direct to the root zone of SDI crops, irrigation at higher rates (but still less than 100 % ETc) saturate the root zone of SDI crops in heavy clay soils and, therefore, rhizosphere becomes hypoxic. The benefit of aerated irrigation water was evaluated to overcome the hypoxia caused by SDI at higher irrigation rates in heavy clay soil (chapter 4 of the thesis).

Salinity is one of the major environmental threats with huge impact in agriculture. Salinity in clay soil is often associated with sodicity, which reduces porosity in the soil, thereby reducing soil O_2. SDI allows delivery of aerated water in irrigation and, therefore, enhances availability of oxygen in the root zone in such saline soils. Chapter 5 describes the detail of crop performance across a range of salinity levels, with or without superimposed aeration and reports that oxygation improves crop performance in saline soil leading to greater yield and WUE with aerated treatments at all salinity levels tested.

'Oxygation' is a very novel, new and potential agricultural irrigation technology (the term 'Oxygation' as is proposed for the first time in this thesis). Field application of this technology has tremendous potential to change the face of world irrigation practice and contribute towards making SDI a more environmentally-friendly and water saving method. Finally, the conclusions and recommendations that were made in chapters 2-5 are summarized in chapter 6. This thesis study contribute towards optimization of the SDI system, and make SDI more attractive to growers, with potential for minimizing application loss and gaining maximum benefit out of every drop of irrigation water.

2
Literature review

The literature review is organized and presented on three major thematic area: i. subsurface drip irrigation (SDI) for cotton in heavy clay soils; ii. SDI crops in heavy clay soil experience hypoxia, therefore, and iii. oxygation improves plant performance in saline heavy clay soil. The review on first theme includes current SDI practices, potential and alternative uses, response of SDI crops in different soil types, and irrigation rates effects on yield, quality, water use efficiency (WUE) and water balance. The second theme comprises information regarding occurrence of hypoxia/anoxia in SDI crops, review of previous work on plant response to hypoxia; opportunities for using SDI to deliver air into the crop root zone; existing theoretical and experimental approaches for subsurface aeration; plant physiological response under hypoxia; and potential benefits of oxygation in different soil types, moisture levels and crops. The third theme reviews the threat of salinity and sodicity which also causes waterlogging leading to hypoxia/anoxia because of dispersed clay structure upon salinization. The impact of anoxia and salinity on plant physiology, metabolism and mechanisms of adaptation, and the role of oxygen in the root zone to overcome the salinity stress are examined. The potential for the use of oxygation technology for the improvement of plant performance in saline soils, mediated through increased salt exclusion by an aerated rhizosphere is also discussed.

2.1 SUBSURFACE DRIP IRRIGATION OF COTTON IN HEAVY CLAY SOILS

This section provides information about SDI in general and application of SDI technology in heavy clay soil in particular. Previous studies pertinent to the development of SDI technologies, comparison of SDI with other irrigation methods in terms of IE and cotton performance in relation to irrigation method and irrigation rates are reviewed and presented in this section.

2.1.1 Overview of Irrigation Methods

The term irrigation refers to technology that serves the purpose of distributing water to a crop on a field. In general irrigation methods can be divided into five categories: surface, sprinkler, micro (drip/trickle), subirrigation, and hybrid irrigation systems (Kruse *et al*., 1990). Crucial advances have been made in the development of irrigation technologies since the 1970s. The drive for rigorous research on irrigation arose due to growers demand for irrigation technologies that reduce water and labour inputs. The transition from surface to pipe irrigation, followed by a transition from the use of sprinklers to drip irrigation in intensive cropping has taken place after intensive research in the fields of plant husbandry and engineering aspects of irrigation technologies (Mayer, 2001). A third generation of irrigation technologies (precision irrigation and computer control) is now entering for commercial use.

Surface irrigation includes flood and contour ditch, border dike, graded furrow, corrugation and level basin. In surface irrigation, the irrigation water supply is introduced at one edge of a field, and flows across the soil surface by gravity, infiltrating into soil while the stream advances across, or is ponded within the field. Generally irrigation efficiency (IE) for surface irrigation is poor and loss of water occurs due to runoff, drainage and evaporation. Sprinklers can involve set systems or mobile systems (linear move, travelling big gun, centre pivot, skid tow, solid set sprinkler, side roll and boom types). The mobile sprinkler irrigation systems are those where water is supplied in a pressurized network and emitted from sprinkler heads mounted on emitters fixed on moving supports. IE of sprinkler irrigation is moderate and loss of water occurs due to evaporation. Micro-irrigation (drip/trickle, subsurface, bubbler and spray) water is often distributed in plastic conduits and emitted through drippers, trickles, bubblers, small misters, foggers or sprayers. IE of micro, especially subsurface drippers, is high and loss due to evaporation, drainage and runoff can be controlled effectively in this system. The surface, sprinkler and micro - irrigation are commercially important irrigation methods. Subirrigation is an uncommon technology, which provides water to crops by controlling the water table level. Crop roots can then reach the capillary fringe above the water table and extract their water needs from it (Kruse *et al.*, 1990). Lastly, hybrid methods exist that combine low energy precision application systems with a closed conduit gravity systems. Hybrid irrigation methods are those systems that do not easily fall within the categories of the former methods.

Irrigation for agriculture consumes the major share of the global fresh water supply. With the increasing global concern over the last few decades for water use in irrigation, there is a crucial need to optimize efficiency of irrigated agriculture (Schultz and Wrachien, 2002). In response, substantial research work is being carried out and many earlier studies have been published about water saving irrigation, drainage, and runoff associated with irrigation systems (Framji *et al.*, 1982; Bucks *et al.*, 1982; Higgins *et al.*, 1987; Jensen *et al.*, 1990).

2.1.2 Subsurface Drip Irrigation (SDI)

Irrigated agriculture contributes 40% of the world food supply (Schultz, 2001). Furrow and flood are widely adopted irrigation methods around the world. However, IE – expressed as the ratio of crop water use to applied irrigation water of these conventional methods is poor, at the range of 50-60% (Raine and Foley, 2002b). Increased water cost, public pressure for greater environmental flow, domestic use of water and reduced ground water reserves have resulted in a trend of declining allocation for agriculture, forcing growers to look for alternatives which improves IE compared to the traditional surface irrigation. Given the circumstances of increasing limitation to the access of irrigation water, systems with poor IE will not be able to produce sufficient food for the nine billion-world population expected by the middle of this century (Davis and Hirji, 2003). Hence, modernization of irrigation technologies for increasing IE are imperative.

SDI uses significantly less water than furrow irrigation through minimization of drainage, runoff and lower evaporative losses due to close monitoring of crop water use (Alam and Broner, 2001). Israeli experience showed that it is possible to reduce water demand to about 60% for the production of potatoes, apples and bananas and to about 30% for avocados and cotton using SDI relative to furrow irrigation (Anonymous, 2003). Therefore, SDI offers tremendous scope to increase both area under irrigation and agricultural production, without increasing water use (Xie *et al.*, 1993).

With a judicious rate of water application, SDI also allows a substantial dry soil zone to be maintained in the inter-row spaces, which increases the potential for rainfall infiltration thus reducing the incidence of runoff (Lamn *et al.,* 2000). The volume of effective dry root zone is influenced by soil type, drip tape configuration and timing and rates of irrigation application (Davis *et al.,* 1985). A reduction in run-off can also serve to reduce off-farm environmental impacts of cotton production.

The Australian cotton industry extensively uses furrow irrigation (Raine and Foley, 2002a). SDI has traditionally been restricted to horticultural crops with some limited use on broadacre crops. Intense limitation on irrigation water has already forced industries in various parts of the world to move to SDI for water saving. The use of drip irrigation on row crops is increasing (Camp *et al.*, 1997). SDI offers greater precision of irrigation water application with respect to location and also scheduling the amount and time of irrigation. Such higher precision on irrigation offers growers with potential for increasing the profit due to reduction on water, fertilizer, cultivation costs and increase in yield (Hanson *et al.*, 2002). Drip tapes with different emitter rates are available from different manufacturers.

The row length of drip-irrigated crop varies greatly, however, a length of 200-400 m is the common in Australia (Milroy and Tennakoon, 2002). The use of larger diameter tapes makes lateral length of 400-800 m possible, while maintaining acceptable emission uniformly along the lateral length. Drip tapes are available for different wall thickness, emitter spacing, and discharge rates making option for SDI technology more adaptable to different crops, soil types, environments and scale of irrigation operations (McHugh, 2001a).

SDI is not a long established irrigation practice. There are also scanty recorded experiences of growers with SDI cotton. Many of the early establishments of SDI mal-functioned due to their poor management in terms of root intrusion and inappropriate schedulings. However, there are some SDI establishments, which have accumulated vast experience over time. The Sundance farms (cotton, melons and other horticultural crops) in USA started evaluating SDI as an alternative to furrow, flood and sprinkler in 1976. Over time the expansion from a 0.4 ha test plot to a commercial operation of more than 1000 ha under SDI has taken place. SDI was first adopted in central Queensland, Australia for irrigation of horticultural crops but poor management in general and lack of understanding of soil water movement and storage as well as inadequate soil moisture measurements contributed to failures.

In spite of rapid developments of SDI technology, and many potential benefits, adoption of SDI is still slow due to the high establishment cost (Cuykendall *et al.,* 1999). Experience shows that even with the higher fixed and capital expenditure, drip irrigation can produce a greater net operating profit than furrow irrigation over the longer life span of the installed tapes (Hawkes, 2000). Over the years, a range of accessories and new applications have been developed for SDI (Ayars *et al.*, 1999). A new use for drip irrigation includes the speeding up of the growing season of vegetables in temperate regions by delivering warm water in the root zone (Hanson *et al.,* 2002). Recent work by Bhattarai *et al.* (2004)**,** Goorahoo *et al*. (2002) and Huber (2000) has demonstrated that SDI can be effectively utilized for the delivery of aerated water to overcome the problems of hypoxia associated with SDI crops in heavy clay soils. In the light of decreasing allocation and increasing price for water, adoption of SDI is an appropriate option for sustainable irrigated agriculture. Also potential exists for yield increment with SDI by optimizing water and nutrient use as well as designing SDI suited to the specific crops, soils and environments.

2.1.3 SDI in Heavy Clay Soils

Crop performance with SDI not only depends on manufacturing and design but to a large extent on the management of drip for irrigation. Frequency, timing, amount of irrigation water and fertigation schemes also influence performance significantly (Howell *et al*., 1997). Performance of the SDI system has been traditionally extensively evaluated on light textured soils; therefore, there has been a rapid adoption of SDI on such soils particularly in for horticultural crops (McHugh, 2001b). However, there is a knowledge gap regarding the suitability of SDI for heavy clay soils (McHugh, 2001a). There is a general perception that loss of water is relatively low when irrigating with furrow in heavy soils. However, significant loss of irrigation water in heavy clay soil has been documented (Raine and Foley, 2002a).

According to the Australian soil classification system *vertosols* are the fifth most common soil type in Australia covering 11.5% of the land (0.9 million km^2). Cracking clays are the most extensive in Queensland, covering one third of the state (McKenzie *et al.*, 1999). Heavy clay is one of the important soil types for the agricultural industry in Australia. A large acreage of cotton and other industrial crops are grown in this type of soil (Milroy and Tennakoon, 2002). Improving the WUE of this soil using SDI, therefore, holds major significance.

Daily crop water use by cotton can be reduced to 6 mm with SDI on light textured soils without significant reduction in yield (McHugh, 2001a). The soil moisture characteristics of heavy clay soil, which hold more water due to greater micro porosity and are less susceptible to drainage, increase the potential for greater gains in WUE and decreases intensity of crop water loss with SDI. Researchers in Israel and the USA have indicated that substantial increase in yield and WUE can be achieved through the installation on SDI for a number of crops on heavy clay soils, including cotton (Ayars *et al.,* 1998). However, such benefits have not been consistently realized in many SDI installations in Australia due to mismanagement of the operation of SDI, with failure to operate to the maximum potential of the system (McHugh, 2001a; Raine and Foley, 2002b). In this thesis, the plant and soil-based indicators for the irrigation management of cotton in heavy clay soil were evaluated and are presented in Chapter 3.

Conversion from furrow to drip irrigation, with its frequent application of small amounts of water, has a dramatic impact on cotton yield and quality in Texas, USA (Hanson *et al.*, 2002). Along with SDI, alternate row irrigation system, i.e. one tape for two rows of cotton has been reported to lead to higher yield throughout west Texas (Enciso *et al.*, 2003). It is not only the total amount of water applied to a crop that determines the performance, but also the mode of application, and stages at which it is applied that have large effects. High frequency irrigation of cotton under both drip and sprinkler systems has also received much attention. Higher irrigation rates and frequent irrigation application predispose the SDI crops to anoxia/hypoxia due to greater water content in the root zone, especially in the heavy clay soils (Handson *et al.,* 2003).

2.1.4 Soil Water and Solute Dynamics in SDI

The geometry of the wetted soil volume under trickle irrigation takes a spherical or ellipsoidal shape when water is applied from drippers along a line source, the dimension depending on hydraulic properties of the soil, emitter discharge rate and duration of irrigation (Feddes *et al.,* 1974). The soil volume around the emitter is fully wetted, which is surrounded by reasonably drier soils in the inter row spacing. In addition, water content distribution within the wetter volume is not uniform, decreasing with the radial distance from the water source.

When a line of equally spaced emitters is used to irrigate row crops the normal procedure is to space the emitters in such a way so that a predetermined overlay between adjacent wetted soil volumes is obtained. Thus, the geometry of the wetted soil under a point source is representative of most practical situations in trickle irrigation design. The approaches for the estimation of the wetted soil volume under a given trickle system are to use analytical or numerical solutions of the two- or three- dimensional unsaturated flow as described by Brandt *et al.* (1971); Bresler (1978); Schwartzman and Zur (1986); Zur (1996). Mmolawa and Or (2000) further reviewed various models for the solute dynamics and concluded that the Convection-Dispersion Equation (CDE) that takes into account the three main mechanisms of solute transport often describes solute transport in the wetted soil volume. In convective transport, solutes are carried by mass flow of water. Diffusive transport occurs as solutes diffuse from locations of higher solute concentration to lower concentration. Because the soil has different sizes and shapes of pores, there are differences in solute flux velocities. Thus solutes are transported at different rates to different locations. This leads to mixing of incoming solutes with resident concentrations. This phenomenon is referred to as hydrodynamic dispersion (McLaren and Cameron, 1996).

In SDI, the area across which infiltration takes place is very small compared with the total soil surface, and the infiltration is three- dimensional against one- dimensional in flood or sprinkler irrigation systems. SDI maximizes the time-average soil water potential by increasing irrigation frequency (Battam *et al.,* 2003), although it decreases spatial averaging. As injection frequency increases, the infiltration period becomes more important and the irrigation cycle is changed from an extraction-dominated process to an infiltration-dominated process. The effect of any irrigation method on the soil water regime of a given soil depends primarily on the conditions prevailing at the soil surface boundary layer (i.e. layer of a clear land surface to free air where the concentration immediately above the surface layer is not zero). In the case of drip irrigation, these conditions may be defined by the trickle discharge (Q) measured as the amount of water per unit time (or amount per unit time per unit length of laterals), and by the hydraulic properties and rate of evaporation at the soil surface, which determine the horizontal area across which infiltration takes place (Mmolawa and Or, 2000). The rate of evaporation becomes an important factor only when the potential evaporation is extremely high and the saturated hydraulic conductivity of soil is very low.

Successful water management in SDI requires monitoring of soil and plant water status as well as an understanding of the plant water, climate and other production inputs. The effect of under- or over-irrigation is soon manifested in plant growth and development. Plant and soil-based measurements should, therefore, be a basis of SDI management. Many workers (Hearn, 1998; Hearn, 2000; Tennakoon *et al.*, 2003) have advocated the *"You cannot manage it if you are not measuring it"* mantra for the irrigation management of cotton. Soil water movement both laterally and vertically, and water budgeting with respect to different SDI rates and furrow as well as linking soil water content with root growth pattern and off farm movement of water and nutrients will provide insight for sound management of irrigation water.

2.1.5 Cotton Response to Irrigation

Cotton in general is a water thirsty crop. Although cotton is also grown under rainfed conditions, the crops performance in terms of yield and quality is much higher and stable under irrigation. The cotton crop responds to irrigation, particularly in relation to SDI at various stages of crop growth and associated physiological responses to irrigation are reviewed and described in this section.

2.1.5.1 Germination and plant establishment

Germination and plant establishment are the earliest responses to soil water content. Favourable moisture in the seedbed, optimum seed depth, high soil O_2 and soil temperature above 17.8^oC ensures that cotton seedling emergence occurs 5-15 days after seeding (Grimes and El-zik, 1990). Early establishment of SDI crop is assured either by planting seeds in the moisture filled soil profile or by applying sprinkler or by furrow irrigation after seeding. SDI tape buried at the depth of 40 cm would not normally be able to moisten near the surface where seeds are sown without a profile filled with water. It is customary to use a first application of water by sprinklers or furrow method before the SDI is started for the season (Ayars *et al.,* 1998). In a farm trial, Wuertz (2000) found that small seeded crops such as lettuce and spinach germinated better when sprinklers were used in combination with drip irrigation. Sprinklers help to break thermal and salt induced seed dormancy on saline soils. However, flood irrigation has been implicated as affecting early establishment by inducing seedling death due to rot in the field, particularly in heavy clay soils (Allen *et al.,* 2004).

2.1.5.2 Vegetative growth

The vegetative growth period establishes the framework for roots, vegetative and fruiting branches, and partial leaf canopy in the first 40-45 days (Crozat *et al.,* 1999). A fully developed cotton plant has a prominent, erect main stem consisting of a series of nodes and internodes. The number and length of internodes, which determine plant height, are influenced by a number of factors including nutrients and moisture availability to the active root zone (Grimes and El-zik, 1990). Plant population, temperature, stress, and excessive moisture, coupled with ample soil N early in the plant growth period, influence location of the first fruiting branch**.**

The first fruiting branch usually develops on the fourth to ninth node depending on the variety, soil moisture and other stress. The higher the first fruiting branch, the longer it will take for the plant to complete fruiting and for boll maturity to be reached (Mauney, 1986). Crop duration has direct bearing on the number and amount of irrigation, fertilizer and pesticide inputs all of which have both an environmental and monetary cost. An early crop not only incurs less irrigation and other inputs but also offers a window for integration of winter crops in the cropping system. The reproductive development and yield of cotton is highly dependent on vegetative growth, which is greatly influenced by irrigation treatments. SDI at different rates imparts marked effects on the development, vegetative-reproductive growth relationship, as well as partitioning, and, this needs to be determined for SDI crops in the heavy clay.

2.1.5.3 Root growth, development and root mass

The amount and frequency of irrigation influences root growth, development and mass (Machado *et al.,* 2003). Cotton has a primary root with many laterals. The taproot can grow very fast, up to 2.5 cm per day, initially (McMichael, 1986). Lateral roots appear about the time seedlings start to straighten up and the cotyledons begin to unfold. Soil moisture has a strong influence on the depth of taproot penetration. The roots can grow as deep as 2.5 m, but largely roots are confined in the top 50 - 60 cm of the soil profile and may spread up to 2 m laterally. Root growth starts to cease by the onset of flowering (Grimes and El-zik, 1990; Ashraf and Ahmad, 1995; Ashok *et al.*, 1999).

Irrigation rates and methods affect the rate and pattern of root growth (Thongbai *et al*., 2001). Unlike furrow, SDI develops a limited wet soil volume. As water is delivered to

SDI crops through emitters (point sources), the majority of root growth is expected to be confined in the moist soil around the emitters (Hutmacher *et al.,* 1998). This water and root effects on root distribution will affect nutrient uptake patterns from the soil (Battam *et al.,* 2003). A better understanding is required of these changes in order to optimize crop response to irrigation and fertigation. Plant water and nutrient uptake patterns play an important role and determine the success of drip irrigation system design and management (Coelho and Or, 1996). A study conducted by Hutmacher *et al.* (1998) on SDI cotton revealed that a furrow irrigated plot receiving full irrigation had a root length density (RLD, expressed as cm of root cm^{-3} of soil) value significantly lower than SDI plots within the plant row, but significantly higher values from the furrow area. Under full irrigation, the root systems of SDI plants were more concentrated (higher RLD and root mass) near the emitter (within 35-45 cm) than near the surface or at greater depths or distance from the emitters. Variation of root development and density between crops, soil and season has also been reported by Zade *et al.* (1981).

The root biomass also influence the above-ground performance of the crops. In a study on cotton conducted by Nikolov (1975) a positive correlation between root weight and photosynthetic potential and between yield of above-ground parts and biomass of fruiting organs was found. Therefore, it is important that the root activities, as influenced by SDI irrigation rates on heavy clay, will have a profound effect on water relations and crop performance.

2.1.5.4 Reproductive growth

A proper balance between vegetative and reproductive growth is crucial in determining yield. The weather conditions, nutrition, moisture supply, agronomic practices and crop variety have a large effect on vegetative-reproductive growth balance. Fruit formation in cotton begins with the appearance of the first square (flower bud), normally 5-

8 weeks after planting. Squaring may be delayed due to physiological factors resulting from environmental effects, poor growing conditions, and/or pests (El-Zik *et al.,* 1980). Shedding of some squares, flowers and small bolls is a natural process. However, it is increased by adverse factors such as too much or too little soil moisture, inadequate number of fertilized ovules (Boquet and Moser, 2003), inefficient nutrient supply, excessive heat or cold, extended periods of cloudy weather, and damage from insects and diseases (Guinn, 1982).

Following anthesis and fertilization of ovules, the young boll grows rapidly, reaching full size in about 3 weeks. Another 3-5 weeks are required for complete maturation of the bolls. Boll development is controlled by the relative strength of various competing sinks (El-Zik *et al.,* 1980). Conversion of flowers to bolls that will be retained by the plant is more effective in earlier than in the later part of the season. Crop development rate is influenced by cotton cultivar, soil moisture, and insect and disease infestation (Steger *et al.,* 2000). Moisture stress and extreme temperatures cause premature cut out (i.e. period of reduced growth and square production following a fruiting cycle, usually deemed to start at 4 NAWF (nodes above white flower)), reducing yield and fibre quality (Turner *et al.,* 1986). The degree to which boll growth, maturation and cut-out are affected by varying rates of SDI on heavy clay soil needs further investigation and understanding.

2.1.5.5 Crop physiology

Cotton irrigation rates influence morphogenesis and development, and also affect numerous physiological processes involved in growth, defined as the increase in size and mass of the organ produced by morphogenesis and development. Cell expansion in cotton is more sensitive than stomatal closure to water deficit (Jordan *et al.,* 1975). Consequently processes dependent on cell expansion, such as expansion of leaf area and increase in height, are more sensitive to water deficit than those associated with stomatal closure, such as photosynthesis and transpiration (Yordanov *et al.,* 2000.). Effects of water deficit on physiological processes are three-dimensional. The first order processes affected by deficit are cell expansion, mesophyll resistance, and stomatal resistance, followed by second order processes - leaf growth rate and rate of photosynthesis at leaf level, and so on until yield is affected. The third dimension is related to timing of deficit in life cycle of the plant. As canopy approaches closure, further cell expansion, leaf growth and LAI expansion become less important as determinants of yield that can be affected by water deficit (Hearn, 1994).

Deficit or excess of irrigation or inappropriate irrigation have a marked influence on gross physiological responses of cotton. Cotton evapotranspiration (ET) differs due to variety, climatic and soil factors at any location. ET of a crop at a given time during the growing season is dependent on the effects of climate on a computed reference crop ET (ET_o) and the crop coefficient (K_c), K_c is a value that is assigned to plants indicating the rate at which they lose water. The coefficient allows the irrigators to adjust the watering requirements, and scheduling by simply using "crop coefficient" as a percentage of need, which can be expressed as $ET_{crop} = K_c \times ET_o$ (Allen *et al.,* 1998). As ET (crop) of cotton grown under different SDI rates and furrow will be different, it is imperative to compute Yield-ET functions so that yield maximizing and optimizing ET can be calculated. SDI allows for complete control over the quantity of irrigation; the most effective level of ET crop for maximising or optimising yield can then be delivered through the SDI.

Recent studies have shown that an increase in stomatal conductance accompanied increases in cotton lint yield (Lu *et al.*, 1996). Cotton stomatal conductance is a dynamic phenomenon, and is closely related to soil moisture (Krieg and Sung, 1986). Maintaining high stomatal conductance which supports evaporative cooling of leaves at supra-optimal temperature without severely depleting soil moisture level would be one of the approaches for physiological adaptation giving high yield and best WUE (Ulloa *et al.*, 2000).

Measurement of stomatal conductance can also be a good guiding tool for irrigation management. Gerik *et al.* (1994) found high stomatal response on cotton plants subjected to different levels of irrigation. Stomatal closure occurs at a lower leaf water potential for well-watered plants compared to higher water potential for those plants subjected to water stress (Chaves *et al.,* 2002). While stomatal conductance varied with leaf position, leaf age (closed stomata at old age), leaf N content (at low N stomata close) and abaxial and adaxial position (stomatal resistance on the top of the leaf is high), the most profound effects are observed in response to soil moisture content (Sojka, 1992). Recent studies with Pima showed that increases in stomatal conductance accompanied increases in cotton lint yields (Ulloa *et al*., 2000). Lu *et al*., (1996) suggested that the level of stomatal conductance at high temperature was positively correlated with stomatal sensitivity to temperature and independent of photosynthesis. This increased conductance may reduce leaf temperature and confer tolerance to high temperature, especially during critical fruiting periods. Both the extent to which irrigation rates affect the stomatal conductance, and determining whether SC can be an indicator for irrigation scheduling, shall also be the part of the proposed research.

With increased water stress, cotton net photosynthesis generally declines (Turner *et al*., 1986). The critical cotton leaf water potential for stomatal response to water stress is, however, a dynamic process (Steger *et al.,* 1998) and is different for each leaf position in the canopy; for the upper verses lower surface and under contrasting water stress history (Wanjura *et al*., 1996). The interrelationships between growth, yield and transpiration were studied extensively by Bierhuizen and Slatyer (1965). The authors concluded from assimilation and transpiration characteristics that cotton growth is directly proportional to transpirational water use, but inversely dependent on atmospheric vapour pressure deficit. Tanner and Sinclair (1983) later developed daily biomass production (W) in terms of daily transpiration (T) and mean daytime vapour pressure deficit (D), where W= k Pr [T/D] (k accounts for several factors, including the biochemical pathways for photosynthesis, and production rate (Pr) accounts for a difference in biomass production per unit of hexose, and also depends on the species). Although plant biomass is proportional to the transpirational water use, excess of transpiration is wasteful (Hanks, 1983). An optimum transpiration can be achieved with an appropriate rate of irrigation encouraging optimum vegetative and reproductive growth balance. Hence, evaluating the effect of different SDI rates would enable determination of an optimum level that gives the best compromise between the transpiration, assimilation and partitioning.

2.1.6 Water Relations

Cotton plants exhibit luxuriant growth when soil moisture is not a limiting factor. The crop response to low soil moisture is manifested in terms of reduced growth. The adaptive mechanisms to soil water stress consists of osmotic adjustment that provide positive turgor pressure for some degree of continued growth, even at relatively low values of leaf water potential (Grimes and El-zik, 1990). Possible mechanisms include solute accumulation or osmoregulation, small cell size, and greater cell wall elasticity.

An analysis of leaf water potential and relating it to growth at different stages of the crop will allow an understanding of the relative capacity of the crop and variety to adjust to different levels of irrigation with SDI. Crop water stress studies and advances in infrared thermometry were also combined in the early 1980s to form a simple technique for measuring crop water stress (Pinter and Reginato 1982; Jackson, 1991). The validity of the crop water stress index (CWSI) was shown through studies of its relationship with other plant parameters such as soil-induced leaf water potential and leaf stomatal conductance which both decreased as the CSWI increased (Reginato, 1983). Furthermore, Idso (1982) showed that the relationship between net photosynthesis and CWSI could be considered linear. Fangmeier *et al.* (1993), in a study with cotton in Arizona, observed that the wettest (trickle) treatment with average CWSI value near 0.1 gave the highest yield and had highest soil water content before irrigation (CWSI ranges from 0-1, when 0 is the unstressed plant, and 1 is the completely stressed plant). The yield increased nearly linearly with decreasing CWSI while the WUE was highest for the 1 consumptive use (CU) treatment. CU is defined as total amount of water taken up by vegetation for transpiration or building of plant tissue, plus the unavoidable evaporation of soil moisture, snow, and intercepted precipitation associated with vegetation growth. Wanjura *et al.* (1995) concluded that CWSI of 0.3 at the flowering stage in Acala cotton reduced lint yield by 25% compared to the non-stressed plots. Water deficit during critical growth stages can significantly reduce crop yield (Shouse *et al.,* 1982).

Less is known about early season water management, particularly for short season cotton. Sometimes SDI failed due to inaccurate timings for the first irrigation; either it was too early, which restricted root growth and lateral expansion or too late which induced stress in very critical stage such as squaring (McHugh, 2001a). Accurate timing of the initial post-plant irrigation is critical as it controls early season growth that provides the initial framework for fruiting sites and is influenced by climatic conditions and soil moisture content (Wanjura *et al.,* 1996). The early season water management should encourage both the development of sufficient vegetative structure and a timely transition to reproductive development. A common practice has been to stress cotton LWP as low as -1.8 to -2.03 MPa prior to first irrigation (Hatfield *et al.,* 1984). Steger *et al*. (1998) demonstrated benefits in terms of yield while initiating first irrigation at -1.5 MPa compared to -2.3 MPa in a short season cotton variety. LWP is the property of the crop, variety and their interaction with environmental parameters. In-season dynamics of LWP in response to varying irrigation rates for SDI cotton in heavy clay soil is not well understood. An understanding of the effects of irrigation rates on LWP and employing it for scheduling the first irrigation should help avoid stress in early establishment stage of the crop.

2.1.7 Nutrition and Soil Microbiology

Cotton plants are heavy feeders. Fertilizer management plays a major role in determining cotton yield and quality. The requirements for NPK are generally high (Silvertooth, 2001). Optimum soil physical and chemical properties as well moisture are required to make these elements readily available for plant use (Brady and Weil, 1999). The cotton nutrition management will be very different when the crop is irrigated with SDI as opposed to furrow irrigation (Camp, 1998) which will have a significant effect on the crop performance. A change in the irrigation system and rates brings about a significant change in root spread and dynamics. The exploration of a large volume of soil by roots favour greater nutrient acquisition by the plant. However, SDI crops develop root activities mostly confined around the emitters (Machado *et al.,* 2003) reducing root exploration thereby affecting the acquisition of nutrients and water, but is compensated by frequent fertigation and pulsing of irrigation water.

The role of micronutrients in plant function and metabolism is also critical. Deficit moisture levels in the soil can cause nutritional stress, even if adequate nutrients have been applied to the soil. Stress due to lack of nutrients affects vegetative and reproductive growth and ultimately yield and fibre quality (Bisson *et al*., 1994). Although all nutrients interact with soil and plants differently at different levels of soil moisture, the behaviour of nitrogenous fertilizer is most prominent. The plant content of elements such as P, K, Ca, Mg, B and possibly Zn affect the fruiting index whereas nutrients such as N and Mn that have direct effects on leaf photosynthesis and control stomata profoundly in response to water stress (Joham, 1986). Hence, assessment of plant performance at different irrigation rates, as influenced by the interactions of soil nutrients and soil moisture, will be important.

Converting to drip irrigation requires changes in many production practices (e.g. fertilizer uses). The response and requirements of both macro and micronutrients in SDI system is quite different (fertigation) compared to that of furrow irrigation. Therefore, in-season nutrient monitoring becomes an integral part of SDI (Pier and Doerge, 1995). SDI, if used properly, can also impact salt management dramatically. Although cotton is relatively salt tolerant (Brady and Weil, 1999), a yield reduction of 50% has been reported at electrical conductivity of a saturated soil extract (EC_e) of 7.7-17 dS m^{-1}. Establishment of good stands of grain and cotton in saline soils (EC_e 7.2 - 25 dS m^{-1} in the top 2.5 cm) was possible by root zone salt flushing for SDI water distribution in the soil profile takes place at higher pressure (68.9-82.7 KPa or 10-12 PSI) unlike furrow irrigation (Wuertz, 2000)**,** regardless of porosity difference. Thus flood irrigation aimed for salt leaching can be avoided which also significantly contributes to rising of groundwater. Because of pressurised water and shallower root system of SDI crops, the whole root zone is flushed. This helps remove salt from the effective root zone and therefore minimizes the impact of salts to the crop.

Reduction of soil salinity following the conversion of furrow irrigation plot to SDI was noted (Wuertz, 2000). However, salinity build up at the edges of the wetted fronts between the beds in SDI crops is possible when the irrigation water is saline. Conversely, in an extensive study in California, Burt *et al.* (2003) revealed no consistent pattern of salinity on the periphery of the wetted area on SDI crops. Although there were patterns of salinity with respect to depth, the salinity was fairly evenly dispersed across the row crop bed. While the salt and water dynamics through the soil profile are likely to vary significantly in response to rate of SDI, the phenomenon is not well documented.

2.1.8 Yield and Quality

Yield of cotton with SDI varies depending on soil types. Raine *et al.* (2000) reported an additional yield of up to 2.7 bales/ha in SDI compared to surface irrigation, and where water was short, SDI yield was similar to surface irrigation but with 38% water saving. Yield increased with SDI in sandy soil by 16% (DeTar *et al.,* 1993). Fangmeier *et al.* (1993) and Ayars *et al.* (1999) reviewed SDI work on cotton and reported a significant yield improvement and reduction in water use compared to furrow irrigation. Wuertz (2000) reported an increase in cotton yield from 1350 to 1890 kg per acre in SDI compared to furrow, with just half of the water use in a medium textured soil on Sundance Farm, USA. An appropriately managed SDI constantly showed significant water saving and comparable or increased yields of cotton (Camp *et al.*, 1997).

The performance of SDI for cotton in vertosols is, however, not well researched. Most experiments have been carried out in light textured soils. From a four-year continuous experiment on Acala cotton, DeTar *et al.* (1993) reported a better performance of SDI with poor sandy soil compared to good uniform light textured soil. There are no specific studies reported on SDI in black heavy clay soils.

Both deficit and excess moisture can affect the growth, development and yield of cotton, but also affect greatly the fibre quality. The quality of lint is extremely important in order to compete in the global cotton market. New technologies place increasingly severe technical demands on textile fibres, raising the importance of other properties of cotton: strength, uniformity, maturity, fineness, elongation, neps (i.e. a small knot of entangled and unorganized fibres causes formation of short, thick places in yarns and therefore less uniform fabric appearance, their presence in yarns or fabrics greatly detracts from the quality and value of the finished cotton product), short fibre content, spinning performance and dyeing ability as well as shipment uniformity and consistency and free from contamination. Foreign matter, stickiness and seed coat fragments are also among the serious problems affecting the cotton quality for the industry worldwide. Modern high-speed machinery requires more exacting fibre characteristics to operate at maximum efficiency. Discounted price is offered if the export does not meet criteria (Estur, 2003).

Physiologically, fibre quality of a specific cotton is a composite of fibre shape and maturity properties that depend on complex interactions among the genetics and physiology of the plants producing the fibres and the growth environment prevailing during the cotton production season (Bradow and Davidonis, 2000). Fibre shape properties, particularly length and diameter, are largely dependent on genetics. Fibre maturity properties, which are dependent on deposition of photosynthate in the fibre cell wall, are more sensitive to the changes in the growth environment. The effect of growth environment on the genetic potential of a genotype modulate both shape and maturity properties to a varying degree. Fibre length is generally not affected unless the water deficit is great enough (LWP –2.5 to –2.8 MPa) at the flowering period (Hearn, 1976). Severe water deficits during the fibre elongation stage reduce fibre length (Hearn, 1994) by affecting the mechanical and physiological process of cell elongation. Drip irrigation and placement of the drip irrigation tubing under or between the plant rows also affected fibre length (Bradow and Bauer, 1997). Fibre length distributions, both according to fruiting site and within the locules, were also modified by irrigation method. Earlier research indicated that fibre strength is related to genotype and negatively correlated with the yield (Green and Culp, 1990). Fibre strength is also responsive to the growth environment than fibre length (Smith and Coyle, 1997) and fineness (Bradow and Davidonis, 2000). Fibre maturity is very responsive to environmental variation including water stress, through effects on photosynthetic C fixation and cellulose synthesis, which modulate cotton fibre wall thickness and consequently fibre physiological maturation (Murray and Brown, 1997).

It is not only the amount of water, but also the stage at which water is applied that determines the performance of the crop and lint quality to a large extent. With SDI, there is greater flexibility to allocate irrigation water in terms of time, space and quantity. The advantage with such high flexibility can be better utilized in such a way that even the small amount of water can be given to a crop in the most critical stages to achieve maximum benefit with the limited water supply. The information on the effect of SDI rates on lint quality is meagre, and it will be critically examined in the thesis research.

2.1.9 Irrigation Efficiency, Water Use Efficiency and Water Balance

SDI plays an important role in water conservation (Chandler, 2001). By irrigating plants via emitters buried under the soil surface, surface soil wetting is lessened, and as a result, less water is lost to soil surface evaporation. Previous experiments showed a transpiration rate more or less equal but a significant decrease in evaporation with increasing emitter depths in sandy loam soil (Heuberger *et al.,* 2001). Overall, conservation of up to 10% irrigation water can be accomplished by subsurface drip irrigation with emitters placed at a depth of 30 cm compared to the tape place on the surface (Anonymous, 2002a). Higher WUE in SDI is achieved not only by reducing the evaporation losses but also by reducing run off and deep drainage. Additionally, transpiration can also be essentially managed through manipulation of the canopy at a rate regulated by appropriate irrigation rates. The dry soil surface offers scope for storing rain, which can be effectively used later by the crop. SDI is capable of distributing small amounts of irrigation uniformly over the entire field, which is not possible with furrow irrigation. This feature tremendously increases irrigation efficiency. SDI has significantly high IE (Burt *et al.,* 2001). Schneider and Howell (1999) reported the IE with SDI as close to 100%, against furrow with only 60-70%. The higher efficiency is possible by curtailing runoff and deep drainage in SDI, unlike in furrow irrigation.

Higher WUE and greater yields can be achieved with SDI compared to furrow application if the right amount and timing are achieved for the appropriate location, soil type and crop. WUE is defined as yield per unit area (Y, often t ha^{-1}) per unit of water use per unit area (ET, often ML ha^{-1}). WUE is the outcome of an entire suite of plant and environmental processes operating over the crop period that determines both Y and ET (Hood, 2002). Consequently biomass production per unit ET has been used extensively to determine the crop WUE. However, the term 'water use efficiency' is ambiguous. It may imply water conservation (increasing productivity per unit of water applied) or transpiration efficiency (increasing productivity per unit of water transpired). An understanding of both aspects is important in order to improve the WUE in cotton production. The direct observation from infrared gas analyser (IRGA) for transpiration (E) and assimilation (A) provides information for assessment of instantaneous WUE (A/E), which can be computed from the measurements of photosynthesis and transpiration. However, to primary industry the crop water use efficiency (yield/applied water) is a more meaningful term because it provides information for overall irrigation management of the paddock.

There is a strong link between crop growth and transpiration because of the commonality in processes and pathways shared between transpiration and CO_2 assimilation. Similarly there is a strong link between crop growth and ET because dry matter accumulation and maximum ET are so tightly coupled with solar radiation. By definition, crop yield in water-limited environments can be improved by increasing the ratio of dry matter or yield per plant, (Y) to water loss or transpiration per plant, (T). Transpiration efficiency may be estimated on a leaf (TE_L), whole plant (TE_P), or canopy basis (TE_C). On a gas exchange basis transpiration efficiency may be expressed as: A/E where A is the assimilation of CO_2 by the leaf and E is leaf conductance of water vapour (transpiration). On a whole plant or canopy basis, transpiration efficiency may be estimated gravimetrically and expressed as grams of accumulated dry matter per litre water transpired. Higher irrigation rates generally encourage excessive vegetative growth that produce wasteful transpiration. An irrigation rate is desired that supports an optimum balance between vegetative and reproductive growth, and which gives the highest CO_2 assimilation per unit of H_20 transpired will be the most productive one. Earlier studies conducted on cotton in light textured soil with SDI consistently showed greater IE compared to furrow (Ayars *et al.*, 2001). The thesis research with different irrigation rates determine an appropriate irrigation level for cotton in a heavy clay soil.

An indirect method for measurement of transpiration efficiency is available, which employs the carbon isotope discrimination (Δ ‰, the difference in C isotope composition between the plant and the CO_2 in air in which it is grown). A positive, linear relationship between Δ ‰ and Ci/Ca (where Ci is CO_2 concentration in the sub stomatal cavity of mesophyll cells of leaf and Ca is CO_2 concentration in the atmosphere) and a negative, linear relationship between Δ ‰ and transpiration efficiency/WUE has been verified for several C_3 crops, including cotton (Farquhar *et al.*, 1989). For example, Jensen *et al.*, (2002) employed Δ ‰ techniques in orchardgrass and ryegrass at four irrigation levels and found that discrimination decreased as water stress increased. There is potential to use this technique to determine the WUE in relation to different irrigation rates on SDI and furrow irrigated cotton. WUE is generally increased with SDI compared to furrow, but the gain is subject to crop, climate, location and soil specific parameters (Camp, 1998). Determining the relationship between TE and Δ ‰ of the cotton leaf allows the use of Δ ‰ to estimate WUE of cotton with respect to change in irrigation rates.

2.1.10 Radiation Use Efficiency

Radiation use efficiency (RUE) of a crop is a function of several interacting physiological phenomena (Reynolds *et al.,* 2000). Biomass production can be modelled as a linear function of intercepted photosynthetically active radiation (PAR), defined as solar radiation in the range of light wavelength between 400- 700 nm, and the efficiency with which it is utilized (Monteith, 1977). The slope of this relationship is the RUE that is particularly constant for cotton when growth is not limited by water, nutrient shortage or adverse climatic conditions that may decrease the efficiency of metabolic and other processes that determine RUE. Using biomass to study RUE implies a long-term experiment since, on a short-term time–scale, biomass increases are difficult to measure. On a short-term time scale, RUE can be studied by using gas exchange, although the results are difficult to compare with long-term changes in biomass since crop respiration needs to be assessed and accounted for (Rosati and Dejong, 2003).

Determination of the resource use efficiency in relation to different irrigation rates of SDI helps relate the interrelationship between irrigation rates and other production resources such as light and nutrients for the production of biomass and lint. This relationship will provide the basis for determining the optimum level of irrigation with respect of these inputs depending on price for water, nutrients and lint.

2.2 SDI CROPS EXPERIENCE HYPOXIA: THE NEED FOR OXYGATION

The root zone in SDI crop is saturated during and for sometime after irrigation (Silberbush *et al.,* 1979; Bar-Yosef *et al.,* 1989; Hutmacher *et al.,* 1998). This potentially creates a zone of anoxia close to the emitters, and hypoxia further apart, with normoxia prevailing between the rows depending on the rate and duration of irrigation, crop, soil type and environment. Continuous saturation of the root zone limits effective root functioning due to reduced O_2 diffusion to the rhizosphere. It is hypothesized that reduced O_2 concentration in the rhizosphere (particularly in the wetting front) is a major limitation for the performance of SDI crops at higher irrigation rates.

Details on the pathways of O_2 entry to the soil, and the relative importance of these pathways to plant growth are covered extensively in the reviews by Grable (1966) and Armstrong (1979), which discusses principles of aeration and aeration modelling, techniques for measurement, and of aeration under saturated and unsaturated conditions. Drew (1997) reviewed root metabolism focusing on injury and acclimation under hypoxia and anoxia. However, for crop adaptation to hypoxic environment, the opportunities regarding oxygation as an agronomic approach for overcoming the effect of poor aeration on heavy clay soils are not addressed adequately so far. The thesis illustrates evidence on occurrence of hypoxia in SDI crops and suggests methods to ameliorate hypoxia by oxygation.

Oxygation is defined as aerated water irrigation directly into the crop root zone using SDI (Bhattarai *et al*., 2005c). In many occasions oxygenation and aeration will be used interchangeably in the text of this thesis. Soil aeration status can also be improved using physical/mechanical options (ripping, tillage and soil amendment focusing on soil structure), biological options (tolerant species, high radial O_2 transfer companion crop), chemical options (lime, gypsum, polyligonosulfonates) to improve structure, management options (root drying, high frequency pulsing, etc), engineering options (piercing cavities, compressor and perforated hose, subsurface drainage). These options are not viable in their efficacy and, in general, costly. Oxygation technology aims to solve this century-old dilemma and may offer a breakthrough in irrigation technology.

2.2.1 SDI develops wetting fronts: Cause of Hypoxia

In irrigated agriculture, crops can be exposed to saturated soil conditions at different stages of the crop cycle depending on the soil types, intensity and frequency of irrigation. The irrigation front travelling down the soil profile during flood irrigation can push air through the profile, to the benefit of root respiration. However, overall, furrow-irrigated crops frequently suffer temporal hypoxia after irrigation, mostly in heavy clay soils (Camp, 1998; Mukhtar *et al.*, 1996).

Unlike furrow, SDI is delivered through emitters at a point source in the root zone and moves in all dimensions. SDI delivers water to plants at specific depths (20-40 cm below the ground from emitters), and tends to saturate the soils close to emitters, while inter-row spaces remain dry and such wetting fronts are prominent on heavy compared to light soils (Figure 2.2.1 and Figure 2.2.2). The wetting front will displace air especially near the emitters. Meek *et al.* (1983) observed that a daily trickle irrigated tomato crop at 100-120% ETc in a clay soil decreased O_2 concentration (measured with double-membrane polarographic sensors at 20- and 40-cm depths in the plant row, midway between plant) in the soil air to 0.03-0.06 L L^{-1} at 20 cm. With weekly trickle irrigation, soil O_2 oscillated between 0.06-0.15 L L^{-1}. However, in the same soil with furrow irrigation at 4-5 days intervals, soil O_2 oscillated between 0.06-0.16 L L^{-1}. The study also documented low O_2 (0.03 L L^{-1}) in soil below 20 cm depth over many weeks in the daily trickle irrigated crops.

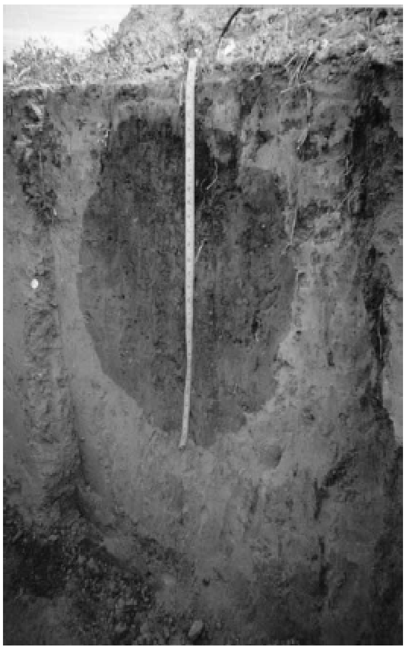

Figure 2.2.1 Position of the wetting front after 10 h irrigation applied at 1.7 l h^{-1} from simulated emitter installed at a depth of 0.30 m in a loamy soil (Source: Battam *et al*., 2003).

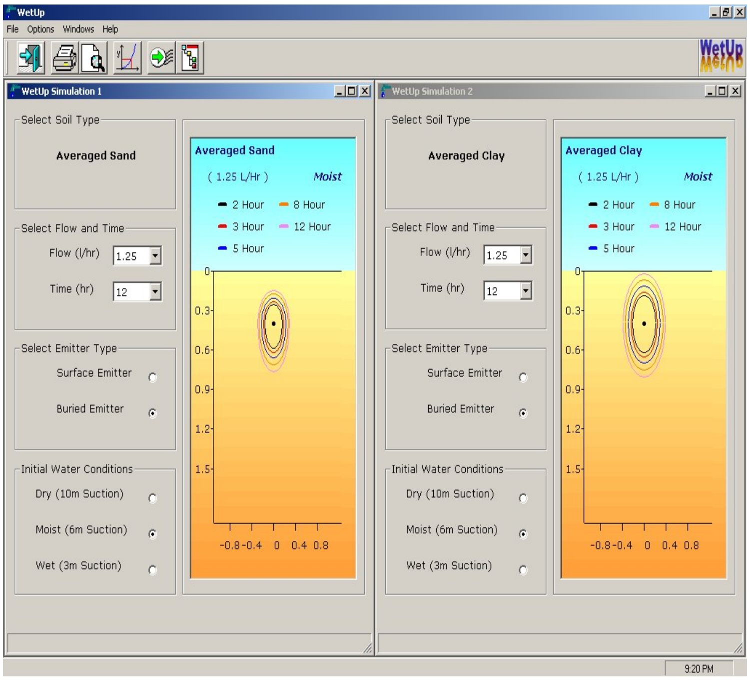

Figure 2.2.2 Position of the simulated wetting front after 12 h irrigation applied at 1.25 l h^{-1} from emitter installed at a depth of 0.40 m in sandy (left) and clay (right) soil (Source: Thorburn *et al.,* 2001).

A positive linear relationship commonly exists between ET and biomass. Crop yield is expected to increase with increasing irrigation rates up to 100% of ETc. A lack of response in yield to the irrigation rate at ≥ 90% of daily ETc in SDI crops suggest that limitations exist for uptake of water and nutrients by the plants particularly at higher irrigation rates (Bhattarai *et al*., 2004). Study suggested that yields increase on SDI crops were not significant when irrigation water applied at non-limiting evapotranspiration rates (Raine and Foley, 1999). If yield with SDI can be improved to cover part of the investment in SDI, then it will be a financially viable option for growers. Soil compaction, salinity, sodicity, and other biotic and abiotic stresses that impede the effective uptake of water and nutrients under low soil O_2 are non-amicable for crop performance (Rengasamy, 2002). Hence it was hypothesized that in heavy clay soil, rhizosphere becomes saturated at the higher irrigation rates and supply of O_2 becomes limiting, slows root functioning and reduces the benefit to increased irrigation on SDI crops. Oxygation of the rhizosphere can overcome the hypoxia of SDI crops.

2.2.2 How Low is Low O_2 in the Soil for Root Activities

O_2 must diffuse from the atmosphere via gas-filled pores in the soil and through soil water films, and through the respiring root tissues themselves. The O_2 concentration at different parts throughout the interconnecting network of gas filled pores is generally fairly uniform provided there is uniform temperature; root and microbial activities exist in the soil profile (McLaren and Cameron, 1996). However, the concentration gradients of O_2 across water films and root tissues are large in saturated soil. For this reason, the water content of soils and the thicknesses of water barriers to O_2 movement around the roots greatly influence O_2 availability (Armstrong, 1979).

Active roots typically respire at a rate of approximately 200 μmol O_2 /gDW/h at 25°C (e.g. Grable, 1966; Walsh, 1995). To this demand must be added the demand of aerobic soil organisms present in the soil, although under a typical crop, the respiration rate of plant roots is many times than that of soil microbial respiration (by as much as 3 orders of magnitude in some cases) (Armstrong, 1979). The top one metre of a soil profile has around 20-25 hours supply of O_2 (see box below) contained in the soil pore space at the air filled porosity of 5%, typical for most heavy clay soil at field capacity.

Oxygen demand by the root = 200 μmol O_2 g^{-1} DW h^{-1}

Given 1 tonne of root DW ha^{-1} = 1000 kg ha^{-1} = 0.1 kg m^{-2} = 100 g m^{-2}, requiring 20,000 μmol O_2 m^{-2} h^{-1}
Given air filled porosity of 5%, then
$1m^3$ = 1000L there will be 50 L × 20.8% O_2 = 10.4 L O_2 m^{-2} (in 1 m depth)
Which is equivalent to 10.4÷24.5 = 0.424 mole O_2
Given a respiration rate of =20,000 μmol O_2 m^{-2} h^{-1} and a soil O_2 content of 424,000 μmol O_2 m^{-2} then
There is a O2 store in the soil equivalent to 424 ÷ 20= 21.2 hours

The proportion of actively absorbing roots (fine roots) in any crop is in the range of 10-15% of the total root biomass (McCully, 1999). Considering the total root dry biomass of 1 ton DW ha^{-1}, estimated actively absorbing root would be 100 kg DW ha^{-1}. A calculation based on the root O_2 consumption at the rate of 200 μmol O_2 g^{-1} DW h^{-1} indicates a total O_2 demand of 11760 L ha^{-1} d^{-1}.

Actively growing oxygated SDI crops supplying 10 mm water d^{-1} (average irrigation rate for crop in dry tropics/subtropics) would receive 100 KL ha^{-1} d^{-1} of aerated irrigation containing 2520 L of O_2 in the form of micro bubbles (12% air by volume of water mixed with mazzei air injector). This source is thus equivalent to 20% of the total O_2 requirements of the crop. Dissolved oxygen (DO) in the irrigation water at 240 μm, contributes to additional 588 L O_2 ha^{-1} d^{-1}, equivalent to 5% of crop requirements. Diffusion of O_2 through the soil to the root will recommence as the wetting front passes/dissipates. Meek *et al.* (1983) suggested that O_2 concentrations as low as 5% at 20 cm and 3-7% at 40 cm did not significantly reduce tomato yield. Glinski and Stepniewski (1985) reported that a root respiration rates as high as 50% of maximal could be achieved at 2% O_2 if soil porosity is high, in crops such as mustard, maize, cotton and dwarf peas.

2.2.3 Measurement of the Soil O_2

Quantification of the O_2 status of soils is fraught with difficulty. Traditionally a number of measurements have been made. Measures of air volume, i.e. percent air-filled porosity (Wessling and Wijk, 1957; Jayawardane and Meyer, 1985; Glinski and Stepniewski, 1985), are perhaps the most simple. Other indices include: (i) concentration of component gases i.e. their partial pressure in the open pores and in the water phase (Grable, 1966; Armstrong and Gaynard, 1976; Blackwell and Wells, 1983; Meyer and Barrs, 1991), (ii) diffusion rates (in the gas phase, and through the gas-liquid-root phase, the O_2 diffusion rate (ODR), (as measured with subsoil O_2 probes, e.g. Lemon and Erickson, 1952; Letey and Stolzy, 1967; McIntyre, 1970; Armstrong, 1979; Blackwell, 1983), and, (iii) estimate of diffusivity coefficients. These indices have varying degrees of relatedness. For example, Mukhtar *et al.,* (1996) showed a close relationship between O_2 concentration in the gaseous phase, the ODR and redox potential in an inundated and drained soil. Silberbush *et al.*, (1979) showed a linear correlation between the ODR and volumetric soil air content. Diffusion may also be indirectly estimated as respiration-related consumption of O_2 or output of carbon dioxide.

The simple measure of air-filled porosity (εa), can be calculated from the soil bulk density and water content values as:

$$\varepsilon_a = \varepsilon - \theta_v \,,$$

where, ε = total porosity at FC, and θv = volumetric moisture content (McLaren and Cameron, 1996). Measurements of air-filled pore space in soil (a capacity factor) is relatively simple but give no insight into what proportion of gas is occupied by O_2.

Conceptually, a measurement of the ODR (proportional to the O_2 concentration gradient between that in the soil and the external air, and the diffusion coefficient of O_2 in the soil) through the liquid phase is most relevant to equate with soil aeration as experienced by the plant root system. Values of < 0.2 μg cm^{-2} min^{-1} are often quoted as the minimum ODR for effective root and leaf function (e.g. Sojka and Stolzy, (1980); Phene, (1986)). Nevertheless, parameters that relates to the concentration of O_2 in the soil, and to the volume of soil air is still employed in the literature.

The development of the platinum electrode technique has enabled measurement of O_2 diffusion rate (ODR) in the soil. There is high correlation between ODR and plant performance (Bryce *et al.,* 1982). Earlier observations revealed that roots could not grow into soil where the ODR is 0.2 μg cm^{-2} min^{-1}. An ODR of between 0.2 and 0.3 μg cm^{-2} min^{-1} was associated with moderate growth, and an ODR rate above 0.50 or 0.60 μg cm^{-2} min^{-1} gave healthy looking growth (Drew and Stolzy, 1996). Sojka (1992) showed that as ODR declined to below 0.2 μg cm^{-2} min^{-1}, leaf diffusive resistance increased dramatically, eventually leading to complete stomatal closure and cessation of photosynthesis.

Earlier Letey (1961) reported similar results for turf grass where low ODR (< 0.2 µg gm cm^{-2} min^{-1}) was accompanied by poor looking grass, and ODR > 0.5 µg cm^{-2} min^{-1} was associated with good green appearance. Mukhtar *et al.* (1996) reported that an O_2 concentration in soil pores > 80 % of atmospheric composition was needed for ODR and redox potential (Eh) value to be above the critical values of 0.2 µg cm^{-2} min^{-1} and 600 mV, respectively depending on soil type and moisture. They also observed that within hours of inundation in loamy soil, O_2 concentration and ODR values were reduced to below critical levels (0.2 µg cm^{-2} min^{-1}) at all the sampling depths (15 to 60 cm). Following drainage, O_2 concentration and Eh increased to acceptable values, but a corresponding increase in ODR was not observed, suggesting discontinuity in many air-filled pores, or their blockage by water films, that constrain the availability of O_2 for root respiration.

Measuring the ability of soil to transmit gases in response to a pressure difference, i.e. air permeability, based on the Darcy law (VanAmerongen, 1946) has been used as an indicator of soil aeration, but gas exchange in most soils largely depends on diffusion (Reicosky, 2002), and not mass flow. Thus this measure is of limited use for soil aeration and more applicable to soil structure studies.

Determination of soil air composition is common in soil aeration studies. Soil air consists of numerous gases, however, O_2 and CO_2 is frequently reported. Following early methods for volumetric O_2 determination (based on absorption in sodium anthraquinone-B-sulfonate), paramagnetic O_2 analysis (using the principle that the O_2 is the only gas attracted by a magnetic field) has been used in both field and laboratory studies, but because of its requirement for a large air sample (>50 cm^3), it is not practical. Many early studies depended on methods developed by Smith and Dowell (1973), who proposed sampling by withdrawal of soil air or soil water through buried porous hollow cylinders i.e. piezometers and subsequent analysis by gas chromatography. Dissolved O_2 in the water was detected in

10 mm^3 samples using a column with Propak ® T and molecular sieve 5A (for H_2O absorption), with the use of an electron capture detector as described by (Hall, 1978).

A determination of O_2 in soil air by mass spectrometry has been described by Robertson and Bracewell (1979), but the application of method in field studies is limited due to time-consuming procedures.

Willey and Tanner (1963), employed buried polarographic membrane O_2 sensors in a silty clay loam in the field and claimed a robust approach for *in situ* determination of soil O_2. However, its use is limited due to its requirement for frequent calibration.

With some measuring techniques such as those with fibre optic O_2 sensors, no air sampling is required and the probe is directly placed in the soil. These optical sensors measure O_2 partial pressure (pO_2) in the gaseous and liquid phases, which makes them suitable for measurements in the soil. The fibre optic O_2 sensor is coated with a flourophor captured in a sol-gel. As O_2 binds to this material its fluorescence level is quenched (Klimant *et al.,* 1995). The sensor tip is illuminated with a pulsed blue LED and the fluorescence is measured by a spectrometer.

Measuring pO_2 in the soil is, however, a challenging task because of the great heterogeneity of the soil. The smaller the sensor and the higher the required spatial resolution, the higher the influence of such heterogeneity. The fibre optic optode sensor consists of a needle type of about 2 mm diameter, easy for field measurements but the results will be very influenced by soil heterogeneities.

Quantification of the oxygen diffusion rate (ODR) is based on the principle described by Lemon and Erickson (1952). It consists of amperometric measurement of electric current intensity that corresponds to the O_2 reduction on a platinum cathode placed in the soil. Measuring the ability of the soil to supply O_2 (a rate factor) provides the best characterization of soil aeration because it can be directly related to biotic response (for root respiration is continuous process, and an uninterrupted exchange of O_2 between atmosphere, soil, and plant is crucial), regardless of other soil mineral and physical properties (Sojka and Scott, 2000). Waterproof platinum and zircon ODR sensors are stable when left buried in soil for continuous measurements (Ishii and Kadoya, 1991). As the O_2 concentration experienced by the root is determined by the balance between the rate of supply by the soil and the rate of O_2 consumption in respiration, a buried platinum electrode provides a measure of the ability of the soil to supply O_2 that resembles root activity, and it remains in principle a measurement to plant O_2 requirements (Drew, 1992).

Soil aeration can also be quantified through steady or non-steady state measurements of the diffusion coefficient of a gas. In the first, the concentration of diffusing gas is measured in a chamber connected via the soil sample to the atmosphere, and in the second the chamber is omitted and measurement is performed directly on the soil sample or column. Measurements of gas diffusion coefficient with gas chambers are limited to small samples (Rolston, 1986), and are of limited relevance to root accessibility of O_2 due to slow diffusivity of O_2 to root surface and root interior, not representing field conditions.

Measuring soil respiration using soil respiration chamber (Parkinson, 1981), where a chamber of known volume is placed on the soil and the rate of increase in CO2 within the chamber is monitored. With this IRGA system, the air is continuously sampled in a closed circuit through the EGM or CIRAS, and soil respiration rate is calculated by the analyser. The air within the chamber is carefully mixed to ensure representative sampling without generating pressure differences which affect the evolution of CO_2 from the soil surface.

Redox (Eh) measurements are useful indicators of soil aeration particularly in relation to the physical chemistry and microbiology of reducing soil (Linebarger *et al.,* 1975). However, it remains to be demonstrated whether the Eh *per se* is of any direct significance to plants once molecular O_2 has disappeared (Drew, 1992). The measurement of Eh become useful under waterlogged soils that result in O_2 depletion and the other measures of soil aeration such as ODR and O_2 content becomes insensitive (when the rhizosphere becomes anoxic and the ODR and O_2 concentration become zero).

Soil O_2 budgets need to take into account O_2 inputs (e.g. from irrigation water, from aerated irrigation water, diffusion from the atmosphere to the rhizosphere and the radial O_2 diffusion through plants to soil) and the consumption-comprising root and microbial respiration and possible requirements for chemical processes (if any). The determination of O_2 enrichment in aerated water is largely dependent on bubble size distribution, which in soil solution depends on phenomena such as breakage, coalescence, growth, nucleation and shrinkage of bubbles, the relative velocities between the dispersed and continuous phase and transportation of bubbles in and out of the balance region with convection (Laakonen *et al.*, 2002).

The measurement of O_2 in bubble aerated soil water is complicated by the variable size of bubbles, and the mixtures of gases in the air. When air is dispersed in water in the form of bubbles, the interfacial area of air-liquid contact increases as the number of bubbles into which it is dispersed increases and the average size of the bubbles decreases. This can be represented as described by Winkler (1981) and Laakonen *et al.* (2002).

$$AB = \frac{6VG}{dB}$$

Where AB = Total interfacial area between the dispersed gas and the liquid (m^2m^{-3}), VG = Volume of the gas dispersed (m^3 per m^3 solution), dB = Bubbles diameter (mm).

Estimation of the soil aeration has been largely guesswork in the past due to lack of appropriate instrumentation. However, the latest advances in equipment offer an opportunity to carry out soil aeration experiments in a much better set up than used to happen in the past.

2.2.4 Soil Aeration: Effect of Soil Moisture

For optimal growth, the water potential of the soil should be kept close to zero (i.e. saturation), but if a low water potential is maintained in a clay soil, plants will suffer from suboptimal levels of O_2 supply in the root zone (Silberbush *et al.,* 1979). If an O_2 deficit occurs, permanent damage is likely to be sustained by the root (McCully, 1999). Therefore, it is crucial that the root requirements for both water and O_2 are well coordinated, with maintenance at a low soil water tension and adequate with gas exchange between the root and atmosphere.

Water is an effective barrier to the diffusion of O_2, as the rate of diffusion of O_2 through water is 10,000 times slower than through a gaseous phase (Grable, 1966). Adequate diffusion of O_2 to the rhizosphere is required for aerobic respiration in plant roots (Huang *et al.,* 1994).

Plant roots commonly experience temporary periods of O_2 deprivation when soils are irrigated to saturation (figure 2.2.3 and 2.2.4), i.e. irrigation more than field capacity. Thus, hypoxia is a common form of stress caused by poor drainage or periodic flooding (Drew and Lynch, 1980). Hypoxia also occurs on SDI crops in heavy clay soil, when soil aeration is transiently impeded by excess water around the root zone, which fills the soil pore spaces that are normally available for diffusion and convection (Zur, 1996)**.** Roots soon consume O_2 in entrapped soil air and dissolved in the soil water (dissolved oxygen (DO) in the water at STP is about 240 μmol or 4.56 ppm)) and any entrapped air.

Numerous earlier studies have consistently pointed out that low aeration in soils constrain plant growth seriously (Durell, 1941; Melsted *et al*., 1949; Wiersma and Mortland, 1953; Herr and Jarrel, 1980; Argo *et al.,* 1996)**.** Previous reviews of soil aeration (Letey, 1961; Grable, 1966; Armstrong, 1979; Everard, 1985; Barrett-Lennard, 2003) highlighted the occurrence of hypoxia on irrigated crops, effects of low O_2 on plant metabolism and O_2 dynamics in soil under different soil environments as influenced by soil water content. A number of studies have also reported that crops under SDI suffer root hypoxia especially in medium to fine textured soils (Huber, 2000; Heuberger *et al.,* 2001; Goorahoo, *et al* 2002; Bhattarai *et al.,* 2004). The thesis reviews occurrence of hypoxia, effect on the plants and amelioration of hypoxia by oxygation for a range of crops.

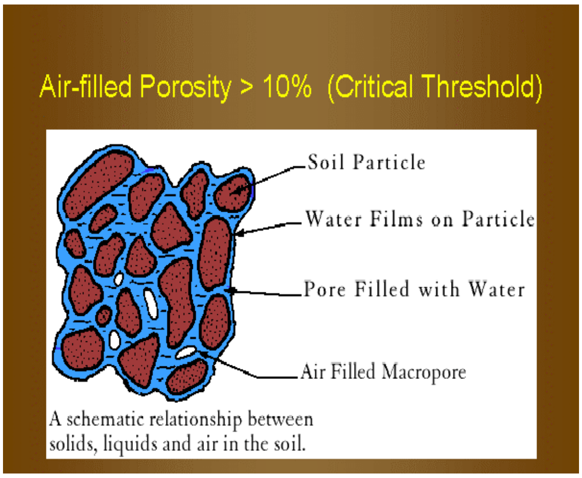

Figure 2.2.3 The relationship between solids, liquids and air in the soil is dynamic (Source: McBride, 2002).

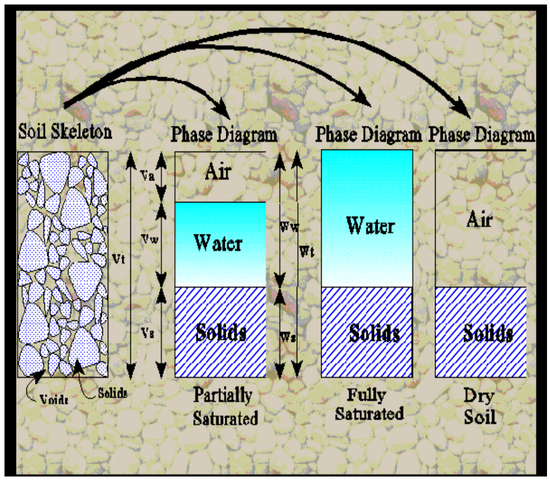

Figure 2.2.4 Soil water content largely determines aeration status and saturation fills pore spaces by water in soil (Source: McBride, 2002).

2.2.5 Hypoxia is Related to Soil Type

Soil is basically a three-phase system consisting of solid, liquid and gas. Although the solid part is fairly stable, the gas and liquid phases are dynamic. A satisfactory balance between these three phases is crucial for successful crop production (Mukhtar *et al.*, 1996). Composition of the soil air is different from the atmosphere in terms of the relative proportion of different gases. O_2, CO_2 and N_2 comprise 20.8, 0.035 and 79% respectively in the atmosphere, whereas in the soil O_2 reduces to less than 20%, CO_2 is 0.3 – 3 %, with N_2 remaining stable (Brady and Weil, 1999).

The amount of air filled porosity in the moist soil (at FC) is directly influenced by soil texture. In sandy soils it is of the order of 25% v/v or more, in loamy soils 15 - 20% and in clayey soils that tend to retain the most water, it can fall below 10% of the total soil volume (Mukhtar *et al.*, 1996). Aggregate size, level of compaction, tillage and amount of water in the soil directly influences the air capacity of any soils (Anonymous 1999). Smaller soil particles (such as silt and clay) reduce soil aeration because they pack together too tightly to allow air spaces between them. Larger soil particles (sand) and organic matter increase soil aeration because they leave gaps in the soil volume that can be filled by air (Cogger *et al.,* 1992). However, if soil pores are too large, the soils has poor water holding capacity and become susceptible to leaching and dry out soon (Brady and Weil, 1999; Fernhout and Kurtz, 2002).

Vertosols, which include the cracking clay types of Australia, are very prone to deficient aeration. In these soils following saturation, dissolved soil O_2 falls to zero, roots die back in the saturated zone and plants show typical signs of flooding injury (Thongbai *et al*., 2001). Vertosols are the fifth most common soil type in Australia, covering 11.5% of the land, and are most extensive in Queensland, covering one third of the state. Vertosols are productive and rich soils when there is assured irrigation. Most researchers in the past have been careful to provide adequate nutrients and water, but have overlooked soil aeration. Aerating the hypoxic rhizosphere by oxygation can unlock the yield potential of SDI crops grown under oxygen-limited environments.

2.2.6 Hypoxia and Soil Processes

Aeration status in the soil can have major impacts on soil nutrient availability, manifested largely through soil pH and the oxidation/reduction potential. The influence of aeration on these are summarised in this section. Soil aeration do impart significant effects on soil biological processes, but the analysis of soil biology in relation to aeration is beyond the scope of this thesis, and so is not discussed.

2.2.6.1 Oxidation-reduction potential

Depending on the O_2 flux into the soil profile, field soils can experience redox conditions varying from well oxidised to strongly reduced (DeLaune *et al.*, 1990; Masscheleyn *et al.*, 1993). Redox potential (Eh) of a soil depends on both the presence of electron acceptors (O_2 or other oxidising agents) and favourable pH (Grable, 1966). Generally there is a positive correlation between soil air and Eh. In an oxidised soil Eh ranges from *c.* +600 to +350 mV, whereas for most reduced (anaerobic) soils the Eh varies from *c.* –300 to +350 mV (Masscheleyn et al., 1993). Values as low as -300 mV have been recorded in anoxic conditions in warm soils rich in organic matter (Grable, 1966). A study by Bryce *et al.* (1982) on tomato showed Eh values below 320 to 340 mV even 48 hours after flooding of a peat-sand potting mix. This result indicates that O_2 depletion following flood irrigation remains for some time, for reduced transpiration under flooding slows the process of removal of water from the root zone. Hydrogen peroxide treatments under flooded conditions did not bring Eh to levels that indicate adequate O_2, although values were higher than those without peroxide.

2.2.6.2 Soil pH

The response of soil pH to hypoxia is variable. Soil with poor aeration may show an increased pH because anaerobic conditions favour denitrification of the soil nitrate to nitrogen gas and of sulphates to H_2S (Stevenson, 1992). Severe leaching of bases and increased CO_2 in anaerobic soils, however, increase soil acidity. In saturated soils, the build-up of CO_2 from respiration has a dominant effect and the pH tends to drop, and most flooded soils eventually develop a neutral pH between 6.7-7.2 (McLaren and Cameron, 1996). Although the direct effect of change in pH to plant performance is minimal, indirect effects may be large due to the effect of pH on nutrient availability (Allegre *et al.*, 2004;

Igamberdiev and Hill, 2004). Oxygation, therefore, can buffer soil pH against unpredictable change that can develop due to hypoxia in clay soil at higher irrigation rates.

2.2.7 Effects of Low Rhizosphere Oxygen on Plant Physiology

Adequate soil aeration is extremely important in order to optimise the plant growth under oxygen-limited environments. Plant growth and development processes are negatively affected by O_2 limitation. Effects of low O_2 on the plant vary with species, duration and intensity/magnitude of hypoxia.

Although it might be thought that aeration stress would affect shoot growth more, hypoxia reduces root respiration because the roots get little O_2 to respire. Poor root respiration reduces the uptake of water and nutrients, and chemical changes in the soil can produce toxins that limit overall plant growth (Anonymous, 2002a). Hence poor aeration induces a notable effect on plant growth in general rather just on root growth.

2.2.7.1 Root growth and seedling establishment

The plant roots respond to low O_2 concentration at the first instance. Poor aeration affects both the depth of penetration and vigour of the roots. The catchment volume for both water and nutrients is determined by the extent of the root system. On hot dry days plants with a very poor root system can actually wilt (Ort *et al.,* 1994) even though soil moisture is not limiting. Limited root spread and hypoxia make plants express the mid day depression as small roots are incapable of drawing water to meet the transpiration needs of the foliage (McKee, 1996). Nitrogen fixation in legume roots nodules is also slowed and VAM association that normally enhances phosphorus uptake fails to develop in hypoxic soil (Andrade *et al.,* 1998.).

Young plants are particularly susceptible to a low soil O_2. The susceptibility varies with genotype and species (Huang and NeSmith, 1990; Baruch, 1994). O_2 deficiency severely limits seedling establishment. Inferior stand establishment can occur due to inhibitory effects of low O_2 on germination (Cantliffe, 1998) and subsequent root elongation, proliferation, viability, respiratory capacity, carbohydrate accumulation, hormone synthesis, and water and nutrient uptake. Poor aeration by waterlogging predisposes the young seedlings to various kind of pathogenic rots particularly in clay soils.

2.2.7.2 Plant growth and development

As the plants develop beyond the seedling stage the O_2 concentration experienced by the roots depends on the balance between the rate of supply by the soil and the rate of consumption in the respiration and the internal transport of the O_2 within the plant. For dry-land crops, restricted aeration in the rooting zone is a temporary problem caused by excess of rainfall input relative to the drainage and crop use. However, in the irrigated crop the deficient root zone O_2 can continue over a longer period and become a major limitation for crop production (Wolf, 1999). The plants reaction to soil O_2 is also dependent on temperature. Generally there is a slow rate of O_2 depletion in winter/low temperature compared to summer/high temperature. Low level of O_2 availability for roots is likely, therefore, in crops grown in the summer in tropical/subtropical regions with heavy clay and a full profile of soil moisture.

The effect of hypoxia on shoot growth is also severe depending on the duration and intensity of hypoxia. Leaf growth and stem elongation are severely restricted by root hypoxia in the short term either as a consequence of lack of N or other major nutrients (Tsai and Chu, 1992). In the long term, slow growth rate may persist because of the accumulation of metabolic toxins or the lack of water and nutrients. Net assimilation rate and photosynthetic rate decline in plants experiencing lack of O_2 in part due to stomatal closure partly due to biochemical modification (Sojka, 1992).

2.2.7.3 Yield and quality

Continuous or episodes of deficient aeration can prevail in SDI crops depending on soil type and intensity of irrigation. Yield reduction of many crops grown in heavy clay soils, particularly in the wet season, have been partly interpreted as being due to depletion of O_2 in the root zone (Baruch, 1994). Meek *et al.* (1983) reported a significant yield reduction on tomato trickle irrigated at 100-120% of pan evaporation registering O_2 content of 0.03-0.06L L^{-1} at 20 cm. In the irrigated wheat and cotton areas of southeast Australia, warm temperatures in spring and summer, combined with poor soil drainage on heavy soils, cause yield reductions as a result of O_2 depletion during and following each irrigation (Meyer *et al.*, 1985). In undisturbed monoliths of clay loam sown with wheat, soil O_2 reduced to less than 0.021 L L^{-1} in 48 h of an irrigation event and gradually returned to normal concentration over the next 10-15 days (Meyer *et al.,* 1985). Very low O_2 fluxes were determined in cores extracted from similar soils in the field following furrow irrigation (Hodgson and MacLeod, 1998).

Aeration of SDI water was first reported by Goorahoo *et al.* (2002) suggesting a 33% increase in bell pepper count and 39% increase in total fruit weight in the loam and sandy loam using Mazzei air injector (venturi). Dry weight for root and shoot significantly increased with aerated water compared with plants receiving water only. Similarly the study by Huber (2000) and Heberger *et al.* (2001) suggested yield gain in a range of vegetable crops with the use of hydrogen peroxide for oxygation in light to medium textured soils. This PhD research includes representative crop species from very susceptible, susceptible and moderately tolerant species to hypoxia and investigates the physiological basis and yield response by these in a heavy clay soil at different soil moisture regimes.

2.2.8 Hypoxia: Effects on Water Relations and WUE

Poor aeration affects the absorption of water by plant roots (Visser *et al.*, 2000a). O_2 deficiency causes decreased root permeability, particularly in intolerant species (Vartapetian and Jackson, 1997). Such an apparent decrease in permeability due to hypoxia can be interpreted in two ways: a change in the ability of membrane to allow the passage of water, or a reduction in the driving force acting across the membrane (Else *et al.,* 2001).

Increased levels of abscisic acid (ABA) are likely related to stomatal closure under hypoxic conditions. Hypoxia also reduces the uptake of potassium and this combined with slower water flux from root to shoot can reduce K levels in the guard cells, resulting in stomatal closure (Pezeshki, 1994). The osmotic component of the water uptake under anoxic conditions can be affected by increasing membrane leakiness such that no osmotic gradient remains, or by reducing active ion uptake (due to reduced ATP supply). The overall manifestation of root hypoxia is a reduction in water absorption and stomatal conductance (Vasellati *et al.*, 2001). Forced aeration of the hypoxic/anoxic rhizosphere confers greater membrane integrity, sustaining aerobic respiration and greater ATP generation. As biomass increases with an increase in ET the aeration should be able to increase the yield of aerated crops. Low O_2 levels in the root zone have been implicated with reduced water uptake and transport by the plants (O'Neil and Carrow, 1983), possibly due to decreased hydraulic conductance and root permeability (Anderson *et al.*, 1984). Everard and Drew (1989) and Anderson *et al.* (1984) reported that reduction of root hydraulic conductivity under root anoxia was related to an occlusion of xylem vessels and restricted axial water movement through roots. Drew (1983) concluded that decreased root conductance of water under hypoxic conditions induced stomatal closure resulting in reduced transpiration and photosynthetic rate which leads to poor water use efficiency. Extensive deep drainage is implied for crops where root growth is limited due to hypoxia.

Forced aeration, having significant effects on promoting root growth, potentially contribute towards reduced deep drainage of SDI crops in heavy clay soil.

2.2.9 Hypoxia: Effect on Mineral Nutrition

In general, in waterlogged soils NO_3^-, Mn^{4+}, Fe^{3+} and SO_4^{2-} will eventually be reduced, decreasing plant access to those nutrients. Nitrate is reduced to nitrite, which is unstable under anaerobic conditions, and tends to be further reduced to nitrogen gas and lost from the soil. Under waterlogged conditions, sulphates (SO_4^{2-}) are reduced to hydrogen sulphide (H_2S). Solubilities of Mn^{4+} and Fe^{3+} increase with anoxia and they are found at toxic levels.

The effect on nutrient uptake under the hypoxia is also ion specific. In fact poor soil aeration affects potassium uptake more than any other major nutrient with levels of uptake being suppressed to 45% of normal (Armstrong, 1979). Analysis of the shoot for the various minerals indicated that increased O_2 enhanced K and P uptake. The total Ca^{2+} and Mg^{2+} uptake does not appear to be greatly influenced by O_2. In contrast to the other minerals, Na^+ increases with a decrease in O_2 and was very markedly higher at the lowest O_2 treatment (Letey, 1961). This observation indicated that poor aeration could cause an apparent Na^+ problem even though the soil is not particularly high in Na^+.

The uptake of plant nutrients under hypoxic environments is reduced not only by the direct effects of low O_2 on nutrient acquisition and transport (Visser *et al.*, 2003) but also indirect on soil chemistry such as Eh and pH that affect nutrient availability. A change in soil pH due to waterlogging has an effect on the availability of plant nutrients such as P and Mo for which availabilities increase as pH rises but Zn becomes less available with the increase in pH. The availability of Cu and Co decreases with pH extremes but sharply decreases as pH levels increase (Brady and Weil, 1999). Aeration as oxygation, therefore, is expected to significantly improve plant nutrient uptake and minimise the loss due to leaching and protect nutrients against the negative effects of their reduced state.

Hypoxia induced inhibition of nutrient ions transport by roots to the leaves may be due to insufficient energy to maintain the activity of ion pumps on the plasmalemma or, alternatively, a disruption of membrane integrity may dissipate the proton gradient across the membrane that drives ion and nutrient transport systems (Everard, 1985). The mineral uptake by plants is an energy dependent process. Inadequate O_2 in the rhizosphere results in decreased root respiration - source for ATP - the high-energy compound required for mineral uptake. ATP supplied by anaerobic respiration is not sufficient to provide energy for mineral uptake. Decreased permeability and growth of roots results in inability to meet the mineral requirements of the shoot under hypoxia. Consequently, the altered ion transport due to poor aeration imposes a number of stresses on the shoot, consisting of both acclimation and irreversible injuries. Phloem unloading in the root ceases, as does transport of metabolites and growth regulators between the root and shoot (Zwieniecki *et al.*, 2003).

Poor aeration not only has an effect on limiting growth but also increases the intensity of root related diseases (Allmaras *et al.*, 2003), causing inefficient use of nitrogen and other nutrients applied to crops (Hocking *et al.*, 1997). Losses of N from a hypoxic rhizosphere occur due to denitrification and leaching (Focht, 1992). Continuous saturation of the root zone with high SDI rates induces a loss of nitrogen due to denitrification and leaching particularly in heavy soils.

2.2.10 Hypoxia: Effects on Growth Regulators

Hormone physiology in relation to a well-coordinated whole plant is still not fully understood, however, it is recognized that O_2 deficiency inhibits the synthesis of IAA, GA and cytokinins by the root, whereas the production of ABA increases (Zhang and Davies, 1990). Hypoxia moreover causes an imbalance in plant growth regulators. Well-aerated roots function as a synthetic organ supplying the shoot with growth substances and, in most species, amino acids with high nitrogen content (the end product of nitrate assimilation).

Cytokinins, GA and ABA are the main categories of hormones manufactured in aerated roots and a number of symptoms displayed by plants grown under inadequate soil aeration are similar to those that are associated with an interruption in the supply of these hormone groups (Everard, 1985). The hormone production and translocation in roots is also greatly interrupted by hypoxia. Likewise, plant hormones manufactured in the shoot (auxin and ethylene) accumulate in the leaves and stem under hypoxia (Reid and Bradford, 1984).

Hiron and Wright (1973) observed stomatal closure in beans and tomatoes with hypoxia where ABA levels in the plant were 6-8 times higher than in the non-flooded control, showing a direct relationship between ABA levels and stomatal closure. Evidence also suggests that ABA levels of leaves rise (as much as 50 times) in response to water stress effecting rapid stomatal closure. Stomata remain closed until ABA levels drop again (Fedina *et al.*, 1994). ABA production increases in the root in response to dry conditions. It is transported to the shoot via the xylem. Under normal conditions the xylem sap is slightly acidic, favouring the uptake of ABA by the mesophyll cells. During water stress, the xylem sap becomes slightly alkaline, favouring the dissociation of ABA to ABA^-. As a result, less ABA is taken up by the mesophyll cells and more reach guard cells. Whether the guard cells physiology with respect to ABA is same under the dry and hypoxia stress is not confirmed.

Under anoxic conditions, the production of the ethylene precursor (ACC) rises rapidly, at least in tomato (Bradford and Yang, 1980). Major hormone imbalances occur in the shoot, and possibly root which result directly or indirectly in at least some features of abnormal shoot development without adequate root aeration (Figure 2.2.5). Interactions between the growth regulators on plant performance under limited aeration are not adequately understood. It seems more likely that the symptoms in roots and shoots due to poor aeration are not solely caused by changes in the level of the individual hormones but are due to the disruption of the very delicate balance between the hormone groups critical for the normal growth and development of plants (Jackson *et al.*, 1992).

Figure 2.2.5 Model of ethylene flux in flooded plants, showing changes in transport of growth regulators in plants with flooded roots and an aerobic shoot (Source: Department of Agronomy, Penn State University, USA).

A high concentration of auxin in the shoot is known to cause stem hypertrophy and adventitious rooting. This symptom is commonly observed under reduced aeration. The explanations for high concentration of auxin in the shoot under root anoxia are the prevention of auxin transport to the roots, or a stimulation of its production in the shoot. Auxin is transported within plants by two pathways, in the phloem, or by the polar auxin transport system. Both these mechanisms require metabolic energy and are inhibited by anoxia (Qureshi and Spanner, 1973).

2.2.11 Hypoxia: Tolerance, Avoidance and Management

Species differ considerably to hypoxia stress. Tolerance to hypoxia can vary from only a few hours to many days or weeks depending on species, the organs directly affected, stage of development and external conditions such as temperature (Gibbs and Greenway, 2003). For roots, these include metabolic adaptations such as avoidance of self-poisoning and cytoplasmic acidosis, maintenance of adequate supplies of energy and sugar, modification of gene expression and metabolic acclimation to tissue anoxia by previous exposure to partial O_2 shortage.

Morphological escape mechanisms are based on arenchyma development and internal aeration pathways. Their mechanism of tolerance can include metabolic adaptations and developmentally passive tolerance. Escape mechanism for shoots are based on active, sometimes, increasingly rapid shoot extension in the presence or absence of O_2 (Setter and Waters, 2003). Systematic signalling between roots and shoot integrate their physiology and limit indirect damage to shoot tissues by low O_2 (Vartapetian and Jackson, 1997).

2.2.12 Mechanism of Sensing Oxygen Deficiency

The regulation of hypoxic metabolism is a complex phenomenon. The adaptive structural and metabolic features in response to O_2 deficiency in plants include a decrease in adenylate energy charge, cytoplasmic acidification, anaerobic fermentation, elevation of cytosolic Ca^{2+} concentration, changes in redox state and a decrease in membrane barrier function (Richard *et al*., 1994; Tadege *et al*., 1999). Aurisano *et al.* (1995), and Ratcliffe, (1995) provided evidence for accumulation of gama-aminobutyrate (GABA) under anaerobic conditions. Patterson and Graham (1987) opined that accumulation of GABA may be a consequence of cytoplasmic acidification, stimulating the activity of glutamate decarboxylase, which has an acid pH optimum (~5.8). The O_2 status of SDI rhizosphere is very dynamic depending on irrigation and plant water uptake rate, therefore, O_2 status undergoes several transitions (hypoxia, anoxia, and reoxygation characterized by different O_2 concentrations) within the short and long term period. Excessive reactive oxygen species (ROS) generation is also associated with hypoxia. HP accumulates under hypoxic conditions in the roots and leaves in many species (Hunter *et al*., 1983; Kalashnikov *et al*., 1994**;** Chirkova *et al*., 1998; Biemelt *et al.,* 2000). However, exogenous application of HP to the plants roots in the aerated irrigation water had no reported negative effects.

2.2.13 Options for Improvements

Modifying the root zone environment by injecting air (particularly in clay soil) can increase crop yield. Many theoretical experiments have shown the improved benefits of rhizosphere oxygenation on the performance of plants (Stolzy and Letey, 1964; Grable, 1966; Armstrong, 1979). However, the air only injection system is an expensive proposition in terms of cost of installation and operating energy (typically air pumps must run at about 300 kPa for pumping about 150 L air per minute). Chemical options for aeration involves the repeated use of hydrogen peroxide (HP), which also turns out to be an expensive option ((AU$ 1300 ha^{-1} as capital cost (last a minimum of 10 years) for air injection against AU$ 4000-6000 ha^{-1} (recurrent cost per crop) for HP)). With the growing popularity of SDI among growers around the globe in the face of the increasing crisis for water on agricultural industries, it becomes practical to couple air injection with SDI systems. Injection of air alone through SDI tape does not end up with a uniform distribution of the air in the profile, rather it results in a vertical stream from the emitters to the surface of the soil. This is likely to minimally affect soil volume due to the chimney effect directly above the emitters (Goorahoo *et al.*, 2002). Therefore, circumventing this problem by aerating the irrigation water in the line before delivery may offer a practical solution to the problem.

Different kinds of air injectors can be used for soil aeration. The 'mazzei' model air injector is one of these, which can be used for injecting air into pressurized water systems (Figure 2.2.6). These operate on the venturi principle and differential pressure injectors with internal mixing vanes. When a sufficient pressure difference exists between the inlet and outlet ports of the injectors, a vacuum is created inside the injector body, which initiates suction through the suction port (figure 2.2.7).

Figure 2.2.6 Mazzei mode air injector fits in line with SDI, close to the irrigation plot. Pressure differential can be adjusted for air injection to the desired levels.

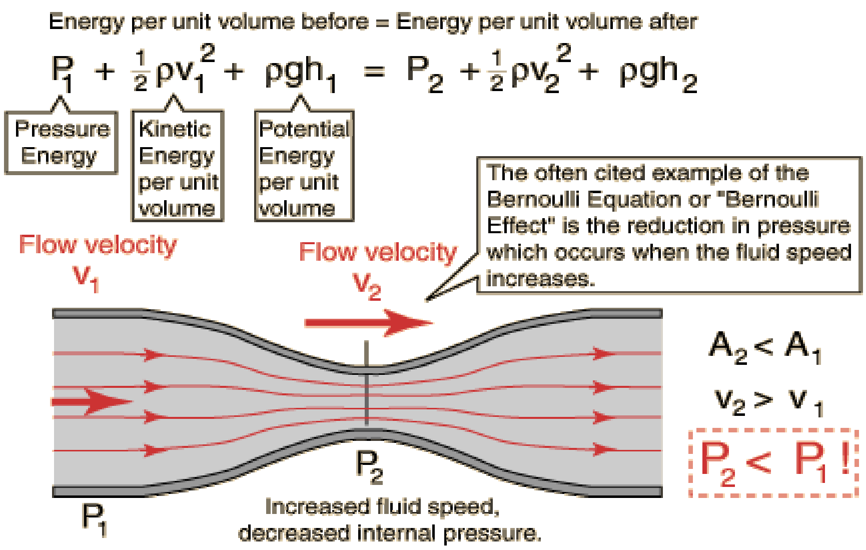

Figure 2.2.7 A sketch schematic presentation of principles and operation of air injection unit and Bernoulli's equation (Source: Glen Research Institute, 2003).

Another alternative for improved root zone aeration is the use of hydrogen peroxide (HP). It is an unstable chemical compound that is decomposed by the soil enzyme catalase to water and molecular O_2. Experimental evidence suggests that HP can be employed to alleviate O_2 stress under short term flooding conditions. HP injected at the rate of 5L ha^{-1} (equivalent to 1617 L O_2) after each flooding event increased the total yield of field – grown waterlogged zucchini by 25% compared to control (Huber, 2000). Melsted *et al.* (1949) also reported an increase in yield of maize and soybean with the HP treatment compared to control. With an O_2 requirements of the crop roots of 12000L ha^{-1} d^{-1}, 18.5 L of HP would be required daily for supplying 50% of the O_2 for the crop root respiration costing about AU$ 50-60 daily for HP.

In an experiment on the tomato in containers filled with a potting mix of peat moss and sand, and subjected to combinations of treatments with and without flooding and peroxide addition, peroxide benefited yield in the presence of flooding (Bryce *et al.*, 1982). HP could be useful as an O_2 source and offers potential for use as a source for rhizosphere aeration of crop plants. Root O_2 demand can be met by adjusting the amount HP in the irrigation water. Chapter 4 of the thesis presents research investigating the effect of HP and air injection as a source of supplementary oxygen supply to root in different crop at a range of soil moisture in a heavy clay soil. The results consistently showed that oxygation of rhizosphere enhances plant performance though improved root processes.

2.3 OXYGATION IMPROVES PLANTS PERFORMANCE IN SALINE SOILS

Salinity and sodicity reduce soil porosity by dispersing the soil particles in clay soil (Kahlown and Azm, 2002). Reduced aeration of saline soils exacerbates salt damage to plants by increasing indiscriminate salt uptake (Letey, 1961). Forced aeration of the rhizosphere can offer a significant benefit by delivering more O_2 to the root zone, allowing plant roots to exclude salt uptake.

2.3.1 Salinity: a Widespread Threat to Agriculture

Salinization of the agricultural land is increasing particularly in the arid and semiarid regions of the world (Ghassemi *et al.,* 1995). It is estimated that about a third of the world's irrigated land and half of the lands in semiarid and coastal regions are affected by salinization and 10 million ha of irrigated lands are abandoned annually because of excessive salinity (Abrol *et al.,* 1988). The causes of salinity can be natural, clearing of the natural vegetation (dryland salinity), or irrigation (Anonymous, 2002b). Salinity is often accompanied by other changes in soil, such as sodicity, alkalinity or toxicity of other ions in the soil, which exert their own specific effects on plant growth. Salts in the soil causing salinity are primarily chlorides and sulphates of sodium, calcium, magnesium and potassium (Munns, 2002).

Salinity and sodicity are separate and unique descriptions of all impacts of soluble salts in soils and water environments. Salinity refers to the total concentration of all salts in the water or soil. Soil sodicity represents the relative preponderance of exchangeable Na^+ compared to other exchangeable cations, chiefly Ca^{2+} Mg^{2+}, K^+, H^+ and Al^-.

A sodic soil has too much Na^+ associated with the negatively charged clay particles, which causes excessive swelling of the soil and results in structural collapse – dispersion. These soils are prone to waterlogging due to reduced porosity (Qureshi and Barrett-Lennard, 1998). The details about causes, spread, effects, and management options for salinity and sodality have been rigorously reviewed (Munns, 1993; Szabolcs, 1994; Ghassemi *et al.*, 1995**;** Robertson, 1996; Anonymous, 2001; Barrett-Lennard, 2003; Tester and Davenport, 2003). This review chapter focuses on the effect of hypoxia under saline conditions, discusses on the issues of waterlogging and salinity interactions on plant performance, effects on nutrients, ions and water uptake as well as other physiological processes affected by hypoxic saline rhizosphere. The benefit of oxygation of the rhizosphere in saline soils is highlighted.

The salinity limit for irrigation water is 1.2 and 2.7 mS cm^{-1} for sprinkler and drip irrigation respectively (Stevens *et al.*, 2000). Yield generally does not decrease significantly until a salinity threshold is exceeded, and decreases linearly thereafter with further increases in salinity.

Drip irrigation offers several benefits to the control of salinity. i. Application of irrigation water to the soil avoids contact with plant foliage (sprinkler irrigation with saline water can cause salt damage to foliage), ii. SDI may be effective at flushing salt out of the root zone if the drip tape is properly placed (Tanji, 1996), iii. Drip irrigation also allows the use of saline water for irrigation, by directly dripping water in to the root zone without too much of salt loading in to the soil, and iv. SDI allows oxygation of saline/sodic soils supplementing O_2 into the root zone and improves plant performance by greater salt exclusion by aerated roots (Letey, 1961).

2.3.2 Salinity Measures, Units and Classes

Salinity measure includes electrical conductivity of a solution or soil and water mix, weight of salt in a given amount of water, and the quantity of molecules of salts in a solution. A popular field measurement tool is the EM- 38 (Electromagnetic Induction Meter), which estimates electrical conductivity (EC). The standard measurement technique involves the measure of electrical conductivity of a 1: 5 mix of soil and water.

Sodicity is quantified as Sodium Absorption Ratio (SAR), which is the measure of the relative preponderance of dissolved Na^+ in water compared to the amount of dissolved Ca^{2+} and Mg^{2+}, whereas Exchangeable Sodium Percentage (ESP) is the proportion of the cation exchange capacity (CEC), occupied by the sodium ions and is expressed as a percentage. Sodic soils are categorized as soils with an ESP of 6-14% and strongly sodic soils have an ESP of greater than 15%. The units for salinities include grams per gallon, milligram per litre, milliSiemens per metre, deciSiemens per centimetre and many more. Units vary within and between countries, but dS m^{-1} is common in scientific writing. The salinity classes for plants in this case range from susceptible to tolerant, whereas for soil salinity classes range from non-saline to extremely saline.

Rengasamy and Churchman (1999) summarized the physical manifestation of soil sodicity as crusting, hard setting, waterlogging of soil and the range of side effects of water movement into the soil profile including reduced infiltration and plant available water capacity. The soil structure of heavy clay, especially when it is saline or sodic, is poor and permeability is low. Good permeability allows greater circulation of water, gases (O_2 and CO_2) and solutes to plant roots. If a sodic clay layer (Bt - B horizon with accumulation of clay) occurs near the surface of soil, it often acts as a barrier to root growth. Most roots are restricted to the topsoil above the clay pan, because movement of water, nutrients and gases is too slow in the sodic B-horizon. In fact, when dry, the B-horizon can be so hard that it is also a physical barrier to root penetration (Koyro, 1997). The overall effect on plant growth is one of stress similar to that caused by extremely dry or saline conditions.

A recent survey also showed that sodic soils in South Australia registered slow accumulation of small amounts of salts in the subsoil layer (subsoil transient salinity) that can be detrimental to crops (Stevens *et al.,* 2000). This phenomenon of 'subsoil transient salinity' in the root zone of sodic soils is different from the secondary seepage-salinity found in association with rising water tables (Rengasamy, 2000). This subsoil transient salinity fluctuates with depth or season spreading to as much as 30% of the land in the wheat belt in Southern Australia (Rengasamy, 2002). The subsoil layers between 0.3 and 0.6 m accumulated salt with an ECse (Electrical conductivity of saturated paste extract) range 4.0-16 dS m^{-1}. Such high salt concentration may cause osmotic effects, preventing soil water absorption by the plant.

2.3.3 Effect of Salinity on Plant

2.3.3.1 Plant Growth and Development

Effects of salinity on plant growth are complex because they involve osmotic stress, ion toxicity, and mineral deficiencies (Hasegawa *et al.,* 2000). Plants vary tremendously in their ability to tolerate salt in water (Ashwath, 1987). Salts dissolved in soil water inhibit plant growth because of reduced water uptake and increase in salt ingress into plants. According to Munns (2002), the primary stress on plants at the beginning (hours to few days) of exposure to salt is osmotic, while ion toxicity becomes important in affecting plant growth after prolonged exposure. Pardossi *et al*. (2004) stated that water stress is one of the first and most evident effects of salinity and that the determination of water relations is, therefore, critical for any study of plant resistance to salinity.

The impact of sodicity on plant performance is typically manifest as apparently poor seedling emergence; poor establishment and poor root development, causing significant economic losses for crop production (Rengasamy, 2002). Symptoms of salinity on plants also include slow and low seed germination, sudden wilting, stunted growth, marginal burn on leaves, yellowing of leaves, leaf fall, restricted root development, and sudden and gradual death of plants (Munns, 2002).

An example of a long-term effect of salinity is the reduction of leaf size, resulting in less light interception (Kozlowski, 1997). The most common effects of salinity are suppressed canopy growth and photosynthesis. Cultivars may differ slightly in their response to salinity (Muhling and Lauchli, 2002). The indirect effects on crop growth and development due to salinity affect the crop behaviour to such an extent that its susceptibility to other stresses may change. A well-known example is the interaction between salinity and verticillium wilt. Under salt stress, the yield decline in tomato caused by verticillium wilt is much greater (Besri, 1990).

2.3.3.2 Plant Physiological Processes

In most of the arid and semi-arid regions, the combination of salinity and waterlogging is also a problem. The combined effects of excess water and O_2 deficiency are highly damaging. The response is species specific. In sensitive species such as *Leptochola,* reduction of growth was related to accumulation of higher amounts of Na^+, Cl^-, K^+ and Ca^{2+} in its shoots as well as reduced leaf osmotic potential (Ashraf and Ahmad, 1995). Similar observations were made by Barrett-Lennard *et al.*, (1999) suggesting that hypoxia substantially increased net Na^+ and Cl^- uptake by the shoots, Na^+ and Cl^- concentrations in the expanded leaves but not in the expanding leaves and these changes preceded adverse effects on the shoot growth.

Salinity affects almost all plant processes starting with germination (Esechie *et al.*, 2002), through to growth and production (Murillo-Amador *et al.*, 2001**;** Fricke and Peters, 2002). Increased salinity level reduced stomatal conductance, photosynthetic rate, transpiration, and leaf relative water content (Lopez *et al.*, 2002). Osmotic induced reduction of water uptake by the roots and/or decreased stomatal conductance is a possible explanation for reduced transpiration. Likewise, the photosynthetic activity was also reduced in salt-stressed plants governed by decreased stomatal conductance, reduced carboxylase activity, limited tissue CO_2 availability, and inhibition of light reaction mechanisms (Hagermeyer, 1997).

2.3.3.3 Movement of Water

Plants absorb large amount of water to meet transpirational demand. Plants transpire as much as 30-70 times more water daily than they retain. In salinity tolerant species, roots act as filters excluding as much as 95% of the salt in transpired soil water, while maintaining a leaf cell sap concentration about twice the soil solution (Atwell *et al.,* 1999).

2.3.3.4 Movement of Salt from Soil to the Plant

The entry of Na^+ into the cytoplasm is considered to be the most important primary reaction of plant cells for the expression of disturbed metabolism due to salinity. K^+ is an essential nutrient. Therefore, maintenance of high level of K^+, but low levels of Na^+, in the cytoplasm is essential for the activities of many enzymes in the plants. Hence, uptake and accumulation of K^+ must be ensured for the growth and development of plants when exposed to salinity. K^+/Na^+ selectivity is, therefore, an important factor for the tolerance of salinity by plants (Kafkafi and Brenstein, 1996). Na^+, however, can cross the membrane through ion channels but its permeability is just one half the membrane permeability for K^+.

In saline soils the ratio of K^+ to Na^+ is often extremely low, and Na^+ ions can inhibit uptake of K^+ ions. If K^+ uptake is not maintained, tissue Na^+ concentrations become too high, an unfavourable cytoplasmic K^+ to Na^+ ratio results, and enzyme functions are inhibited. Fortunately, K^+ transporter proteins in plasma membranes of plant cells have highly specific mechanisms for uptake of K^+ and so forestall ion imbalance under mild salinity. Salt tolerant species generally maintain effective K^+ uptake more than sensitive species (Atwell *et al.,* 1999).

Low O_2 concentration on the rhizosphere has been implicated for reduced K^+ absorption by plants due to an effect of anaerobiosis on uptake mechanisms of plant roots (Trought and Drew, 1980). Such a marked decrease in the K^+ uptake in saline soils is not solely inhibited by the presence of Na^+ but partly due to the anaerobic conditions around the root zone in the saline soil which inhibit the uptake of K^+.

In addition to the species difference in salt exclusion, the ability of plant roots to exclude salt is also highly affected by the root zone O_2 level. In a study conducted with various crop species at different salt levels with and without aeration, aeration had a greater effect on reduced level of salt accumulation of shoots and leaves of plants as the concentration of NaCl increased in the medium (Barrett-Lennard, 1986).

2.3.3.5 Plant Membranes Regulate Salt Tolerance

Under non-saline conditions Cl^- is taken up actively, but under saline conditions some additional Cl^- enters the symplasm through passive flux. This passive flux is low under aerobic conditions because of a high membrane potential (-100 mV). The maintenance of a high membrane potential is at least partly achieved by an active H^+ pump, and could require 19 - 26% of the ATP produced under aerobic conditions (Drew, 1992; Greenway and Gibbs, 2003). Under anaerobic conditions the membrane potential may be lowered considerably, resulting in a massive influx of Cl^- into the symplast (Zhang and Blumwald, 2001). Oxygation in a saline environment may, therefore, exert a greater positive effect on the exclusion of salts by conferring a greater membrane potential.

Under saline conditions Na^+ also probably enters the symplasm pathway mainly by passive influx (Greenway and Gibbs, 2003) and lower Na^+ concentrations in the symplasm are achieved primarily by active efflux across the plasma membrane (Pitman, 1969; Munns *et al.*, 1983). It was estimated that this process would cost a plant about 45% of the ATP produced under anaerobic conditions compared with only 2.4% of that produced under aerobic conditions (Barrett-Lennard, 1986).

Water and ions move concurrently across roots from epidermis to xylem via apoplasmic and symplasmic pathways. However, the endodermis (with Casparian strips in radial cell walls) blocks the continuity of apoplasmic pathway between the cortex and stele. Hence solute crosses the endodermis via passage cells within this layer traversing a plasma membrane. Root membranes have a low permeability to Na^+ and Cl^- ions, hence, the endodermis strips restrict inward flow to xylem of these ions (Atwell *et al.*, 1999). For the details of the salt movement in various organelles of plant see Figure 2.3.1.

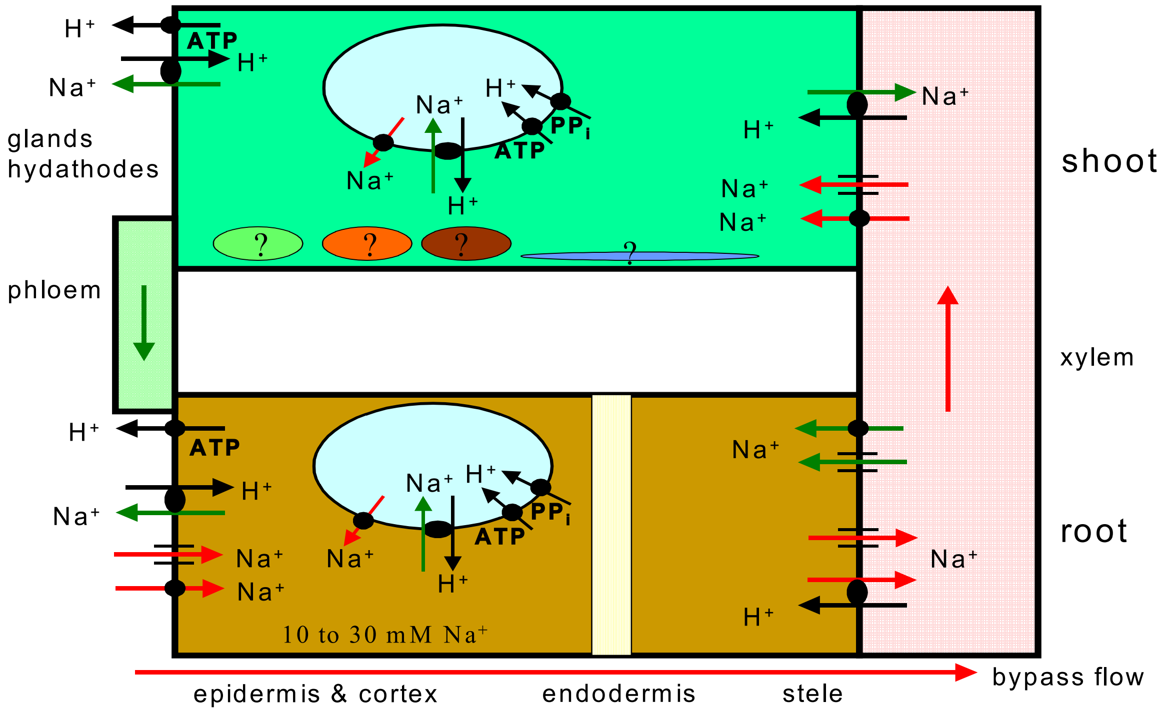

Figure 2.3.1 Na^+ transport processes influencing Na^+ tolerance in higher plants. Red arrows indicate Na^+ movement, the minimization of which would increase tolerance; green arrows, the maximization of which would increase tolerance. The coloured shapes in the leaf represent chloroplast (green), mitochondria (orange), peroxisomes (red) and endoplasmic reticulum (dark blue). Na^+ transport processes in to and out of these organelles are unknown (With the permission of Mark Tester- Cambridge University).

Plants grown under anoxic and saline environments demonstrate altered rates of biosynthesis of growth regulators, and also develop specific responses to exogenous application of growth regulators. Kinetin application ameliorates the deleterious effect of salinity and O_2 deficiency (Hagermeyer, 1997), and is associated with a reduction in Na^+, Ca^{2+} and Cl^- accumulation, and improved K^+ uptake under salinity and waterlogging stress. This effect is ascribed to reduced membrane injury induced by dehydration and heat stress and improved plant water status under both aerobic and anaerobic conditions. Gadallah (1999) concluded that kinetin application helped wheat plants to grow successfully in areas subject to the combined effect of salinity and O_2 deficiency, such as found in salt marshes.

2.3.4 Effect of Salinity on Nutrient Uptake

Uptake of most nutrients is affected by salt stress. However, the response depends on species, level of salinity, and other soil properties. In *Brassica* the concentrations of Ca^{2+}, Mg^{2+}, K^+, Cl^-, Na^+, and total N^+ was significantly affected in salt-stressed plants, and Ca^{2+} may play a regulatory role in this species. In tomato, however, out of five cultivars, one resistant cultivar exhibited increased shoot accumulation of Na^+ and Cl^- under saline soil but reduced K^+ in the shoot, whereas others excluded Na^+ and Cl^- ions from the shoot and retained these ions in the roots and maintained their K^+ selectivity under salt stress, indicating that there is no standard salt resistance mechanism (Perez-Alfocea *et al.*, 1996). The forms of N in the root medium also exert different response in nitrogen uptake by the plants. Barley plants produced more dry matter and yield when grown with mixed N nutrition than with NH_4^+ or NO_3^- alone in the presence of salinity (Ali *et al.*, 2001).

In addition to direct effect on plants roots, aeration is also considered to have positive effects on soil micro-organism activities, which are greatly reduced in the saline environments that are particularly anaerobic (SubbaRao, 1999). Enhanced soil microbial activity by oxygation in saline soil confer positive response on plant nutrition as well.

2.3.5 Water and Radiation Use Efficiency

The effects of salinity on WUE follow different patterns according to the nature of salts. If salinity stress is due to ion toxicity, resulting in increased respiration or decrease in photosynthesis, decreased amount of assimilates will be allocated to plant growth per unit transpired water, resulting low WUE (Hester *et al.,* 2001). However, if the stress is a result of decreased osmotic potential, plants respond by stomatal closure. Since photosynthesis is less strongly affected by stomatal conductance (SC) than transpiration, WUE is expected to increase with salinity (Brugnoli and Björkman, 1992**;** Ben-Gal *et al.,* 2003). However, agronomic WUE (DW/applied water, ML) will tend to decline with increasing salinity and hypoxia, the proportion of total irrigation water that is utilized through transpiration is reduced compared to the total irrigated water (Gucci *et al.*, 1997).

In unstressed crops, the major determinant of biomass production is the amount of photosynthetically active radiation (PAR) they absorb (Idinoba *et al*., 2002). Crop growth can be described as the product of the incident PAR, the fraction of PAR intercepted by the green leaf (f) and the efficiency with which the PAR is used (ε). PAR depends on the location and time of the year; while seasonal f is affected by the duration and the area of the effective canopy (Chapman and Edmeades, 1996). Salinity and hypoxia have negative effects on leaf and canopy development, which leads to reduced PAR interception and biomass production (Kozlowski, 1997)**.** Radiation use efficiency (RUE) depends on the distribution of direct and diffused light within the canopy and the efficiency with which leaf photosynthesis occurs. Having a direct effect on canopy development as well as on the efficiency of photosynthesis, salinity exert a negative effect on RUE in saline and hypoxic environments (Muchow *et al*., 1993). Alvino *et al.* (2002) recorded a decrease in RUE with an increase in salinity, and more so at high rates of irrigation in sunflower.

2.3.6 Crop Adaptation and Tolerance

Genetic variation occurs within and between species for salt tolerance. Plant tolerance to salinity involves processes in different parts with their manifestation at disparate levels of organization, such as gross morphology, membrane transport, biochemistry and gene transcription. The exclusion of the salt by the exodermis is by far the most efficient mechanism. However, multiple adaptations to high sodium operate concurrently within a tolerant plant. These adaptive mechanisms can occur at two levels of organization, i.e. cells or whole plant. Though salt tolerant cells can contribute towards a salt tolerance of plants, more importantly are the processes involved in the management of Na^+ movements within the plant through coordinated actions of these specific cell types in relation to catalysing the transport of Na^+ into and within the plant (Tester and Davenport, 2003). Cellular adaptations to high Na^+ are best achieved by intracellular compartmentation. The most direct way to maintain low cytoplasmic Na^+ is to sequester it in vacuoles within each plant cell. Zhang and Blumwald (2001) demonstrated that transgenic tomato plants over-expressing a vacuolar Na^+/H^+ antiport were able to grow, flower, and produce fruits in the presence of 200 mM NaCl solution and argue that modification of that single trait significantly improved the salinity tolerance of tomato. A relationship of relative crop yield compared to the salinity of the soil solution (EC_{se}) is shown in figure 2.3.2.

Crop growth, development and yield are generally perturbed in saline soil particularly for the non-halophytes. Most of the crop species of economic importance are either sensitive, or are only moderately tolerant to salinity. There are only a few crops of economic importance that are tolerant to salinity (e.g., beetroot, sugar beet). Hence, production of many sensitive and moderately sensitive crops has to contend with the inclemency of the saline soil environment.

Figure 2.3.2 Crop salinity response curve (Source: USDA, 1954)

2.3.7 Approach for Mitigation of Hypoxia in Saline/Sodic Soils

Aeration of the rhizosphere has been found to ameliorate saline conditions in terms of crop growth (Letey, 1961). Xu and Adams (1994) conducted an experiment on tomatoes and rice grown for 66 days in solution culture with and without aeration, and at two different salinity levels. Root growth was reduced significantly in non-aerated solution and without interplanted rice. Inter-planted rice stimulated tomato root and shoot growth compared without aeration, and increased total dry weight, leaf area and fruit yield by up to 26, 34 and 22%, respectively. The dry weight of tomato plants grown with rice was only 60% that of the aerated ones but the area of corresponding upper leaves was 73%. Water and nutrient uptake were reduced by non-aeration. An enhancement of growth in the tomato inter-planted with rice compared to without aeration can be explained by tomato using O_2 which escaped by the process of radial O_2 losses from the rice roots. High radial release of O_2 from rice roots in anoxic conditions was also reported by Kim *et al*. (1999). Therefore, it is convincing that increased aeration can improve performance of a crop under saline environments. There are no reports if field research on aeration effects on crop growth in saline environments. Chapter 5 of this thesis brings the results together showing that oxygation improved plant performance and yield in saline in heavy clay soil.

3
Subsurface drip irrigation of cotton in Vertosols

3.0 BACKGROUND

Cotton is one of the most water–demanding crops. It can be grown as an irrigated or rainfed crop; however, global cotton production is gradually shifting towards irrigated cropping. Irrigated cotton offers high returns to other production inputs such as fertilizers and agro-chemicals, and leads to predictable quality and yield.

Cotton can be irrigated by various methods such as flood, furrow, sprinkler, central pivot and sub-surface drip irrigation (Anonymous, 1999). However, furrow is by far the most common method for cotton irrigation worldwide. Increased competition for water with other sectors of society and the recent trend for pricing of irrigation water have resulted in sub-surface drip irrigation (SDI) as one of the prime choices for efficient irrigation. Cotton is quite deep-rooted crop and planting in wide row spacings makes it suitable for SDI.

Earlier research on cotton SDI has focused more on light and medium textured soils. Knowledge on SDI cotton in heavy clay soils is scanty and the practice is poorly understood. Cotton production in many parts of the world, including Australia, uses furrow irrigation on sizable acreages of heavy clay soil, accruing significant loss of irrigation water (McHugh, 2001a).

SDI can offer benefits in such soil provided the right SDI rates and crop management methods are developed. Therefore, experiments were conducted over 2001/02002 and 2002/2003 seasons with cotton on a heavy clay soil, irrigated at the rate of 50, 75, 90, 105 and 50, 75, 90, 120% of daily crop evapotranspiration rate respectively with SDI and were compared with the conventional furrow irrigation method.

The effects on cotton growth, development, yield, lint quality, root and soil water pattern in the profile, water balance and resource use efficiency with respect to different irrigation rates in SDI and the furrow method were investigated in the experiments. These results are presented in two sections in this chapter, covering the response on yield and quality in the first, and water use, water balance and resources use efficiency in the second:

Section 3.1. Subsurface drip and furrow irrigation of cotton in a heavy clay soil: Effects on growth, development, yield and lint quality.

Section 3.2. Subsurface drip and furrow irrigation of cotton in a heavy clay soil: Effects on soil water distribution, root growth, water balance and light and water use efficiencies.

Some of the information presented on these two sections is also already published, in two conference proceedings (refereed) and a journal, and one manuscript is submitted to the Journal of Experimental Agriculture for publication. These are listed as footnotes in respective sections.

Image 2 A view of furrow irrigation (A), the SDI control system (B) and a SDI field.

3.1

Subsurface drip and furrow irrigation of cotton in a heavy clay soil: Effects on growth, development, yield and lint quality[1]

ABSTRACT

The practice and management of subsurface drip irrigation (SDI) on heavy clay soils is poorly understood. Experiments conducted in 2001/02 and 2002/03 on cotton (*Gossypium hirsutum* L.) in a heavy clay soil in Australia evaluated the effect of subsurface drip irrigation (SDI) at various application rates on cotton yield and quality in comparison with conventional furrow irrigation. When 50% of daily crop evapotranspiration (ETc) was supplied by SDI, the maturity of the crop was hastened by 19 to 30 days compared to furrow and higher SDI rates of irrigation. A shorter season may favour logistics when integrating winter crops with summer cotton and reduces the number and cost of pesticide spray and irrigation. Yield plateaued when 75% of daily ETc was supplied by SDI as compared to water application that satisfied 90, 105 or 120% of ETc. Yields from plots with farmer-managed furrow irrigation were similar to the highest SDI yields in the first year, but in the second year, with improved irrigation practice, lint yield exceeded that of the best SDI treatment by 23%. Light interception, and some of its formative components e.g., node and branch number, increased with increasing rate of irrigation, as did plant height and the position of the lower-most flowering node. Leaf chlorophyll concentration declined with increasing irrigation rate. Yield was more closely associated with number of bolls per plant than with individual boll weight. Although the effects of irrigation on cotton quality were found to be significant, the differences were too small to have any practical significance. Rather, the response to irrigation was not consistent across years suggesting, because different varieties were used in each year, that the response is highly variety specific.

[1] Part of this section has been published in *the Proceedings of 11th Australian Crop Science Congress* (2003), with the title: "Physiological responses of cotton to subsurface drip irrigation on a heavy clay soils", Authors are Surya P. Bhattarai, A.D. McHugh, G. Lotz and D.J. Midmore and part has been submitted for publication to the journal*, Experimental Agriculture*, under the title: "Cotton under subsurface drip and furrow irrigation in a heavy clay soil". Authors are Surya P. Bhattarai, A.D. McHugh, G. Lotz and D.J. Midmore.

3.1.1 INTRODUCTION

Irrigated agriculture occupies about 18% of cultivated land and produces one third of the world's food (Davis and Hirji, 2003). However, the conventional methods of flood and furrow irrigation are neither efficient in terms of water application nor are they environmentally friendly (Jensen *et al.,* 1990). The irrigation efficiency (defined as the amount of water added to the root zone divided by the amount of water taken to the field) varies markedly between different methods of irrigation. For example, the efficiency of furrow irrigation is only about 56% (Goyne and McIntyre, 2002), sprinkler irrigation about 75% whereas the efficiency of subsurface drip irrigation (SDI) can reach 90% or higher if properly managed (Kruse *et al.*, 1990). As irrigation water becomes more and more scarce for agriculture worldwide, and more attention is paid to issues of environmental integrity, harnessing the advantage of SDI is an imperative for the irrigated agricultural industries.

Subsurface drip irrigation not only offers greater irrigation efficiency in crop production, it also offers a multitude of advantages over other commonly adopted methods of irrigation. Compared to furrow irrigation, these include raising water use efficiency (WUE), i.e. the production of marketable unit of a crop per unit of water consumed in evapotranspiration (ET), and reducing negative environmental impacts due to lessened movement of off-site runoff, sediment, pesticides and nutrients. The associated benefits in reduced disease; insect/pest and weed infestations have also been reported with SDI (Camp, 1998). There is growing interest in the use of SDI globally, not only because of its ability to increase WUE, but also because of the significant pressure to conserve water and the ready access to sophisticated and reliable SDI technologies.

Research elsewhere for a number of crops has quantified the substantial increase in yield and WUE over sprinkler or furrow irrigation achieved through the installation of SDI (Camp *et al.*, 1997). In hot arid climates with low and unreliable rainfall, yield with SDI has been shown to substantially improve by 25%, particularly in light textured, highly permeable soils (Bresler, 1977). It has been on light textured soils or in areas where conventional furrow irrigation methods are considered unsuitable, that SDI has been successful (Camp *et al*., 1997). The cotton crop has been found to be responsive to SDI (Plaut *et al.*, 1996) notably on sandy and loamy soils. However, a large proportion of irrigated cotton is also grown on heavy clay soils, and whether the realised benefits of SDI from light textured soils still hold true for heavy clay soils is not known (McHugh, 2001b).

As heavy clay is one of the dominant soil types around the world, and as cotton is one of the important and water-demanding crops grown on such soils, we evaluated the performance of SDI for cotton on a heavy clay soil in order to validate SDI as an alternative irrigation method to the conventional furrow irrigation.

This section of the thesis presents data from the comparison of SDI over different irrigation rates (based on a function of the daily evapotranspiration rate of the crop) to that of traditional furrow irrigation. The latter dominates irrigation practice for cotton worldwide (Eldeiry *et al.*, 2004). Aspects of cotton growth, development, yield and quality are presented herein and data on physiological attributes, WUE and radiation use efficiency (RUE) and their response to the different irrigation rates in SDI and furrow treatment are presented in the accompanying section 3.2.

3.1.2 MATERIALS AND METHODS

3.1.2.1 Experimental Site

The experiments were conducted on cotton (*Gossypium hirsutum* L) over two years, 2001/02002 and 2002/2003, on a soil designated as 6Aug-9 (Australian soil classification system), which is classified as gypsic vertosol, at Emerald in central Queensland, Australia ($23^0 28^, 22.4''$ S, $148^0 19^, 49.8''$ E; elevation 190 masl).

3.1.2.2 Crop Details

The experiment in 2001 was planted on 26 September with cotton variety NuTopaz, Ingard™ and on 15 September 2002 with variety Sidcot 289i. Both varieties incorporate Bt genes, are determinate, short stature, high yielding and of the same maturity class. The two varieties, therefore, resemble each other closely. Crops were sown with a tractor-driven seeder in metre spaced rows on low permanent 2 metre centre beds with a crop establishment of 12 plants m^{-1}.

3.1.2.3 Experimental Design and Treatments

The experiment was laid out as a randomised complete block design with three replications for both years. Individual plots were 270 m x 16 m, i.e. 16 rows of 270 m length and data in each plot were collected from 10 plants per row of four randomly selected bordered rows. An Environdata™ Weathermaster 2000 weather station located adjacent to the SDI site monitored rainfall, temperature, wind speed and direction, humidity, solar radiation and ETo (Modified Penman-Monteith). Accumulated heat units after planting (HUAP) and related cotton growth stages (Anonymous, 2005) were used to determine local crop factors (Kc) to convert daily ETo to crop evapotranspiration (ETc). Four daily irrigation treatments, 50, 75, 90, and 120% of ETc (approximately 6, 8, 10 and 12 mm d^{-1}) randomised in three blocks were applied to the twelve SDI bays. In the second year the 120% application was reduced to 105% and peak daily applications were capped at 6, 8, 10 and 12 mm d^{-1}.

The levels of irrigation were designed to provide differing levels of soil dryness, so that rainfall would be stored in the soil and rain-induced runoff limited, yet without compromising yield. The four irrigation levels, therefore, provided a means to a) determine WUE of cotton under adequate and deficit irrigation, b) manipulate soil water profile conditions, c) increase in-crop rainfall storage and therefore d) decrease negative environmental impacts associated with runoff and deep drainage. Irrigation in the furrow plots was a standard check for comparison with SDI treatments in each year. Furrow irrigation management followed farmer's best practice, i.e. optimised furrow irrigation was adopted. Due to logistic reason, the furrow irrigation treatment could not be incorporated into the experimental design with the SDI treatments. In the first year SDI was automated with volumes adjusted every 3 to 5 days according to daily ETc. Irrigation was applied during the day. In the second year applications were automated and adjusted daily on a three-day rolling average, applied exclusively at night and capped at predetermined levels. An in-line water metre measured total applied water and the SDI computerised controller monitored volumes applied to individual plots. In the second year in the furrow irrigation treatment, early season water stress was reduced (Figure 2), the flow rate was increased by 1 L s^{-1}, and irrigation ceased before tail water was produced. Tail water is the water that exits the field area as surface runoff during or after an irrigation or rainfall event.

Conducted for two consecutive years on the same field, treatment plots were re-randomised within blocks in the second year. All plots were managed uniformly, except for irrigation applications. The farmer managed the furrow site in the same manner as the rest of the property, except for pest and growth control (i.e. the use of Pix® to reduce plant height (Edmisten, 1994), which was the same as for the SDI treatments. All crop nutrients were supplied by the drip system uniformly to all the treatments as per the standard recommendation. Furrow plots also received the same amount of fertilizer as the SDI plots, but split on four occasions. All the plots received exactly the same nutrients, irrespective of the water quantity applied.

3.1.2.4 Irrigation Design and System

An automated SDI system capable of irrigating 12 mm day^{-1} was installed by a tractor-mounted global positioning systems (GPS) Agsystems Beeline ® row crop unit with auto-steer to 2 cm accuracy for SDI plots. The SDI plots as mentioned comprised twelve 0.4 ha bays, and water to each bay was individually controlled and measured. The SDI tapes were installed on 1 m centres on 8 bays (two blocks) and 2 m centres on 4 bays (one block). The laterals were buried at 40 cm depth and had emitters spaced at 40 cm delivering 0.7 and 1.4 l hr^{-1} in 1 and 2 m configurations, respectively. The furrow plots were 530 m in length and consisted of blocks of 8 rows and 16 rows in the first and second year, respectively. The furrow rows were configured as 10 cm high beds centred on 1 m, and irrigated in alternate rows by siphons.

The volume of irrigation water applied to the furrow-irrigated site was calculated based upon the siphons diameter, the head difference, the irrigation time, and standard tables. Head ditch water level during irrigation was monitored by a Millitronics ultrasound water level sensor and a Monitor TM logger.

3.1.2.5 Instrumentation

Real time soil moisture content was monitored by Enviroscan soil moisture probe systems (time domain reflectometry), consisting of 15 moisture probes (one in each furrow irrigated bay and one in each of the SDI plots). Probes were located close to the drip tape row adjacent to an emitter, approximately 0.1 m from the 1 m spaced drip tape or 0.5 m from the 2 m spaced tape in each plot, and 20 m from the end of each furrow site. However, in the second year the centre of each SDI probe location was triangulated at 0.1 m from the tape and 0.1 m from the emitter. Each probe supported 4 or 5 sensors (depending on the probe length of 80 cm or 100 cm) at 20 cm intervals, but data were only collected as the mean value over the whole probe. Probe calibration was for an adjacent cotton property on similar soil. The soil moisture data are presented as mm water per 100 mm of soil depth.

For SDI and furrow the drainage below the active root zone, was calculated as the difference between applied water and crop water use + tail water. Tail water is water that exits the field area as surface runoff during or after an irrigation or rainfall event and is measured at the bay discharge pipe. Crop water used was estimated according to Martin *et al.* (1993). Water not accounted for in crop water use and runoff was presumed to be lost below the root zone.

3.1.2.6 Data Collection for Crop Growth and Development

Data were collected to quantify soil moisture, water delivered, crop physiological responses, and yield and yield attributes. The observations for the growth and development and flowering parameters were made on five plants in each of four randomly selected rows in each plot. The selected plants were marked and all subsequent observations were made on the same plants. The percentage light interception was measured using an AccuPAR ceptometer (Decagon Devices Inc. USA). The leaf chlorophyll concentration (SPAD units) was monitored throughout the season on attached leaves using a Minolta chlorophyll metre SPAD-502. Data collected with the SPAD apparatus were converted to the chlorophyll concentration after extracting chlorophyll from the sample leaves and developing a calibration curve (Anonymous, 1994).

Ten randomly selected plants per plot were taken to determine dry matter partitioning at final harvest. Plants were harvested when the cotton crop was mature, before the application of defoliant (Freefall® WP @ of 150 g plus 2 L Ampol D-C-TRON cotton spray oil). Depending upon treatment, harvest for dry matter partitioning was 105-134 and 100-127 days after sowing in 2001/02 and 2002/03, respectively. The plants were separated into roots, stem, leaf, and fruits, and then dried at 70^{o}C to a constant weight. For the root, three soil cores per plot were taken at 5, 25, 50 cm from the emitter in the tape and one core 50 cm away from the tape between two emitters, to a depth of 120 cm in 30 cm segments, and roots from the cores were recovered by washing the roots using 1% solution of 'Groundbreaker' (active constituent 10 g L^{-1} buffered polylignosulfonate) produced by Multicrop (Aust.) Pty. Ltd. Washed roots were then scanned for the measurement of root length and diameter using a Hewlett Packard scanner and Delta-T software.

3.1.2.7 Yield Determination

Cotton yield was quantified using a commercial harvester, which individually harvested the central eight rows of the SDI bays and the central four rows of the furrow bay. The harvester was weighed prior to and at the end of each run to measure treatment yield. Yield was calculated using a gin turn-out factor of 36 percent (Shaw, 2002). Grab samples from each site were taken from the harvester for seed and lint quality, with analysis undertaken at DPI Biloela and CSIRO Narrabri, respectively. After harvest, 10 plants in four rows from each plot were randomly selected and were hand-harvested to assess field machine harvest losses (which did not differ due to treatment), and this was added to the yield.

3.1.2.8 Data analysis

The cotton yields, their components and data on biomass distribution were subjected to an analysis of variance to determine the effect of level and method of irrigation. The data were not subjected to a combined analysis over years, because the variety used in each year was different, and there was also a slight change in the treatment composition over two years, specifically the 120% of ETc was changed to 105% of ETc for the second year, and modifications were made to the farmer's furrow irrigation treatment in the second year. All statistical analyses including correlations were computed using the statistical software Systat version 9.0 (SPSSInc, 1999).

3.1.3 RESULTS

3.1.3.1 Local Weather, Water Application Rate and Soil Moisture

The daily mean temperature and range during the growing seasons of the two years was similar [*c*. 25.5 ^{o}C (18.6-33.9 ^{o}C) and 25.0 ^{o}C (17.5-33.3 ^{o}C)], however, the seasonal total rain was 181.2 mm and 113.0 mm in 2001/02 and 2002/03, respectively (Figure 3.1.1). The average daily evaporation recorded was 8.51 mm (range 1.9 - 11.6) and 9.61 mm (range 3.2 – 13.9) with the season mean relative humidity of 52.6 and 46.3 percent respectively, for the first and second year experiments. Likewise, the daily average solar radiation over the season was 24.8 (7.7-31.6), and 26.2 (9.2-32.1) MJ m^{-2} and growing season totals were 3692 and 4324 MJ m^{-2} for the first and second year respectively.

The season-long depths of applied water, expressed in mm for each treatment and added to the rainfall, are presented as Tables 3.1.1 and 3.1.2. The changes in soil water content averaged over the soil depth to 80 cm for different treatments throughout the crop season are presented in Figure 3.1.2. Soil water content averaged over the 80 cm depth profile over the season (note that this included some surface soil that was quite dry in some treatments) was consistently higher for SDI 120 or 105 followed by 90, 75 and least for SDI-50% ETc. The SDI treatments had almost stable soil water content whereas the furrow plots showed greater variation with high water content after irrigation followed by slow then more rapid drying.

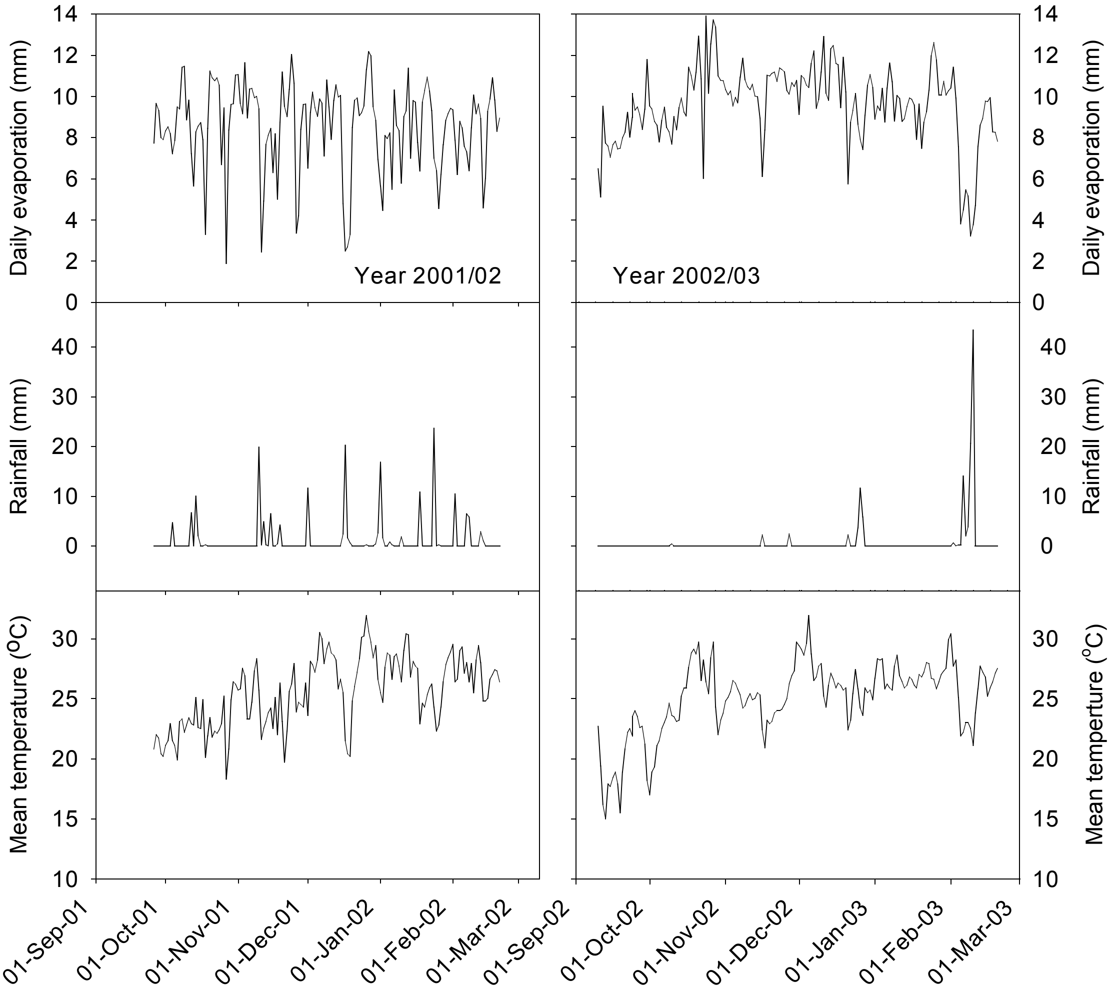

Figure 3.1.1 Daily mean ambient temperature, precipitation and pan evaporation over the cotton growing periods in 2001/02 (left), and 2002/03 (right) at Emerald, Central Queensland, Australia.

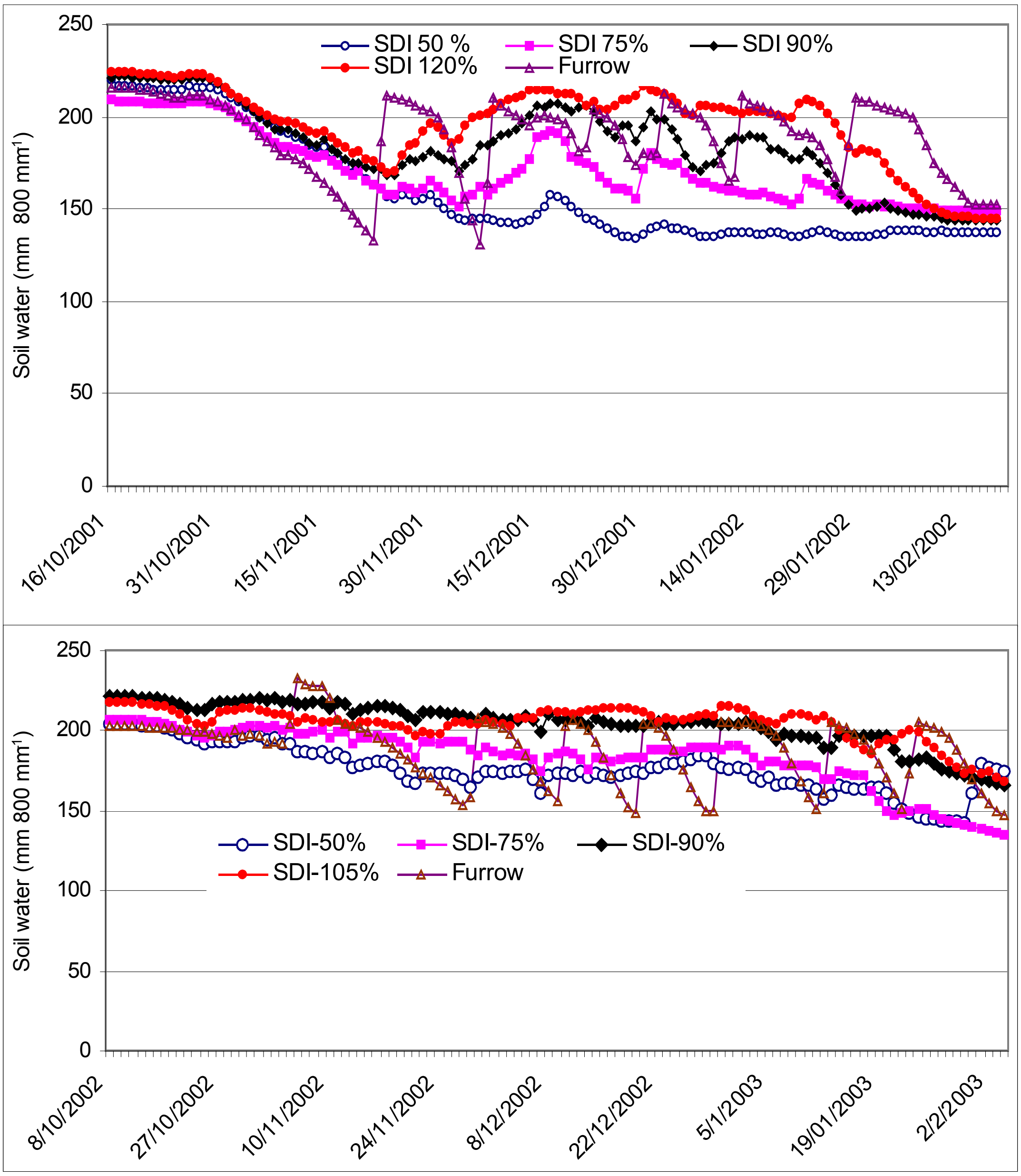

Figure 3.1.2 Changes in soil water content (soil water mm 800 mm $^{-1}$ of soil depth) over the crop period for different irrigation treatments of cotton in a heavy clay soil at Emerald during 2001/02 (top) and 2002/03 (bottom) season.

3.1.3.2 Growth Parameters

Plant height, number of nodes, number of vegetative branches, internode length and location of lower-most flowering nodes significantly differed with respect to irrigation rates and type of irrigation. Plant height, internode length and number of branches per plant increased significantly with one exception in response to increasing quantity of irrigation in both years. Cotton irrigated at 50% of daily ETc produced significantly ($P \leq 0.05$) shorter plants and fewer branches compared to other treatments in both years (Tables 3.1.1 and 3.1.2). Internode length differed due to treatments in 2001/02 but not in 2002/03. In 2001/02, the internode length was reduced significantly ($P \leq 0.05$) in SDI 50, 75 and 90% of daily ETc compared to SDI at 120% and furrow treatments. Position of the lowermost flower in the stem of cotton is indicative of crop maturity and earliness. The effect of irrigation treatments on the position of the lower most flowering node was significant ($P \leq 0.05$) in the first year such that the crop irrigated at 50% of ETc had the lowest nodal position for the first flower compared to all other treatments in both years (Tables 3.1.1 and 3.1.2). In general the crop in the 2002/03 season was shorter, and had fewer nodes and branches and shorter internodes compared to the crop in 2001/02.

3.1.3.3 Canopy Light Interception and Leaf Chlorophyll Content

Percentage light interception by the canopy averaged over the season (Table 3.1.1 and 3.1.2) indicated a gradual increase as rate of irrigation increased. The lowest light interception was for SDI 50% ETc whereas furrow had the greatest canopy light interception ($P \leq 0.05$). Complete canopy cover was never achieved in either year although furrow irrigation was close to achieving it. Leaf chlorophyll concentration was significantly greater at lower irrigation rates compared to that for rates of irrigation delivering >100% of ETc, including the furrow irrigation treatment in 2001/02 and 2002/03 seasons. The SDI at 50% ETc had the highest chlorophyll concentration throughout the growing season in both years compared to all other treatments (Tables 3.1.1 and 3.1.2).

Table 3.1.1 Water input and cotton plant and leaf characteristics as affected by SDI rates and furrow irrigation at Emerald, 2001/02 season.

Treatment[1]	Irrigation and rainfall (mm)	Plant height (cm)	Nodes (No.)	Vegetative branch (No.)	Inter-node length (cm)	Lower-most flower node	Light interception[2] (%)	Chlorophyll concentration (µg cm^{-2})	Boll set (%)
SDI- 50% ETc	423	82.2	19.0	12.1	4.3	5.5	72	132.3	75
SDI-75% ETc	460	98.5	20.9	16.3	4.7	6.2	78	129.7	79
SDI-90% ETc	561	96.5	20.0	15.9	4.8	6.6	78	124.0	81
SDI-120% ETc	732	117.0	21.0	18.9	5.5	6.6	83	121.8	81
LSD (6 df)		6.8	ns	2.0	0.14	0.34	3.74	4.6	2.22
Furrow	1044	115.1	20.0	19.8	5.7	7.2	86	122.1	81
SE (n=3)		1.09	0.58	0.31	0.06	0.17	1.16	0.59	1.20

Table 3.1.2. Water input and cotton plant and leaf characteristics as affected by SDI rates and furrow irrigation at Emerald, 2002/03 season

Treatments[1]	Irrigation and rainfall (mm)	Plant height (cm)	Nodes (No.)	Vegetative branch (No.)	Internode length (cm)	Lower-most flower node	Light interception[2] (%)	Chlorophyll content (µg cm^{-2})	Boll set (%)
SDI- 50% ETc	430	67.7	16.7	11.0	4.1	5.3	64	123.3	72
SDI-75% ETc	576	77.8	19.8	13.0	3.9	6.7	68	116.4	77
SDI-90% ETc	673	86.2	21.8	15.0	3.9	6.5	74	114.5	80
SDI-105% ETc	694	81.2	19.2	17.0	4.2	6.3	72	112.6	79
LSD (6 df)		13.0	3.1	0.12	ns	ns	6.7	4.2	2.56
Furrow	927	94.8	20.5	18.0	4.6	6.8	75	118.1	78
SE (n=3)		1.30	0.50	0.58	0.13	0.17	0.86	0.06	2.73

[1] See text for details [2] Average of weekly readings over the season starting 45 das.

Table 3.1.3 Dry weight (g plant^{-1}), its partitioning at harvest and, yield attributes in response to SDI rates and furrow at Emerald, 2001/02.

Treatments[1]	Root	Stem	Leaf	Fruit	Above-ground biomass	Total biomass	Shoot:root ratio	Fruit wt (g boll^{-1})
SDI- 50% ETc	21.2	20.7	11.4	66.5	98.7	119.9	4.6	5.25
SDI-75% ETc	23.3	32.7	14.7	90.1	137.6	160.8	5.9	6.93
SDI-90% ETc	23.3	29.3	15.8	77.9	123.1	146.4	5.3	5.31
SDI-120% ETc	23.6	46.0	21.1	94.1	161.3	184.9	6.9	6.01
LSD (6 df)	ns	13.3	ns	19.6	37.6	42.7	ns	ns
Furrow	20.4	36.4	21.0	91.4	148.9	169.3	7.2	5.78
SE (n=3)	0.58	0.75	1.91	0.69	3.00	3.00	0.15	0.14

Table 3.1.4 Dry weight (g plant^{-1}), its partitioning at harvest and, yield attributes in response to SDI rates and furrow at Emerald, 2002/03.

Treatments[1]	Root	Stem	Leaf	Fruits	Above- ground biomass	Total biomass	Shoot:root ratio	Fruit wt (g boll^{-1})
SDI- 50% ETc	21.4	26.3	18.8	59.6	104.7	126.1	4.9	6.62
SDI-75% ETc	20.3	30.4	23.4	83.9	137.7	158.0	6.8	6.71
SDI-90% ETc	22.3	33.4	23.9	87.9	145.3	167.7	6.5	7.64
SDI-105% ET c	23.9	31.6	21.1	68.8	121.4	145.3	5.1	6.88
LSD (6 df)	ns	ns	ns	18.7	ns	ns	ns	ns
Furrow	19.5	27.3	24.6	96.6	148.5	167.9	7.6	7.72
SE (n=3)	1.78	3.1	1.86	10.12	14.87	16.54	0.30	0.69

[1] See text for details

3.1.3.4 Reproductive Development and Crop Maturity

Seasonal development of cotton fruiting forms in relation to rate of SDI irrigation or furrow is shown in Figure 3.1.3. Fruit formation began with the appearance of the first square, which was substantially earlier in SDI at 50% of daily ETc, and was followed by 75% of ETc, and was latest on SDI treatments of >100% of ETc and furrow irrigation in both years. The same trend followed for first flowering, formation of green bolls and the boll opening. The crop maturity, expressed in terms of 100% of bolls opening, was shorter by 30 days and 20 days in SDI 50% ETc compared to SDI >100% ETc and furrow treatments in 2001/02 and 2002/03, respectively.

3.1.3.5 Dry Matter and its Partitioning at Harvest

The total dry biomass of the plants at harvest was lower, significantly ($P \leq 0.05$) so in the first year, for SDI at 50% of daily ETc compared to all other treatments (Table 3.1.3 and 3.1.4). However, SDI at 75% of ETc had comparable total biomass to that of the furrow and other higher-rate SDI treatments. Likewise, there was a significant difference between treatments for the stem, and fruit and total above-ground dry biomass, but not for the root or leaf biomass between the treatments in 2001/02 (Table 3.1.3). Leaf biomass did show a tendency to increase with increasing irrigation. The treatment effects for biomass of root, stem and leaf, as well as above-ground dry biomass were not significant in 2002/03 (Table 3.1.4). Furrow irrigation resulted in a higher shoot: root ratio compared to all SDI treatments in both years (Table 3.1. 3 and 3.1.4).

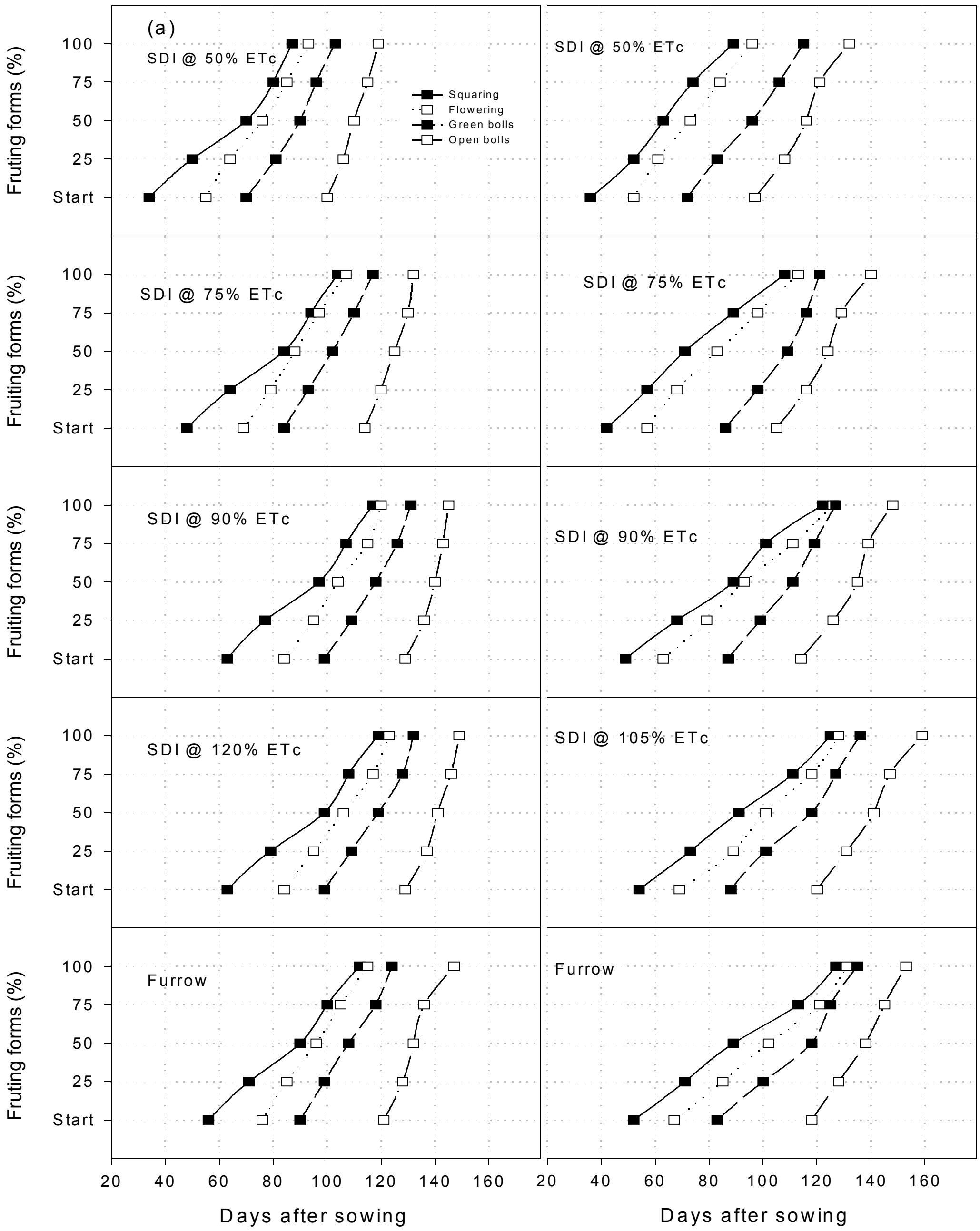

Figure 3.1.3 Development of fruiting forms as influenced by irrigation rates in SDI and furrow irrigation at Emerald, Central Queensland, Australia in (a) 2001/02 (left) and (b) 2002/03 (left).

3.1.3.6 Yield and Yield Components

Cotton lint yield was significantly ($P \leq 0.05$) lower in SDI 50% ETc compared to all other treatments in both years (Table 3.1.5 and 3.1.6). The highest lint yield was recorded for the furrow in 2001/02, but the yield difference between SDI at 75% ETc and furrow treatment was not marked (Table 3.1.5). However, in 2002/03 yield for the furrow treatment was considerably greater than that of all SDI treatments (Table 3.1.6). In general, seasonal mean yield across all SDI treatments was higher for the 2001/02 compared to 2002/03 seasons, but not for the furrow treatment.

Boll set (%) varied significantly ($P \leq 0.05$) due to level of irrigation in both years (Tables 3.1.1 and 3.1.2), and there was a significant reduction in fruit set in dry SDI treatments, particularly SDI at 50% ETc, compared to other treatments. However, the final effect of treatment on number of bolls per plant was not significant ($P \leq 0.05$) in either year. Nevertheless, fewer bolls were recorded per plant in SDI 50% ETc in both years compared to the number in other treatments. Mean weight per boll (Tables 3.1.3 and 3.1.4) did not differ between treatments in either year. Harvest index (HI), which is the ratio of lint yield to above-ground total dry biomass, differed significantly ($P \leq 0.05$) between treatments in the first year (Table 3.1.5). HI of the crop was greatest in SDI at 50% ETc and less for the wetter and furrow irrigated treatments. In the second year the HI did not differ between treatments, although that of the furrow irrigation tended to be higher than those of SDI treatments.

The seed yield differed significantly ($P \leq 0.05$) due to irrigation treatments in both years. The seed yield, as for lint yield, was also significantly smaller for SDI at 50% ETc compared to most other treatments in both years. The crop at 75% of ETc produced comparable seed yield to the furrow crop in the first year, whereas in the second year, the furrow treatment, as for lint yield, out-yielded all other SDI treatments. The differences in seed yield between SDI at 75, 90 and 105/120% ETc were not marked in either year.

3.1.3.7 Lint Quality

The effect of irrigation treatment was significant for fibre length in the first year (Table 3.1.5) and for fibre strength in the second year (Table 3.1.6). The standard set for staple length is 2.5%; span length should be a minimum of 27.4 mm. The cotton sample in 2001/02 from SDI at 50% ETc had span length value below this standard. The micronaire minimum is 3.8 and maximum is 4.4. In 2001/02 micronaire values were close to acceptable for all treatments except for SDI at ETc 50% and ETc 75%, and in 2002/03 all the treatments except SDI at 50% ETc had values beyond the normal range. The strength was within the acceptable (> 28 g tex^{-1}) range except for the driest SDI treatment in 2001/02. Uniformity-wise the produce was fine (≥ 83%) in the first year (a value of c. 84% is considered acceptable), but marginally acceptable in the second year (c. 83%). Quality in terms of elongation was within the normal range (≥ 6%) for 2001/02 but completely out of range in 2002/03. The short fibre index in the experiment was outside of the acceptable range (≤ 5% index) irrespective of the irrigation treatments in both years. As the variation between the irrigation levels and soil moisture content and between weather patterns was not markedly different between the years, the observed differences between the two years in terms of elongation and uniformity can be implied to be varietal.

Table 3.1.5 Lint and seed yield, and lint quality parameters in response to SDI rates and furrow irrigation at Emerald, 2001/02 season.

Treatments[1]	Yield and lint quality parameters for cotton									
	Lint yield (t ha^{-1})	Seed yield (t ha^{-1})	Bolls $plant^{-1}$ (No.)	HI	[2]Lint quality indicators					
					Length (mm)	Length uniformity ratio (%)	Short fibre content (% index)	Strength (g tex^{-1})	Elongation (%)	Micronaire
SDI- 50% ETc	1.80	2.50	12.7	0.26	26.9	83.2	7.1	26.63	9.4	4.67
SDI-75% ETc	2.02	3.27	13.0	0.25	28.4	84.4	6.4	28.53	8.9	4.40
SDI-90% ETc	1.98	2.85	14.7	0.24	28.7	84.8	6.3	28.90	9.0	4.40
SDI-120% ETc	1.94	3.46	15.7	0.22	29.7	83.6	7.2	28.00	9.6	4.47
LSD (6 df)	0.09	0.66	ns	0.04	1.5	0.92	ns	ns	ns	ns
Furrow	2.04	3.33	15.8	0.23	28.4	84.4	5.3	30.20	8.9	4.40
SE (n=3)	0.01	0.05	0.58	0.001	0.02	0.006	0.006	0.009	0.03	0.06

Table 3.1.6 Lint and seed yield, and lint quality parameters in response to SDI rates and furrow irrigation at Emerald 2002/03 season.

Treatments[1]	Yield and lint quality parameters for cotton									
	Lint yield (t ha^{-1})	Seed yield (t ha^{-1})	Boll $plant^{-1}$ (No.)	HI	[2]Lint quality indicators					
					Length (mm)	Length uniformity ratio (%)	Short fibre content (% index)	Strength (g tex^{-1})	Elongation (%)	Micronaire
SDI- 50% ET c	1.54	2.47	9.0	0.22	28.7	82.9	8.4	29.85	5.6	4.30
SDI-75% ET c	1.84	2.96	12.5	0.23	28.4	82.7	9.1	28.87	5.5	4.73
SDI-90% ET c	1.81	2.91	11.5	0.23	28.2	82.7	9.4	29.13	5.4	4.77
SDI-105% ET c	1.84	2.96	10.0	0.22	28.9	83.1	8.9	29.47	5.4	4.93
LSD (6 df)	0.19	0.31	ns	ns	ns	ns	ns	0.88	ns	0.26
Furrow	2.26	3.65	12.5	0.25	29.7	83.7	8.0	30.17	5.9	4.87
SE (n=3)	0.057	0.09	0.81	0.006	0.08	0.10	0.21	0.64	0.07	0.07

[1] See text for details [2]The minimum bench mark value for different quality parameters are Length = 27.4 mm, Length uniformity ratio = >83%, Short fibre index = ≤ 5%, Strength = > 28 g tex^{-1}, Elongation = > 6% and Micronaire = 3.8-4

3.1.4 DISCUSSION

The reproductive performance and yield of cotton depends on prior vegetative performance. The rate of vegetative growth prior to onset of flowering in cotton is highly dependent on temperature as well as being very sensitive to soil and plant water status (Gerik *et al.*, 1994). Reduced plant height, number of nodes, branches and leaf number as well as leaf area noted in the drier SDI treatments were linked with reduced biomass yield. Although HI was higher in the more water-stressed treatment in both years, it was not sufficiently high to offset the total reduction in biomass, therefore, lint yield was also lesser in the drier SDI treatments.

The cotton plant establishes its basic vegetative structure within 1-2 months after sowing. Soil moisture at this establishment phase has a large effect on the development of vegetative and subsequent reproductive forms (Pace *et al.*, 1999). Restriction of water application reduces canopy size, and the extent of the reduction depends on the availability of soil moisture and dryness of air throughout the growing season. Irrigation at 50% ETc constrained light interception when compared to that of treatments with higher rates of irrigation, from the time measurements were made till 150 days after sowing. Water stress in cotton affects crop performance by decreasing the rate of growth, by decreasing the rate of leaf initiation and the ultimate size of new leaves, and by increasing the rate of senescence of existing leaves (Gerik *et al*., 1994).

While the rate of photosynthesis was reduced as the irrigation application rate was reduced (Bhattarai, *et al*., 2003a submitted), leaf chlorophyll concentration increased markedly. As the treatments were provided with the same amount of fertilizer, treatments with a smaller canopy and leaf area index showed a greater concentration of chlorophyll in the leaf. Such an increase in chlorophyll concentration in response to deficit irrigation has been observed in other crops (Poorter and Evans, 1998).

Soil water availability is one of the primary edaphic factors which acts to influence and perhaps even control, directly or indirectly, production of potential fruiting points, retention of squares and bolls, and yield of cotton (Jordan, 1986). Reduced water application rate hastened the initiation of fruiting forms, and, therefore, the crop maturity, and significantly fewer fruiting forms were evident with 50% ETc (Tables 3.1.4 and 3.1.5). Location of the first fruiting branches, an indicator of crop earliness, is highly dependent on variety, climate and soil moisture; and generally occurred at the 5-7th nodes. That flowering was observed at lower nodes in the deficit irrigation (50% ETc) compared to the wetter treatments is in agreement with the findings of Grimes and Yamada (1982). The actual number of potential fruiting forms depends on the rate of production of successive nodes and on the ratio between, and location of, vegetative and fruiting branches. Reduction in vegetative growth rate associated with limited soil water availability has been reported before (Wrona and Kerby, 1994). Therefore, under deficit moisture, the production of total fruiting forms is also likely to be reduced, and that was clearly seen in the data when the crop was irrigated with 50% ETc as compared with higher irrigation rates. Production of total number of fruiting points and fruits per plant in cotton has been shown to be related to plant height (Hearn, 1994).

The total fruit load, i.e. fruit number, in the first year, showed a near linear correlation with plant height during early fruiting stages, such that the positive relationship between height and fruit load was sustained until harvest across irrigation treatments. This suggests that increasing the plant height is perhaps an option for increasing fruit load. However, in the second year, with the shorter variety, there was no association between fruit load and final plant height. The total fruit load in that year was reduced by the lowest irrigation rate, that that lead to the shortest height, but there was no significant gain in fruit load once the application rate exceeded 75% ETc.

Yield performance of cotton (i.e. lint yield) is dependent on soil moisture in the root zone. Lint yields were linearly related to number of bolls per plant (combined data for both years, r = 0.58 P = 0.06) and to a lesser extent to mean boll weight (but somewhat more so in 2002/03). Late in the fruiting period, the cotton plant started to "cut-out", i.e. no new nodes, fruiting branches, or squares were formed. Moisture stress induced by 50% and 75% ETc caused premature cut-out (Figure 3.1.3 and also reflected by earlier harvest) and reduced yield and fibre quality (Table 3.1.5 and 3.1.6).

Low cotton yield was linked to low fruit set, fewer bolls per plant, and to a lesser extent to smaller mean boll weight. Reduced numbers of fruiting forms due to deficit moisture was also reported by (Krieg and Sung 1986) for a short season cotton variety. Significant reduction in yield at irrigation rates of 50% ETc or less with SDI compared with 75 to 100% has been observed in a number of other crops and soil types (Ayars *et al*.,1999). The significant gain in the lint yield with SDI at 75% ETc compared with the driest treatment is in agreement with the work by Dippenaar *et al*. (1994) on a red clay soil. Lint yield was lower for SDI treatments in the second year compared to the first year, but not so for furrow. Part of this difference is possibly related to varietal characters associated with structure and function of the root system, in part to the difference in relative humidity between years and possibly because night-time irrigation in the second year was more favourable for furrow irrigation, allowing for some drainage and re-aeration of the soil before daylight-induced plant root function is renewed.

Bhattarai *et al*. (2004) have shown the importance of aeration of the soil solution for optimal root function and growth. In addition, other management practices differed between years on the furrow plots. Early season stress was reduced in the second year (Figure 3.1.1), the flow rate was increased by 1 L s^{-1}, and irrigation ceased before tail water was produced, which reduced waterlogged conditions and water loss to drainage (Bhattarai *et al.,* 2005a).

Lint quality is responsive to soil water content during the cotton production season (Jordan, 1986). Unfavourable growing conditions, including moisture stress, can reduce fibre quality significantly (Grimes and El-Zik, 1990). Cotton is differentiated by quality parameters for the purpose of trade. There are different quality parameters and any export cotton lint not meeting the benchmarks quality would face the discounted price. Traditionally cotton pricing was largely determined by factors such as staple length, grades, colour and micronaire. Spinners are more inclined to scrutinise fibre properties that affect the quality of their yarn and the efficiency at which they produce that yarn, yet longer and finer fibres result in longer and finer yarns. However, the ranking depends on types of spinning such that length is ranked first before strength and micronaire in ring spinning, and strength ranks first before micronaire and length for rotor spinning (Estur, 2003).

Response of many quality parameters to irrigation treatments was not consistent over the two years. Fibre length and strength decreased below acceptable levels in driest (50% ETc) SDI treatment in the first year but not in the second. It is possible that the varietal effect was the overriding factor, as the genetic makeup of a cultivar largely controls fibre quality traits (Davidonis, *et al*., 2000). Marked difference was noted particularly for short fibre index and elongation of lint between years (Table 3.1.5 and 3.1.6), possibly due to the difference between cultivars. El-Rifai (1994) also noted, in line with this data, that cotton lint quality does not vary as greatly in response to soil moisture contents as it does to difference in genotype.

3.1.5 CONCLUSION

It is clear that SDI should be of interest to growers of cotton on heavy soils as an alternative to furrow irrigation. Through precise manipulation of the irrigation rates with SDI, it would be possible to manipulate crop maturity and temporal and spatial soil water content in the soil profile. The data suggest that SDI cotton in heavy clay soil can adapt to low levels of irrigation without severe loss of lint yield. A 25% reduction of crop water requirements based on ETc and delivered by SDI produced as much lint yield as crops supplied with full crop evapo-transpiration requirements in a heavy clay soil. A 75% supply of the daily ETc supplied with SDI was more efficient than higher rates in terms of maintaining a higher yield, a control of the balance between vegetative and reproductive growth and, as discussed in following section 3.2, improving the efficiency of water use by the crop. Reducing the level of irrigation to 50% ETc significantly enhanced crop earliness, and resulted in reductions in water, fertiliser and pesticide applications to the crop. These all have significant bearing when planning crop rotation, weed control and disease management. It also widened the window for integration of a winter crop in cotton-based cropping systems. Yield did not increase significantly as irrigation was raised to a level beyond that necessary to satisfy >75% of daily ETc. The significance of this for WUE and runoff is discussed in the accompanying section 3.2.

3.2

Subsurface drip and furrow irrigation of cotton in a heavy clay soil: Effects on water distribution, root growth, water balance and light and water use efficiencies[1]

ABSTRACT

Experiments conducted in 2001/02 and 2002/03 on cotton (*Gossypium hirsutrm* L.) in a heavy clay soil evaluated the effect of subsurface drip irrigation (SDI) at various application rates on root growth, soil water balance, an economic analysis of the water-lint production function, water and radiation use efficiency and physiological performance in comparison with conventional furrow irrigation. SDI at 50 and 75% ETc (i.e., the product of crop factor and daily reference crop evapo-transpiration (ETo)) maintained a dry upper soil profile throughout the season which could potentially store c. 250 and 100 mm of extra rain during the season, respectively, compared to SDI 90% ETc, and even more compared to furrow.

Irrigation at 50% ETc consistently sustained higher crop water stress, lower leaf water potential and a decreased leaf net photosynthesis compared with the higher irrigation rates and furrow treatments. Net photosynthesis increased with increasing leaf water potential. Considerable water saving was possible with appropriate SDI management. Average applied water (irrigation + rain) during crop growth over the two years was 43, 53, 63, and 73% of that of the furrow in SDI 50, 75, 90 and 120/105% ETc, respectively. An economic analysis based on the water-lint production function, assuming AU$ 3 and AU$ 2 per mm water and kg lint, respectively, showed highest yield with 621 mm, however, the highest

[1] Part of this section has been submitted for publication the journal Experimental Agriculture, with the title: "Cotton under subsurface drip and furrow irrigation in a heavy clay soil". Authors are Surya P. Bhattarai, A.D. McHugh, G. Lotz and D. J. Midmore. Part of this section has also been published in the Indian Journal of Plant Physiology, 2003, Special issue, Volume 8, Part 1, page 55-62, under the title: "Studying the economical and physiological basis for cotton production on subsurface drip irrigation in heavy clay soils of central Queensland, Australia: An analysis of water-lint productive function". Authors are Surya P. Bhattarai, A.D. McHugh, G. Lotz and D. J. Midmore

economic return to irrigation was calculated for SDI at 523 mm. Water use efficiency (WUE) of lint production tended to decrease with increasing irrigation rates in SDI. Averaged over the seasons, WUE for SDI 75% ETc was higher compared to that of the furrow irrigation treatment, yielding 386 and 273 kg lint per ML of applied water, respectively. It is reasonable to conclude that SDI at 75% of ETc is an appropriate irrigation rate for heavy clay soils because it offered significant benefit in terms of saved irrigation water, it resulted in the highest average WUE for lint production over the two years, and it reduced drainage and runoff compared to higher SDI rates and furrow irrigation.

3.2.1 INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is a crop with high water demand (Hearn, 1994). Cotton produces a more stable yield and higher quality lint when it is grown as an irrigated rather than a rain-fed or dry land crop. Furrow irrigation is the most dominant practice for cotton irrigation worldwide. As water becomes more limiting for irrigation, especially as the needs of environmental flow gain more attention, there is great need to improve water use efficiency (WUE) of irrigated cotton. Subsurface drip irrigation (SDI) is one such feasible option that saves as much as 50–60 percent of water when compared to furrow and flood irrigation (Wanjura *et al.,* 2002). The performance of SDI has been widely tested and it has become a commonplace irrigation option in light textured soils for the cotton production (Ayars *et al.,* 1999), but information on the performance and efficacy of SDI in heavy clay soils is lacking (McHugh, 2001b).

Water use efficiency in SDI is enhanced by minimizing runoff and evaporation from the soil surface when compared to furrow or sprinkler irrigation. Study on cotton also revealed that SDI could also influence the dynamics of the underground deep drainage (Hutmacher *et al.,* 1999). Improvement of WUE by SDI, and reduction of runoff and deep drainage thereby minimising environmental impact of irrigation, are achieved because of the flexibility for accurate control of irrigation rates, uniformity of application and pulsing, but the magnitude of the benefits depends on the crop, soil type, growing environment and intensity and frequency of irrigation (Ayars *et al.,* 1999). The crop root system in SDI is concentrated near to the emitter, and the release of irrigation water directly into the root zone improves plant access to water (Dippenaar *et al.,* 1994).

Research elsewhere indicates that substantial increase in yield and WUE can be achieved for a number of crops using SDI (Camp, 1998)**.** In hot arid climates with low and unreliable rainfall, yield has been shown to markedly improve, particularly in light textured, highly permeable soils. It has been on the light textured soils or in areas where conventional furrow irrigation is considered unsuitable, that SDI has been successful (Camp *et al.,* 1999). The cotton crop has been found to be responsive to SDI (Plaut *et al.,* 1996)**.** However, a large proportion of cotton is also grown on heavy clay soils, but recent data (Bhattarai *et al.,* 2005a) suggest that the realised benefits of SDI on light textured soils also hold true for heavy clay soils.

Water movement in clay soils is very different to that in other soils. Clay soils are relatively more prone to run-off compared to light textured soils particularly in high irrigation and rainfall events. Such loss of water, and suspended soil, can be minimized by employing SDI techniques in heavy clay soils that only wet-up soil beneath the soil surface. As heavy clay is one of the dominant soil types throughout the world and cotton is one of the major crops grown on such soils, evaluating the performance of SDI for heavy clay and cotton is imperative in order to develop sustainable irrigation methods as alternatives to furrow irrigation in heavy clay soils (McHugh, 2001a)**.** Indeed, research has shown (Bhattarai *et al.,* 2005a) that SDI with an application rate equivalent to 75% of ETc (i.e., the product of crop factor and daily reference crop evapo-transpiration (ETo)), maintained yield comparable to that of SDI with higher irrigation rates or to that of furrow irrigation. Comparisons of soil water movement for different irrigation rates and, thereby, the dynamics of the soil water balance in a cropped heavy clay soil under SDI and furrow irrigation, could assist in optimizing water use and minimising drainage.

This section presents data on the effects of SDI at different irrigation rates, based on the daily calculated evapo-transpiration rate of the crop, and of traditional furrow irrigation on soil water movement and root growth patterns of cotton in a sub-tropical environment in a heavy clay soil. Crop physiological responses in relation to varying irrigation levels and their influence on WUE and radiation use efficiency (RUE) of cotton are also presented. The irrigation rates were chosen to provide differing levels of surface soil wetness, so that rainfall could be stored in the soil and limit runoff and at the same time yield would not be compromised yet WUE improved.

3.2.2 MATERIALS AND METHODS

3.2.2.1 Experimental Site

The field experiments at Emerald (23^0 $28^'$ $22.4^{''}$S, 148^0 $19^'$ $49.8^{''}$ E, elevation 190 asl) in central Queensland, Australia, were conducted on cotton (*Gossypium hirsutum* L) in two seasons 2001/02 and 2002/03, on a soil typed as 6Aug-9 (Australian soil classification system), which is classified as *gypsic vertosol.*

3.2.2.2 Crop Details

Experiments were planted with cotton variety NuTopaz, Ingard^{TM} on 26 September 2001 and on 15 September 2002 with a variety Sidcot 289i. The crop was planted in metre-spaced rows on low permanent 2 m beds with a crop establishment of 12 plants per metre achieved with a tractor-driven seed dibbler.

3.2.2.3 Experimental Design and Treatments

A randomised complete block design, replicated three times, was used for each trial for both years. Specific details of the design, treatments, plot sizes, irrigation design and instrumentation are presented in the previous section. In essence the irrigation treatments were 50, 70, 90 and 120 (2001/02) or 105% (2002/03) ETc delivered by SDI, and farmer managed furrow irrigation on plot size of 270 m x 16 m were compared.

3.2.2.4 Soil Water Movement and Root Distribution

Soil moisture in the 2002/03 season was monitored on 18 occasions at approximately 5-day intervals using a Micro-Gopher (a TDR capacitance sensor from Soil Moisture Technology, Australia) and access tubes installed to a depth of 110 cm from the surface. Days immediately following furrow irrigation were avoided because access was very difficult. The moisture monitoring access tubes in SDI plots were located midway between two emitters at 5, 25, and 50 cm from the drip tape (emitter spacing was 40 cm). In the furrow irrigation plots they were located at the same distances perpendicularly to the planted row. Moisture monitoring through the access tube was recorded at 10, 30, 50, 70, 90 and 110 cm depth from the surface and volumetric water content was determined as mm of soil water per 100 mm of soil depth. Root samplings for root length and biomass (74 days after sowing in 2002/03 and at harvest in both years) were performed for each location of the Micro-Gopher access tubes employed for soil moisture monitoring, but on the opposite side of the irrigation pipe as presented in Bhattarai *et al*. (2005a).

3.2.2.5 Measurement of Runoff and Water Balance

The twelve SDI plots and the furrow plots were isolated and fitted with 0.3 m and 0.25 m diameter PVC discharge pipes, respectively, to quantify the contribution of cropping and irrigation management on water quality and runoff from the cotton crop. Runoff from each SDI and furrow irrigation plot flowed through bed load traps (0.4 m^3) prior to entering the bay discharge pipes.

Water height during irrigation bay discharge (runoff) was measured using stilling wells housing "Dataflow" capacitance height recorders attached to the 15 discharge pipes. A pilot port located at the end of the discharge pipes connected individual stilling wells and allowed water level in the stilling wells to rise and fall with corresponding water level in the pipe. The California pipe equation (Grant and Dawson, 1997) was used to convert water height to discharge volume and each pipe had been calibrated against a V notch weir. Loggers recorded data, time and voltage from capacitance probe and tips from tipping bucket rain gauge. Output from the loggers triggered 3 automated water quality pumping samplers when there was flow of at least 0.015 m through their associated discharge pipes. The twelve SDI discharge pipes were monitored in groups of six by two instrument stations, each consisting of 2 loggers (4 and 8 channels), solar panels, batteries, cooling system, signal converters, pluviometer, weather proof casing, stand, ISCO 3700 automated samplers, and manual rain gauge. A single instrument station located at the furrow irrigation site was similar and monitored three discharge pipes. For SDI and furrow the drainage below the active root zone, i.e., presumed to be lost to the roots, was calculated as the difference between applied water and crop water use + tail water. Tail water is water that exits the field area as surface runoff during or after an irrigation or rainfall event and is measured at the bay discharge pipe. Crop water used was estimated according to Allen *et al*. (1998).

3.2.2.6 Leaf Parameters

The leaf water potential of fully expanded top leaves (predawn leaf water potential) was assessed using a Scholander pressure bomb. Data were collected on five occasions at approximately fortnightly intervals starting 50 days after sowing in 2001/02, and once only in 2002/03. Canopy temperature at mid-day was determined on a fortnightly basis using infrared thermometry (Ag. Multimeter from Everest Inc, USA). The stress values (DeTar *et al*., 1993) range from 0 (no stress) to 1 (severe stress when leaf transpiration ceases completely). Specific leaf area (SLA) was calculated as leaf area/leaf weight (cm^2 g^{-1}) according to Harrington *et al.* (1997). Light interception was measured fortnightly, close to midday, using an AccuPAR ceptometer (Decagon USA) by measuring the radiation receipts above and below the canopy at five different locations per plot.

3.2.2.7 Leaf Gas Exchange

Leaf gas exchange (net photosynthesis, transpiration, stomatal conductance) was measured at fortnightly intervals between 10-12 am on five plants (one leaf per plant) in each plot with an infrared gas analyser (IRGA) model LGA-4 (ADC UK).

3.2.2.8 Resource Use Efficiencies

Resource use efficiencies, namely RUE and WUE, were calculated separately for each plot. RUE was measured at two scales. RUE_i (instantaneous radiation use efficiency) was calculated as μmol CO_2 per quanta of light derived from IRGA data, and season long radiation use efficiency (RUE_{sl}) calculated as dry biomass and lint per MJ of light intercepted by the crop. Likewise, WUE was also measured at two scales. WUE_i (instantaneous water use efficiency) was calculated as μmol CO_2 fixed per mmol of water transpired by the leaf derived from IRGA data, and WUE_{sl} (season long water use efficiency) was calculated from biomass and lint yield per ML of water consumed by the crop (soil moisture before planting + irrigation + rainfall - soil moisture at harvest). Data on dry matter partitioning and lint yield were collected as outlined in the previous section. The WUE quantified through carbon isotope discrimination was determined following the method described by Farquhar *et al.* (1989).

3.2.2.9 Data Analysis

Data were subjected to an analysis of variance following the general linear model. Means were compared using the LSD. All statistical determinations were made at $P \leq 0.05$. As the irrigation levels were slightly different between the two years (SDI ETc 120% in the first year was replaced by ETc 105% in the second year) data were not combined across years. The data, therefore, were analysed separately for each year. All statistical analyses including correlations were calculated using the statistical software - Systat Version 9.0 (SPSSInc, 1999).

3.2.3 RESULTS

3.2.3.1 Spatial Soil Water Content in the Profile

The pattern of soil water content with respect to different SDI rates and furrow was very different (Figure 3.2.1). In SDI soil water content increased with increasing soil depth to 90 cm irrespective of the lateral distance from the emitter. It also increased with depth to 90 cm in furrow irrigated plots. The crops irrigated with SDI up to and including 90% ETc were found to be very dry from the surface to 30 cm if measured 25 and 50 cm away from the emitter rows. However, above the tapes 50% ETc which was quite dry whereas for the other treatments it was moist directly above the tapes. Soil water content deep in the profile (>90 cm) on many occasions exceeded field capacity (43 mm) below the tape line, particularly in the SDI 105% ETc and furrow plots.

3.2.3.2 Root Characteristics and Pattern

The length of taproot increased significantly with increase in rate of irrigation in SDI, and with furrow compared to dry SDI treatments, in both years (Table 3.2.1). But the effect of irrigation treatments on total root weight was not significant in either year.

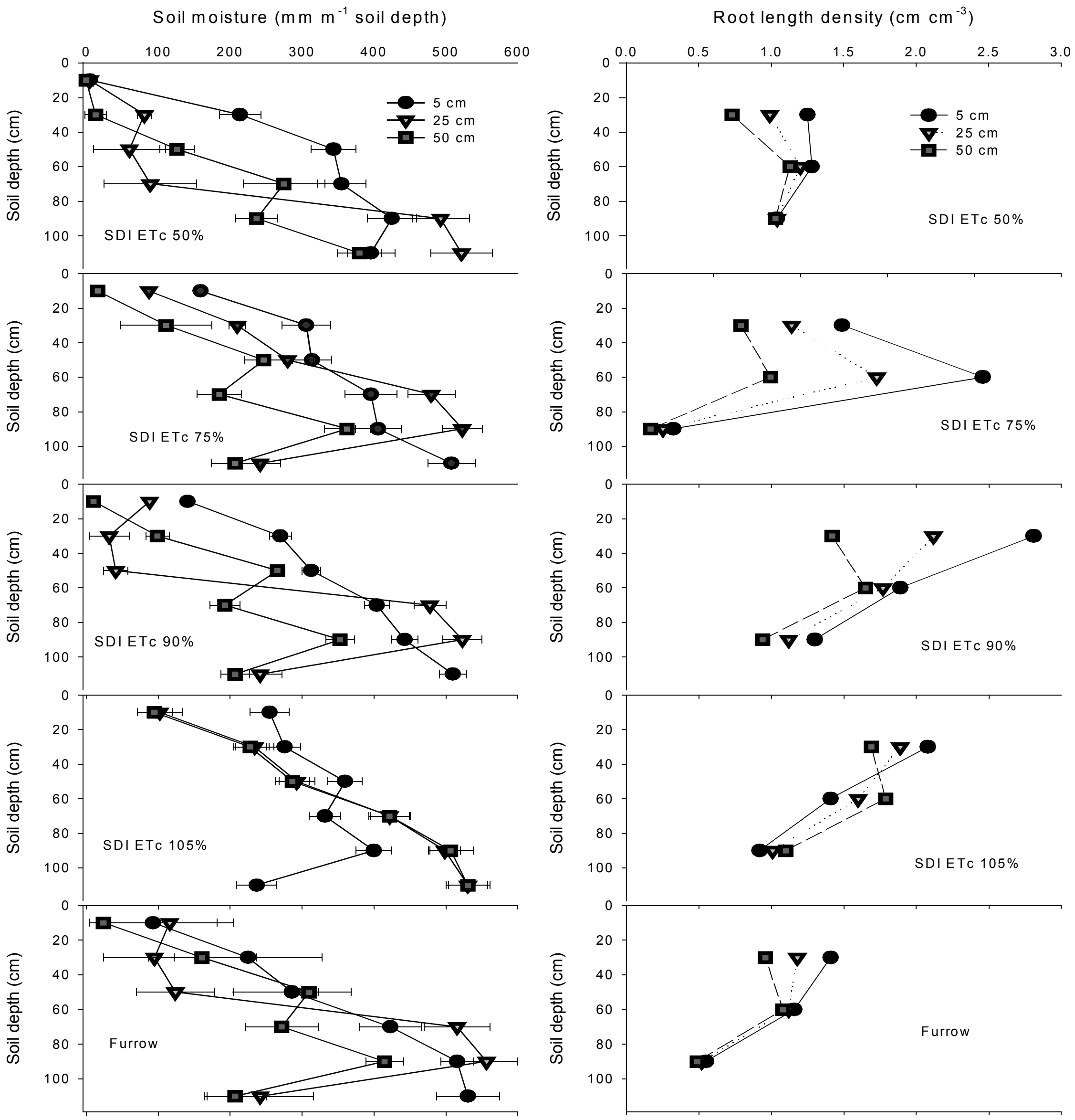

Figure 3.2.1 Spatial distribution of soil moisture after irrigation (mm m^{-1} of soil depth) (left) and root length density (cm root cm^{-3} of soil) at fruiting stage of cotton (right) with respect to irrigation rates and methods in a heavy clay soil (●-5 cm, ▼- 25 cm and ■-50 cm from drip tape) Emerald in the 2002/03 season.

The diameter of the fibrous root did increase significantly ($P \leq 0.05$) in wetter SDI treatments and furrow compared to all dry SDI treatments in the first season, but the effect of irrigation treatments on root diameter was not significant in 2002/03. Root length density (RLD) averaged throughout the profile did not differ significantly between irrigation rate or type in 2001/02, but in the second season RLD was significantly higher ($P < 0.005$) at SDI at 90% ETc followed by SDI at 105% ETc and 75% ETc. The SDI at 50% ETc and furrow treatment had the lowest RLD in both years (Table 3.2.1). Dry matter percentage in the taproot differed significantly due to irrigation rates in both years. It increased significantly with decreasing irrigation rates in SDI. Cotton roots in the furrow irrigation treatment had similar dry matter content to that of the crop irrigated with SDI at the highest rate.

Analysis of the spatial distribution of fibrous roots at the early flowering stage (i.e., 74 days after sowing) in relation to the irrigation type revealed that, with the exception of the two driest treatments, RLD decreased significantly with increasing depth directly under the emitter (Figure 3.2.1). With increasing irrigation rate up to 90% ETc, there was an increase in RLD at the 0-30 cm depth in the proximity of the tape compared to that at greater distance from the tape (Figure 3.2.1). In the 105% ETc and the furrow irrigation, there was less difference in RLD close to the surface between distances from the tape.

Table 3.2.1: Root characteristics (expressed plant^{-1}) as affected by SDI rates and furrow irrigation in a heavy clay at Emerald, 2001/02 and 2002/03.

Treatment[1]	2001/02					2002/03				
	Root weight (g)	RLD (cm cm^{-3})	Root diameter (mm)[2]	Taproot length (cm)	Dry matter in taproot (%)	Root weight (g)	RLD (cm cm^{-3})	Root diameter (mm)[2]	Taproot length (cm)	Dry matter in taproot (%)
SDI- 50% ETc	21.21	0.73	0.551	32.5	40.0	21.38	1.268	0.323	28.8	39.0
SDI-75% ETc	23.25	0.69	0.579	29.7	38.8	20.31	1.528	0.284	28.8	36.0
SDI-90% ETc	23.33	0.61	0.605	31.4	36.4	22.33	1.760	0.319	32.76	34.2
SDI-120/105% ETc	23.61	0.66	0.607	38.2	35.1	23.93	1.573	0.309	35.10	32.1
LSD (6 df)	ns	ns	0.01	3.6	2.17	ns	0.22	ns	3.9	2.3
Furrow	20.44	0.57	0.614	37.5	33.3	19.45	1.318	0.356	40.97	32.0
S E (n=3)	0.58	0.006	0.007	0.57	0.56	1.51	0.05	0.007	2.39	0.68

[1] See text for details [2] Root diameter was measured for the sample fibrous root recovered from the soil cores at final harvest

Table 3.2.2: Leaf water potential, crop water stress index, and specific leaf area as affected by SDI rates and furrow irrigation in a heavy clay soil at Emerald, 2001/02 and 2002/03 seasons.

Treatment[1]	2001/02				2002/03			
	LWP[2] (-kPa)	CWSI[3]	Canopy temperature (°C)	SLA (cm^2 g^{-1})	LWP (-kPa)	CWSI	Canopy temperature (°C)	SLA (cm^2 g^{-1})
SDI- 50% ETc	2340	0.36	33.4	121.8	2400	0.48	34.0	116.1
SDI-75% ETc	2080	0.29	32.6	127.6	2050	0.38	32.7	129.8
SDI-90% ETc	1930	0.25	31.8	128.3	1830	0.23	31.2	128.6
SDI-120/105% ETc	1960	0.17	30.1	132.9	1780	0.22	30.9	127.6
LSD (38 df)	1510	0.06	1.17	2.8 (6 df)	3.3 (6 df)	0.05 (138 df)	0.86 (138 df)	ns (6 df)
Furrow	1750	0.25	30.7	135.1	1920	0.12	29.8	138.8
S E (n=15)	68	0.020	0.38	6.8	120	0.033	0.373	9.5

[1] See text for details [2]Leaf water potential [3]Crop water stress index.

3.2.3.3 Leaf Water Potential, Crop Water Stress Index, Specific Leaf Area

Pre-dawn leaf water potential of the cotton leaves differed significantly with respect to rate of irrigation in both years. The leaf water potentials were significantly ($P < 0.001$) lower in the driest SDI treatment (50% ETc) followed by SDI at 75% ETc, and highest for 90, 105/120 ETc and furrow treatments (Table 3.2.2). An analysis of leaf water potential over the 2001/02 season revealed that the LWP became more negative with the age of plants until the commencement of flowering and then remained stable under the constant rates of irrigation (data not presented). Leaf temperature increased with lower irrigation rates in both years, and the crop water stress index (CWSI) measured at midday was responsive to the relative levels of stress imposed by the irrigation treatments in both years (Table 3.2.2). Irrigation of SDI cotton at 50% ETc induced the greatest stress, followed by 75% ETc; the rest of the treatments showed almost the same level of stress over the crop season. Crops at the early establishment stage and at boll filling were more stressed than the crops at the vegetative and at flowering stages (mean CWSI = 0.39 and 0.37 for early establishment and boll filling vs 0.15 and 0.11 for squaring and flowering in 2001/02 (LSD = 0.05, 48 df), and CWSI = 0.33 and 0.59 for early establishment and boll filling vs 0.19 and 0.21 for squaring and flowering in 2002/03 (LSD = 0.09, 166 df)). There was a trend for SLA to increase with increase in rate of irrigation in SDI, and in furrow irrigation, but the effect was only significant in the first year (Table 3.2.2).

3.2.3.4 Leaf Gas Exchange

Net rate of leaf photosynthesis differed significantly due to irrigation treatments in 2002/03, and showed the same trend in 2001/02 (Table 3.2.3). In the first season net leaf photosynthesis was lower in SDI 50% ETc compared to the other treatments (Table

3.2.3). However, in 2002/03 net leaf photosynthesis was markedly higher in furrow, followed by SDI at 105 and 90% ETc and was least in SDI 50 and 75% ETc. Stomatal conductance in 2001/02 was greater for furrow and SDI at 75% ETc compared to other SDI treatments (Table 3.2.3) but there was no clear trend in the following year. Greater average net photosynthetic rate (18.23 (SE = 0.755) vs. 16.20 (SE = 0.133) µmol $m^{-2}s^{-1}$) and stomatal conductance (0.23 (SE = 0.013) vs. 0.13 (SE = 0.003) µmol $m^{-2}s^{-1}$) was noted in 2001/02 compared to 2002/03, respectively. The average leaf transpiration rate differed significantly ($P < 0.05$) between seasons in the same manner as stomatal conductance. In the first season transpiration rates were significantly greater than the second season. A higher leaf transpiration rate was noted in furrow and SDI 75% ETc compared with other SDI treatments, whereas in the second season leaf transpiration rate did not vary greatly in different treatments (treatments with higher net photosynthesis) but higher leaf transpiration rate was recorded for the furrow irrigation.

3.2.3.5 Radiation Use Efficiency (RUE_i and RUE_{sl})

Instantaneous radiation use efficiency (RUE_i) differed according to rate of irrigation in both the years (Table 3.2.4). In 2001/02 RUE_i was higher in furrow compared to all SDI treatments, and SDI 75% ETc had a greater RUE_i than did other SDI treatments (Table 3.2.4). However, in 2002/03 there was a significant trend for an increase in RUE_i as the irrigation rates increased and it was highest for furrow irrigation as in the previous season. Mean RUE_i averaged over treatments and dates was 8.84 and 9.16 µmol CO_2 mol $^{-1}$ of PAR respectively for 2001/02 and 2002/03.

Season-long radiation use efficiency (RUE_{sl}) calculated for biomass and lint yield, differed significantly between treatments in both years. The RUE_{sl} for biomass in 2001/02 varied between 1.08 and 1.39 g MJ^{-1}, and RUE_{sl} was highest for SDI 75% ETc, followed by SDI 120% ETc (Table 3.2.4). The RUE_{sl} for SDI at 50% ETc was as high as that for the furrow irrigation treatment and SDI 90% had the lowest RUEsl for biomass. In 2002/03, biomass RUE_{sl} was lower than in the previous year, and varied from 0.89 to 1.15 g MJ^{-1}. Furrow was higher compared to all other treatments and amongst the SDI treatments, SDI 75% ETc recorded the highest biomass RUE_{sl}. The RUEsl for lint in 2001/02 varied between 0.169 and 0.250 g MJ^{-1} and RUE_{sl} decreased progressively as rate of irrigation increased in SDI and furrow. The RUE_{sl} 2002/03, however, as for biomass RUE_{sl}, was lower for the driest SDI treatments, and only varied from 0.135 to 0.164 g MJ^{-1}. Furrow was higher than all other treatments, and amongst the SDI treatments, 75% ETc had the highest RUE_{sl} for lint (Table 3.2.4).

3.2.3.6 Water Use Efficiency (WUE_i and WUE_{sl})

In 2001/02 the instantaneous water use efficiency (WUE_i) tended to be greater as the rate of irrigation increased with SDI, but furrow had the lowest WUE_i (Table 3.2.4). In contrast, in 2002/03 the highest WUE_i was for furrow and the wettest SDI treatment. Average WUE_i was recorded as 4.61 (SE = 0.237) and 5.62 (SE = 0.213) mmol CO_2 fixed per mmol H_2O transpired for 2001/02 and 2002/03, respectively.

For biomass a higher season long WUE (WUE_{sl}) was evident in the SDI treatments in the first season when compared to the furrow treatment. However, in the second season the biomass WUE_{sl} was, with the exception of 105% ETc, quite similar between treatments. Differences between treatments for lint WUE_{sl} were significant in both seasons. In 2001/02 WUE_{sl} was greatest for SDI 75%, followed by 50, 90, 120% ETc and least in furrow (Table 3.2.4). In contrast, in 2002/03 the highest WUE_{sl} was noted for furrow, followed closely by SDI 50% ETc compared to SDI 90 and 105% ETc. Season long water use efficiency (WUE_{sl}) for lint was 332 (SE = 20) and 314 (SE = 13) kg ML^{-1} of water in 2001/02 and 2002/03 season, respectively. WUE measured as leaf carbon discrimination showed that SDI at 50 and 75% ETc significantly reduced

Table 3.2.3 Leaf photosynthesis, stomatal conductance and transpiration rate as affected by SDI rates and furrow irrigation in a heavy clay soil at Emerald, 2001/02 and 2002/03 seasons.

Treatment[1]	2001/02			2002/03		
	Net leaf rate of photosynthesis (μ mol m^{-2} s^{-1})	Stomatal conductance (mol m^{-2} s^{-1})	Leaf transpiration rate (mmol m^{-2} s^{-1})	Net leaf rate of photosynthesis (μ mol m^{-2} s^{-1})	Stomatal conductance (mol m^{-2} s^{-1})	Transpiration rate (mmol m^{-2} s^{-1})
SDI- 50% ETc	16.12	0.21	4.15	14.89	0.13	3.25
SDI-75% ETc	19.26	0.25	4.52	14.88	0.13	3.13
SDI-90% ETc	18.00	0.22	4.06	16.19	0.14	3.40
SDI-120/105% ETc	18.90	0.23	4.13	16.76	0.13	3.31
LSD. (30 df)	ns	ns	ns	1.12 (154 df)	ns (154 df)	0.28 (154 df)
Furrow	20.11	0.28	5.80	18.83	0.13	2.86
s.e. (n = 12)	1.48	0.024	0.37	0.871 (n=24)	NS (n=24)	0.122 (n=24)

[1]See text for details. (Values are means of 4 & 8 different dates of observation over the 2001/02 and 2002/03 crop seasons, respectively.)

Table 3.2.4 Cotton WUE and RUE as affected by SDI rates and furrow irrigation in a heavy clay soil at Emerald, 2001/02 and 2002/03 seasons.

Treatment[1]	2001/02							2002/03						
	Water use efficiency (WUE)				Radiation use efficiency			Water use efficiency (WUE)				Radiation use		
	[2]WUE_i	[3]Lint WUE_{sl}	[4]Biomass WUE_{sl}	[5]Δ (‰)	[6]RUE_i	[7]Lint RUE_{sl}	[8]Biomass RUE_{sl}	WUE_i	Lint WUE_{sl}	Biomass WUE_{sl}	Δ (‰)	RUE_i	Lint RUE_{sl}	Biomass RUE_{sl}
SDI- 50% ETc	4.17	441.52	1890	19.9	8.30	0.250	1.28	5.11	356.62	2151	19.6	7.75	0.135	0.90
SDI-75% ETc	4.72	452.87	2130	20.2	9.30	0.224	1.39	5.00	319.39	1952	20.4	8.32	0.151	1.08
SDI-90% ETc	5.47	336.19	1770	20.6	8.34	0.180	1.08	5.19	273.08	1903	20.4	8.91	0.137	1.06
SDI-120% ETc	5.25	244.25	1940	20.7	8.84	0.169	1.36	5.80	260.14	1563	20.7	10.47	0.136	0.89
LSD (6 df)	ns	19.9	ns	0.23	ns	0.02	0.25	0.80	74	528	0.22	2.64	0.07	0.198
Furrow	3.47	185.46	1420	20.4	10.5	0.179	1.26	7.36	360.48	2071	20.2	10.69	0.164	1.15
s.e. (n=3)	0.119	1.1	58.0	0.12	0.29	0.028	0.071	0.512	9.26	207.4	0.22	0.672	0.012	0.084

[1] See text for details, [2] Instantaneous water use efficiency (WUEi) = μmol CO_2 m^{-2} s^{-1} (A) /mmol H_2O m^{-2} s^{-1} (E),[3] Lint season long water use efficiency (WUE sl) = kg lint ML^{-1} of applied water ,[4] Biomass season long water use efficiency (WUEsl) = kg biomass ML^{-1} of applied water ,[5] Carbon discrimination, [6] Instantaneous radiation use efficiency (RUEi) = mmol CO_2 m^{-2} s^{-1} (A)/mol PAR (R), [7] Lint season long radiation use efficiency (RUE sl) = g lint MJ^{-1} of intercepted PAR, [8] Biomass season long radiation use efficiency (RUEsl) = g biomass MJ^{-1} of intercepted PAR

CO_2 discrimination suggesting high WUE compared to higher SDI rates and furrow in 2001/02 season. In 2002/03 season, the carbon discrimination was significantly reduced only in SDI 50% ETc but not in other higher irrigation rates in SDI and furrow.

3.2.3.7 Water Balance

The water balance details for both years are presented in Figure 3.2.2. The crop water use in relation to supply (irrigation + rainfall) was closely matched in SDI treatments up to and including 90% ETc. A quadratic function was choosen over an asymptotic, because with irrigation more than optimal root functioning will decrease with deficit in soil oxygen. The difference between the irrigation input and crop water use increased at the highest SDI irrigation rate, and the difference was greatest for furrow irrigation in both years. In the first year there was no runoff of irrigation water in SDI until the irrigation rate reached that sufficient to supply 90% ETc. Sizable runoff was recorded for 120% ETc (64 mm) and furrow (209 mm) whereas in 2002/03 runoff was only registered (238 mm) in furrow irrigation. That the runoff in the furrow treatment was greater than the rainfall reflects the fact that some runoff took place during irrigation events. Deep drainage was significant in both years in the furrow treatment and for 120% ETc in 2001/02.

3.2.3.8 Applied Water-Lint Function

The relationship modelled for lint yield (kg/ha) and applied water (mm) combined over years is presented in the figure 3.2.3. The applied water (AW) in the experiment consisted of water stored in the soil before irrigation and crop planting + in season irrigation + rain – residual moisture at harvest. Results from the yield-AW analysis were also combined with the economic analysis and presented in the figure 3.2.3. The marked area in the figure shows the zone of rational water use (the region between the upper and lower limit for applied water) when the price for water is considered at AU$ 3 mm^{-1} and lint at AU$ 2 kg^{-1}. Following the analysis of marginal rate of return (MRR, which is change in net income divided by change in cost expressed as percentage) in this figure the upper limit for AW was calculated at 621 mm and this is the point at which maximum yield was obtained. However, the lower limit for AW was determined at the point in which maximum average product (AP) was obtained. It is calculated as AP = YL (yield)/ AW (applied water). The point of maximum AP, in this experiment (combined analysis of SDI treatments over the two years period) was determined at 355 mm and becomes the lowest limit. Applied water to maximise profits always falls between the lowest limit and the highest limit i.e. point of maximum yield (the limits of this rational water use zone). For example, if water costs were AU$3 mm^{-1} and cotton lint price is AU$ 2 kg^{-1} a profit maximisation would be calculated at 523 mm of AW. This was derived from an analysis of the marginal rate of return (MRR), and the most economic level of irrigation was obtained with MRR at unity. MRR measures the increase in net income (Δ NI), which was generated by each additional unit of expenditure on variable cost (VC), which in this case was the cost of water. Hence, MRR = ΔNI/ΔVC. If traditional production economics are used, AW is used up to an amount that balances the cost of the last millimetre used with the value of the product resulting from this last increment of AW; mathematically, $\Delta YL/\Delta AW = P_W/P_{YL}$ where P_W and P_Y are the respective water cost and lint price. For this experiment the profit maximising AW amount was 523 millimetres, a value significantly below the yield-maximising AW quantity, which was 621 mm. It was confirmed that the most economic irrigation level, i.e. 523 mm was close to SDI 75% which combined over two years provided 518 mm.

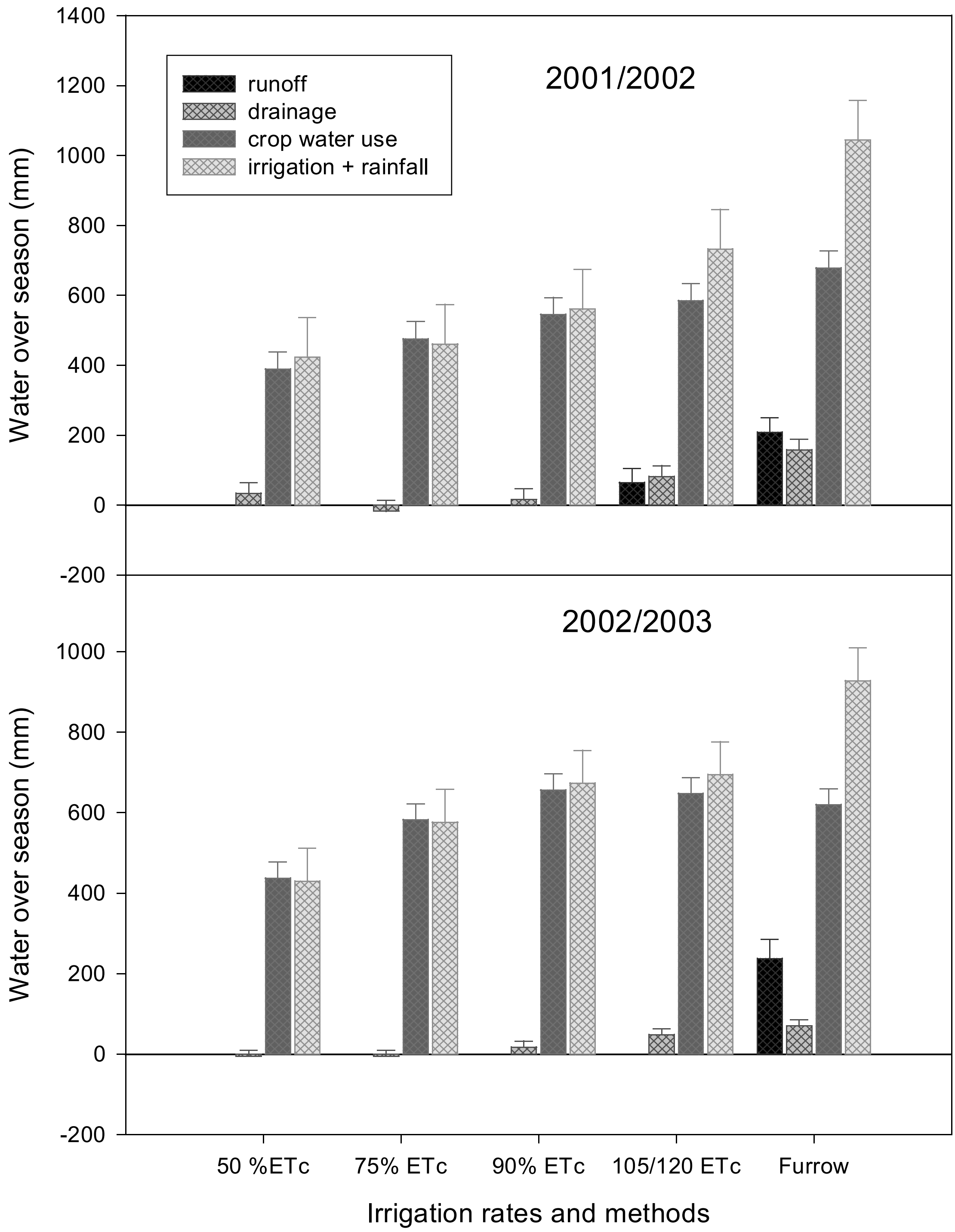

Figure 3.2.2 Water balance in the cotton seasons as affected by irrigation rate and type in 2001/02 (top) and 2002/03 (bottom) in a heavy clay soil.

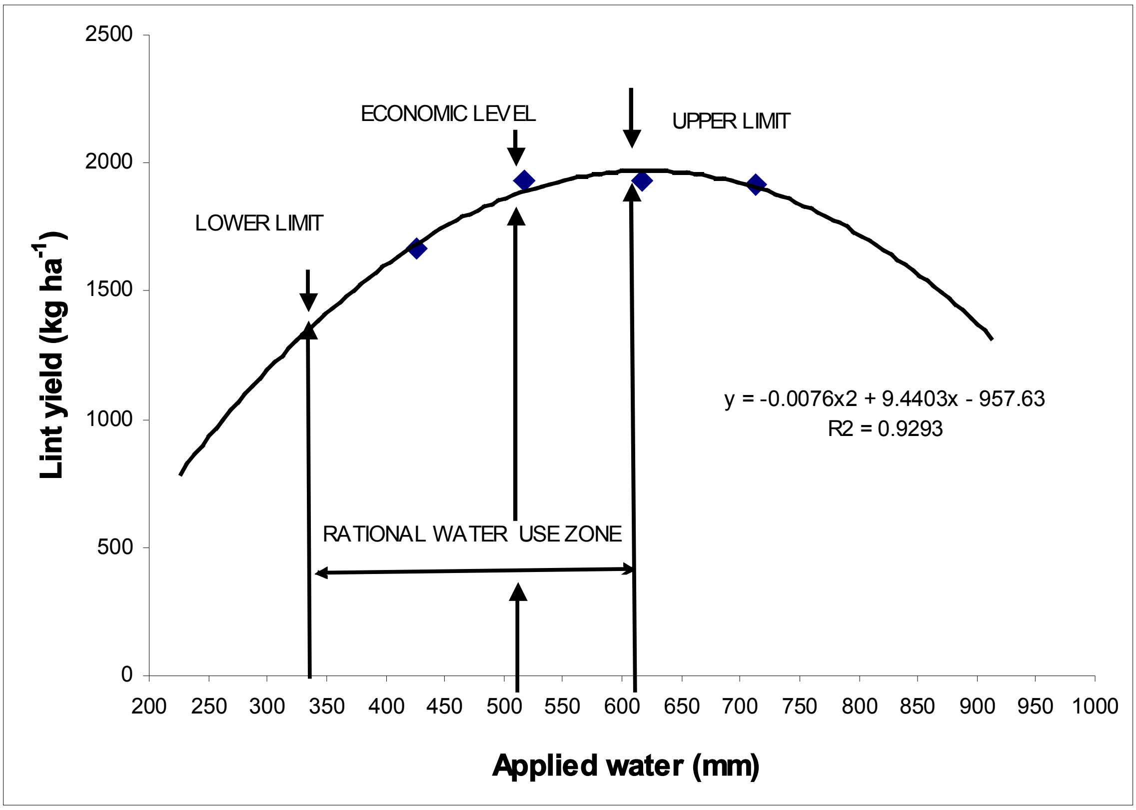

Figure 3.2.3 Yield-applied water functions for cotton developed for Emerald, Central Queensland, Australia, where, Y_{L}= lint yield kg/ha, and AW= millimetres of water applied to the crop during the growing season (including irrigation and rainfall).

3.2.4 DISCUSSION

Crop maintained at 50-90% ETc with SDI always had very dry surfaces in the planted rows. The soil at the site has a field capacity of 43 mm H_2O per 100 mm of soil depth, and the top 30 cm soil in the inter-row spaces of those treatments consistently maintained soil moisture at less than the refill point (the refill point is considered as 32 and permanent wilting point for this soil is 22 mm per 100 mm soil). This allowed for immediate infiltration and storage of rainwater for crop use later in the season, and also helped in reducing the likelihood of runoff. With such dry soil surface weed growth was minimized unlike in the higher rate SDI and furrow plots. However, against the advantage of storing rainfall in the upper soil in the drier treatments is the fact that they had fewer roots there to capitalize quickly on additional rainwater.

Although the water movement in a drip irrigation system is a three dimensional flow (Bresler, 1977), because of the tape placement at 40 cm depth and because crop demand for water in the low rate of irrigation was higher than the supply, the upward capillary movement of water was conditioned by root water uptake. This was evident even in this heavy clay soil where upward capillary movement would be substantial. At the highest rate of irrigation in 2002/03 (105% ETc) and in the furrow irrigation treatment, the soil moisture beyond 70 cm depth from the surface exceeded FC (Figure 3.2.1). Although soil moisture was not measured down the profiles in 2001/02, drainage was evident based upon the water balance (Figure 3.2.2) in the highest rate SDI and furrow treatments. As a quantitative example of the capacity of drier treatments to absorb more rainfall, in the 2002/03 season soil in the drier treatments (50% and 75% SDI) received 14% and 36% less water than did the 90% ETc treatments (Figure 3.2.2), and the profile in the latter was constantly or nearly full (Figure 3.1.1). Water added to the SDI 90% ETc was 673 mm (Table 3.1.2) and maintained a full profile, hence, SDI 75% could potentially store 673 - 576 mm = 97 mm, and SDI 50% could potentially store 673 - 430 mm = 243 mm, of in-season rainfall.

Irrigation application to the 120% treatment was reduced to 105% of ETc in the second year and this coupled with the limited rain resulted in no runoff for SDI treatments (Figure 3.2.2). Deep drainage in the first year was substantial at 158 mm and 82 mm (15% and 11% of applied water) for the furrow and wettest SDI sites, respectively. In 2002/03, optimization of the furrow-irrigated plots by matching the irrigation with soil water deficit to reduce runoff i.e., by allowing soil moisture deficit to reach 32 mm 100 mm^{-1} soil depth measured at 20-40 mm in the furrow plots with the Environscan probes before irrigating corresponding to c. 150 mm 800 mm^{-1} of soil profile in Figure 3.1.2. of section 3.1, by hastening the water flow rate in the furrow by 1 L s^{-1}, by discontinuing irrigation before tail water was produced, and by reducing the 120% SDI treatment to 105% of ETc reduced drainage below the root zone by one half (Figure 3.2.2).

Irrigation efficiencies (IE), expressed as the ratio of crop water use to applied furrow irrigation water increased from 65% in the first year to 67% in the second year (Figure 3.2.2). Efficiency of SDI irrigation treatments, especially those of 50, 75 and 90% Etc, were much higher and close to 100% for both years, whereas SDI 120% ETc in 2001/02 resulted in 80% IE and 105% ETc in 2002/03 in 93% IE.

Rooting pattern and soil moisture content were quite different between SDI and furrow irrigated crops. Earlier work on maize by Phene *et al.* (1991) and cotton by Plaut *et al*. (1996) also showed a concentration of root mass close to the depth of the tape and drip emitters. The data in this experiment showed that with only a few exceptions, at depths from 30 to 60 cm and across the distances from the planted rows, greater RLD was associated with greater soil moisture content (Figure 3.2.1). At greater depths, as soil moisture increased to FC and above, RLD declined. Higher RLD was evident close to the tape row and decreased away from tape line in 75 and 90% ETc suggesting more root activity perpendicular to the tape as opposed to higher irrigation SDI and furrow treatment where distance from the planted row was of less significance. Decreasing root density at the depth of 90 cm in SDI 105 ETc and furrow (Figure 3.2.1) was possibly responsible for the deeper loss of irrigation water resulting in deep drainage (Figure 3.2.2) simply because of the reduced root mass at depth under the higher irrigation rate. There is also evidence that the root diameter increased at the higher rates of irrigation, reflecting the likelihood of excess soil moisture (Visser *et al.,* 2000b). Root diameter has also been reported to increase in a waterlogged situation compared to drier heavy clay soils in crops irrigated with SDI (Bhattarai *et al.,* 2004)**.** Although the taproot length increased with an increase in soil moisture, total root biomass did not differ with respect to irrigation treatments, however, lower dry matter content in the taproot was evident in the wetter compared to the drier SDI rates.

There was a causal link between soil water content, transpiration and crop stress as measured by the CWSI. The drier treatments (50 and 70% ETc) had a CWSI that reflected stress >0.3 as indicated by Howell *et al.* (1984) in both years, and the stress was greater in 2002/03, the year with higher daily evaporation. Although 2001/02 had on average a higher rate of transpiration that would explain the lower CWSI in that year, among treatments there was no obvious relationship between CWSI and unit transpiration rate. Indeed, the CWSI was lowest in furrow in 2002/03, perhaps because the soil surface of the between-row space was more frequently wet and this reduced transpiration and canopy temperature. The same reason it could be argued explains the lack of relationship between CWSI and transpiration for the higher two SDI rates too.

The relationships between cotton growth and yield and leaf water potential and CSWI were notable, as reviewed by Grimes and Yamada, (1982). Leaf water potential declined over the SDI treatments in accord with the reduction in rate of irrigation in both years, and as such could also be a reliable indicator of relative plant stress. Similar relationships between LWP and CWSI had also been reported by Irmak *et al.* (2000) for maize and by Keener and Kricher (1983) for soybean.

Treatments effects on net leaf photosynthetic rate varied between years in the experiment. In the first year 50% ETc showed the lowest rate and the other treatments were all similar. In the second year the rate increased with increasing water supply. On average, net photosynthesis increased in each year with increasing leaf water potential (r = 0.852* in 2001/02 and r = 0.569 ns in 2002/03).

A significant polynomial relationship also existed between net photosynthesis and leaf temperature, with an increase in photosynthesis up to 33 °C and a decline thereafter (Figure 3.2.4). Leaf temperature on many occasions exceeded 35 °C, particularly in the driest SDI treatment (Table 3.2.2). The gradual decrease in leaf photosynthesis over the season after flowering was possibly due to ageing of the crop and simultaneous increase in leaf temperature above 35 °C on a regular basis. Neither transpiration rate nor stomatal conductance was found to be closely related to net photosynthesis in either year. Under the long term water deficit, such senescence effects on canopy photosynthetic activity (i.e. size of canopy) may be quantitatively more important than the direct effect on leaf photosynthesis through leaf turgor and stomatal conductance (Gerik *et al.,* 1994)**.** The smaller cotton plants in the 50 and 75% ETc treatments (LAI less by an average of 10 and 15% respectively for 50 and 75% ETc SDI compared to furrow) imply the possible contribution of greater rate of senescence in the drier treatments.

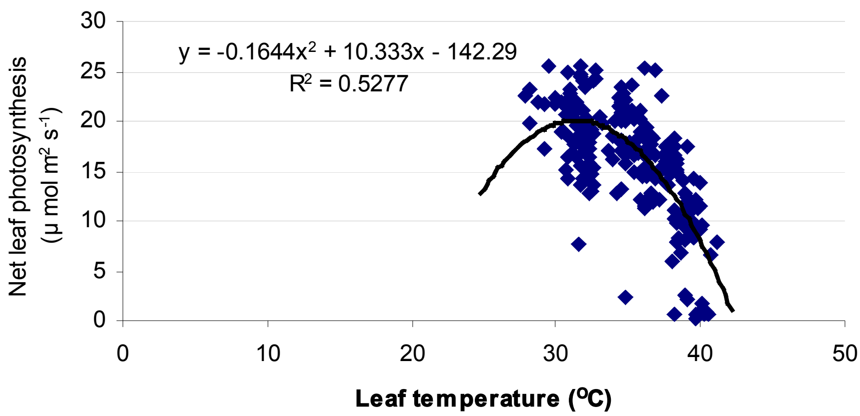

Figure 3.2.4 Relationship between cotton leaf temperature and rate of net leaf photosynthesis (µmol m^{-2} s^{-1}) of cotton over the seasons, 2002/03**.**

Crop growth can be described as the product of the incident PAR, the fraction of PAR intercepted by green leaf (*f*); and the efficiency with which the PAR is used, i.e. a measure of RUE (Monteith, 1972). RUE is a crop-dependent coefficient widely used in crop simulation models and in the physiological interpretation of crop response to the environment and management practices. Yield is dependent on the production of biomass and the partitioning of biomass to a product of economic value. The theoretical maximum value for RUE is 2.5 g MJ^{-1} when calculated from total solar radiation absorbed or 5 g MJ^{-1} when calculated per absorbed PAR (Russel *et al.,* 1989). For well-farmed C_3 crops RUE is approximately 1.5 g MJ^{-1} on the basis of total radiation (Sinclair and Gardner, 1999). The RUE_{sl} for biomass of SDI 75% ETc was as high as 1.39 g MJ^{-1} compared to 120% ETc with 1.36 and furrow with 1.26 g MJ^{-1} in 2001/02. However, in 2002/03 RUE_{sl} of biomass increased with irrigation rate, up to 90% ETc and then decreased at 105% ETc, and the highest RUE_{sl} was for furrow. The RUE expressed in terms of lint yield did not show the same relationship. RUE of lint yield decreased as water application rate increased in SDI, and this was due to a relatively greater partitioning to bolls in drier compared to wetter SDI treatments (Bhattarai *et al.*, 2005a). The RUE of lint varied between 0.169 and 0.25 g MJ^{-1}, the highest being SDI 50% ETc and lowest being the SDI at 120% ETc in 2001/02. Biomass RUE generally increased with an increasing irrigation rate compared to non-irrigated conditions (Sinclair and Gardner, 1999), but decreasing pattern of lint RUE with increase in irrigation in this trial was possibly due to decreasing HI with an increase in irrigation rate (Table 3.1.5). In 2002/03 RUE_{sl} for both biomass and lint was lower than in 2001/02. The RUE of lint yield varied from 0.135 g to 0.164 g MJ^{-1}, the lowest being for 50% ETc and highest for furrow. The crop at 75% ETc had the greatest RUE_{sl} amongst SDI treatments (Table 3.2.4). A lack of clear effect of treatments in RUE in the year 2002/03 was possibly related to variety as well as the physiological disorder that was quite significant in the SDI plots. The instantaneous RUE, RUE_i, increased with increasing water supply, over all treatments in both years. This value captures the plant's ability to fix CO_2 per unit of intercepted radiation, but does not account for possible differential diurnal patterns of respiration between treatments that may impact upon RUE_{sl}.

With the exception of furrow in 2002/03, the drier the irrigation regime the greater was the WUE, whether calculated as season long lint or biomass, or measured through carbon discrimination (Table 3.2.4). The smaller cotton plants in the 50 and 75% ETc treatments used less water than the larger plants in the wetter treatments, but they were still more stressed as indicated by the greater CWSI and more negative LWP. The greater LAI and greater water use and RUE recorded at higher irrigation rates did not contribute towards heavier lint yields, largely because of their lower harvest index (Bhattarai *et al.*, 2005a**.** The lack of correspondence between WUEi and the carbon discrimination data is strange; while the photosynthesis data followed the expected in terms of response to irrigation rates, transpiration as discussed earlier, did not. As the transpiration data were collected between 10 - 12 am, the residual soil moisture from irrigation the night before was possibly sufficient to maintain a non-limiting stomatal behaviour for transpiration. This phenomenon can be further substantiated by the observation that the LWP were observed to be different in the afternoon but not in the morning.

High yield potential, relatively low water use and high water use efficiencies are possible under SDI in light textured soils (Hutmacher *et al.*, 1994**)**. Considerable water savings were made for cotton on a heavy soil with the SDI system compared to furrow irrigation in both years in the current study. Based on data from two years, viable cotton could be grown with an SDI system using 5 ML ha^{-1} on a heavy clay soil (the average of 4.7 and 5.8 ML ha^{-1} for 75% ETc in 2001/02 and 2002/03), whereas under fully optimised furrow irrigation in 2002/03 6.2 ML ha^{-1} would be required. In a season with substantial rainfall, the required volume of irrigation water would be less. However, the SDI would have distinct advantages at the time of rainfall events over furrow irrigation due to the greater capacity of the former to accommodate excess water and, therefore, minimize run-off. As the price for irrigation water and price of the lint are going to be deciding factors for determining the amount of water to be applied for crops based on an analysis of MRR, SDI is to be favoured as it allows for control and delivery of the most economical levels uniformly to the crop.

The data suggest that under SDI cotton can adapt to lower levels of irrigation than that required to satisfy ETc without appreciable loss of yield. Generally when water is applied, cotton yield increases up to a point where the soil becomes wet enough to allow drainage below the active root zone. Irrigation beyond the FC in heavy clay leads to waterlogging, which reduces yield (Wanjura *et al.,* 2002). Reasonable yield was achieved at 50% of daily ETc, which maintained adequate soil moisture very close to emitters, but soil moisture away from emitters, as close as 25 cm at the rooting depth (Figure 3.2.1), was below wilting point. In most furrow irrigation systems, plant available water and soil moisture conditions cannot be manipulated in this way, and generally for 3 to 5 days, seven to eight times in a cropping season, the profile is above FC (Figure 3.1.1) and very susceptible to runoff events and groundwater contamination, should rainfall occur. Under conventional furrow irrigation, considerable volumes of water were also lost below the root zone, as was evident in the first year (Figure 3.2.2). This could have serious consequences for ground water contamination and for the elevation of water tables, and/or increasing soil salinity as reported by

Dippenaar *et al.* (1994). Improved grower furrow irrigation practice in 2002/03 halved the drainage losses (Figure 3.2.2).

A greater possibility also exists for the optimisation of furrow irrigation in the heavy clay soil. As demonstrated in the 2002/03 trials where optimization was carried out, WUE_{sl} of furrow irrigation approached and surpassed those of SDI treatments and exhibited reduced water loss to drainage below the active root zone, waterlogging and yield and WUE_{sl} increased substantially compared to the previous year.

Where SDI can outperform, in terms of WUE, furrow irrigation is on lighter soils, and areas of unsuitable topography where furrow irrigation function efficiencies are known to be poor. This is not to say that SDI does not work on heavy clays; it will out-perform or at least equal yield of furrow irrigation if the correct agronomic requirements are met. In order to make SDI more attractive a significant increase in yield with SDI over furrow should be assured. Hence, it is recommended that optimization of SDI must be the focus of future SDI research for cotton on heavy clay soils, for 30% of cotton (out of a total 0.24 million ha) in Australia and 20% of cotton (out of global total 32.7 million ha) in the world is grown on heavy clay soils. One way to achieve this may be to aerate SDI irrigation water, for such treatments enhanced cotton yields by 14 to 28% under experimental glasshouse conditions (Bhattarai *et al.*, 2004).

The AW and yield of cotton have a direct relationship. Jordan (1986) reported a linear increase in lint yield from 140 to 670 mm of AW. However, yield does not increase indefinitely in response to increased level of AW (Howell, 2001). For the majority of crops and environmental conditions the relationship between yield and AW is linear up to AW values that result in maximum productivity. Such a phenomenon is observed mostly on those crops for which above-ground biomass represents yield.

However, in cotton yield partitioning is quite different where lint yield is only a small portion of the total above-ground biomass. Hence, a curvilinear function appears most appropriate for this crop (Grimes and El-Zik, 1990).

Some early work that analysed yield-AW production function did incur some price for water and cotton (Grimes and El-Zik, 1990). However, this was for a furrow irrigated crop with different amounts of AW. As the quantity of water to be applied through furrow irrigation decreases, efficiency of application declines and it is very difficult to maintain uniformity in application. However, with SDI, it is possible to deliver even a small amount of water quite uniformly across the field. With this inherent benefit of the SDI system it is easy to maintain greater control over water application rate, frequency and volume. The approach described herein analyses the water-yield functions and focuses on monetary terms. Hence it assists growers to make an ex-ante analysis of how much to irrigate. For example, if water price were to double from AU$ 3 to AU$ 6 mm^{-1}, the optimum irrigation would drop to 425 mm. Only SDI offers the precision and control over the application of that amount to be irrigated. Once the price of water and lint is known, then it becomes a very good decision making tool for the cotton industry. It is not only the absolute amount of water but also the stage, the frequency and the amount by which the crop is irrigated that determines the performance of cotton (McHugh *et al.*, 2003). Hence variety, location, and price specific decisions for water application with SDI have to be made for maximum return.

3.2.5 CONCLUSION

Controlling the subsurface and surface water content to reduce deep drainage and runoff loss was effective by reducing the rate of irrigation supplied to cotton with SDI was 75% ETc or less. Higher irrigation rates with SDI and furrow irrigation resulted in runoff on a heavy clay soil. Maintenance of a dry surface as observed in 50 and 75% ETc could also reduce significant surface evaporative loss of water and could increase the interception and store of seasonal rain.

However, in terms of WUE, while between SDI treatments those with lower rates of application led to higher lint WUE_{sl}, largely because of their higher harvest index, SDI did not invariably show greater lint WUE_{sl} than the furrow treatment. Indeed, while in the first year lint WUEsl with furrow irrigation was considerably less than that of SDI treatments, in the second year it was equally as high as the highest SDI treatment. Refined management of furrow can considerably enhance lint WUE_{sl}.

The drier treatments exhibited greater stress as measured by their greater CWSI, despite their smaller canopy and perhaps because of their lower water use. The greater CWSI of drier SDI treatments was related to lower rates of photosynthesis, and lower instantaneous RUE_i and WUE_i. Supplying 75% of ETc through SDI was found to be the most appropriate irrigation treatment for heavy clay soils as it offered significant benefits in terms of saving water and reducing the environmental hazards compared to higher rates of SDI or to the practice of furrow irrigation.

Presently there is tendency of perceiving water as a cost free input. There is a tendency to apply copious amounts of water to cotton if available. Once water is priced to reflect realistic costs, decision-making will be based completely on the basis of investment in water and the returns it brings to the grower. Arbitrarily assigning price of AU$ 3 and AU$ 2 for each mm of water and kg lint, it is not the highest yield and higher water application rate which is economical, it is some point, based on the MRR analysis, for which the last unit of water gives a marginal rate of return to unity that is the most rational level. In this experiment combined over seasons it was at 532 mm over the crop season.

SDI offers greater control over water application even at small amount; hence there is scope for harnessing this property for delivering the most economical level of water to the crop. It is not only the total amount of water, but frequency and timing to match crop water requirements that is also crucial. The approach presented here provides insight for an ex-ante analysis and decision-making in irrigation to determine the most economical level of irrigation based on price of water and lint in a given season.

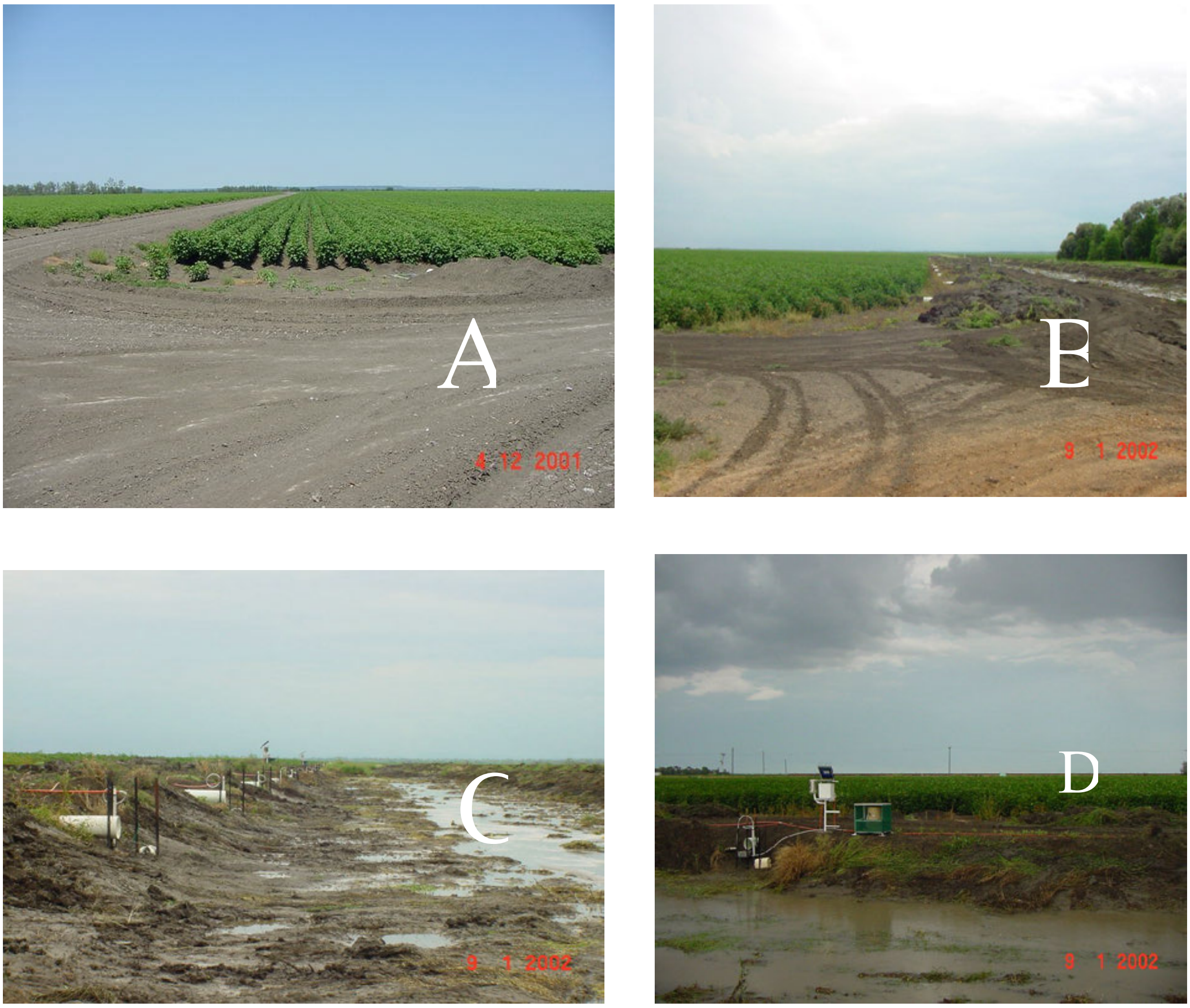

Image 3. Subsurface drip irrigation plot (a) with bedload trap (b), and runoff collection siphon (c) and the automatic run- off sampler (d).

4

Effect of oxygation on crop phenology, physiology and water use efficiency in a heavy clay soil [1, 2]

ABSTRACT

Inadequate O_2 concentration in the root zone is a constraint to plant performance particularly in heavy, compacted and/or saline soils. Sub-surface drip irrigation (SDI) offers a means of increasing O_2 to plant roots in such soils, provided irrigation water can be hyper-aerated or oxygenated. Methods were developed for hyper-aerating the irrigation water either with hydrogen peroxide (HP) or with an inline air injector (venturi). Using aerated water in irrigation through SDI has been defined as "Oxygation". Two pot experiments with vegetable soybean (*Glycine max* L. Merrill) and cotton (*Gossypium hirsutum* L.) compared the effectiveness of HP and air injection using a Mazzei ™ air injector (a venturi), throughout the irrigation cycle in raising crop yield in a heavy clay soil kept at saturation or just under field capacity. The third experiment on tomato (*Lycopersicon esculentum* L.) investigated the benefit of aerated water (12% air by volume of water) irrigation in the heavy clay soil irrigated at field capacity (FC) and at deficit moisture (50-75% FC). Fresh pod yield of vegetable soybean increased by 82-96% in aeration treatments compared with the control. The yield increase was associated with more pods per plant and greater mean pod weight. Significantly higher above-ground biomass and light interception were evident with aeration, irrespective of soil water treatment. Similarly cotton lint yield increased by 14-28% in aeration treatments compared with the control. The higher lint yield was associated with more squares and bolls per plant, which accompanied greater above-ground biomass and an increase in root mass, root length and soil respiration. In tomato, aerated irrigation water increased fruit yield

[1] Part of this chapter (soybean and cotton) has been published in the journal Annals of Applied Biology, 144:285-298 titled "Aerated subsurface irrigation water gives growth and yield benefits to zucchini, vegetable soybean and cotton in heavy clay soils". Authors are Surya P. Bhattarai, S. Huber and D.J. Midmore.

[2] Data on tomato has been submitted to the journal Scientia Horticulturae, in a paper titled "Root aeration improves yield performance and water use efficiency of tomato in heavy clay and saline soils". Authors are Surya P. Bhattarai, L. Prendergast and D. J. Midmore

by 12% compared to the control and the effect of aeration was significantly greater at FC compared with the deficit soil moisture treatment. The increase in fruit yield was accompanied by greater fruit size and harvest index in the aerated treatment. Aeration invariably increased crop applied water and this was accompanied by higher stem sap flow with aeration compared to the control. Consistently higher root respiration possibly contributed towards higher sap flow which then impacted on greater leaf and canopy activities as observed by higher radiation use efficiency (RUE) for aeration treatments compared to the control. Air injection and HP effected greater water use, but also brought about an enhancement of water use efficiency (WUE) for pod, lint and fruit yield, and increased leaf photosynthetic rate in soybean and cotton but had no effect on transpiration rate and stomatal conductance per unit leaf area in any of the three species. Aeration-induced enhanced root function was arguably responsible for greater fruit set and yield in all three crops, while in vegetable soybean greater canopy cover, radiation interception and total vegetative biomass were responsible for additional yield benefit. Increased aeration of the root zone in heavy clay soils employing either air injection or HP proved beneficial to SDI irrigated crops, irrespective of the soil water conditions, and can add value to grower investments in SDI.

4.1 INTRODUCTION

For optimal crop growth the above-ground atmosphere must supply sufficient quantities of CO_2 for photosynthesis, and O_2 for respiration, and much attention has been placed particularly on the supply of CO_2 (Drew and Stolzy, 1996). However, supply of sufficient quantity of air to the root system has received much less attention, and could open avenues of crop yield improvement, should the levels of particularly O_2 be suboptimal within the soil. Respiring plant roots consume large amounts of O_2, equivalent to 5 ml O_2 h^{-1} g^{-1} of dry tissue (Grable, 1966) and to this must be added the demand by aerobic soil micro-organisms present in soils when calculating soil O_2 requirements (Glinski and Stepniewski, 1985). Continuous exchange of the soil gas is, therefore, necessary for effective rhizosphere function. Of major importance is the comparison of the amount of O_2 present in the soil with potential soil respiration rates. Such a comparison reveals that the O_2 reserve in the soil is insufficient to sustain the crop and soil respiration for a long term particularly when the O_2 exchange is impeded (Mukhtar *et al*., 1996)**.** It is estimated that soil pore space in the top one-metre of a soil profile contains a supply of O_2 sufficient to meet the respiratory demand of a crop for about 3-4 days without replenishment (Focht, 1992). An effective exchange of gases in the soil, therefore, must ensure adequate O_2 replenishment and removal of the waste products, if respiratory processes are to be sustained.

Lack of O_2 commonly prevails in heavy clay soils and those compacted, saturated or with impeded subsurface drainage (Letley, 1961). The importance of aeration on the functioning of higher plants and effects of limited aeration (Grable, 1966; Armstrong, 1979; Blokhina *et al.,* 2003) and anaerobiosis and its consequences are well studied (Vartapetian and Jackson, 1997; Visser *et al.,* 2003). In spite of these known impacts of poor aeration on the root and soil function, practical options for soil aeration suitable for large acreages are not readily available.

Lack of soil O_2 directly affects root growth. Root growth is sensitive to O_2 deficiency, which reduces root elongation in many species (Aguilar *et al*., 2003). Reduced O_2 in the rhizosphere leads to a root system incapable of sustaining water and nutrient requirements. Threshold O_2 concentration at which root extension begins to decrease is commonly about half that in air (Huang *et al.,* 1994). Root O_2 supply also plays a crucial role in shoot growth. Increased O_2 enhances K and P uptake (Letey, 1961).

In practice, in the field continuous or episodic events of induced deficit aeration can prevail. The intensity, however, differs with the soil type, rainfall duration and intensity, method and rate of irrigation. Meek *et al.* (1983) reported a drop of O_2 concentration at 20 cm depth from an optimum of 0.206 L L^{-1} to 0.03-0.06 L L^{-1} for a tomato crop with daily trickle irrigation equivalent to 100-120% of pan evaporation compared with 0.06 - 0.15 L L^{-1} for a crop irrigated weekly with trickle in a clay soil. Such a depression of O_2 in the root zone may limit the performance of subsurface drip irrigation (SDI) crops. Yield reduction of many major crops grown in heavy clay soils, particularly in the wet season, has been partly attributed to depletion of O_2 in the root zone. In the irrigated wheat and cotton regions of southeast Australia, warm temperatures in spring and summer, combined with poor soil drainage on heavy soils, cause yield reductions as a result of O_2 depletion during and following each irrigation (Meyer *et al.,* 1985; Baruch, 1994). In undisturbed monoliths of clay loam sown with wheat, soil O_2 virtually disappeared at depths between 12.5 and 85 cm within 24 hours of an irrigation event, with a gradual return of the surface horizon to normal concentration (0.206 L L^{-1}) over the next 10-15 days (Meyer *et al.,* 1985). Very low O_2 fluxes were determined in soil cores extracted from such soils in the field following furrow irrigation (Hodgson and MacLeod, 1998).

As water becomes increasingly scarce for irrigation, SDI offers significant increases in WUE over traditional irrigation (e.g. cotton (Bhattarai *et al*., 2003b), soybean and wheat (Camp, 1998) and other crops (Ayars *et al.,* 1999). However, yields tend to be similar between irrigation systems. While the benefits of soil aeration have long been recognised at the experimental (Berry and Norris, 1949) and theoretical levels (Bryce *et al*., 1982; Bathke *et al*., 1992; Huang *et al*., 1994)**,** application of these findings to the field scale has been limited due to lack of suitable delivery technologies. Recently, some research has shown that aeration may be effected through SDI, using venturi to supply a slurry of air and water (Goorahoo *et al*., 2002) or a solution of hydrogen peroxide (HP) (Huber, 2000). In this research, pot experiments on tomato, vegetable soybean and cotton were conducted to examine the effects of these promising aeration systems with a non-aerated control under saturated soil conditions and near-field capacity, as well as suboptimum (referred as deficit) soil moisture conditions and quantified the effects of aeration on the performance of crop root and above-ground shoot production and on some physiological parameters. Results consistently showed the benefits of aeration under saturation, field capacity and even with deficit soil moisture regimes in a heavy clay soil.

4.2 MATERIALS AND METHODS

4.2.1 Location and Crop Details

Pot experiments were carried out in the screen-house (67% full sunlight) for vegetable soybean (*Glycine max* L.) and tomato (*Lycopersicon esculetum* L.) and in the open for cotton (*Gossypium hirsutum* L.) at the Central Queensland University (CQU) Rockhampton campus (latitude: 23^0 22’ 0.345’’ S and longitude: 150^0 31’ 0.53’’ East, and altitude: 10 masl) over the period of 2002-2003. The first trial on vegetable soybean (*Glycine max* L. cultivar C784-1-2-1 from CSIRO) was planted in the screen-house on 12 July 2002. The second on cotton (*Gossypium hirsutum* L. variety Sicot 289i ™ Inguard from Monsanto seed company) was planted on 2 November 2002 at Rockhampton, in the open. The third on tomato (*Lycopersicon esculetum* L.) variety Improved Apollo was planted on 29 April 2003 in the screen house. Weather data were recorded from an adjacent weather station. Average daily temperature, sunlight intensity, relative humidity and weekly soil water content and soil temperature were recorded throughout the period of the experiments. For tomato one plant per pot was maintained by thinning at the three-leaf stage. Plants were individually staked, and pruned to single stem, whereas for cotton and vegetable soybean three plants in each pot were positioned along the pot diameter parallel to the row.

4.2.2 Soil and Experimental Pot Setup

All three experiments were set up using a heavy cracking clay soil from Emerald, Central Queensland, which is referred to as a Vertosol according to the Australian soil classification (Isbell, 1996). The aeration effect was tested in three different crops in various soil moisture contents in a heavy clay soil. Field capacity was determined for the soil according to the procedures described by Brady and Weil (1999), and the permanent wilting points for the soil were determined as the soil water content at which plants underwent permanent wilting, for each crop species separately, also according to Brady and Weil (1999). Field capacity for the soil was 43 mm 100 mm^{-1} soil and permanent wilting point was 20, 22 and 21 mm 100 mm^{-1} soil for cotton, soybean and tomato respectively. Soil collected from the field was filled in the sealed pots (25 cm diameter x 45 cm height) for experiments each with 26 kg soil to maintain bulk density at 1.3 g cm^{-3} in order to ensure uniform soil porosity and aeration before imposition of the treatments. Soybean in the screen-house was planted at 60 cm between and 10 cm within row spacing, cotton was planted at 1 m between and 10 cm within rows whereas tomato was planted at 75 cm between and 60 cm within rows; these spacings reflected those of field-grown crops. For soybean each plot consisted of five containers accommodating 15 plants whereas cotton consisted of four containers per plot accommodating 12 plants and tomato experiment consisted of four containers per plot accommodating four plants per experimental plot. Further, a foliar application of a foliar liquid fertilizer “Stop It”-manufactured by Phosyn Plc., UK which contains calcium chloride 16% (W/V) as a 1% solution was sprayed twice during the crop season in an attempt to control blossom end rot on tomato and Ca deficiency on cotton and soybean plants.

4.2.3 Irrigation Setup and Fertigation

All pots were fitted with Netafim pot drippers placed at 25-30 cm below the soil surface. The dripper delivery was 1 L $hour^{-1}$ and was operated under the pressure of 62-76 KPa (9-11 Psi) at the return to the water pump. The use of pot drippers was to mimic the SDI system in heavy clay soil in the field. Soil water was measured weekly in one pot per experimental plot using a calibrated Micro Gopher system (Soil Moisture Technology Pty Ltd, Australia) the probe of which consists of a capacitance sensor. The fertilizer requirement of the crop was supplied through fertigation using a general-purpose water-soluble fertilizer (20:8.7:16.6 NPK and 0.01%B, 0.004%Cu, 0.05%Fe, 0.03%Mn, 0.001%Mo, 0.003%Zn) at the rate of 0.5 g L^{-1} continuously throughout the crop season. To account for different uptake rates of water between treatments, at times irrigation was applied without fertigation to ensure that all plots received the same amount of nutrients. This resulted in application of 37.3 g fertilizer $plot^{-1}$ for soybean, 78.3 g $plot^{-1}$ for cotton and 242.0 g $plot^{-1}$ for tomato. The amount of water delivered to each experimental plot within each experiment was recorded.

4.2.4 Experimental Design and Treatment Details

Experiments on soybean and cotton were laid out as factorial randomised complete block designs (RCBD) with four replications. Two factors tested were method of aeration (three methods of aeration - air injection, hydrogen peroxide and non–aerated control) and soil water status (two levels of soil water - field capacity and saturation, i.e. soil water maintained between 25-40 mm and called field capacity: soil water maintained between 43-50 mm and called saturation). Each experiment, therefore, comprised of 24 experimental plots. The experiment on tomato was also laid out as a factorial RCBD with three replications. Two factors tested were methods of aeration (air injection and control) and soil moisture levels (FC and deficit irrigation (50-75% of FC)). The experiment on tomato comprised a total of 12 plots. The soil moisture treatments were initiated as soon as the first pairs of true leaves fully expanded.

4.2.5 Air Injection and Monitoring of Soil Oxygen

Air injection was accomplished by mixing air at the rate of 12% by volume of the irrigation water employing Mazzei air injector model 384-X (which is a pressure differential venturi) coupled in the pressurized irrigation line following methods described by Goorahoo *et al.* (2002). The manifolds in the irrigation lines were fitted with dual flow metres, pressure gauges and pressure regulators. The air injection manifold was fitted with a Mazzei (patented) injector gas inlet port, a throttling valve and set up to attach to a rotameter. The air suction through the venturi tube of the Mazzei injector takes place following Bernoulli's principle [for details see Anonymous (2003) and Goorahoo *et al.* (2002)]. For the HP treatment in soybean and cotton experiment, H_2O_2 (50% v/v) was mixed in the irrigation water at the rate of 1ml L^{-1} of irrigation water. The control irrigation plot simply received water mixed with fertilizer.

Normally irrigation water contains O_2 concentration at 3-8 mg L^{-1} whereas the aerated water with air injection (12% by volume of air) reached a concentration of as high as 42 mg L^{-1}. The mixture of HP in pure water under controlled conditions at the rate of 1 ml L^{-1} produces a theoretical maximum O_2 concentration ten times greater than can be produced by mixing 12% air in a litre of water. Measurement showed that only one tenth of the potential O_2 stayed in the irrigation water ten minutes after application. Hence, the net O_2 available in irrigation water with HP and from air injection in the experimental period in each experiment was similar. O_2 in heavy clay is also consumed by organic and inorganic reductants, therefore, not all of the additional O_2 was available to the plant roots (Herr and Jarrel, 1980). Both air and HP injection occurred throughout each irrigation cycle starting 13 and 27 days after sowing, for soybean and cotton, respectively. Unlike two aeration methods used for cotton and soybean, in the tomato experiment only one method of aeration was used. Aeration of tomato was performed using air injector (12% air by volume of water with mazzei air injector), which started as soon as first true leaves appeared, and continued for the whole crop duration. O_2 concentration in the soil was monitored in the tomato experiment using PSt3 O_2 sensitive fibre optic minisensors with a Fibox-3 O_2 oxygen metre (PreSens GmbH, Germany). It is an optical sensor that measures pO_2 in the gaseous as well as liquid phase, making it suitable for soil measurements (Klimant *et al.*, 1995). Sensors were placed in the pots at 15 cm depth, and left for 3 days before output data were recorded for the measurement of root zone O_2 concentration.

4.2.6 Plant Based Data Recording

4.2.6.1 Growth and development

Performance of the three species in terms of phenology, yield, and physiology were assessed on the bordered plants per experimental plot. Growth and development parameters such as plant height, number of shoots, number of nodes, stem diameter, leaf number, leaf area, leaf size; and reproductive parameters such as days to flowering, fruit set, and lower- most flowering nodes were recorded from individual plant at fortnightly interval and at final harvest. The crops in the experiments were allowed to reach their harvestable stage, i.e. tomato was harvested as fruits ripened, vegetable soybean at R7 stage (completely filled green pods), and cotton when 100% boll opening was achieved. The dry matter data for leaf, stem, roots and fruits as appropriate were derived from the final harvest of the plant, which were then dried for at least 48 hours at 70 ^{o}C or until a constant weight was achieved for such dry weight.

4.2.6.2 Root sample analysis

Root samples (one core sample per pot - collected 107, 154, 164 days after sowing for vegetable soybean, cotton and tomato respectively) were obtained by coring with a 3 cm diameter soil corer to the entire depth of the pot. The collected core samples were soaked in 1% solution of ground breaker (active constituent 10 g L^{-1} buffered polylignosulfonate) for 2-3 hours and roots were separated from soil using a 45-micrometer sieve following the floatation technique. The living roots were separated manually by discarding the dead based on visual observation of tissue colour as described by Caldwell and Virgina (1991) and the root length and diameter of the former was determined using a Hewlett Packard scanner and Delta-T software. The prepared root samples were placed on the transparent trays, using a special mesh panel to hold the roots flat against the base of the root tray. The sample was then scanned into an image file, which was then passed to Delta-T Scan software, which offers superior resolution over a much larger area than is possible with systems based on a video camera, and because the scanner delivers digitized images with a precise number of dots per mm, no specific calibration is required. Delta-T Scan provides a comprehensive range of analysis and measurement function for length, diameter and density with alternative algorithms of which Newman (1966) was followed to allow the measurements of overlapping root samples. The accuracy of the measurement for the root length was within 1% of the calibration for the sample. The washed and imaged root samples were then oven-dried for 48 hours at 70 ^{o} C for the determination of dry mass.

4.2.6.3 Leaf and soil gas exchange

Soil respiration was measured at pod setting (67 days after sowing (das) for vegetable soybean), boll filling stages (91 das for cotton), and fruit ripening stage (145 das for tomato), using the IRGA principle with an EGM-3 from PP Systems, UK. Rates of leaf photosynthesis (A), transpiration (E), stomatal conductivity (SC) and instantaneous water use efficiency (A/E) were measured fortnightly with an infrared gas analyser (IRGA) model LCA-4 from ADC-UK. IRGA measurements were made on three youngest fully expanded exposed leaves per plot on each occasion between 1000-1500 h.

4.2.6.4 Relative water content

The relative water content of the leaf tissue was determined following Barrs and Weatherley (1962) and calculated as

RWC = (FW-DW)/(TW-DW), and expressed as a percentage.

Two fully expanded top leaves for cotton and soybean or ten leaflets for tomato were used that were collected at vegetative, flowering and fruiting stages for the determination of RWC.

4.2.6.5 Leaf water potential

Midday leaf water potential of leaf petioles was determined on 3 different occasions (prior to flowering, flowering and fruit development stages) using the pressure bomb apparatus following Scholander *et al*. (1965) from Soil Moisture Equipment Corp., USA, immediately after the two fully-expanded leaves were excised per plot. The xylem sap was exuded further from the samples used for determination of LWP, and collected by micropipette in sterile 1.5 mL Eppendorf vials (on ice) and stored at - 80 ^{o}C for the determination of osmotic potential (only for tomato). Stored xylem sap samples were thawed, 10 μL of sample was placed in the paper disc and the readings were made with a Wescor vapour pressure osmometer (Model 5500C, Wescor Inc., Logan UT) following the method described by Gebre *et al*. (1997). Osmometer readings are presented in m mol kg^{-1}.

4.2.6.6 Leaf weight ratio and specific leaf area

Leaf weight ratio (LWR; g/g) is the ratio of leaf dry biomass to total plant dry biomass and thus a measure of the proportion of the plant dry biomass residing in the leaf material. Specific leaf area (SLA; leaf area (cm^2)/ leaf dry biomass (g)) is the ratio of leaf area to leaf plant dry biomass and thus a measure of leaf thickness. SLA analysis was performed following methods described by Garnier *et al.* (2001) at the same time as leaves for LWP were collected. For SLA, leaf area was determined using a Hewlett Packard scanner and Delta- T software as described in the section 4.2.6.2. and instead of measuring length, leaf area was measured and leaves were weighed using an analytical balance after drying for 5 days in an oven at 80° C. Specific leaf area (SLA) was expressed in cm^2 leaf area g^{-1} dry weight. LWR was calculated as proportion of the total leaf dry weight to the total above-ground dry weight of the sample plants at harvest.

4.2.6.7 Canopy temperature and crop water stress index

Crop water stress index and canopy temperatures were measured using a Model 210 Ag Multimeter (Everest Interscience Inc., Fullerton, CA) portable hand-held infrared thermometer. The instrument base was calibrated using a method described by Blad and Rosenberg (1976). In each measurement the infrared thermometer was held above the plant canopy at an angle of 15^{o}C below the horizontal so that plant parts, but no soil were viewed. Canopy temperature (Tc) were taken at each plot starting from early establishment to the final harvest on fortnightly intervals. In each determination, four canopy temperature measurements were taken from four sides and then averaged. These measurements were carried out between 1300-1500h in all species tested. At each measurement time, the IR thermometer also recorded dry and wet-bulb temperatures, above the canopy surface, detrained air temperature (Ta) and vapour pressure deficit (VPD) which then calculates the relative CWSI in the range of 0-1, 0 being non stressed and 1 being completely stressed (DeTar *et al*., 1993).

4.2.6.8 Light interception

Photosynthetically active radiation (PAR) was measured for the determination of light interception, fortnightly between 1100-1300 h. Two readings per treatment were averaged, each consisting of one reading above the canopy and 4 readings beneath the canopy (ground level) taken by placing the AccuPAR ceptometer (Decagon USA) almost parallel to the crop row. Percent light interception was calculated as the difference between PAR above and below the canopy, % intercepted PAR = [(above-below)/above] X 100.

4.2.6.9 Leaf chlorophyll determination

The leaf chlorophyll concentration was measured fortnightly on one fully expanded leaf per plant using the Minolta SPAD-502 metre that allows a non-destructive determination of relative chlorophyll concentration in the leaves. Sample leaves were analysed using acetone chlorophyll extraction method following EPA (Anonymous, 1994) to calibrate SPAD data as described by Levy and Skiles (2000).

4.2.6.10 Soil microbiology

Soil from the soybean experiment was sampled at pod filling stage at two different depths (top 5 cm and 10-20 cm). Following a 1: 5 soil dilution, 1 mL aliquots were used for the plate count agar (PCA) method for the enumeration by APHA-AWWA-WPCF (1980) and presented as the most probable number (MPN) of the soil microbes per gram of dry soil.

4.2.6.11 Water use efficiency

Season-long water use of each species was obtained by summing the daily additions of water over the entire season assuming that the evaporative loss from the containers was insignificant (pot surfaces had a black colour plastic cover above the soil surface). The season-long water use efficiency, WUE_{sl} was calculated by dividing the total plant dry weight by the season-long water use. Thus, WUE_{sl} represents the amount of dry biomass accumulated over the season for each unit of water transpired by the plant (g dry weight L^{-1} H_2O). WUE was also expressed as instantaneous water use efficiency, WUEi, calculated as amount of CO_2 (µmol) fixed per unit of water (m mol) lost by transpiration in photosynthesis. The inputs for this analysis were derived from the IRGA gas exchange data.

4.2.6.12 Sap flow determination

Water use by the plant through transpiration was measured using stem gauges (model SGA 13, Dynamax, Houston, TX, USA) attached to the stem of one plant in each treatment for tomato over the period of 5 days, during the fruiting stage. Sap flow rate was expressed as g h^{-1} and cumulative flow (g) over the period of a day. Sap flow was measured using a heating power of 0.15 W, the lowest pre-dawn values for the sheath conductance (Steinberg et al., 1989), and the average of beginning and ending values of stem diameter. The sap flow value compared with the gravimetric value over the period of 24 hours run of the experiment showed that sap flow was ± 93% of the gravimetric determination.

4.2.6.13 Carbon isotope discrimination

At the flowering stage of the crop, 10 leaflets of tomato, and 10 leaves each of vegetable soybean and cotton were collected from outer exposed positions of the canopy. Leaves from the fifth internode from the top were randomly collected and pooled for each plot for the analysis. The leaf samples were dried in an oven at 70 ^{o}C until the constant weight was achieved and then ground to a fine powder. The $^{13}C/^{12}C$ ratio of samples was subsequently determined by mass spectrometry at the Central Queensland University, Australia. Samples of 0.8-1.2 mg were combusted in an elemental analyzer (EA 1108, series 1, CHN analyser, Carlo Erba Instrumentazione, Milan, Italy) and the $^{13}C/^{12}C$ ratio was measured with an isotope ratio mass spectrometer (Europa Scientific Limited, UK 20-20 Stable IRMS) operated in continuous flow mode. A system check for elemental analysis was achieved with an interspersed working standard of standardised flour. Stable carbon isotope composition was expressed as $\delta\ ^{13}C$ values, where:

$$\delta\ ^{13}C\ (‰) = [R\ sample/R\ standard)-1] \times 100, \text{ and R is the } ^{13}C/^{12}C \text{ ratio.}$$

A secondary standard of flour calibrated against Peedee belemnite (PDB) carbonate was used for comparison. The accuracy of the $\delta\ ^{13}C$ measurements was ± 0.04-0.13‰ (CV 1.7 ‰). Following Farquhar *et al.,* (1989)**,** Δ was further calculated from $\delta\ ^{13}C$ as $\Delta = (\delta_a - \delta_p)/(1 + \delta_p)$, where δ_a and δ_p refer to air and plant respectively. On the PDB scale, free atmospheric CO_2, δ_a, has a current composition of approximately -8‰.

The WUE in terms of carbon isotope discrimination was determined following the method described by Thumma *et al.* (1998).

4.2.6.14 Plant sample analysis for nutrients

Leaf samples of soybean, cotton and tomato were collected at the flowering stage, from outer exposed positions of the canopy. Leaves from the fifth internode from the top were randomly collected and pooled for each plot for nutrients analysis. The leaf samples were dried in an oven at 70 ^{o}C until a constant weight was achieved and then ground to a fine powder and stored in sealed glass containers until processing. The leaf samples were analysed for total nitrogen (0.4 g sample digested by concentrated H_2SO_4 plus selenium catalyst for 3 hours, N_2 measured in segmented flow analyser), nitrate nitrogen and chloride (0.4 g sample boiled in deionised water for 1 hour, nitrate and chloride measure colormetrically in segmented flow analyser), total phosphorus, sulphur, potassium, calcium, magnesium, sodium copper, zinc, manganese, iron, aluminium and boron (1.6 g sample digested in concentrated HNO_3 measured using ICP AES (inductively coupled plasma, argon emission spectrometer) following the standard procedures in the Australian accredited commercial laboratory of CSBP, Western Australia. Leaf petiole sap of tomato was also tested for sap nitrate content during the flowering stage using Reflectoquant test strips of Merck, Germany.

4.2.6.15 Yield and yield components

At final harvest, pod yield and its components for vegetable soybean, and lint yield and its components for cotton were measured. For tomato, staggered harvests as fruits matured were taken, and accordingly the fruit yield and its components for tomato computed. Nine bordered plants for soybean and cotton and two bordered plants for tomato per plot were used for the determination of yield and yield components. Whole plants were then dried at 70^{o}C for $\geq$ 48 hours until constant weight was reached for above-ground biomass determination.

4.2.6.16 Quality parameters

Tomato fruit wet chemistry (total soluble solids (TSS), total titrable acidity (TTA), pH, ascorbic acid (AA)), physical tests (firmness), and dry matter percentage were assessed on eight fruits (at the same maturity stage) per plot. A composite fruit sample was prepared by homogenizing with a stomacher and 4 replicates were frozen at -20°C for compositional analyses. Fruits were partially thawed, homogenized and filtered. A juice sample was used directly for determination of soluble solids by a temperature-compensated "refractometer" (calibrated Leica AR200 digital hand held Refractometer with IR receiver/transmitter, Leica Microsystems Inc., USA). A 10 ml sample was used for determination of pH and acidity by titrating with 0.1 N NaOH to a pH 8.2 endpoint. Titratable acidity was calculated as % citric acid as per AOAC Official Methods of Analysis (AOAC, 1990). Compositional data are the average of 3 replicates over times. Ascorbic acid in the tomato sample juice was determined by reflectometric determination after reaction with molybdophosphoric acid to phosphomolybdenum blue using the Reflectoquant Ascorbic acid test by Merck, Germany and expressed as mg L^{-1}. The firmness of the fruits were assessed with the Wagner fruit ripeness tester, FT 327 by Wagner instruments, Inc. USA and expressed as kg; the more the pressure required to puncture the fruits, the firmer the fruits. Fresh tomato fruits were weighed, and were dried at 70 ^{o}C until final constant weight achieved and the dry matter (DM) content was calculated as:

$$DM\% = (DW/FW)*100$$

4.2.7 Data Analysis

The data collected were subjected to analysis of variance (ANOVA) using GLM for a factorial RCBD employing SYSTAT version 9 (SPSSInc, 1999). Where interactions were not significant, only main effects are presented. As the interaction effects between aeration and soil moisture were not significant for most of the parameters, the specific interaction effects are only presented in the graphical form and all main effects are presented in the tables. The means were compared by Fisher's protected 'Least Significant Difference' test. The 5% level of significance was used in all comparisons. Simple pair-wise correlations, and linear and polynomial regression were performed where appropriate to examine interrelationship between variables.

4.3 RESULTS

4.3.1 Tomato Experiment

4.3.1.1 Environmental parameters and weather

The mean ambient temperature measured outside the screenhouse averaged 19.5 ^{o} C and ranged from 10.4 to 25.3^{o} C whereas soil temperature averaged 24.8^{o} C and ranged from 20 to 31 ^{o}C. There was a gradual decrease in temperature from April to July and a slight increase from August to October. RH averaged 26% and ranged from 17% to 43% and solar radiation within the growing environment averaged 10.6 MJ m^{-2} d^{-1}, with a minimum of 1.6 to a maximum of 17.7 MJ $m^{-2}d^{-1}$ (Details included in the appendix).

4.3.1.2 Soil water input, water content and oxygen concentration

The cumulative water applied throughout the season was greater for FC compared with the deficit treatment (Figure 4.3.1.1) but aeration *per se* had no effect on the amount of water applied. Soil water content was maintained effectively at 24-28 and 40-43 mm H_2O per 100 mm soil depth throughout the season in deficit and FC treatments, respectively (Figure 4.3.1.2).

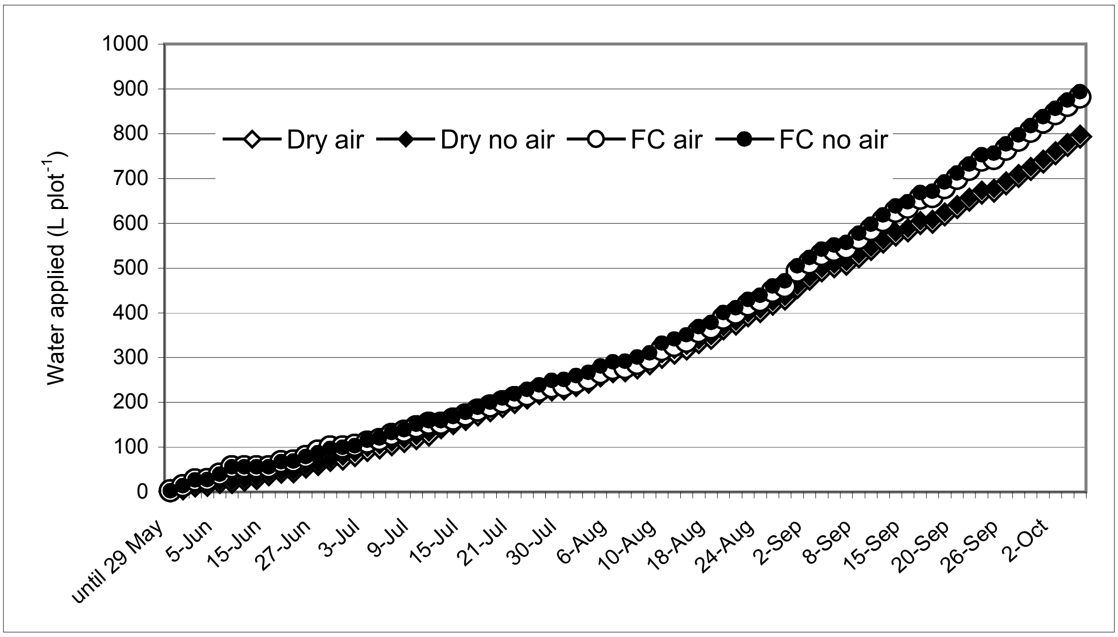

Figure 4.3.1.1. Cumulative applied water over the crop period for aerated (open symbol) and non-aerated (closed symbol) tomato at two soil water contents in versotol.

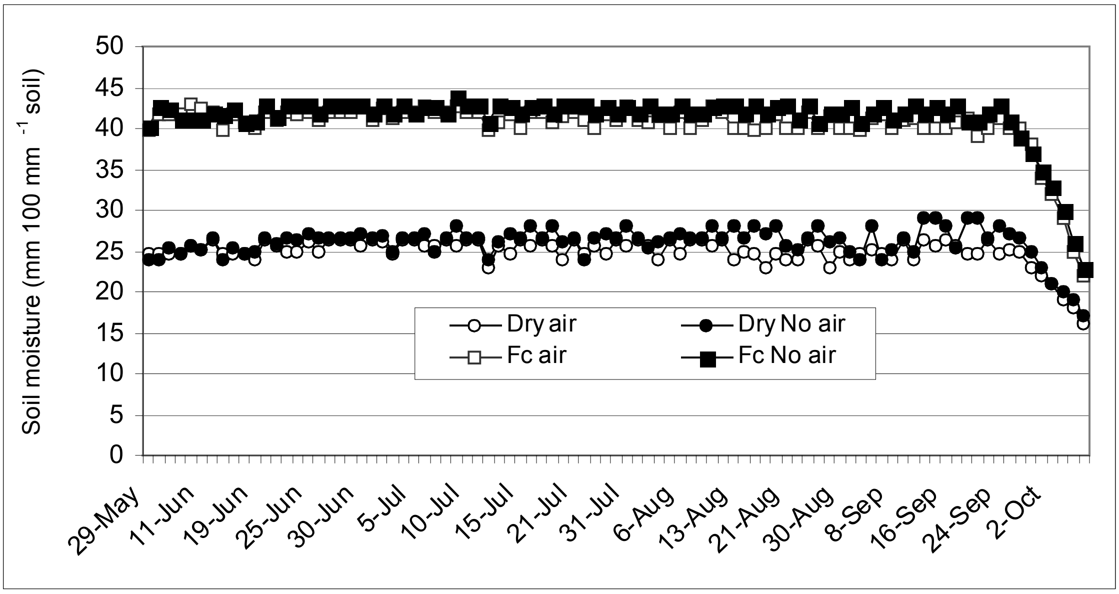

Figure 4.3.1.2 Soil water content (mm H_2O per 100 mm of soil depth) in field capacity and deficit treatments on tomato with (open symbols) and without aeration (closed circle). The irrigation was withheld close to harvesting.

Following irrigation dissolved O_2 declined by 45% in non-aerated pots while in aerated pots soil O_2 decreased by only 25% (Figure 4.3.1.3). O_2 measurements in the rhizosphere over a 72 hour period during the flowering stage revealed greater DO concentration with aerated treatments compared with the control at both FC (8.1 ± 0.96 vs 7.1 ± 1.0 mg L^{-1}) and deficit (9.2 ± 0.82 vs 8.1 ± 1.39 mg L^{-1}) moisture conditions. In general, dissolved O_2 concentration was observed to be higher at night and lower in the middle of the day (Figure 4.3.1.3).

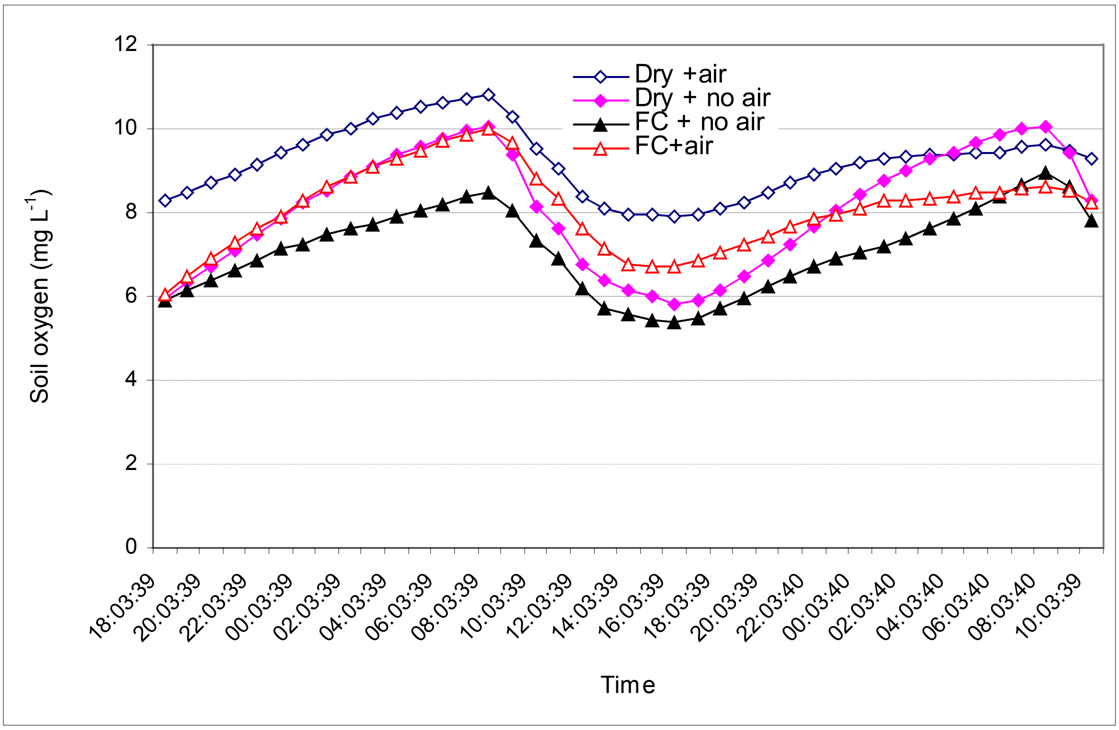

Figure 4.3.1.3 Concentration of soil O_2 as affected by aeration (open symbols) or no aeration (closed symbols) at two soil water contents in a heavy clay soil with tomato.

4.3.1.3 Plant growth characteristics

Plant height at harvest did not differ due to aeration, but plants under FC were somewhat taller than in the deficit treatment (Table 4.3.1.1). A marked positive effect of aeration was observed on leaf area per plant, primarily because of larger individual leaves (262 vs 239 cm^2, LSD (6 df) = 11.7 cm^2), however, these leaf properties were not affected by soil moisture treatment (Table 4.3.1.1). The interaction effect on leaf area was significant, showing a greater positive effect of aeration at FC than with the deficit irrigation (Table 4.3.1.1.) (Aeration = 0.790, control = 0.729 for deficit vs aeration = 0817, control = 0.673, LSD = 0.093 (18df) m^2 per plant). Stem diameter did not vary in response to soil moisture or aeration (Table 4.3.1.1)

4.3.1.4 Reproductive performance

There were tendencies for the first flowering node to occur at a relatively lower node number under aeration compared with the control, but this was not affected by soil moisture (Table 4.3.1.1). Similarly, first flowering tended to be earlier for aeration, and the drier treatment was also earlier compared with FC (Table 4.3.1.1). Higher fruit set percentage of tomato was recorded for FC compared to the dry (69 vs. 67%) and aerated compared to the control (69 vs. 67%) but the differences were not significant (Table 4.3.1.1).

4.3.1.5 Fruit yield and yield components

Fresh fruit yield was significantly greater for aeration compared to the control and almost so for FC compared to the dry treatment (Table 4.3.1.2). Although the effect of aeration and soil moisture was not significant for number of fruits per plant, the individual fresh fruit were significantly heavier due to aeration compared to the control. The soil moisture effect on weight per fruit was not significant. Fruit dry yield per plant did not differ significantly in response to soil moisture but aeration increased fruit dry yield compared to the control (Table 4.3.1.2).

Table 4.3.1.1 Effect of soil moisture and aeration on plant height, leaf properties, stem diameter, flowering and root properties of tomato in a heavy clay soil

Variables	Levels	Plant height (cm)	Leaves /plant	Leaf area/ plant (m^2)	Leaf size (cm^2)	Stem diameter (cm)	Lower most flowering node	Days to first flowering	Fruit set (%)	RLD[1] ($cm\ cm^{-3}$)	Root diameter (mm)
Moisture	Field capacity	192.2	30.5	0.745	245	14.4	9.3	47.2	69	4.0	0.850
	Dry	181.7	29.7	0.760	257	14.3	9.3	45.7	67	3.9	0.873
	LSD (df = 6)	23.2[a]	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Aeration	Air injection	190.0	30.7	0.803	262	14.4	9.11	45.3	69	3.5	0.848
	Control	183.8	29.5	0.701	239	14.2	9.40	47.5	67	4.4	0.874
	LSD (df = 6)	n.s.	1.53[a]	0.04	11.78	n.s.	n.s.	n.s.	n.s.	0.69	n.s.
M x A	LSD (df = 6)			0.093[a]	16.66						

[1] RLD = Root density expressed as length of root (cm) per cm^{-3} of the soil volume ($cm\ cm^{-3}$), [a] $0.05 \geq P \leq 0.10$

Table 4.3.1.2 Effect of soil moisture and aeration on fruit parameters, dry matter partitioning and harvest index of tomato in a heavy clay soil

Variables	Levels	Fruits/ plant (No.)	Weight per fruit (g)	No. of nodes	Fruit weight (kg/plant)	Dry weight (g/plant)				Above-ground biomass (g/plant)	HI[1]
						Root	Stem	Leaf	Fruit		
Moisture	Field capacity	31	129.98	46.6	4.03	12.19	55.38	97.83	315.88	467.37	2.07
	Dry	29	130.04	46.6	3.81	11.11	49.53	93.37	312.76	455.67	2.19
	LSD (df=6)	n.s.	n.s.	n.s.	0.25[a]	n.s.	4.6.	n.s.	n.s.	n.s.	n.s.
Aeration	Air injection	31	135.69	46.8	4.15	10.88	53.26	96.36	343.93	493.56	2.31
	Control	30	124.33	46.5	3.70	12.42	51.64	94.84	284.71	431.19	1.95
	LSD (df=6)	n.s.	n.s.	n.s.	0.25.	n.s.	n.s.	n.s.	10.54	23.10	0.14
M x A	LSD (df=6)						8.18[a]	13.65[a]	14.90[a]	32.69	0.62[a]

[1] Harvest Index (HI) is expressed as ratio of reproductive and vegetative weight (fruit weight (g)/stem and leaf weight (g)), [a] $0.05 \geq P \leq 0.10$

Table 4.3.1.3 Effect of soil moisture and aeration on plant water relations, water use efficiency and radiation use efficiency for tomato in a heavy clay soil

Variables	Levels	Water relations			Water use efficiency parameters				RUE (g/MJ)[3]
		Cumulative applied water (L $plant^{-1}$)	LWP (-kPa)[4]	CWSI[1]	$Biomass_{sl}$ (g/L)	$Fruit_{sl}$ (g/L)	Instantaneous (A/E)[2]	Δ (‰)[5]	
Moisture	Field capacity	110.94	1100	0.18	4.23	36.40	5.43	20.42	2.71
	Dry	99.42	1360	0.26	4.59	38.42	5.50	20.28	2.71
	LSD (df=6)	1.856	72.0	0.04	0.19	2.17[a]	0.365	n.s.	n.s.
Aeration	Air injection	106.68	1220	0.20	4.73	39.15	5.41	20.33	2.83
	Control	105.57	1240	0.24	4.09	35.16	5.52	20.37	2.59
	LSD (df=6)	n.s.	n.s.	0.04	0.19	2.17	n.s.	n.s.	0.178
M x A	LSD (df=6)				0.28	3.06[a]			

[1]CSWI= Crop water stress index (1 completely stressed, 0 no stressed), [2] A/E= μmol CO_2 $m^{-2}s^{-1}$/mmol H_2O $m^{-2}s^{-1}$, [3] above-ground dry biomass per MJ of intercepted PAR, [4] LWP = Leaf water potential, [5]Δ (‰) = Carbon isotope discrimination by the leaf , [a] 0.05 ≥ P ≤ 0.10

Table 4.3.1.4. Effect of soil moisture and aeration on leaf gas exchange properties, fruit DM, root: shoot ratio, SLA and light interception for tomato in heavy clay soil.

Variables	Levels	Leaf nitrate (mgL^{-1})	Osmolality (m mol kg^{-1})	Root: Shoot	SLA[1] (cm^2g^{-1})	Chlorophyll concentration ($\mu g\ cm^{-2}$)	Soil respiration (g CO_2 $m^{-2}h^{-1}$)	Leaf gas exchange properties			
								Photosynthesis ($\mu mol\ CO_2\ m^{-2}s^{-1}$)	Stomatal conductance ($mmol\ m^{-2}s^{-1}$)	Transpiration ($mmol\ m^{-2}s^{-1}$)	LI (%)[2]
Moisture	FC	2950	287	0.026	222	58	0.91	13.35	0.10	2.57	54.8
	Dry	3300	300	0.025	219	58	0.96	13.46	0.11	2.62	53.4
	LSD (df=6)	139	0.56	n.s.	n.s.	n.s.	n.s.	n.s.(158df)	n.s.(158df)	n.s.(158df)	n.s.
Aeration	Air injection	3317	282	0.022	209	59	1.07	13.38	0.10	2.59	55.3
	Control	2933	304	0.029	233	57	0.79	13.32	0.11	2.60	52.9
	LSD (df=6)	139	0.56	0.003	n.s.	2.1[a]	0.22	n.s.(158df)	n.s.(158df)	n.s.(158df)	n.s.

[1] Specific Leaf Area (SLA) presented as leaf area (cm^2) per gram of dry weight of leaf., [2] Canopy light interception (%) averaged across the season, [a] $0.05 \geq P \leq 0.10$

4.3.1.6 Fruit quality

Tomato fruit quality parameters such as dry matter (DM), total soluble solids (TSS), total titrable acidity (TTA), ascorbic acid (AA), pH, and firmness increased whereas the TSS:TTA ratio decreased slightly with the dry treatment (although non-significantly) compared with field capacity (Table 4.3.1.5). Similarly aeration increased DM, TSS, TTA, AA, pH but decreased the TSS:TTA ratio and firmness compared with the control, but only DM and AA were significantly so (Table 4.3.1.5)

Table 4.3.1.5 Effect of soil moisture and aeration on tomato fruit quality in a heavy clay soil.

Variables	Levels	Fruit DM[1] (%)	TSS[2] (%)	TTA[3] (%)	TSS: TTA[4]	AA[5] (mg 100g^{-1})	pH	Firmness (kg)
Moisture	Field capacity	7.83	6.36	0.40	16.53	107.0	4.37	2.82
	Dry	8.19	6.76	0.43	15.86	118.2	4.39	3.09
	LSD (df = 6)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Aeration	Aeration	8.31	6.64	0.42	15.83	130.0	4.41	2.81
	Control	7.71	6.48	0.40	16.56	95.17	4.35	3.11
	LSD (df = 6)	0.59	n.s.	n.s.	n.s.	28.86	n.s.	n.s.
M x A	LSD (df = 6)	0.82						

[1]Dry matter (DM) content in fruit expressed as %, [2]total soluble solid (TSS) expressed as % brix, [3]total titrable acidity (TTA) expressed as %, [4]ratio of total soluble solids and total titrable acidity (TSS:TTA), [5] ascorbic acid (AA) in tomato fruit extract and expressed as mg 100g^{-1} fruit.

4.3.1.7 Dry matter partitioning

Dry weight of root or leaf did not vary significantly in response to soil moisture or aeration. However, stem dry weight was significantly greater at FC compared with the dry treatment but did not differ significantly between aerated and control treatments

(Table 4.3.1.2). Above-ground dry biomass and HI were significantly greater (Table 4.3.1.2) and the root: shoot ratio was lower with aeration compared with the control (Table 4.3.1.4). The effects of soil moisture on these traits were not significant, although they all tended to be reduced by the dry treatment. The interaction effect was significant for above-ground biomass such that aeration showed a greater positive effect in the dry than in the FC treatment (Table 4.3.1.2 and Figure 4.3.1.4).

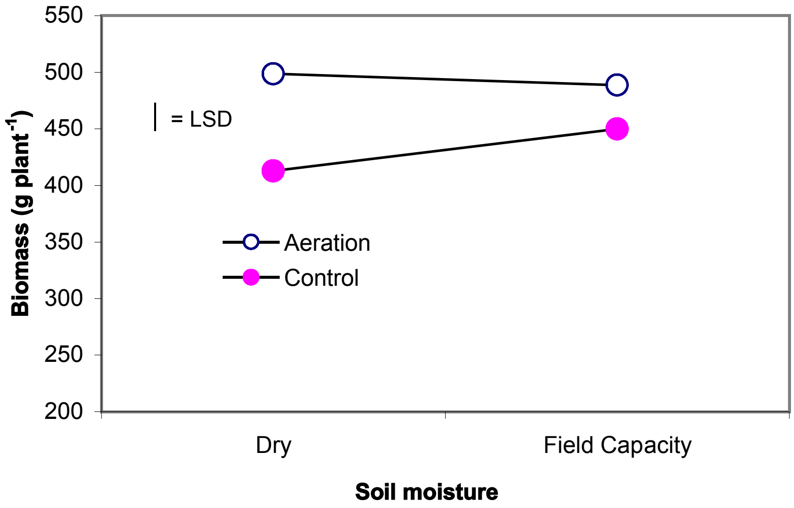

Figure 4.3.1.4 Relationship between the soil water content and aeration on the total above-ground biomass production of tomato in a heavy clay soil.

4.3.1.8 Root properties and soil respiration

Root dry weight (g plant^{-1}) did not vary significantly in response to soil moisture or aeration (4.3.1.2). Likewise, the effect of soil moisture and aeration was also not significant for lateral root diameter. However, the effect of aeration on root length density (RLD) was significant such that higher RLD was recorded for the control compared to aeration but soil moisture had no effect on RLD (Table 4.3.1.1). The root: shoot ratio decreased significantly with aeration compared with the control (Table 4.3.1.4). Soil respiration recorded at the early flowering stage (68 das) showed a higher soil respiration at deficit irrigation compared with field capacity but not significantly different, whereas the aeration treatment registered a significantly higher total soil respiration was evident in the aeration treatment compared to that of the control.

4.3.1.9 Leaf properties

The leaf chlorophyll concentration increased significantly with aeration compared with the control but did not vary with soil moisture (Table 4.1.3.4). The CWSI was much reduced with aeration and FC compared with the dry and control treatments, respectively (Table 4.1.3.3). The effects of aeration and soil water content treatments were not significant for the specific leaf area and average canopy light interception (Table 4.1.3.4). Canopy light interception over the crop period indicated that light interception increased with aeration compared to the control in both field capacity and dry treatments only after 3.5 months following planting (Figure 4.1.3.5).

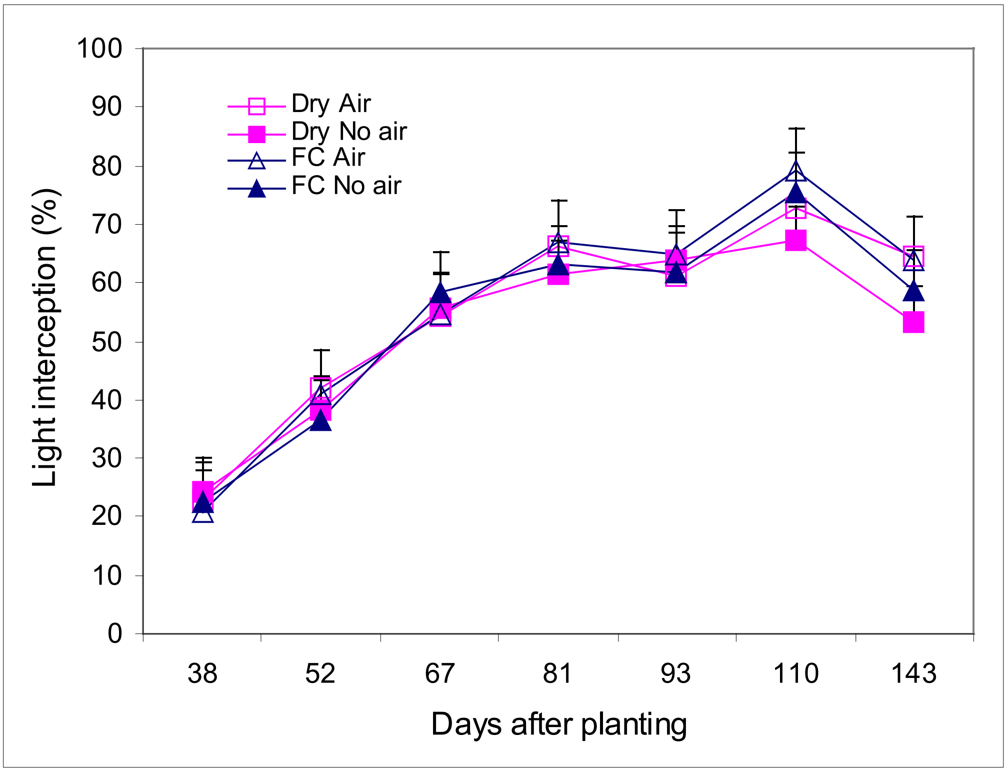

Figure 4.3.1.5 Seasonal canopy light interception with respect to aeration (open) or control (closed symbols) at two soil moisture treatments (Dry control= ■, Dry aeration = □, FC control = ▲, FC aeration =Δ) in a heavy clay soil.

4.3.1.10 Leaf gas exchange parameters

The effect of treatments on leaf gas exchange properties such as net leaf photosynthesis, stomatal conductance and transpiration were not significant (Table 4.3.1.4).

4.3.1.11 Leaf nutrients

Leaf nitrogen (N), phosphorus (P) and potassium (K) concentration varied from 2.7-3.1%, 0.3-0.4%, and 1.7-2%, respectively. Leaf P and K concentrations were lower with deficit irrigation compared to FC whereas N concentration was lower with aeration compared to the control (Figure 4.3.1.6). Nitrate concentration of petiole xylem sap increased with aeration compared to the control and with deficit irrigation compared to FC (Table 4.1.3.4). Petiole sap osmolality increased with deficit irrigation compared to FC and was reduced by aeration compared to the control (Table 4.1.3.4).

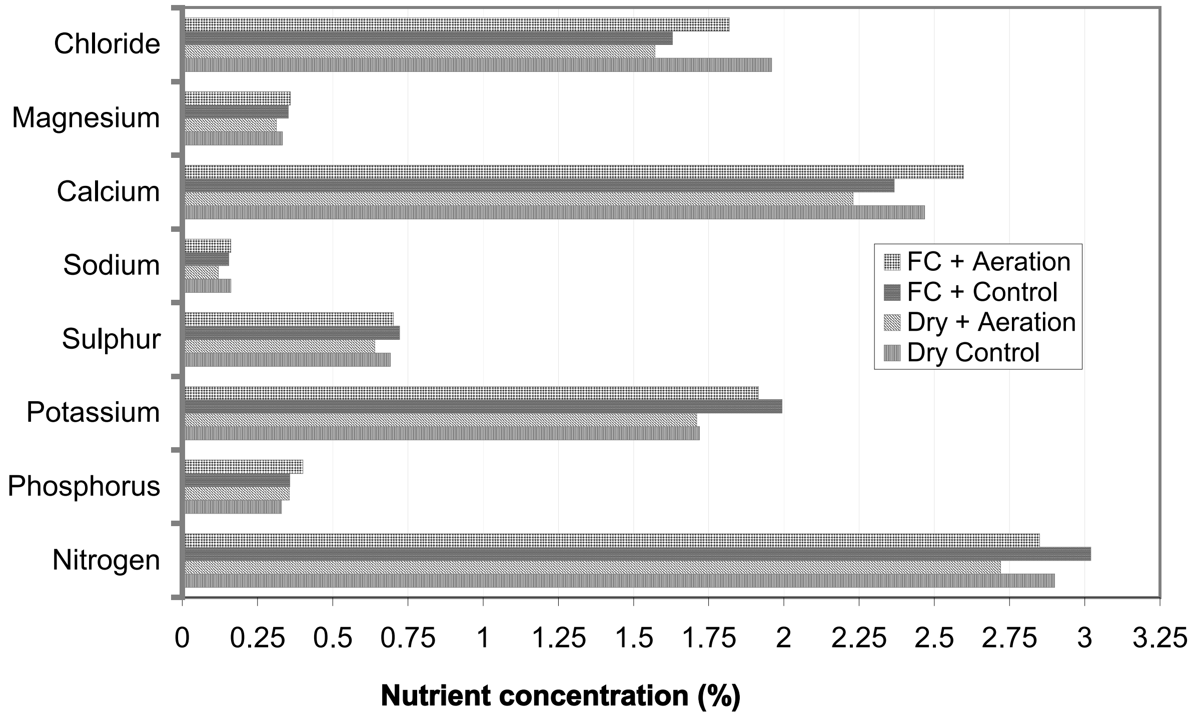

Figure 4.3.1.6. Leaf concentration of the major nutrients in tomato leaves at different soil moisture with and without aeration in a heavy clay soil**.**

4.3.1.12 Plant water relations and water use efficiency

The stem sap flow measured over three days at the flowering of the 6th inflorescence (83 das) indicated that plant transpiration increased by 8% with aeration compared to the control and by 18% with FC compared to the dry treatment (Figure 4.3.1.7). Aeration significantly reduced the crop water stress index (CWSI – derived from the difference between air and canopy temperature) compared to the control (Table 4.3.1.3). Likewise, FC significantly reduced CWSI compared with the dry treatment. The LWP was only affected by the soil moisture treatments such that a significantly more negative LWP was recorded for the dry compared to the FC treatment (Table 4.3.1.4). The WUE_i (i.e. instantaneous water use efficiency) did not differ significantly between treatments (Table 4.3.1.4), but biomass WUE_{sl} (i.e. season long water use efficiency) was significantly higher for the dry treatment compared with the FC and for aeration compared with the control (Table 4.3.1.4). Fresh fruit WUE_{sl} was significantly greater in the aeration treatment compared to the control and differed ($P<0.07$) between the soil moisture treatments (Table 4.1.3.3). WUE assessed by the carbon discrimination (Δ ‰) technique, a surrogate of transpiration efficiency, did not differ significantly due to either soil moisture or aeration treatments (Table 4.1.3.3).

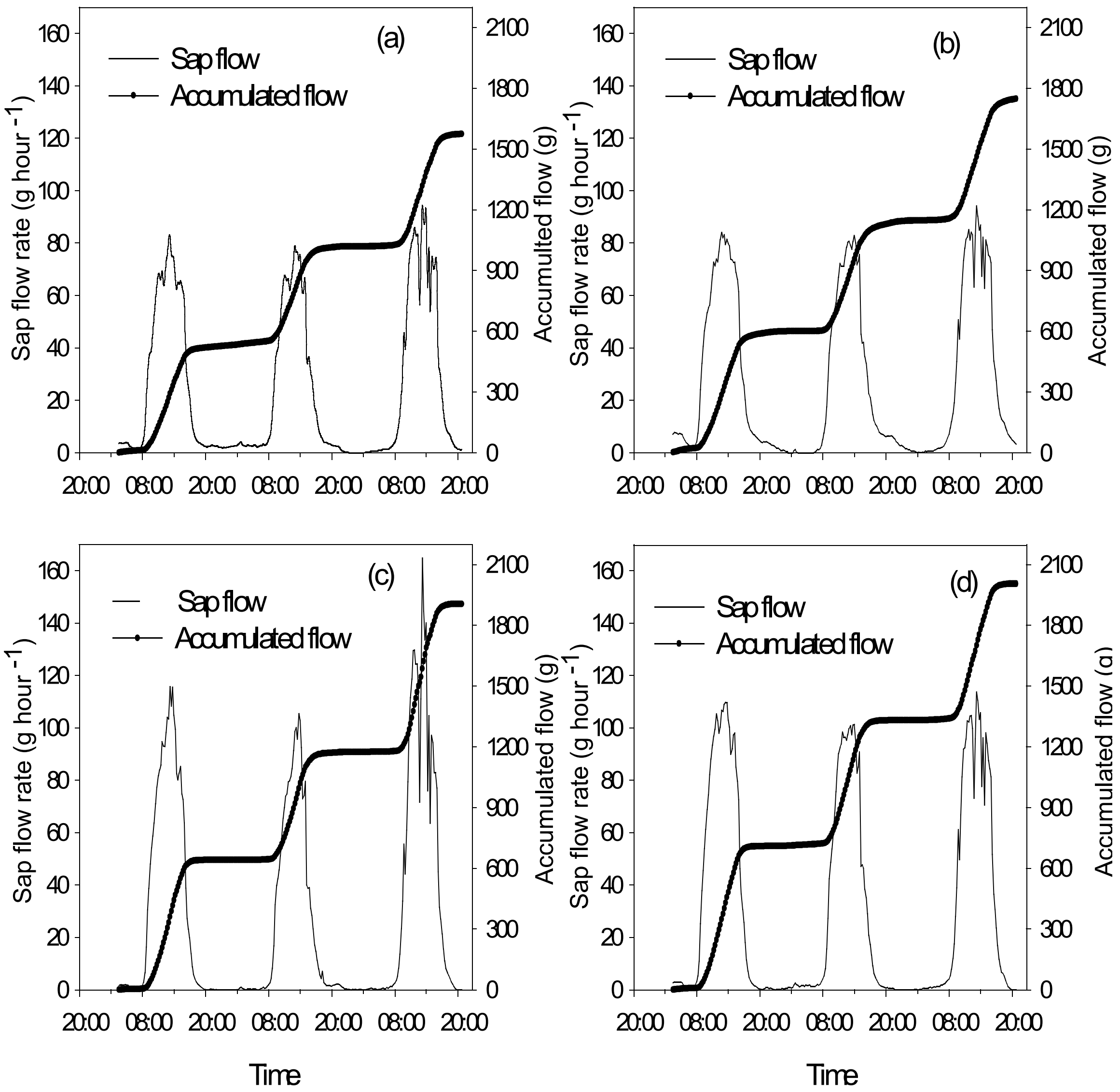

Figure 4.3.1.7 Stem sap flow rate at field capacity or dry treatments with or without aeration over 3 days period (a. dry + control; b. dry + aeration; c. FC + control; d. FC + aeration). Accumulated 3 days flow was, a. 1574 g; b. 1748 g; c. 1906 g, & d. 2005 g).

4.3.2 Vegetable Soybean Experiment

4.3.2.1 Weather and soil water

The daily mean ambient temperature ranged from 13 to 27 ^{o}C representing a gradual increase in temperature over the crop period. Likewise, there was also a gradual increase in incident solar radiation within the screen-house from 9 to 18 MJ m^{-2} d^{-1} over the crop period with the daily average of 12.3 MJ m^{-2} d^{-1} and there were a few occasions where daily average incident light level fell to 3 MJ m^{-2} d^{-1}(see appendix for details).

Table 4.3.2.1. Soil water content (mm H_2O per 100 mm soil) in different treatments for vegetable soybean (July-October, 2002) and cotton (November 2002-March 2003) at Rockhampton, Australia (mean, standard error and range calculated from regular observations over the crop season).

Soil water	Aeration	Vegetable soybean		Cotton	
		Mean	Range	Mean	Range
Field capacity	Air injection	32 ± 2.6	26-37	32 ± 3.1	25-37
	Control	33 ± 2.8	27-39	33 ± 3.5	27-39
	Hydrogen peroxide	30 ± 2.3	26-36	30 ± 3.2	25-36
Saturation	Air injection	46 ± 1.9	41-49	45 ± 1.9	40-49
	Control	47 ± 1.4	42-49	47 ± 1.5	43-49
	Hydrogen peroxide	45 ± 0.8	43-47	45 ± 1.2	42-47

Soil water content for the different treatments in the experiment is presented in Table 4.3.2.1. The soil water in the field capacity plots was well above the refill point (23 mm) throughout the experimental period whereas the water content in the saturated treatment was well above 42 mm for the crop period (Table 4.3.2.1). The soil water content was consistently lower, due to greater removal of water by plants, in the HP and air injection plots compared to the respective control in each irrigation treatment.

4.3.2.2 Yield and its components

There were no significant interactions between treatments for pod yield and its components, hence, main effects only are presented. The fresh pod yield was significantly ($P \leq 0.05$) depressed by the saturation treatment compared to the field capacity treatment (Table 4.3.2.2.). The pod yield with air injection and HP injection were significantly ($P \leq 0.05$) greater than that of the control. However, the difference in pod yield between the two aeration methods was not significant (Table 4.3.2.2).

Table 4.3.2.2 Pod yield and its components and above-ground dry biomass of vegetable soybean as affected by aeration and soil water treatments.

Factors	Treatments	Pod yield ($g\ m^{-2}$)	Pods $plant^{-1}$	No. of pods kg^{-1}	Fresh 100 seeds (g)	Aerial biomass ($g\ m^{-2}$)	Harvest Index
Aeration	Control	429.2	19.2	500	50	301.1	0.60
	HP	779.3	25.1	452	52	549.2	0.63
	Air injection	842.5	27.3	436	54	568.4	0.66
	LSD[1] (df = 15)	321.4	6.6	42.4	n.s.	204.8	n.s.
Water	Saturation	523.2	20.7	497	47	378.1	0.59
	Field capacity	844.4	27.3	428	57	567.7	0.66
	LSD[1] (df = 15)	262.3	n.s.	34.5	5.75	167.1	n.s.

[1]LSD = Least Significant Difference between two means

The greater yields under aeration, and the lower yield under saturation, were matched by similar treatment effects on the number of pods per plant and above-ground biomass (Table 4.3.2.2). Differences in harvest index were not significant between treatments (Table 4.3.2.2).

4.3.2.3 Fruit quality

Data on number of pods per kg of pod weight, a measure of pod quality given that larger and, therefore, fewer pods per kg represent higher quality product, showed that aeration enhanced and saturation reduced quality. In contrast, the fresh 100-shelled seed weight did not differ significantly between aeration treatments and their control. However, saturation significantly ($P<0.001$) reduced 100 seed weight (Table 4.3.2.2).

4.3.2.4 Root properties and soil respiration

Root dry mass (g plant^{-1}) and lateral root length density were least in the control (Table 4.3.2.3), and favoured more by HP at field capacity and by air injection under saturated conditions. Lateral root diameter varied from 0.24 to 0.29 mm and did not differ among treatments (Table 4.3.2.3). Likewise, the root: shoot ratio did not significantly differ among treatments and overall averaged 0.18 ± 0.06 (Table 4.3.2.3).

Table 4.3.2.3. Root properties, water use and chlorophyll concentration of vegetable soybean as affected by aeration and soil water treatments.

Soil water	Aeration	Root weight (g m^{-2})	Root length density (cm cm^{-3})	Water use plant^{-1} (L)	Chlorophyll concentration (SPAD unit)	Root dia. (mm)	Root: shoot ratio
Field capacity	Control	33.0	4.42	9.36	39	0.242	0.122
	HP[1]	139.7	19.18	15.78	37	0.281	0.200
	Air injection	73.3	7.09	13.28	38	0.280	0.121
Saturation	Control	45.0	3.74	10.56	31	0.280	0.221
	HP	70.3	6.29	11.89	38	0.301	0.229
	Air injection	133.7	13.39	14.89	35	0.280	0.221
LSD between any two means (15 df)		59.2	99	0.225	1.85	ns	ns

[1]HP:Hydrogen peroxide (0.05% solution for continuous irrigation)

Soil respiration, which included soil microbial and root respiration, differed significantly ($P \leq 0.05$) between aeration, but not between soil water treatments (Table 4.3.2.4). The rate of soil respiration in the air injection treatment (1.01 g CO_2 m^{-2} h^{-1}) was significantly greater compared to that of the HP treatment (0.68 g CO_2 m^{-2} h^{-1}) and the control (0.45 g CO_2 m^{-2} h^{-1}, LSD (15df) = 0.29). The difference between HP and the control was insignificant.

4.3.2.5 Plant water use and water use efficiency (WUE) parameters

Aeration treatments led to an increase in water use over that of the control (Table 4.3.2.4). While HP resulted in greater water use at field capacity than at saturation, the reverse was so for air injection.

Table 4.3.2.4 Soil respiration, water use efficiency and radiation use efficiency for vegetable soybean as affected by aeration and soil water treatments.

Factors	Treatments	Soil respiration (g CO_2 m^{-2} h^{-1})	WUE for pod yield (g L^{-1})	Instantaneous WUE (A/E)[1]	Biomass WUE_{sl} (g L^{-1})	Δ (‰)[3]	Radiation use efficiency (g MJ^{-1})[2]
Aeration	Control	0.45	2.15	4.03	1.83	19.53	1.03
	HP	0.68	3.32	4.50	2.32	19.49	1.39
	Air injection	1.01	3.65	4.85	2.45	19.63	1.41
	LSD (df = 15)	0.29	1.30	0.51	n.s.	n.s.	0.25
Water	Saturation	0.79	2.51	4.35	1.80	19.74	1.06
	Field capacity	0.69	3.52	4.58	2.60	19.35	1.49
	LSD (df = 15)	n.s.	1.04	n.s.	0.80	n.s.	0.36

[1] A/E= μmol CO_2 $m^{-2}s^{-1}$ /mmol H_2O $m^{-2}s^{-1}$, [2] g above-ground biomass / MJ intercepted radiation, [3] Carbon discrimination

Fresh pod yield WUE differed significantly due to aeration ($P \leq 0.05$) and soil water ($P \leq 0.05$) treatments (Table 4.3.2.4). The WUE for air injection and HP treatments surpassed the control by 70 and 54%, respectively. A higher WUE was evident at field capacity compared to the saturation treatment.

The dry biomass WUE was significantly ($P \leq 0.05$) greater by 31% at field capacity than saturation, but the response to aeration was not significant although it was in line with that of pod WUE (Table 4.3.2.4).

A measure of instantaneous WUE was gained by use of the instantaneous measures of rates of net photosynthesis and transpiration. The instantaneous WUE differed significantly ($P \leq 0.05$) only in response to aeration (Table 4.3.2.4). The instantaneous WUE was significantly higher for air injection and HP, by 20 and 12% respectively, compared to the control. The WUE was also quantified employing the technique of carbon isotope discrimination but no significant difference between the treatments was evident (Table 4.3.2.4).

4.3.2.6 Leaf gas exchange parameters and leaf chlorophyll

Leaf photosynthesis differed significantly due to dates ($P < 0.001$), aeration ($P \leq 0.05$) and soil water ($P \leq 0.05$). Air injection led to a significantly higher mean rate of photosynthesis compared to the control but the HP did not (Table 4.3.2.5). Leaf photosynthesis was greater by 10% at field capacity compared to the saturation treatment (Table 4.3.2.5). Likewise leaf chlorophyll concentration was significantly greater at field capacity than saturated conditions (38 vs. 35, LSD (15 df) = 1.6) in the non-aerated control, whereas it was equally high in the HP and air injection treatments (38), in either field capacity or saturated conditions (Table 4.3.2.3).

The transpiration rate and stomatal conductance differed only due to stage of growth, increasing from 1.8 ± 0.48 to 4.0 ± 0.72 mmol $m^{-2}s^{-1}$ for transpiration and 0.04

± 0.015 to 0.19 ± 0.037 mmol m^{-2} s^{-1} for stomatal conductance, respectively over the season. There were no significant differences in transpiration and stomatal conductance between soil water or aeration treatments (Table 4.3.2.5).

4.3.2.7 Crop water stress index

Crop water stress index, measured by infrared thermometry, did not differ significantly between soil water or aeration treatments (Table 4.3.2.5). However, the crop water stress index differed significantly ($P \leq 0.05$) due to dates representing the crop stages (highest at flowering and towards the end of the crop season).

Table 4.3.2.5. Leaf gas exchange parameters and crop water stress index (CWSI) of vegetable soybean as affected by aeration and soil water treatments.

Factors	Treatments	Rate of leaf photosynthesis (µmol $m^{-2}s^{-1}$)	LI[1] (%)	TR[2] (mmol $m^{-2}s^{-1}$)	SC[3] (mmol $m^{-2}s^{-1}$)	CSWI
Aeration	Control	9.76	33	2.805	0.10	0.279
	HP	10.39	52	2.765	0.09	0.254
	Air injection	11.13	54	2.675	0.085	0.251
	LSD (df = 107)	1.088	5.0	n.s.	n.s.	n.s.
Water	Saturation	9.89	44	2.76	0.09	0.265
	Field capacity	10.96	49	2.73	0.09	0.257
	LSD (df = 107)	0.89	4.09	n.s.	n.s.	n.s.

[1] Light interception by the canopy (average over the season), [2] Leaf transpiration rate, [3] Leaf stomatal conductance.

4.3.2.8 Light interception by the canopy

The progression in canopy light interception over time (Figure 4.3.2.1) showed that the non-aerated controls reached *c.* 60% light interception compared to *c.* 85% for air injection in either saturation or field capacity. While HP in saturated conditions enhanced early light interception by the canopy, by 81 days after sowing there was no benefit, although HP at field capacity consistently gave the highest value of light interception over the season (Figure 4.3.2.1). Light interception averaged over season was increased by 57%, and 64% for air injection and HP treatments, respectively, compared to the control. Similarly light interception at FC was 11% higher compared with the saturation treatment (Table 4.3.2.5).

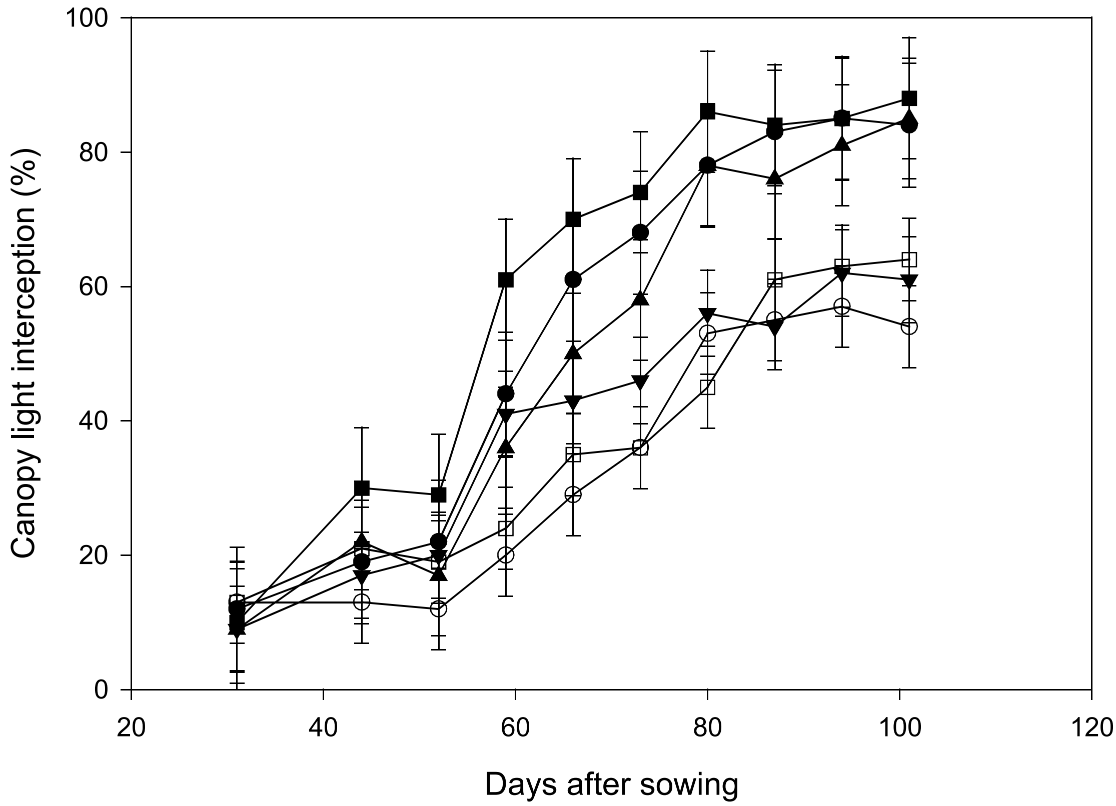

Figure 4.3.2.1 Light interception by vegetable soybean canopy over the season with respect to aeration and soil water treatments. ○- Field capacity + no aeration, ■ – Field capacity +HP, ●- Field capacity + air injection, □- Saturation + no aeration, ▼- Saturation +HP, ▲- Saturation + air injection.

4.3.2.9 Leaf nutrient concentrations

Leaf total nitrogen, phosphorus and potassium concentration varied between 3-5%, 0.25-1.25% and 1.5-1.75% respectively. Plants with the HP treatment showed higher leaf total N compared to all other treatments (Figure 4.3.2.2), and lowest with air injection at saturation. However, concentration of other nutrients, with the exception of P, did not vary greatly (Figure 4.3.2.2.). Phosphorus was greater with HP and least with air injection.

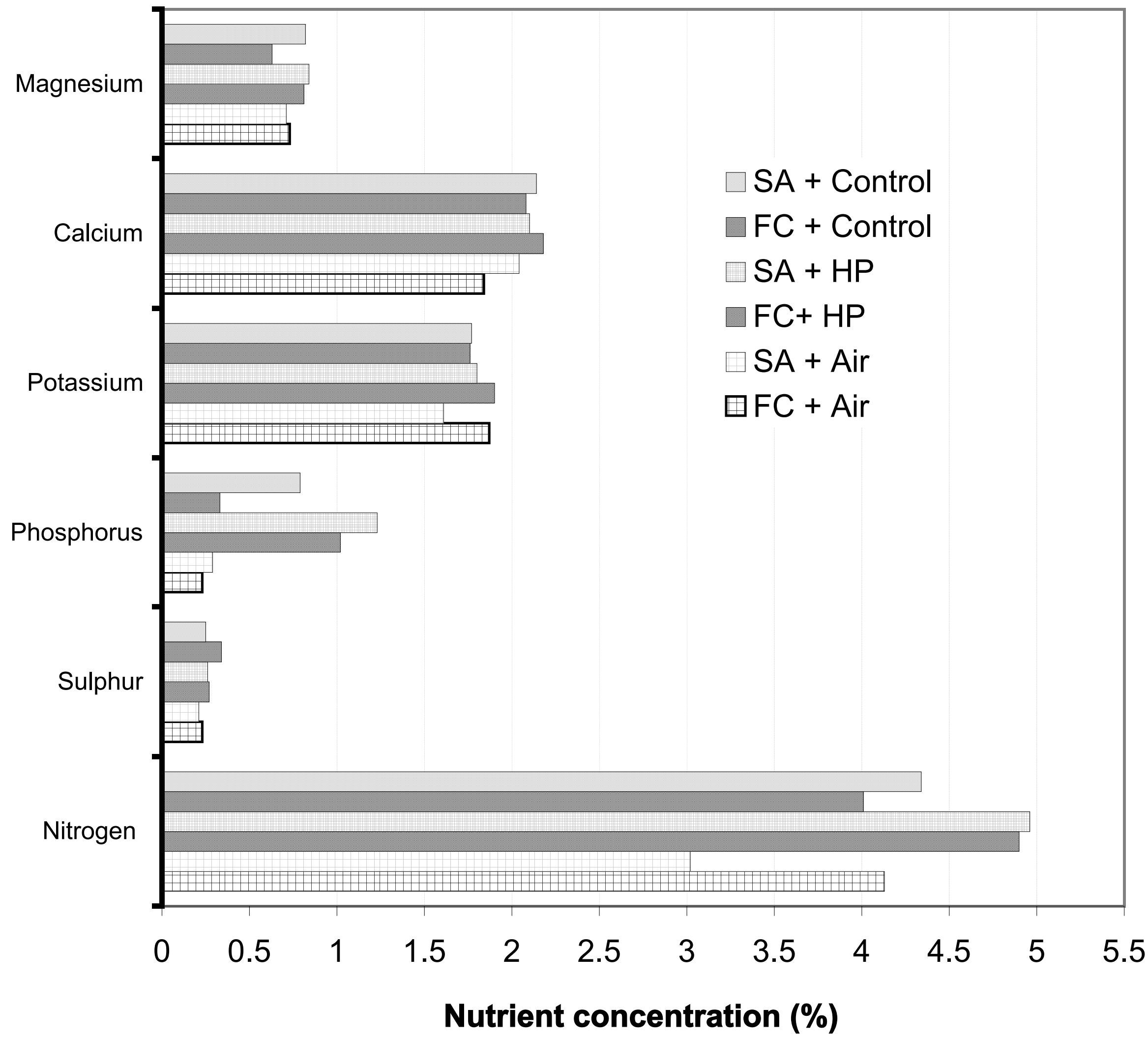

Figure 4.3.2.2 Leaf nutrient concentration of vegetable soybean as affected by aeration and two soil water treatments in a heavy clay soil

4.3.2.10 Soil microbial assessment

Plate culture agar (PCA) indicated that most probable number (MPN) of colony forming units (cfu) representing total soil bacteria from 1 g of dry soil was within the range for normal agricultural soils. Air injection and control treatments had almost similar MPN at both FC and saturation water content (Figure 4.3.2.3). However, with HP the MPN sharply increased with saturation compared to FC. It is apparent that neither of the aeration methods significantly reduced the MPN of the total soil bacteria at either soil moisture level in the heavy clay soil with vegetable soybean.

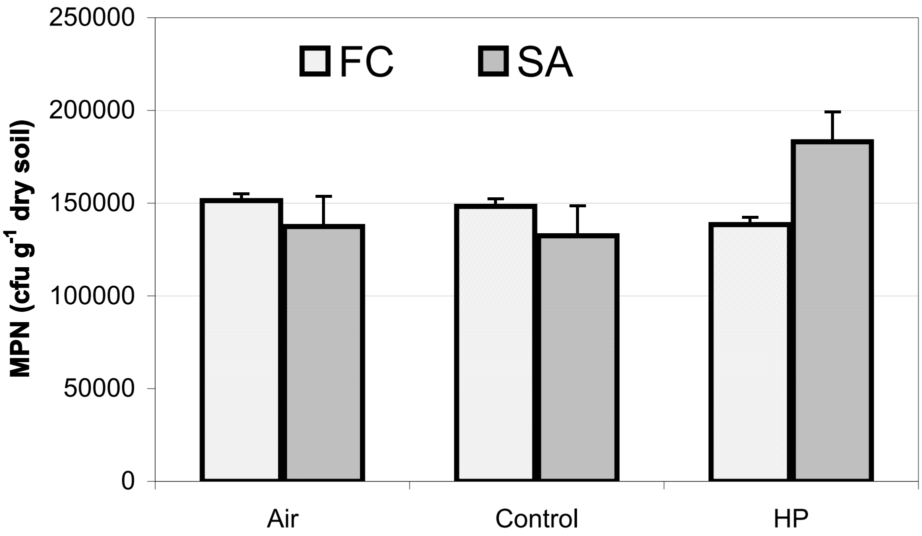

Figure 4.3.2.3. Most probable number (MPN) of colony forming units (CFU) of bacteria recovered in plate count agar (PCA) for the soil samples collected from vegetable soybean with different aeration treatments (air injection, hydrogen peroxide (HP) and at different soil water content (field capacity (FC), and saturation (SA)).

4.3.3 Cotton Experiment

4.3.3.1 Weather and soil water

Average daily solar radiation over the crop period was 23.8 MJ m^{-2} d^{-1}. It was higher for the first two months (c. 26 MJ m^{-2} d^{-1}) and then steadily declined to 21 MJ m^{-2} d^{-1} by crop maturity. The average temperature throughout was c. 26 ^{o}C (details of the weather data are presented in the appendix). The soil water content with respect to different treatments over the experimental period is presented in Table 4.3.2.1. Mean soil water over the crop period in the saturated treatment was 46 mm whereas it was 33 mm for the field capacity treatments. Air injection and HP treatments were found to dry down faster than the respective field capacity or saturation control treatments.

4.3.3.2 Yield and its components

Lint yield differed significantly ($P \leq 0.01$) in response to aeration and soil water (Table 4.3.3.1). Lint yield was significantly greater at field capacity compared to the saturation treatment. The lint yield was also significantly greater due to aeration such that air injection resulted in the highest yield followed by HP and the control. Air injection and HP treatments, respectively, resulted in increases in lint yield of 28 and 14% compared to the non-aerated control. More squares per plant, and more and heavier bolls resulted from the air injection treatment, and more bolls from the HP treatment, although neither parameter was affected by soil water (Table 4.3.3.1).

The above-ground biomass at harvest differed significantly ($P \leq 0.01$) in response to aeration treatments but was not significantly affected by soil water level (Table 4.3.3.1). Air injection and hydrogen peroxide injection resulted in 21 and 9% greater biomass, respectively, than the control treatment. The mean harvest index (HI), calculated as the lint weight as a proportion of the total above-ground biomass at harvest, was significantly greater ($P \leq 0.05$) in the field capacity treatment but there was no effect of aeration treatments (Table 4.3.3.1).

Table 4.3.3.1 Cotton lint yield and some attributes as affected by aeration and soil water treatments.

Factors	Treatments	Lint yield (g m^{-2})	Squares $plant^{-1}$	Bolls $plant^{-1}$	Weight $boll^{-1}$ (g)	Aerial biomass (g m^{-2})	Harvest Index
Aeration	Control	136.8	20.7	9.1	4.70	661.4	0.21
	HP	155.4	26.2	9.5	4.95	723.8	0.21
	Air injection	175.0	27.5	10.9	5.05	802.8	0.21
	LSD (df = 15)	20.63	2.19	1.40	1.40	88.0	n.s.
Water	Saturation	144.2	24.4	9.5	4.83	699.3	0.21
	Field capacity	167.3	25.1	10.2	4.97	759.3	0.22
	LSD (df = 15)	16.83	n.s.	n.s.	n.s.	n.s.	0.012

4.3.3.3 Root properties and soil respiration

Root dry weight and lateral root length per plant did not differ significantly due to aeration or soil water (Table 4.3.3.2). However, the lateral root diameter was greater for the field capacity compared to the saturation treatment. An analysis of the root: shoot ratio indicated no significant effects of aeration or soil water; the overall mean and SE was 0.113 ± 0.047.

Soil respiration was markedly higher in the aeration treatments than in the control but did not differ between soil water treatments. The rate of soil respiration was in the order of 183 and 111% higher for air injection and HP, respectively, compared to the control (Table 4.3.3.2).

Table 4.3.3.2 Root properties and total soil respiration of cotton as affected by aeration and soil water treatments.

Factors	Treatments	Root weight (g m^{-2})	Root length density (cm cm^{-3})	Root diameter (mm)	Soil respiration (g CO_2 m^{-2} h^{-1})
Aeration	Control	77.3	8.04	0.153	0.54
	HP	83.4	9.88	0.148	1.14
	Air injection	87.3	10.32	0.149	1.53
	LSD (df = 15)	n.s.	n.s.	n.s.	0.66
Water	Saturation	76.2	10.23	0.132	1.14
	Field capacity	89.1	8.60	0.168	0.99
	LSD (df = 15)	n.s.	n.s.	0.025	n.s.

4.3.3.4 Plant water use and water use efficiency

While plants at field capacity used significantly more water than did those in the saturation treatment (Table 4.3.3.3), as did the aerated compared to the control, the interaction was also statistically significant, but in absolute terms the difference between treatments was very small.

The lint yield WUE differed significantly between the soil water levels; WUE was greater in the field capacity compared to the saturation treatment (Table 4.3.3.3). Likewise, the difference between aeration treatments was also significant; air injection achieved greatest WUE followed by hydrogen peroxide and the control.

Above-ground biomass WUE varied significantly between aeration treatments, in the same manner as for WUE of lint yield, but the difference between soil water treatments was not significant. The instantaneous WUE, the ratio of photosynthesis to transpiration, was also greater (although not significantly so) for the aeration treatments and significantly so for the field capacity treatment (Table 4.3.3.3). No differences between treatments were evident for WUE measured as carbon isotope discrimination.

Table 4.3.3.3. Water use, water use efficiency (WUE) and radiation use efficiency in cotton as affected by aeration and soil water treatments.

Factors	Treatments	Water use $plant^{-1}$ (L)	WUE lint ($g\ L^{-1}$)	WUE biomass ($g\ L^{-1}$)	Instant-aneous WUE [1] (A/E)	Δ^3 (‰)	RUE^2 ($g\ MJ^{-1}$)
Aeration	Control	37.66	0.38	1.725	3.02	20.38	1.35
	HP	38.24	0.41	1.894	3.42	20.45	1.35
	Air injection	38.11	0.45	2.408	3.95	20.25	1.38
	LSD (df = 15)	0.14	0.057	0.27	n.s.	n.s	n.s.
Water	Saturation	37.80	0.38	1.85	3.03	20.33	1.41
	Field capacity	38.20	0.44	1.99	3.78	20.38	1.31
	LSD (df = 15)	0.149	0.046	n.s.	0.73	n.s	n.s.

[1] A/E= µmol $CO_2\ m^{-2}s^{-1}$ /mmol $H_2O\ m^{-2}s^{-1}$, [2] g above-ground biomass / MJ intercepted radiation, [3] Carbon discrimination

4.3.3.5 Leaf gas exchange parameters and leaf chlorophyll

Combined over dates the rate of leaf photosynthesis differed significantly due to aeration and soil water (Table 4.3.3.4). The air injection led to significantly higher rates of photosynthesis than in the control, and the latter did not differ from that for HP. The leaf photosynthetic rate was significantly higher at field capacity compared to the saturation treatment. The rate of photosynthesis declined over the season (Figure 4.3.3.2) as follows: pre- flowering (14.33 ± 3.82 µmol m^{-2} s^{-1}), peak flowering (13.27 ± 1.74 µmol m^{-2} s^{-1}), boll filling (11.31 ± 4.45 µmol m^{-2} s^{-1}) and boll open (6.57 ± 1.65 µmol m^{-2} s^{-1}) stages. While differences between treatments for chlorophyll concentration were apparently significant, the absolute differences between values were less than the precision of the apparatus (± 2 SPAD units) and hence are not discussed further.

Neither the transpiration rate nor stomatal conductance differed due to aeration or soil water treatments (Table 4.3.3.4), and differed only marginally as the crop developed.

Table 4.3.3.4 Leaf gas exchange parameters, seasonal average canopy light interception, leaf chlorophyll concentration and crop water stress of cotton as affected by aeration and soil water treatments

Factors	Treatment	Rate of leaf photosynthesis (µmol $m^{-2}s^{-1}$)	TR[1] (mmol $m^{-2}s^{-1}$)	SC[2] (mol $m^{-2}s^{-1}$)	LI [3] (%)	Chlorophyll (SPAD)	CWSI[4]
Aeration	Control	10.61	3.91	0.12	74	41	0.37
	HP	11.20	3.74	0.11	79	40	0.31
	Air injection	12.49	3.73	0.11	78	41	0.33
	LSD (df=69)	1.35	n.s.	n.s.	n.s.	0.83	n.s.
Water	Saturation	10.82	3.84	0.11	77	40	0.33
	FC	11.97	3.74	0.11	77	41	0.35
	LSD (df=69)	1.09	n.s.	n.s.	n.s	0.67	n.s.

[1] TR: Leaf transpiration rate, [2] SC: Stomatal conductance of the leaf, [2]LI: Light interception by the canopy (average over the season), [4]CSWI: crop water stress index (0-1 scale)

4.3.3.6 Crop water stress index and canopy light interception

Crop water stress index, measured by infrared thermometry, differed significantly with respect to growth stage (Figure 4.3.3.2) but not due to aeration or soil water (Table 4.3.3.4). Canopy light interception increased as the crop grew until the boll filling stage when it reached 83% although on no occasion did it differ significantly between treatments (Figure 4.3.3.2). The mean canopy light interception over the season did not vary with respect to treatments. Leaf weight per plant of cotton increased with aeration at both soil water contents.

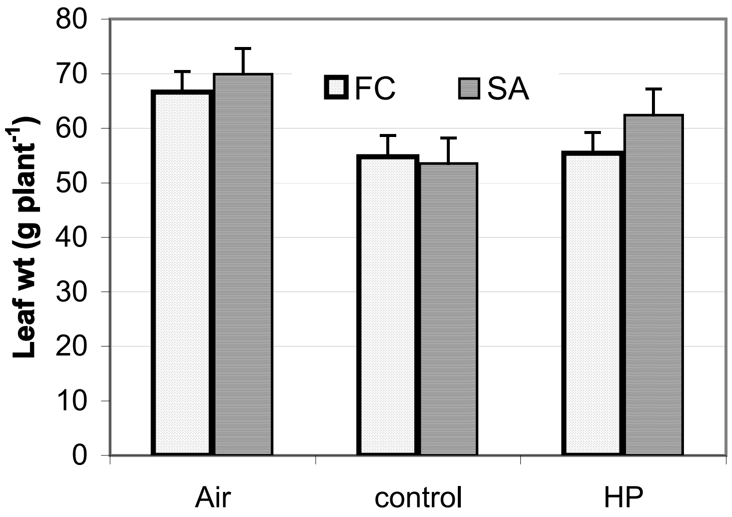

Figure 4.3.3.1 Leaf weight of cotton as affected by the different aeration treatments (air injection, control and hydrogen peroxide (HP)) at two soil water content (field capacity (FC) and saturation (SA)) in a heavy clay soil.

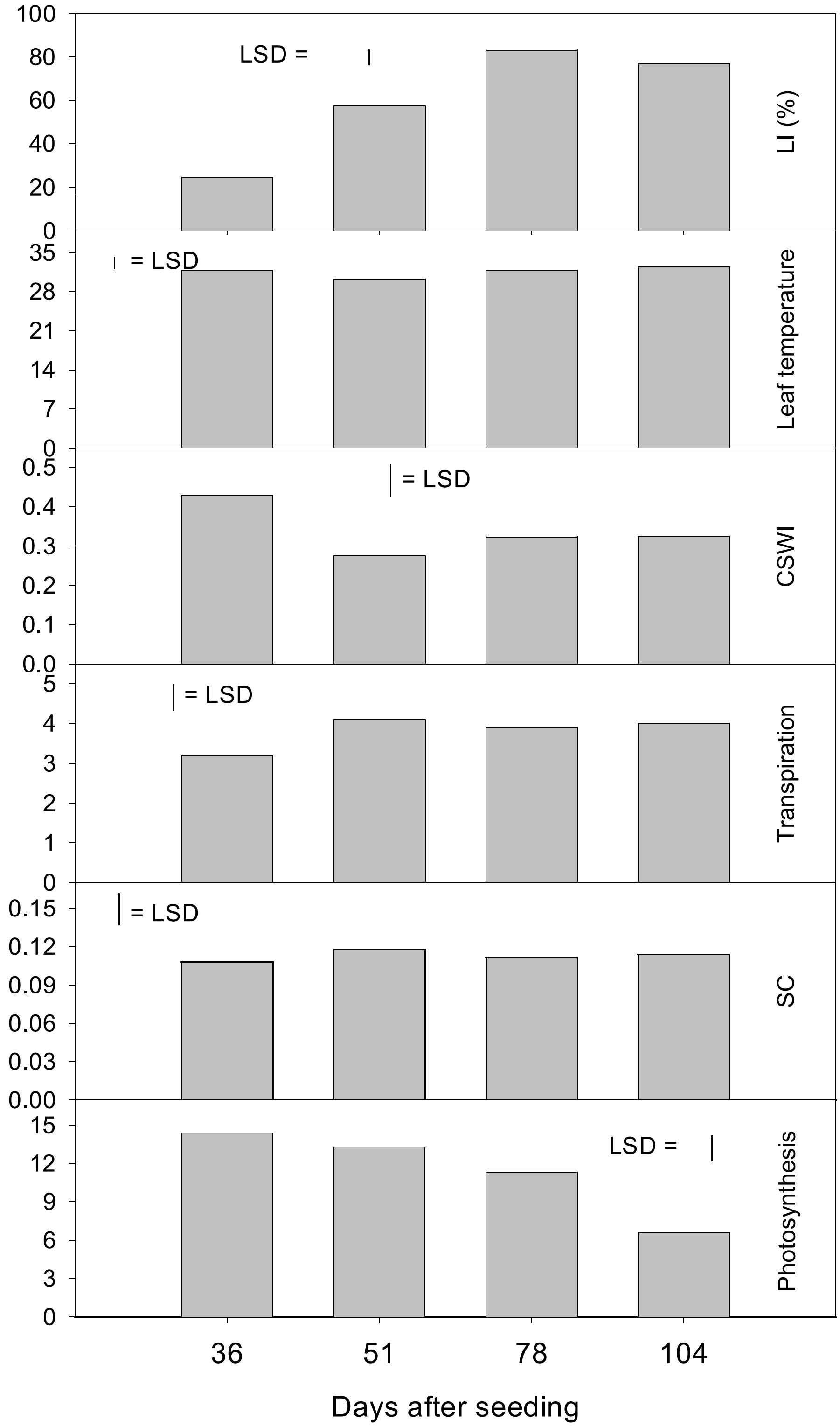

Figure 4.3.3.2 Canopy light interception (LI %), leaf temperature (^{O}C), crop water stress index (CWSI) (0-1 scale), leaf transpiration rate (mmol $m^{-2}s^{-1}$), stomatal conductance (SC) (mmol $m^{-2}s^{-1}$) and leaf net photosynthesis (µmol $m^{-2}s^{-1}$) of cotton over the growing season in a heavy clay soil.

4.3.3.7 Leaf nutrient concentration

The mean leaf N, P, and K ranged between 1.5-2%, 0.25-0.5% and 0.75-1.4%, respectively. The leaf N concentration in the control at saturation soil water content was lower compared to those of other treatments, but the phosphorus concentration was the highest. Leaf potassium concentration was highest in the air injection saturation treatment followed by HP saturation soil water content, and lowest K was recorded in the saturation treatment without aeration (Figure 4.3.3.3). There were negligible trends in the concentrations of the other nutrients.

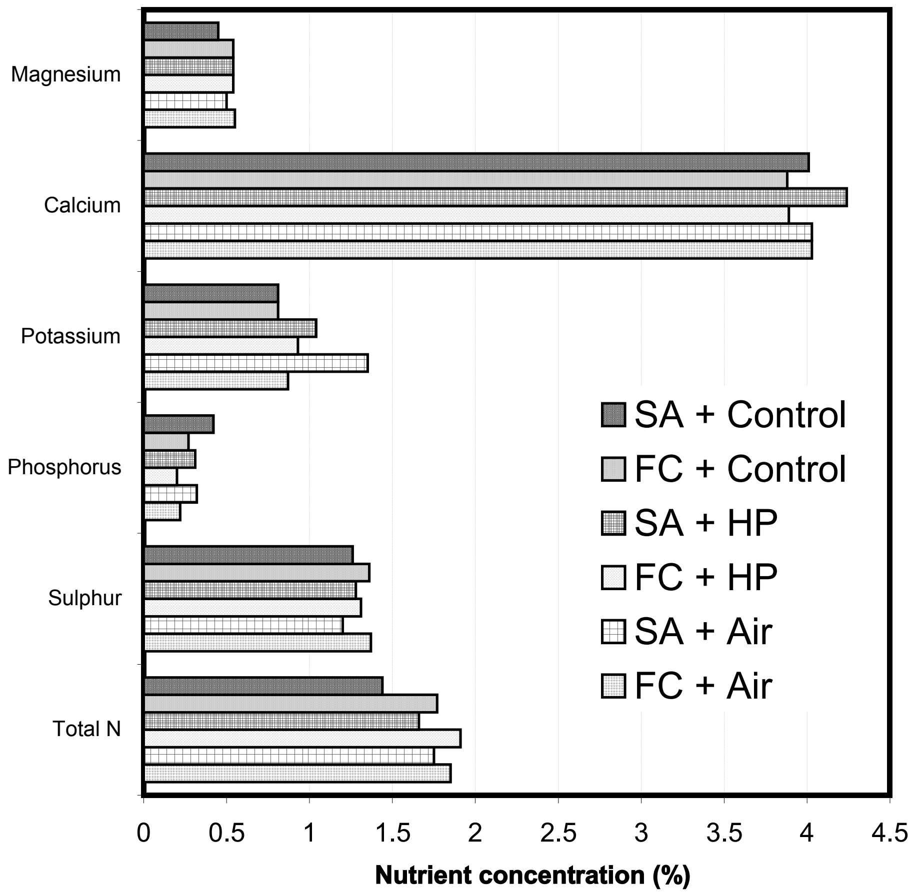

Figure 4.3.3.3 Nutrient concentrations of cotton leaf samples as affected by the different aeration treatments at two soil moisture levels in a heavy clay soil.

4.4 DISCUSSION

In all three-pot experiments, aeration through SDI with HP or air injection led to greater yields than non-aerated controls, whether at saturation, field capacity or at deficient soil water content in the heavy clay soil. These findings show promise that irrigation with aerated water could be an effective approach to unlock the yield potential of SDI crops under field conditions. In the field, water-saturated (i.e. flood irrigated) heavy clay soils with a crop need a few days to drain and reach field capacity and the root zone can remain hypoxic for few days after irrigation. Huber (2000) reported that in a field trial water-saturated red earth soil cropped with zucchini needed about 3-5 days to drain and reach field capacity after flooding. This is in accordance with other studies investigating soil water relations in drying soil profiles (Willson *et al.,* 1985; Mukhtar *et al*., 1996; Brady and Weil, 1999). Soil water content is the main parameter influencing soil aeration status (Boone *et al.,* 1986).

Earlier studies have shown that soil water content above or even below field capacity could impair the gas exchange between soil and atmosphere (Meek and Stolzy, 1978) in heavy textured soils. This results in oxygen diffusion rates (ODR) and gas diffusion coefficients (D/D_0) that are detrimental for root growth, such as was shown by Mukhtar *et al.* (1996) and Stepniewski (1981). An ODR value of 20×10^{-8} g CO_2 cm^{-2} min^{-1} is generally considered as the lower threshold for optimal root growth (Glinski and Stepniewski, 1985). It is likely that the ODR value could have dropped below this threshold level in these trials particularly in the saturated plots. The assumption that soil conditions in the current trials were adverse for root growth is supported by the observation that the saturated plots often recorded soil moisture well above the field capacity in the middle and top of the pots and this extended period of high moisture without drainage caused retardation of root growth (Table 4.3.2.1 and 4.3.2.2). This suggests that reduced root biomass and root respiration were major limitations for further water uptake. Measurements of the root respiration and sap flow showed that in saturated and control treatments water uptake was reduced which possibly resulted in reduced nutrient uptake by the plants in a most likely oxygen-deficient environment. Direct and immediate effects of hypoxia on reduced root growth, root respiration and transpiration were also suggested by Drew (1992), Bathke *et al.* (1992), Drew (1997), and McCully (1999) under waterlogged conditions. The pot set up was designed to minimize the pot effect on aeration by using the bigger size pots, but lack of drainage hole in the pot, which did not allow water movement to the subsurface, would have modified conditions away from those simulating the field environment.

In earlier research with zucchini, the application of HP after short-term flooding led to a 25% increase in fruit and shoot fresh weight, and increased fruit number by 19% compared to the non-aerated control (Huber, 2000). Many more roots were visible in the HP treatment than in the control, leading to the assumption that the supplied O_2 enhanced root growth (or delayed death of roots) under short-term flooding conditions (Bhattarai *et al*., 2004). Root growth was not benefited by the HP treatment below the A-horizon. It is possible that the applied HP was consumed close to the emitter where roots were concentrated. With the application rate of 5 L ha^{-1} of HP after the irrigation cycle, each emitter discharged 0.15 ml of 50% HP, that potentially releases 48.5 ml of O_2 in the saturated soil over and above that that diffused to the rhizosphere through the soil or through radial O_2 diffusion from the stem through to the roots. Neither is likely to diffuse down below the A-horizon (Bhattarai *et al*., 2004)**.**

The option of using HP was, therefore, promising from a yield perspective for aeration of the root zone under flooded and, therefore, oxygen-limited conditions. Similarly, Bryce *et al.* (1982) reported that growth of flooded tomato was significantly better when peroxide was included in the flooding solution, or the watering solution after flooding, and Melsted *et al.* (1949) found that even for a soil of excellent structure, forced soil aeration (direct air injection into the rhizosphere) or peroxide treatment could improve the growth of corn plants. The same benefit was evident, based upon data reported by Huber (2000)**,** when HP was introduced to the root system via SDI. The cost associated with the required quantity of HP to effect yield benefit in the field was A$ 63 ha $^{-1}$. An absence of information on the effects of HP on soil biology will likely delay commercial adoption of this practice.

An alternative, air injection using the venturi principle, was compared with HP using SDI in the trials with tomato, vegetable soybean and cotton. Equivalent amounts of O_2 were introduced into the root zone by the air injection and HP treatments in these pot trials. Such uniformity for O_2 was maintained by either continuous air injection at the rate of 12% by volume of water or continuous HP (50% w/w) at the rate of 1 ml L^{-1} of irrigation water, during irrigation events.

The average yield increase due to aeration was 12, 21, and 89% for tomato, cotton and vegetable soybean respectively. Enhanced performance of the crops in the aerated treatments compared to non-aerated controls was linked to increased root activity as reflected by significantly higher rates of soil respiration (Tables 4.3.1.4, 4.3.2.4, 4.3.3.2). Greater root length and root dry matter were evident for all three species (significant only for soybean) in aerated treatments, and were likely responsible for this additional soil respiration. An increase in soil respiration in response to increase in aeration of the root system was also reported by Stobovoi (2001). In soybean, combined over soil water treatments, there was a 66 g m^{-2} increase in root dry weight in aerated treatments at harvest compared to that of the control. Based upon the value for respiration of 5 mL O_2 $h^{-1}g^{-1}$ of dry root (Grable, 1966) and an average seasonal root weight increase over the non-aerated control of 33 g m^{-2}, such additional root dry weight due to aeration would have required an additional 1.625 L m^{-2} of O_2, assuming that roots respire at their maximum rate for 10 h per day. With an effective 60-day crop period, a total of 97.5 L of extra O_2 per square metre would be required. The supply from HP based upon actual availability provided 4.8 L O_2, and air injection with 22.73 L of air provided 4.77 L O_2, over that period. Quite clearly the additional O_2 was not sufficient to support the complete respiratory requirements of the additional roots. This is not surprising since the additional roots would also avail of O_2 through the normal channels of diffusion through the soil following water uptake and/or drainage, and radial O_2 diffusion through roots, as takes place even under O_2 limited conditions (Visser *et al.,* 2000b). Hence, HP and air injection would have contributed to the O_2 requirements of the crop rhizosphere in the aerated treatments, but further investigation is required on the critical quantity, and perhaps timing, of the additional O_2 supply. A similar trend for O_2 balance was observed in the cotton experiment with HP and air injection treatments.

Oxygen-limited root respiration, leading to reduced adenosine triphosphate (ATP) production and decreased energy dependent nutrient uptake and transport of nutrients to the shoot, may lead to a reduction of leaf growth and optimal leaf functioning (Barrett-Lennard, 2003). Above-ground growth of tomato, vegetable soybean and cotton benefited from aeration in the experiments. The repeatedly higher rates of photosynthesis in the aerated treatment (except for tomato) compared to the non-aerated controls contributed to higher biomass yield when aerated. A reduction in the rate of photosynthesis in response to low O_2 level in the rhizosphere has been reported previously (Sojka, 1992). For vegetable soybean this may have been related to a lower chlorophyll concentration in the non-aerated control treatments, even though the specific leaf area (SLA) was greater in the aeration treatment (air injection - 285, HP - 256 and control - 231 cm^{-2} g^{-1}, LSD (15 df) = 45.1). However, differences in chlorophyll concentration between aerated and non-aerated treatments were very small for cotton (Table 4.3.3.4), as were differences for SLA (air injection – 162, HP - 152 and control - 156 cm^{-2} g^{-1}, LSD (15 df) = 38.1). Tomato photosynthesis in the experiment did not vary between the treatments, possibly because the vegetative growth was manually controlled by pruning and kept to the minimum and the intact leaves were almost all sunlit, and photosynthesizing to their maximum. Yield enhancement by aeration was due to increased fruit size in tomato, numbers of flowers and pods for soybean and squares and bolls for cotton. Fruits, were heavier for aeration treatments in tomato, so were the pods and seeds in soybean, as were bolls in cotton. Possibly cytokinin production as a result of aeration, may have been responsible for this enhanced flowering and fruiting. Since flowering and fruiting in zucchini were improved by HP application, and flowering and fruiting in many cucurbits is regulated by cytokinin production (Wien, 1997), it may be that HP application promoted cytokinin production and transport. Both are known to be sensitive to O_2 deficiency in the root zone (Jackson *et al*., 1992). The greater effect of aeration on yield of soybean than for cotton and tomato probably was due to the additional effect that aeration had on light interception (Air injection - 54%, HP - 52% vs control -33%, LSD (107df) = 5.01) in soybean. Light interception in cotton (Air injection - 60%, HP - 62% vs control - 60%, LSD (69 df) = 4.11) was not significantly improved by aeration, and potentially the light harvesting capability of tomato was manipulated with single stem pruning to improve the quality, hence the full radiation utilization opportunity was lost.

Soybean radiation use efficiency (RUE), expressed as the slope of the relationship between above-ground biomass (g) and intercepted solar radiation (MJ), and light interception, was greatest in the air injection treatment followed by HP and least in the control in either soil water treatment (Air injection - 1.41, HP - 1.39 vs control - 1.03 g MJ^{-1}, LSD (15df) = 0.25). The RUE averaged over soil water treatments, was greater by 35 and 37% in HP and air injection treatment, respectively, compared to the control. For tomato, the RUE did not vary between soil water treatments, but increased by 9.3% with aeration compared to the control (2.83 vs 2.59 g MJ^{-1}, LSD (6df) = 0.178). For cotton, the RUE did not improve appreciably in response to aeration treatments (Air injection - 1.38, HP - 1.35 vs control 1.35 g MJ^{-1}, LSD (15df) = 0.19). The analysis of cotton leaf samples collected at the 50% boll filling stage revealed that the concentration of nitrogen, phosphorus, potassium and boron in the dry leaf samples were greater in aerated treatments compared to the control (Figure 4.3.3). Maintenance of such a high level of nitrogen, potassium and boron is reported to increase the reproductive performance in terms of greater flowering and fruit set as well as boll filling to produce heavier bolls in cotton (Joham, 1986). Analysis of soybean leaf samples collected at the pod filling stage in general did not show an effect of aeration (Figure 4.3.2.2). In tomato although the petiole sap concentration collected in the early flowering stage showed greater nitrate content (3317 vs 2933 mg L^{-1}, LSD (6df) = 139) for aeration compared to control, no appreciable difference was noted in the leaf nutrient contents (Figure 4.3.1.6). Maintenance of high leaf nitrogen concentration in cotton contributed to higher leaf photosynthesis, and in soybean, leaf photosynthesis is relatively less influenced by the leaf nitrogen content after the critical content in the leaf exists.

All pots were without drainage and water applied closely equated with water used in evapotranspiration. A water balance calculated for each treatment showed consistency between water consumption based upon water balance and water usage based upon metered rates of application (r^2 = 1 (n = 4) for soybean; and for cotton the average water consumption measured by gravimetric method was 38.0 L compared to 38.01 L applied per plant (Table 4.3.3.3). Sap flow provided direct measurements of plant transpiration over three-day periods for tomato and showed a 7.8% increase in transpiration with aeration compared to the control (1740 vs. 1876.5 g per three days per plant). That the quantity of applied water in the soybean and cotton aeration plots was greater than that to the control also supports the argument that the transpirational use of the applied water must have been higher with aeration in those crops too. This result concurs with the measurements of sap flow made in the soybean experiment and reported in Chapter 5.

Prolonged waterlogging is known to result in stomatal closure and cessation of transpiration (Barrett-Lennard, 2003) but in no crop did the unit rate of instantaneous transpiration vary between saturated, field capacity or deficit irrigation rates. Likewise, the effect of aeration on transpiration and stomatal conductance were too small to be statistically significant. This was further supported by the lack of difference between treatments for the crop water stress index with the exception of tomato. It was also surprising that the rate of soil respiration did not differ between deficit and field capacity in tomato and field capacity or saturation in cotton and soybean. However, consistently over different crops, aeration improved the soil respiration compared to the control. Total water use in the aeration treatments for vegetable soybean was greater than that on the control due to their greater canopy size of the former (LAI for Air injection 1.57, HP = 1.49, Control 0.84, SE (n = 24) = 0.133), but not for cotton where canopy size did not differ among treatments. Late planting of cotton in the year (in early November compared to the normal mid-September) may have been responsible for the lack of a significant positive effect of aeration on canopy size (on average a 5% increase in light interception) as high temperature was evident in the early establishment phase, and may have constrained a positive response to aeration.

Various indices of water use efficiency were calculated. From the growers' perspective, yield per unit of water applied is of paramount importance. The greater WUE calculated on this basis associated for the aeration treatments was due to higher yields of fresh fruits, pods and lint in tomato, soybean and cotton, respectively, and not to reduced water use by those treatments (indeed, aeration increased water usage), although data on instantaneous WUE did suggest that aeration treatments were more conservative in water use through transpiration of H_2O per unit of fixed CO_2.

It is interesting to note that there were very few interactions between soil water conditions and aeration treatments for the variables measured. This suggests that, even under field capacity or drier conditions, root systems of drip-irrigated plants on heavy clay soils are temporarily anoxic and respond favourably to aeration.

4.5 CONCLUSION

Aerating the rhizosphere of tomato, soybean and cotton in a heavy clay soil significantly increased yield compared to non-aerated controls, irrespective of soil water content. The increase in yields were associated with enhanced root function (evidenced by higher soil respiration and root mass) and associated effects through enhanced canopy transpiration, higher rates of photosynthesis, and more and heavier fruits, pods and bolls in tomato, vegetable soybean and cotton respectively. Water use efficiency, expressed as the ratio of photosynthesis to transpiration, and of yield to total water use, was greater in aeration treatments, perhaps as a response to enhanced root function. The experiment on soybean revealed that soil microbial population, especially bacteria population, did not alter with respect to aeration methods. The research suggests that, provided the supply of aerated water can be maintained along long stretches of SDI tape, aeration of root zones in heavy clay soils should significantly improve yield and WUE of tomato, vegetable soybean and cotton. It is also expected that these responses will hold true in other similar crops. The conclusion has been derived based on the results of three pot experiments where the soil and plants had limited interaction with environment as it occurs in the field grown crops. However, the field scale verification of this technology is warranted before the application of oxygation for commercial scale application in agricultural industries.

5

Effects of oxygation on crop phenology, physiology and water use efficiency in saline soil[1'2'3]

ABSTRACT

The overriding effect of salinity and higher soil moisture is to limit the diffusion of O_2 to the root zone, which rapidly and dramatically alters both the physical and biological environment of plant roots. Inadequate O_2 concentration in the rhizosphere exacerbates the effect of salt by reducing the uptake of water and indiscriminate salt ingress in plants. In response to this, physiological events occur within plants, which affect growth and development. This study investigated the effects of aeration and salinity on growth, development, yield, and WUE and elucidated the physiological basis of the benefit of aeration on plants in saline heavy clay soil. Three pot experiments (on salt sensitive tomato, moderately tolerant vegetable soybean, and tolerant cotton) were conducted in the screen-house. Each of these species was supplied with subsurface aerated water or non-aerated water to soil with four different salinity levels (tomato: 2, 4, 8.8, 10; soybean and cotton: 2, 8, 14, 20 dS m^{-1} ECe). The results suggest that subsurface irrigation with aerated water (12% air in water) in the rhizosphere stimulates leaf growth and light interception, plant height, stem diameter, and also enhanced the reproductive performance. Effects of aeration were also notable on earliness for flowering

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[1] Part of this chapter (tomato) has been submitted to the journal: Scientia Horticulturae entitled "Root aeration improves yield performance and water use efficiency of tomato in heavy clay and saline soils". Authors are Surya P. Bhattarai, L. Prendergast and D. J. Midmore

[2] Part of this chapter (cotton) has been published in CDROM in "New directives for a diverse planet". Proceedings of the 4th International Crop Science Congress, 26 Sep -1 Oct 2004, Brisbane, Australia. Web site www.regionalorg.au/au/cs, as "Oxygation of rhizosphere with subsurface aerated water improves lint yield and performance of cotton on saline heavy clay soil". Authors are Surya P. Bhattarai and David J. Midmore.

[3] Part of this chapter (soybean) has been prepared for the Agronomy Journal with the title "Growth analysis of vegetable soybean under different salinity levels with and without oxygation in saline heavy clay soil". Authors are Surya P. Bhattarai and David J. Midmore.

and fruiting (cotton was an exception for the latter). Yields were increased by 33, 21 and 13% in tomato (sensitive), soybean (moderately tolerant) and cotton (tolerant) respectively due to aeration compared to the control. Aeration also invariably increased plant water use (as observed in greater sap flow) and improved the season long water use efficiency (WUE_{sl}) for biomass. This increased yield with aeration was accompanied by increased harvest index (HI), greater mean fruit weight, higher bolls (cotton)/ fruits number, an increase in WUE, and decrease in root: shoot ratio, and crop water stress index (CWSI) in both tomato and cotton crops. Similarly in vegetable soybean, aeration increased WUE and decreased root: shoot ratio and CWSI. The rate of net leaf photosynthesis measured during growth did not reveal a great difference between the salinity and aeration treatments on tomato and cotton, however, in soybean the leaf photosynthesis was stimulated when salinity increased from 2 to 8 dS m^{-1} and decreased thereafter.

In general the beneficial aeration effects on saline heavy clay soil were mediated through greater root activity, as observed by general increases in root weight, root length density, and enhanced soil respiration in the three species. Greater root metabolic activities and respiration resulted in a greater uptake of water as observed by significant increases in the sap flow rate and accumulated transpiration accompanied by greater xylem and stem diameters. The increased sap flow contributed to less negative leaf water potential (LWP) and a lower CWSI, and maintained leaf turgor, facilitated leaf growth, and contributed to greater canopy light interception. Enhanced membrane permeability conferred by aeration contributed to a greater exclusion of salts. Therefore, less salt was taken into the leaves in spite of increased sap flow and water use by plants with aerated irrigation water. A less leaky leaf membrane was also indicated by lower relative leakage ratio (RLR) in the aerated treatment. These encouraging results from the controlled environment pot experiments warrant field scale evaluation of this technology in order to make it suitable for commercial use and to harness the productive use and rehabilitation of saline land for agriculture.

5.1 INTRODUCTION

Salinity of agricultural soils is a major environmental threat in many parts of the world (Munns, 2002). Excess of salt in the soil on its own, or in combination with waterlogging, has severe consequences for plant production (Kahlown and Azm, 2002). Salinity affects plants through changes to the osmotic concentration of the soil solution and through the specific action of ions (Zhang and Blumwald, 2001). Many saline soils are also subjected to waterlogging as such soils experience raised water tables and reduced infiltration of applied water (Stevens *et al.*, 2000). Salinity in clay soil is often associated with sodicity, which reduces the porosity in the soil, thereby reducing the available soil O_2 to roots (USDA, 1954). Limitations imposed on plant function due to lack of soil O_2 significantly reduce plant performance and crop yield. Overcoming such combined effect of salt and hypoxia, therefore, has become a major challenge to sustainable and productive plant industries.

Plant roots require adequate O_2 for root respiration as well as for sound metabolic function of the root and the whole plant (Grable, 1966). Barrett-Lennard, (2003) reported that transfer of roots from well drained to waterlogged conditions could decrease ATP production by about 95% in the root. Hypoxia or anoxia-induced low ATP generation can be jeopardizing the survival of plants in saline soils. Hypoxia or anoxia of saline soils has a range of adverse effects on plant performance. Firstly, it affects the growth, namely of the roots, followed by shoot growth (Kafkafi and Brenstein, 1996); secondly, it impairs the process of solute movements across the membranes; and thirdly, the effects of anoxia are expressed in terms of reduced stomatal conductance and/or leaf water potential, reflecting symptoms resembling water stress (Rhoades and Loveday, 1990). Amelioration of the hypoxic root zone, thereby conferring effective soil aeration, is very important in order to improve plant performance under saline conditions.

During irrigation and wet weather, water replaces air in the soil and reduces the mobility and availability of O_2 that remains trapped in air pockets or dissolved in the soil water (Mukhtar *et al.,* 1996). Reduced supply of soil O_2 to plant roots, heavy rainfall or even irrigation can potentially cause large losses in crop yield. Roots of most crop species need a good supply of O_2 in order to supply water and nutrient needs of the shoots (Meek *et al.,* 1983). Paradoxically, initial symptoms of excessive soil wetness are similar to that of drought stress in the leaves. If these conditions prolong for several days, serious damage to plants occurs due to nutrient deficiency (Naidu and Rengasamy, 1993), to build up of metabolic poisons and to increased root diseases.

Most of the agricultural crops are glycophytes. Unlike halophytes, their performance retards with increasing salinity levels. Tolerance to salinity varies greatly between species (Munns and Rawson, 1999). Relative productivity starts to decline from ECe 2 dS m^{-1} and falls to zero when the soil salinity reaches 8-10 dS m^{-1} for sensitive crops such as tomato. In moderately tolerant, such as vegetable soybean, the relative productivity remains unaffected up to 6 dS m^{-1} and then performance declines from 6 dS m^{-1} with a relative productivity of 0 when salinity reaches 24 dS m^{-1}. In tolerant crop species, such as cotton, the relative productivity is unaffected up to 8 dS m^{-1}, and the salinity effect only becomes significant above 8 dS m^{-1} and relative productivity reaches 0 when the soil salinity reaches ECe 28-32 dS m^{-1} (Carter and Fanning, 1964). The negative effect of salinity becomes more severe when waterlogging or hypoxia occurs in the root zone. Uptake of sodium and chloride ions by plants from the soil increases with decreasing O_2 concentration in the rhizosphere (Letey, 1961). Forced aeration in saline liquid culture reduced the Na^+ ingress into plants (West and Taylor, 1980). How far the negative effect of salt can be moderated with increased root zone aeration, using aerated water for irrigation through SDI-oxygation, in sodic/saline soils is not known. Therefore, the role of rhizosphere oxygation in saline soils in increasing salt tolerance needs to be determined and quantified for the application of oxygation technology to irrigated agriculture.

Salinity and poor aeration reduce plant growth rates resulting in smaller leaves, shorter stature and sometimes fewer leaves. The initial and primary effect of salinity, especially at low concentration is due to its osmotic effect (Lea-Cox and Syvertsen, 1993). The degree to which growth is reduced by salinity varies with species and to some extent varieties as well. The vegetative and reproductive development of plants is also influenced by the salinity and depends on the nature and intensity of the salt exposure. Shoot growth and yield decline but variable effects on leaf thickness are reported (Meyer *et al.,* 1985). The severity of salinity responses are mediated by environmental interactions such as RH, temperature, and solar radiation. Depending on the composition of saline soil, ion toxicities or nutritional deficiencies may arise because of the predominance of specific ion or competition effects among cations or anions (Bernstein *et al*., 1974).

Plant salt tolerance is generally thought of in terms of the inherent ability of plants to withstand the effects of high salts in the root zone, but it varies with respect to stage of exposure, and the parts of plants under exposure. Plants in sodic soil may be subjected to the induced parallel ionic and anoxic impacts on growth. Earlier studies by Goorahoo *et al.* (2002), Heuberger *et al.* (2001), and Huber, (2000) consistently showed benefits of oxygation in O_2 limited rhizosphere, but less is known about the effects of aeration in saline soil and whether increased aeration can improve plant tolerance to salinity.

Amelioration of an hypoxic rhizosphere through oxygation provides greater access to O_2 by growing roots, thereby improving root metabolic activities. A number of soil constraints, such as waterlogging and sodicity-induced poor porosity, slow the speed and rate of natural diffusion of O_2 from the atmosphere to the root zone. Therefore, even if there is plenty of O_2 in the air, the root zone is deprived of O_2 to quantities that constrain root function.

Under O_2 limited conditions aeration of the crop root zone can be accomplished by different methods such as injection of air alone, irrigation of the crop with aerated water, or injection of hydrogen peroxide in the root zone. Injection of air alone could be quite an expensive option and the injected air can move away from the root zone directly to the atmosphere due to the chimney effect. Earlier studies by Bhattarai *et al.* (2004) showed promise for the use of aerated water with sub-surface drip irrigation (SDI) in improving crop performance in heavy clay soils for cotton, zucchini and vegetable soybean. Building on to those earlier studies, the effectiveness of aeration on saline soil was investigated.

Experiments were conducted to examine the effect of aerated subsurface irrigation water on tomato, vegetable soybean and cotton (sensitive, moderately tolerant and tolerant species respectively) at a range of salinity levels in a heavy clay soil. The objective was to determine whether there was any improvement in plant tolerance to salinity in heavy clay soils at increased rhizosphere aeration, and if so, the reasons for it.

5.2 MATERIALS AND METHODS

5.2.1 Location and Crop Details

Three pot experiments were conducted in the screen-house (67% of full sunlight) at Rockhampton, Australia (23°, $22^{'}$, $0.345^{''}$S, 150^{o}, $31^{'}$, $0.53^{''}$E, 13 masl altitude) from May 2003 to September 2004 on three crop species. The first experiment on tomato (*Lycopersicon esculentum* L.) variety Improved Apollo was directly sown in the pots on 19 March 2003, the second experiment on cotton (*Gossypium hirsutum* L.) variety- 289 I was sown on 1 September 2003 and the third experiment on vegetable soybean (*Glycine max* L.) variety C 748-1-2-1 was sown on 1 May 2004. Average daily temperature, sunlight intensity, relative humidity and weekly soil water status and soil temperature were recorded throughout the period of the experiments. For tomato only one plant per pot was maintained by thinning at the three-leaf stage. Plants were individually staked, and pruned to a single stem, whereas for cotton three plants and for vegetable soybean six plants per pot in the row were maintained.

5.2.2 Soil and Experimental Pot Set up

A black cracking clay, which is referred as *Vertosol* (Australian Soil Classification System as *6AUG-12*) was used for all three experiments. The soil collected from the field at Emerald cotton property was filled in sealed black pots of 25 cm diameter x 24 cm height with 10.79 kg of soil for tomato and white buckets (lined with black plastic and the pot surface with a light plastic cover) of 25 cm x 45 cm with 26 kg of soil for cotton and soybean to maintain the bulk density of 1.3 g cm^{-3} in all experiments. Plants were spaced 75 cm x 60 cm between and within rows for tomato, one plant each pot with a total of 3 pots per treatment per block. Cotton and soybean plants were spaced at 100 cm x 10 cm between and within rows, three and six plants per pot for cotton and soybean respectively with a total of four pots per treatment per plot. Pots within the row were in contact with each other. Seeds were sown into the pots at a depth of 1 cm for tomato and 2 cm for cotton and soybean.

5.2.3 Irrigation Set Up and Fertigation

All containers were fitted with Netafim pot drippers placed five centimetres above the base of each pot. The dripper delivery was 1 L h^{-1} and was operated under the pressure of 62-76 kPa (9-11 PSI) at the return to the water pump. The use of pot drippers was to mimic the SDI system in the field. Soil water was measured daily initially and then weekly in one pot per plot using a calibrated Micro Gopher system (Soil Moisture Technology, Australia), the probe of which consists of a capacitance sensor. Irrigation was imposed on a 1-3 day interval, between 700 h to 1200 h, based on the readings from the Micro Gopher. The nutrient requirement of the crop was supplied as fertigation (giving fertilizer through subsurface drip irrigation) using a Peter's Professional general-purpose water-soluble fertilizer (20:8.7:16.6 NPK and 0.01% B, 0.004% Cu, 0.05% Fe, 0.03% Mn, 0.001% Mo, 0.003% Zn) at the rate of 0.5 g L^{-1} of irrigation water continuously throughout the crop season. To account for different uptake rates of water between treatments, at times irrigation was applied without fertigation to ensure that all plants received the same amount of nutrients. This resulted in an application of 7.86 g plant $^{-1}$ for tomato, 19.95 g plant $^{-1}$ for cotton and 1.61 g plant $^{-1}$ for vegetable soybean over the crop season respectively.

5.2.4 Experimental Design and Treatments Detail

The experiment on tomato was laid out as a Randomized Complete Block split-plot design. Main plots comprised aeration and control. Sub-plot treatments comprised four-selected NaCl levels equivalent to EC_e 2, 4, 8.8 and 10 dS m^{-1}. Treatments were replicated twice, in separate blocks, and each subplot comprised six pots. Pots were maintained between the refill point (32 mm) and field capacity (43 mm). The appropriate NaCl solutions were introduced in three equal applications of 1161.1 mL. The initial one third (1161.1 mL) was placed in the pots seven days after the majority of seedlings had germinated (day 7), the second and final amounts on day 9 and day 13 respectively.

The experiments on cotton and vegetable soybean were laid out as Randomized Complete Block Designs. The factorial experiment consisted of four salt levels (sodium chloride, equivalent to EC_e of 2, 8, 14 and 20 dS m^{-1}) with and without aeration in three replicates. The salt was introduced to pots 15 and 7 days after emergence for cotton and soybean, respectively, as three instalments in equal volume over three-day intervals.

5.2.5 Air Injection and Monitoring of Soil Oxygen

Air injection commenced as soon as plants had a first true leaf. A "Mazzi" venturi air-injector (Model 384-X) was installed in-line immediately following the pump. Pressure gauges either side of the venturi, in association with a valve-regulated bypass line permitted the control of inlet/outlet pressure and thus the pressure differential within the venturi. This controlled the amount of air ingress into the irrigation line (12% air by volume of water). The air injection using Mazzei followed the Bernoulli's principle. The Mazzei air injector provided ~12% air by volume of water (venturi running at a pressure differential of 15 to 20 psi) for the aeration treatment and the non-aerated control received no additional air. Aerated water was delivered to the soil through the pot drippers. The O_2 concentration in the soil at 15 cm depth was monitored near or at flowering stage for 3 – 7 days run using PSt3 O_2 sensitive fibre optic minisensors with a fibox-3 oxygen metre (PreSens GmbH, Germany) as described by Klimant *et al.* (1995). The sensors were placed in the soil and left for 3 days before readings were recorded.

5.2.6 Plant Based Data Recording

5.2.6.1 Growth and development

Performance of the three species in terms of phenology, yield, and physiology were assessed on bordered plants within each experimental plot. Growth and development parameters (plant height, number of shoots, number of nodes, stem diameter, leaf number, leaf area, leaf size) and reproductive parameters (days to flowering, fruit set, and lower- most flowering nodes) were recorded on individual plants at fortnightly intervals and at final harvest. The data on fruit yield, including number and fruit weight were recorded from plants harvested at 87 days after seeding (das) for tomato, at 100% boll open for cotton and for a once-over harvest at 67 das for vegetable soybean. The vegetable soybean crop was harvested before the pod formation due to potential threat of downy mildew (*Peronospora manshurica*) in all treatments, more so on the higher salinity and non-aerated plots. The dry matter data for leaf, stem, roots and fruits as appropriate were derived from the final harvest of the plant, which were then dried to constant weight at 70 ^{o}C.

5.2.6.2 Leaf and soil gas exchange

Leaf gas exchange parameters (photosynthesis (A), transpiration (E) and stomatal conductance (SC) rates) were measured for all species at fortnightly intervals using an Infrared Gas Analyser (IRGA) LCA-4 (ADC, UK). IRGA measurements were made on two fully expanded topmost sunlit leaves per plot on each occasion between 1000-1200h following the method by Adams *et al.* (2002). Soil respiration was measured on the container (pot) soil 3-5 cm away from the plant main stem at boll filling in cotton and at the R5 stage for vegetable soybean, at 1200-1500h, using the IRGA principle with an EGM-3 from PP Systems (UK) following the method described by Hanson *et al*. (2000).

5.2.6.3 Leaf water potential

Midday leaf water potential was determined on three different occasions as the petiole xylem pressure potential using a pressure bomb apparatus (Scholander *et al.,* 1965) from Soil Moisture Equipment Corp., USA, immediately after the leaves with petiole were excised on two fully expanded leaves per plot. The xylem sap was exuded further from the samples used for determination of LWP, and collected by micropipette in sterile 1.5 mL Eppendorf vials (on ice) and stored at –80 ^{o}C for the determination of osmotic potential. Stored xylem sap samples were thawed, 10 µL of sample was placed in a paper disc and the readings were made in Wescor vapour pressure osmometer (Model 5500C, Wescor Inc., Logan UT) following the method described by Gebre *et al.* (1997). Osmometer readings are presented in mmol kg^{-1}.

5.2.6.4 Canopy temperatures and crop relative water stress index

Canopy temperatures were measured using a Model 210 Ag Multimeter (Everest Interscience Inc., Fullerton, CA) portable hand-held infrared thermometer. The instrument was calibrated for each crop using a method described by Blad and Rosenberg (1976). For each measurement the infrared thermometer was held above the plant canopy at an angle of 15^{o}C below the horizontal so that plant parts, but no soil were viewed. Canopy temperature (Tc) measurements were taken from each plot starting from early establishment to the final harvest at fortnightly interval. For each measurement, four-canopy temperatures were taken from four sides and then averaged. These measurements were carried out between 1300-1500h. At each time of measurement, dry and wet-bulb temperatures were taken above the canopy surface using an Assman psychrometer (Qualimetrics Inc., Sacramento, CA) to determine air temperature (Ta) and vapour pressure deficit (VPD) which are used to calculate the crop relative water stress index. Data are expressed over the range of 0-1, 0 being non-stressed and 1 being completely stressed.

5.2.6.5 Light interception

To determine light interception, photosynthetically active radiation (PAR) was measured fortnightly between 1100 – 1300 h. Two averaged readings per treatments were made, each consisting one reading above and four readings beneath the canopy (ground level) with a PAR ceptometer (Decagon USA). Percent light interception was calculated as the difference between PAR above and below the canopy:

$$\% \text{ intercepted PAR} = [(\text{above-below})/\text{above}] \times 100.$$

5.2.6.6 Chlorophyll determination

Leaf chlorophyll concentration was measured using a Minolta SPAD-520 chlorophyll metre on two youngest fully expanded topmost sunlit leaves for each sample plant (two plants for tomato and four plants each on soybean and cotton respectively) at fortnightly intervals throughout the season. Twenty fully expanded randomly sampled leaves for each species at the flowering stage were also processed using the acetone chlorophyll extraction method (Anonymous, 1994) in order to calibrate SPAD data as described by Levy and Skiles (2000).

5.2.6.7 Leaf weight ratio and specific leaf area

Leaf weight ratio (LWR; g/g) is the ratio of leaf dry biomass to total plant dry biomass and thus a measure of the proportion of the plant dry biomass residing in the leaf material. Specific leaf area (SLA; cm^2 leaf area/g leaf dry biomass) is the ratio of leaf area to leaf plant dry biomass and thus a measure of leaf thickness. SLA analysis was performed following methods described by Garnier *et al.* (2001). Two fully expanded top leaves were sampled at 57 and 82 das for tomato, 29, 46 and 70 das for cotton, and 47 das for vegetable soybean respectively for the SLA determination. LWR was calculated as proportion of the total leaf dry weight to the total above-ground dry weight of the sample plants at harvest.

5.2.6.8 Leaf membrane properties

Membrane properties were assessed from five discs (1 cm diameter) obtained from each of five topmost fully expanded leaves per plot on 82 das for tomato, 115 das for cotton and 50 das for soybean, and data are reported as relative leakage ratio (RLR) and electrolyte leakage ratio (ELR) expressed as percentages. The RLR for leaf membrane permeability was determined by the leakage of UV-absorbing substances (UVAS) according to Redman *et al*. (1986). Sample discs were washed with three changes of deionised water. Leaf samples were then incubated at room temperature (~18-25 ^{o}C) in the presence of 20 mL of deionised water. A 2.5 mL aliquot of the bathing solution was removed from the flasks after 24 h incubation and the absorbance was estimated spectrophotometrically at 280 nm (*A*280). This 2.5-mL aliquot was then added back to the original solution and the flasks were cooled to -30°C for 4 h to destroy cell integrity. A final absorbance measurement (*A*8280') was recorded after thawing and the relative leakage ratio (RLR) of the UVAS was calculated as RLR = *A*280/*A*8280'. For determination of the ELR, the methods described by Navari-Izzo *et al*. (1989) were followed. The relative water content of the leaf tissue was determined following Barrs and Weatherley (1962), calculated as RWC = (FW-DW)/(TW-DW), and expressed as percentage. Two fully expanded upper leaves for cotton and soybean and ten leaflets for tomato per plot were used for the determination of RWC on the same day that SLA was determined.

5.2.6.9 Root sample analysis

One core sample per pot centre, collected at harvest (87 das for tomato, 145 das for cotton and 67 das for vegetable soybean), was obtained by coring with a 3 cm diameter soil corer to the entire depth of the pot. The collected core samples were soaked in 1% solution of ground breaker (active constituent 10 g L^{-1} buffered polylignosulfonate) for 2-3 hours and roots were separated from soil using a 45-micrometer sieve following the floatation technique. The living roots were separated manually by discarding the dead based on visual observation of tissue colour as described by Caldwell and Virginia (1991), and the root length and diameter of the former was determined using a Hewlett Packard scanner and Delta-T software. The washed root samples were oven-dried for 48 hours at 70 ^{o}C for the determination of dry mass.

5.2.6.10 Microscopy for root anatomy

Roots samples were collected at final tomato harvest (87 das) using a 3 cm diameter corer to the entire depth of container. Lateral roots were collected from the middle of the core. To examine the formation of arenchyma (intercellular air filled spaces) changes in the relative size of xylem tissue in the later roots, free hand transverse sections (TS) were cut at 5 cm away from the root tips. The root cross section were stained with Toluidine blue O and were examined and photographed with a Nikon phase-contrast microscope at 300 x. The percentage of the cortex, and size of the xylem was determined with help of a calibrated stage micrometer.

5.2.6.11 Sap flow

Water use expressed on a per plant basis, was measured using stem gauges (Model SGA 5, Dynamax, Houston, TX, USA) attached to the main stem of one plant per treatment over the period of 5 days, one week before the final harvest on vegetable soybean only. Sap flow was measured using a heating power of 0.08 W, the lowest pre-dawn values for the sheath conductance (Steinberg *et al.,* 1989), and the average of beginning and ending values of stem diameter. The sap flow value for water use compared with the gravimetric value over 24 h runs showed that sap flow was ± 95% of the gravimetric determination for the tomato plants in the pot.

5.2.6.12 Yield determination

At final harvest yield and its components was measured on 1, 10 and 20-bordered plants per plot for tomato, cotton and vegetable soybean respectively. The harvested parts were then dried at 70^{o}C to constant weight.

5.2.7 Water Use Efficiency

Season-long water use of each plant was computed by summing the daily additions of water over the entire season assuming that the evaporative loss from the containers was insignificant. The season-long water use efficiency, (WUE_{sl}) was calculated by dividing the plant dry weight by the season-long water application. Thus, WUE_{sl} represents the amount of dry biomass accumulated over the season for each unit of water transpired by the plant (g dry weight L^{-1} H_2O). WUE was also expressed as instantaneous water use efficiency, (WUE_i), derived as the proportion of CO_2 (μmol) fixed per unit of water (mmol) used in transpiration during the process of photosynthesis. The inputs for this analysis were derived from the leaf IRGA data.

5.2.8 Carbon Isotope Discrimination

At the final harvest, ten leaflets of tomato, and five leaves of vegetable soybean from outer exposed positions of the canopy, corresponding to the fifth leaf from the top were collected and pooled for each plot. For cotton, leaf samples were collected at 50% boll opening, and shoot and root samples were also collected at final harvest. The leaves, shoots and roots were dried in an oven at 70 ^{o}C to constant weight, and then ground to a fine powder. The $^{13}C/^{12}C$ ratio of samples was subsequently determined by mass spectrometry at Central Queensland University, Australia. Samples of 0.8-1.2 mg were combusted in an elemental analyzer (EA 1108, Series 1, CHN analyser, Carlo Erba Instrumentazione, Milan, Italy) and the $^{13}C/^{12}C$ ratio was measured with an isotope ratio mass spectrometer (Europa Scientific Limited, UK 20-20 Stable IRMS) operated in continuous flow mode. A system check for elemental analysis was achieved with an interspersed working standard of standardised flour. Stable carbon isotope composition was expressed as $\delta\ ^{13}C$ values, where:

$$\delta\ ^{13}C\ (‰) = [R\ sample/R\ standard)-1] \times 100, \text{ and R is the } ^{13}C/^{12}C \text{ ratio.}$$

A secondary standard of flour calibrated against Peedee belemnite (PDB) carbonate was used for comparison. The accuracy of the $\delta\ ^{13}C$ measurements was ± 0.04-0.13 ‰ (CV 1.7 ‰). Following Farquhar (1989), Δ was further calculated from $\delta\ ^{13}C$ as

$\Delta = (\delta_a - \delta_p)/(1 + \delta_p)$, where δ_a and δ_p refer to air and plant respectively. On the PDB scale, free atmospheric CO_2, δ_a, has a current composition of approximately -8‰.

5.2.9 Plant Sample Analyses for Salts and Nutrients

Leaf, stem and root samples were collected at the final harvest for tomato and vegetable soybean, whereas for the cotton the leaf samples were collected at 50% boll opening and stem and root samples were collected at final harvest from each plot. The samples were dried at 70°C to constant weight. The dried samples were ground and kept in sealed glass containers until processing. The leaf samples were analysed for total nitrogen (0.4 g sample digested by concentrated H_2SO_4 plus selenium catalyst for 3 hours, N measured in segmented flow analyser), nitrate nitrogen and chloride (0.4 g sample boiled in deionised water for 1 hour, nitrate and chloride measured colormetrically in segmented flow analyser), total phosphorus, sulphur, potassium, calcium, magnesium, sodium copper, zinc, manganese, iron, aluminium and boron (1.6 g sample digested in concentrated HNO_3 measured using ICP AES (inductively coupled plasma, argon emission spectrometer) following the standard procedures in the Australian accredited commercial laboratory of CSBP, Western Australia.

5.2.10 Data Analysis

The data collected were subjected to analysis of variance (ANOVA) using generalized linear model (GLM) for a split plot and a factorial randomized complete block design employing SYSTAT version 9 (SPSSInc, 1999). Where interactions were not significant, main effects only are presented. As the interaction effects between salinity and aeration were not significant for most of the parameters, only main effects due to salinity and aeration are presented in tabular form and interactions are presented in the form of graphs.

5.3 RESULTS

5.3.1 Tomato Experiment

5.3.1.1 Environmental parameters and weather data

The daily mean ambient temperature measured outside the screen house averaged 19.5°C and ranged from 10.4 - 25.3°C. There was a gradual decrease in temperature from April to July and a slight increase from August to October. The relative humidity averaged 26% and ranged from 17% to 43%. The solar radiation within the growing environment averaged 10.6 MJ m^{-2} d^{-1}, and ranged from 1.6 to 17.7 MJ $m^{-2}d^{-1}$ (Details in the appendix).

Table 5.3.1.1 Soil moisture (mm H_2O per 100 mm soil) seasonal means for salinity and aeration treatments and cumulative applied water over the crop period.

Salinity EC_e (dS m^{-1})	Soil moisture (mm per 100 mm soil depth)		Cumulative applied water per plant (L)	
	Aeration	Control	Aeration	Control
2.0	22.90	24.17	22.34	21.48
4.0	24.71	26.31	19.83	19.40
8.8	24.01	27.50	19.69	18.23
10.0	27.43	31.18	15.43	16.12
LSD oxygation LSD Salinity	2.20 (7 df) 3.11 (7 df)		0.96 (37 df) 1.35 (37 df)	

5.3.1.2 Water input, soil water content and soil oxygen concentration

Water applied to the crop over the season increased with aeration and deceased with salinity (Table 5.3.1.1). Soil in the aerated plot remained drier most of the time during the season compared to the control treatment.

Soil water content over the season was recorded between 10-37 and 15-37 mm per 100 mm soil depth for aeration and control respectively (Figure 5.3.1.1) and was on average lower with aeration and higher with increasing salinity (Table 5.3.1.1). In spite the plant water use was decreased with increasing salinity and increased with aeration (Table 5.3.1.5).

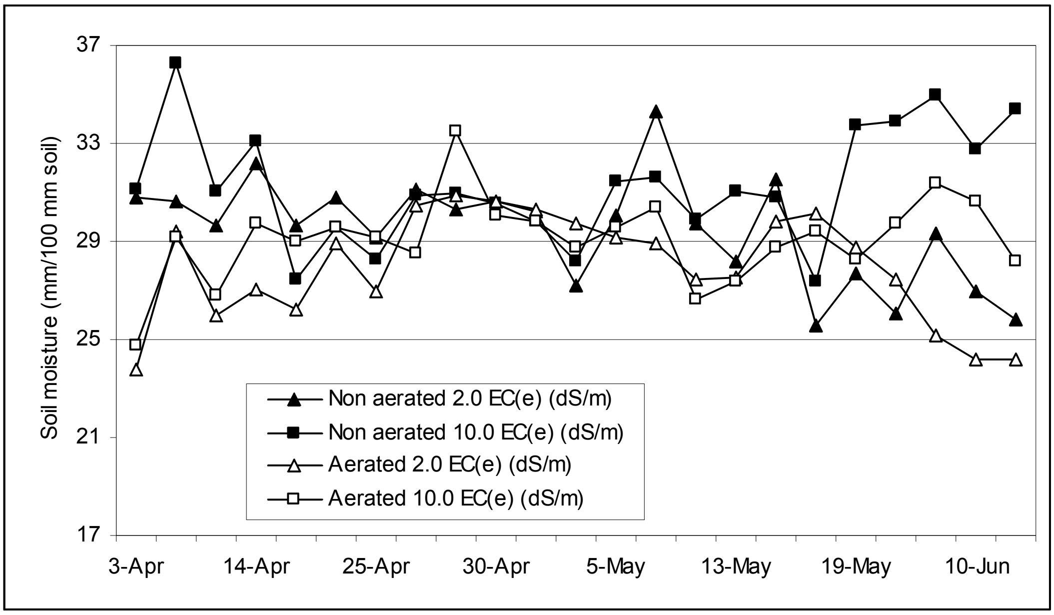

Figure 5.3.1.1 Change in soil water content (mm H_2O per 100 mm of soil depth) with aeration (open symbol) and without aeration (closed symbol) treatments with respect to salinity (2 dS m^{-1}, and 10 dS m^{-1}) in a heavy clay soil.

O_2 concentration in the soil solution was greater for the aeration compared with the control treatment, and decreased with increase in salinity (Figure 5.3.3.2).

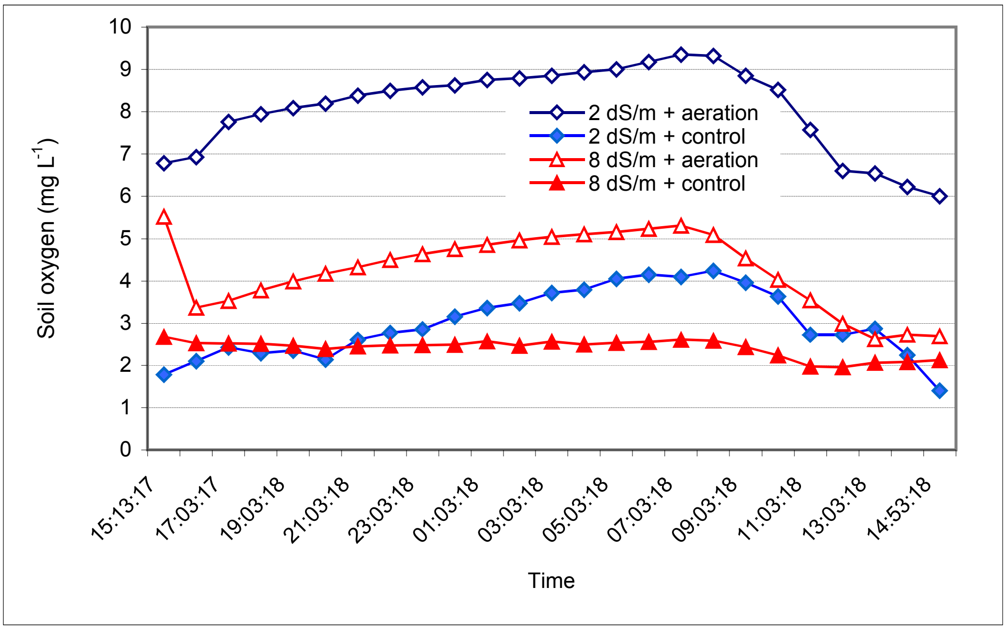

Figure 5.3.1.2. Soil oxygen concentration (mg L^{-1}) as affected by aerated (open symbols) or no aeration (closed symbols) at two soil salinities in a heavy clay soil.

5.3.1.3 Plant growth characteristics

Plant height decreased significantly with increasing salinity and plants treated with aeration were taller than those in the control (Table 5.3.1.2). Total leaf area per plant was lower at the highest salinity level although the difference between the 2– 8.8 dS m^{-1} were not significantly different. Likewise, the effect of salinity on components of leaf area such as leaf number and leaf size were significantly different and were lowest for highest salinity levels. Differences in total leaf area per plant and its components were too small to be significant between aeration and its control (Table 5.3.1.2). However, the SLA was significantly smaller with aeration (317 vs. 366 cm^2 g^{-1}, SED (49 df) = 20.6).

Table 5.3.1.2 Crop growth and leaf characteristics (per plant) for tomato as affected by aeration and soil salinity treatments.

Factor	Levels	Plant height (cm)	Number of trusses	Number of leaves	Total leaf area (m^2)	Leaf size (cm^2)	Leaf chlorophyll concentration (µg cm^{-2})
Salinity	2	148	6	21	0.33	154.08	51
EC_e	4	132	5	21	0.30	145.42	53
(dS m^{-1})	8.8	131	5	20	0.34	163.25	50
	10	94	4	17	0.20	109.25	49
	LSD 5% (38 df)	20	0.76	2.43	0.07	52	ns
Aeration	Aeration	130	5	20	0.29	141.21	51
	Control	123	5	19	0.30	144.79	50
	LSD 5% (38df)	ns	ns	ns	ns	ns	ns

5.3.1.4 Reproductive performance

A marked effect of salinity and aeration was observed on reproductive performance of the crop (Table 5.3.1.3). Number of inflorescences counted at 87 das increased significantly with aeration and decreased with increasing salinity levels. Flowering was delayed significantly by higher salinity but the delay by aeration was not significant. No difference in fruit set was observed between treatments (experimental average = 57%) although number of fruits per plant was greater in the aeration compared to its control and lower at higher salinity levels (Table 5.3.1.3).

Table 5.3.1.3 Flowering, fruit yield and yield attributes for tomato as affected by aeration and soil salinity treatments

Factor	Level	Inflorescences plant $^{-1}$ (87 days)	Days to 50% flowering in the first inflorescence	Fruits per plant at harvest[1] (87 days)	Net leaf photosynthesis (µmol $m^{-2}s^{-1}$)	Transpiration rate (mmol $m^{-2}s^{-1}$)
Salinity EC_e ($dS\ m^{-1}$)	2	5.0	47	7.7	13.96	1.33
	4	4.6	56	7.7	13.43	1.36
	8.8	4.5	60	7.3	14.52	1.44
	10	3.2	67	3.7	12.27	1.20
	LSD 5% (38 df)	0.85	6.1	2.7	ns	ns
Aeration	Aeration	4.5	60	7.8	13.29	1.29
	Control	4.1	55	5.5	13.85	1.37
	LSD 5% (38 df)	0.60[2]	ns	1.9	ns	ns

[1] The crop was harvested once-over at 87 days after seeding without leaving the plant for the full season, P > 0.05 < 0.1

5.3.1.5 Dry matter accumulation and partitioning

With the exception of the root, all other components and total biomass weight decreased significantly ($P \leq 0.05$) with increasing salinity (Table 5.3.1.4) and consequently the root: shoot ratio was greater at higher salinity. In contrast, the HI was greatest at the lowest salinity. The difference between aeration treatments was significant only for fruit weight and total biomass, although the components of the latter were consistently heavier under aeration compared to the non-aerated control (Table 5.3.1.4).

Table 5.3.1.4 Dry matter accumulation and partitioning, root: shoot ratio and harvest index for tomato as affected by aeration and soil salinity treatments.

Factor	Levels	Dry weight (g $plant^{-1}$)					Root: shoot ratio	HI[1]
		Root	Stem	Leaf	Fruits	Total biomass		
Salinity EC_e (dS m^{-1})	2	11.16	18.47	30.31	37.61	97.56	0.13	0.38
	4	14.27	18.86	30.82	25.96	89.91	0.19	0.29
	8.8	13.02	17.37	26.55	20.79	75.46	0.21	0.28
	10	12.02	9.41	13.24	10.31	44.97	0.36	0.23
	LSD 5% (38 df)	ns	4.61	7.36	9.71	19.99	0.20	0.07
Aeration	Aeration	12.77	17.80	28.39	31.25	89.87	0.14	0.35
	Control	12.49	14.71	22.95	17.58	67.51	0.18	0.26
	LSD 5% (38 df)	ns	ns	ns	6.86	14.14	ns	0.05

[1] Harvest index

5.3.1.6 Leaf gas exchange properties

Neither salinity nor aeration significantly affected photosynthesis, transpiration rate or chlorophyll concentration (Table 5.3.1.3) although there were tendencies for photosynthesis and transpiration to decline, and chlorophyll concentration to rise with increasing salinity.

5.3.1.7 Plant water use and water use efficiency

Significant effects of both aeration and salinity were noted for WUE_{sl} of biomass and fresh fruit. Aerated plants achieved higher water use efficiencies for both fruit and biomass compared with the control. WUE decreased significantly with increasing soil salinity (Table 5.3.1.5). Unlike the WUE_{sl} of biomass and fruits, WUE_i did not differ significantly between salinity or aeration treatments. WUE assessed by carbon discrimination revealed a significant improvement in WUE with increasing salinity levels but not due to aeration (Table 5.3.1.5).

Table 5.3.1.5 Water use and water use efficiency for tomato as affected by aeration and soil salinity treatments.

Factor	Levels	Water use (L plant $^{-1}$)	WUE for biomass (g L^{-1})	WUE of fruit[1] (g L^{-1})	Carbon discrimination (Δ ‰)
Salinity EC_e (dS m^{-1})	2	22.91	4.26	1.64	21.39
	4	19.61	4.54	1.32	21.09
	8.8	18.96	4.00	1.07	21.12
	10	15.75	2.85	0.65	20.13
	LSD 5% (38 df)	1.35	0.87	0.45	0.72
Aeration	Aeration	19.32	4.65	1.62	21.01
	Control	18.81	3.56	0.93	20.79
	LSD 5% (38 df)	ns	0.61	0.32	ns

[1] Determination of WUE of fruit based on dry fruit weight.

5.3.1.8 Leaf salt analysis

Leaf tissue concentrations of Na^+, Cl^-, Ca^{2+}, and the K^+:Na^+ ratio were significantly affected by both the aeration and salinity treatments (Table 5.3.1.6). Potassium concentration was not affected. Na^+ concentration in the leaf tissue steadily increased with increase in salinity from 2-10 dS m^{-1} and in non-aerated compared to the aeration treatment. Non-aerated plant Na^+ tissue concentrations were 42% higher than their aerated equivalent (Table 5.3.1.6). Similarly, leaf Cl^- concentration differed significantly due to salinity with the highest recorded at 10 dS m^{-1}. Higher calcium leaf tissue concentrations were evident with increased salinity. The effect of aeration on Ca^{2+} was also significant; non-aerated plants had leaf tissue concentrations greater than those of aerated plants (Table 5.3.1.6). Although differences in the K^+ concentrations in leaf tissue were not significant, the ratio of K^+:Na^+ differed significantly due to salinity and aeration. The ratio decreased progressively with increased salinity, and aeration resulted in a significantly greater ratio than that of the control (Table 5.3.1.6).

Table 5.3.1.6 Salt accumulation in the leaf, membrane integrity, and root properties as affected by soil salinity and aeration on tomato in a heavy clay soil

Factor	Level	Na^+ (g $100g^{-1}$)	Cl^- (mg kg^{-1})	K^+ (g $100g^{-1}$)	Ca^{2+} (g $100g^{-1}$)	K^+: Na+	RLR (%)	RLD (cm cm^{-3})	Root weight density (mg cm^{-3})	Root diameter (mm)
Salinity EC_e (dS m^{-1})	2	0.22	0.99	2.83	1.51	15.4	15	5.53	1.56	0.16
	4	0.25	2.39	3.04	1.82	13.14	18	4.14	1.62	0.23
	8.8	0.31	1.83	2.73	1.85	9.28	20	5.29	1.87	0.23
	10	0.49	2.56	2.04	2.35	6.47	33	3.85	1.35	0.25
	LSD (7 df)	0.14	0.33	0.48	0.34	3.15	17.9 (38 df)	ns	ns	0.118
Aeration	Aeration	0.26	1.41	2.82	1.62	13.78	20	5.07	1.64	0.217
	Control	0.37	1.97	2.49	2.15	7.19	26	4.21	1.56	0.214
	LSD (7 df)	0.10	0.23	0.34	0.10	4.57	ns	ns	ns	ns

5.3.1.9 Membrane properties

The relative leakage ratio of the tomato leaf samples increased with increasing salinity levels. The relative leakage ratio decreased by 23 percent in the aerated treatment compared with the control (Table 5.3.1.6).

5.3.1.10 Root properties

Root length density (RLD) of lateral roots expressed as cm of root cm^{-3} of soil volume was lowest at highest salinity levels compared to control and other treatments. RLD increased in aerated treatment by 25 percent compared to the non-aerated control. The diameter of lateral roots increased significantly with increasing salinity levels (Table 5.3.1.6). Slightly greater root diameter was observed in the aerated treatment compared to the control. Root weight density (expressed as mg root cm^{-3} soil) was lowest at highest salinity level and increased (non-significantly) with aeration compared to the control treatment (Table 5.3.1.6).

5.3.1.11 Root anatomy

Free-hand cut transverse section (TS) of tomato root 5 cm from the root tip also revealed increased root diameter, wider cortical tissues as well as increased xylem size in the aeration treatment. The diameter of the conducting tissues in the aerated treatment was 150 µm compared to only 100 µm in the roots of non-aerated treatment at the salinity levels of 8.8 dS m^{-1} (Plate 5.3.1). The TS also indicated the direct damage of the salt to the mesophyll cells and the epidermal cells of the root tissues in the non-aerated treatment.

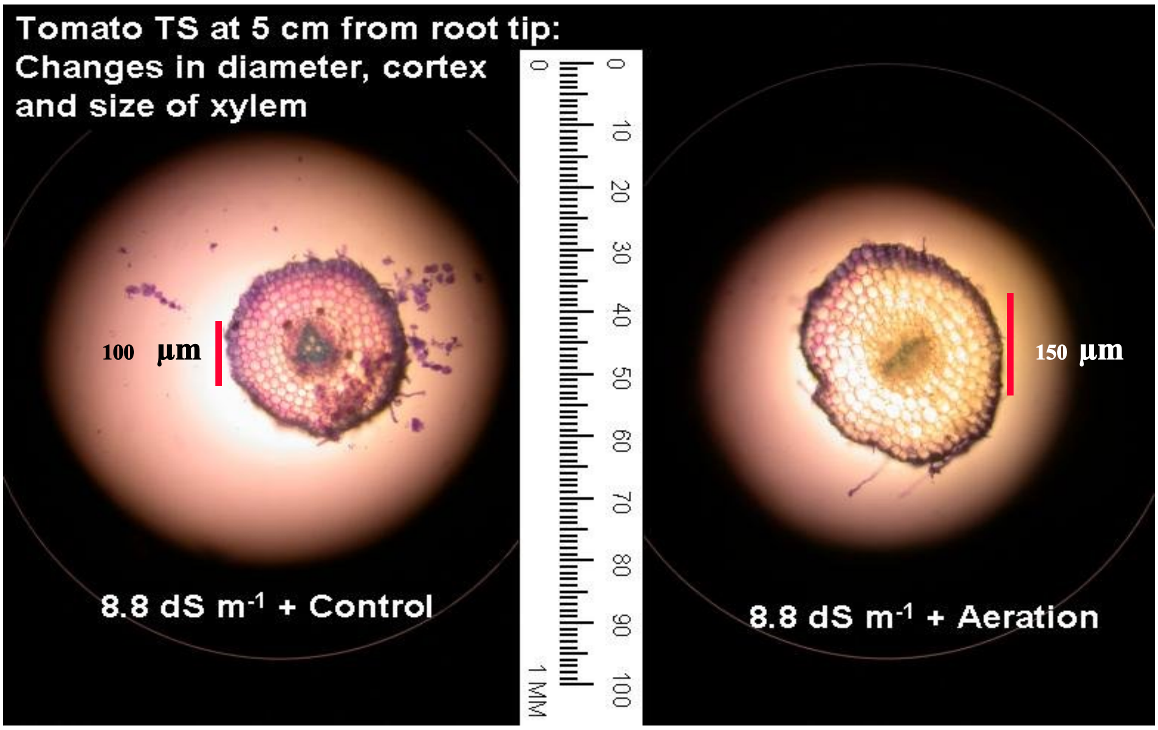

Image 5.3.1 Free hand cut TS of tomato root taken at 5 cm away from the root tip showing effect of aeration on the root at salinity of 8.8 dS m^{-1}.

5.3.2 Cotton Experiment

5.3.2.1 Environmental parameters and applied water to the crop

The daily mean air temperature measured outside the screen-house ranged from 22 to 30°C representing a gradual increase in temperature over the crop period. The relative humidity ranged from 28% to 67%. Solar radiation (measured as PAR) inside the screen house averaged 17.47 MJ m^{-2} d^{-1}, with a minimum of 6.6 to a maximum of 21.5 MJ m^{-2}d^{-}

Season mean rhizosphere O_2 concentration decreased with salinity and increased with aeration treatment (8.75±1.98 mg L^{-1} (range 2.1-10.3) for 2 dS m^{-1} aeration versus 5.95±2.07 mg L^{-1} (range 0.02-8.51) for 2 dS m^{-1} control, and 6.55±0.56 mg L^{-1} (range 5.44-7.55) for 14 dS m^{-1} aeration versus 4.66±2.61 mg L^{-1} (range 0.02-9.18) for 14 dS m^{-1} control.

The soil temperature during the period of rhizosphere O_2 monitoring ranged from 21 to 31°C. In general, rhizosphere O_2 concentration was higher at night and lowest at midday, similar to Figure 4.3.1.3.

Data on water application to the crop over the season for different treatments are presented in Figure 5.3.2.1. Crop water use, equating to water applied, tended to be higher throughout the crop season with aeration and lower salt concentration compared with the non-aerated control and higher salinity treatments.

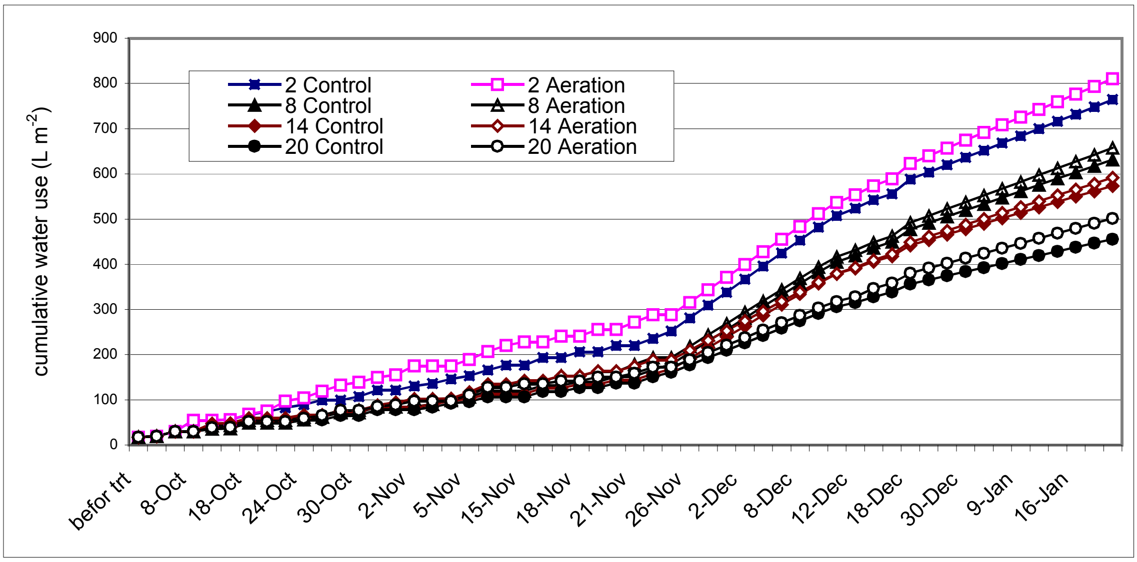

Figure 5.3.2.1 Water used (L m^{-2}) by cotton over season in different salinity levels with and without aeration (□- 2 dS m^{-1} with aeration, ■- 2 dS m^{-1} without aeration, Δ- 8 dS m^{-1} with, and ▲- 8 dS m^{-1} without aeration, ◊- 14 dS m^{-1} with, ♦- 14 dS m^{-1} without aeration, ○- 20 dS m^{-1} with and ●- 20 dS m^{-1} without aeration).

5.3.2.2 Plant growth characteristics

A number of measured parameters did not differ significantly between treatments. These included location of the lowermost flowering nodes, days to squaring to flowering, and to first boll open, and to crop maturity (Table 5.3.2.1). However, plant height and number of nodes per plant decreased significantly ($P \leq 0.05$) with increasing salinity and increased significantly ($P \leq 0.05$) with aeration compared with the respective controls (Table 5.3.2.2). Similarly, the number of shoots per plant decreased with increasing salinity and increased with aeration (Table 5.3.2.3). Likewise, stem diameter increased with aeration and decreased with increasing salinity compared with the control (Table 5.3.2.5).

5.3.2.3 Leaf and canopy characteristics

The number of leaves per plant decreased significantly ($P \leq 0.05$) with increasing salinity, and aeration increased number of leaves per plant. Although the effects of salinity and aeration were not significant for leaf area (leaf size), the total leaf area per plant decreased significantly with increasing salinity and increased with aeration (Table 5.3.2.2). The significant interaction on light interception suggested that the canopy light interception increased significantly by aeration comapared to the control at higher salinity level. At ower salinity level the aeration effect was not significant on light interception. Light interception by the canopy averaged over the season showed that aeration significantly ($P \leq 0.05$) increased light interception by the canopy at higher salinity levels but not in the control and 8 dS m^{-1} (Figure 5.3.2.2). Combined over aeration, light interception decreased significantly with increasing salinity from 8 dS m^{-1}; and combined over salinity aeration significantly increased light interception compared to the control (Table 5.3.2.2). The leaf chlorophyll concentration did not differ significantly with respect to salinity or aeration (Table 5.3.2.2).

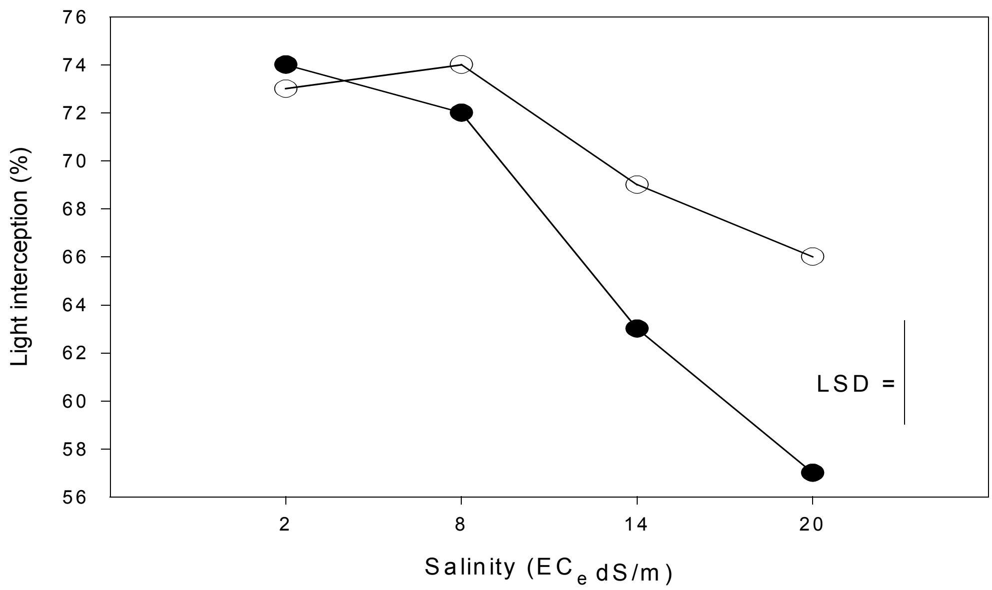

Figure 5.3.2.2 Season-long mean light interception by the cotton canopy at different salinity levels with aeration (open circles) and without aeration (closed circles) in a heavy clay soil.

Table 5.3.2.1 Phenological development of cotton as affected by salinity and aeration in a heavy clay soil.

Variables	Levels	Lowest flower node	Squaring (days)	Flowering (days)	Boll open (days)	Harvest[1] (days)
Salinity (ECe)	2 dS m^{-1}	6	46	63	113	145
	8 dS m^{-1}	6	47	68	114	146
	14 dS m^{-1}	6	48	67	113	145
	20 dS m^{-1}	6	47	65	114	146
	LSD (df=14) (P=0.05)	n.s.	n.s.	n.s.	n.s.	n.s.
Aeration	Aeration	6	47	66	113	145
	Control	6	47	65	113	145
	LSD (df=14) (P=0.05)	n.s.	n.s.	n.s.	n.s.	n.s.
	S x A LSD (P = 0.05)	-	-	-	-	-

[1] The crop was harvested as 100% boll open which varied with treatments.

Table 5.3.2.2 Leaf, canopy and stem characteristics of cotton as affected by soil salinity and aeration treatments in a heavy clay soil, 2003.

Factor	Level	Plant height (cm)	Nodes (#)	Leaves (#)	Single leaf size (cm^2)	Leaf area (m^2)	Chlorophyll (SPAD unit)	LI[1] (%)
Salinity (EC_e dS m^{-1})	2	135.3	23.8	42.8	92.6	3.97	48.0	73
	8	120.5	22.6	39.3	69.1	2.65	47.6	73
	14	112.4	22.2	27.5	71.7	1.96	46.9	66
	20	98.4	21.0	25.0	84.4	2.08	45.1	61
	LSD 5% (14 df)	12.26	1.26	4.61	n.s.	0.797	n.s.	3.62
Aeration	Aeration	120.9	22.7	34.9	77.12	2.68	47.2	70
	Control	112.3	22.0	32.4	81.21	2.65	46.6	66
	LSD 5% (14 df)	8.67	n.s.	n.s.	n.s.	n.s.	n.s.	2.27
	SxA (LSD) P value	-	1.78 0.044	-		-	-	4.55 0.02

[1] Light interception percentage by the canopy

5.3.2.4 Yield, yield components and dry matter partitioning

Lint yield was significantly greater ($P \leq 0.05$) with aeration (21.4%) compared with the control. A significant decrease in lint yield was observed with increasing salinity (Table 5.3.2.4). The lint yield was reduced by 18, 44 and 53% at 8, 14 and 20 EC_e respectively, compared with the control at 2 dS m^{-1} (Figure 5.3.2.3). The effect of aeration on lint yield was greater at higher salinity levels (Table 5.3.2.4) compared to control but the interaction effect due to aeration and salinity was not statistically significant. Fuzz seed (unclean seed), 100 seed weight, root, stem, leaf, boll, above ground and total weight were all significantly less with greater salinity and increased with aeration compared with the control (Table 5.3.2.4). The number of nodes per plant increased signicantly at higher salinity levels with the aeration compared to the control (Graph 1 in appendix).

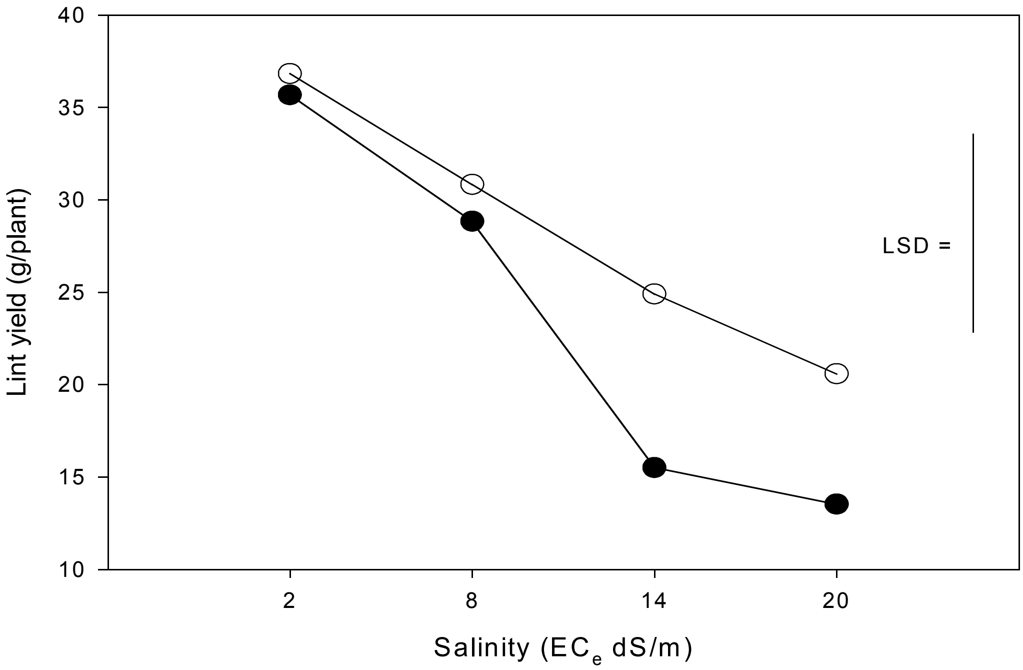

Figure 5.3.2.3 Cotton lint yield per plant over a range of soil salinity levels with aeration (open circles) and without aeration (closed circles) in a heavy clay soil.

Image 6. An overview of the aeration experiment on cotton in saline soil.

Table 5.3.2.3. Dry matter accumulation and partitioning for cotton as affected by aeration and salinity treatments in a heavy clay soil.

Factor	Levels	Dry weight (g plant^{-1})						Root: shoot ratio	Tap root length (cm)	Shoots/ plant	HI
		Root	Stem	Leaf	Boll wt	AGDB[1]	Total biomass				
Salinity EC_e (dS m^{-1})	2	44.79	59.48	34.66	96.43	190.57	235.36	0.24	32.7	16.3	0.19
	8	32.44	46.52	29.93	84.60	161.04	193.48	0.20	32.8	15.7	0.19
	14	31.30	33.39	22.78	56.13	112.30	143.59	0.29	35.2	15.5	0.18
	20	24.26	30.57	21.57	47.70	99.84	124.11	0.25	33.8	14.9	0.17
	LSD 5% (14 df)	9.68	12.68	5.57	16.38	29.93	31.92	n.s.	n.s.	n.s.	0.012
Aeration	Aeration	35.3	44.35	28.80	79.56	152.71	187.98	0.23	34.8	15.9	0.19
	Control	31.1	40.63	25.66	62.87	129.16	160.28	0.26	32.1	15.3	0.18
	LSD 5%	6.84	6.97	3.94	11.58	21.16	22.57	0.055	5.86	0.92	0.008
	(14 df)	n.s.	n.s.	n.s.	0.008	0.032	0.020	n.s.	n.s.	n.s.	0.071
	S x A (LSD)	-	-	-	-	-	-	-	-	1.85	0.0174
	P value									0.090	0.035

[1]AGDB = Above ground dry biomass

Table 5.3.2.4 Lint yield and components and season long water use, and water use efficiency parameters of cotton in relation to salinity and aeration in a heavy clay soil, 2003.

Factor	Levels	Applied water (L plant $^{-1}$)	WUE_{sl} lint (g L^{-1})	WUE_{sl} biomass (g L^{-1})	WUEi	Lint wt (g $plant^{-1}$)	Fuzz seed[1] (g $plant^{-1}$)	100 seed wt (g)	Fruit set (%)
Salinity treatments EC_e (dS m^{-1})	2	65.6	0.551	2.9	4.48	36.25	41.93	9.71	45
	8	53.7	0.556	3.0	5.02	29.83	37.70	9.49	47
	14	48.6	0.415	2.31	4.90	20.20	24.35	9.56	35
	20	39.9	0.427	2.51	4.61	17.07	19.88	8.92	33
	LSD 5% (14 df)	2.18	0.103	0.52	n.s.	6.13	7.18	0.43	10.14
Aeration treatments	Aeration	53.3	0.53	2.85	5.12	28.28	34.65	9.56	42
	Control	50.5	0.45	2.51	4.38	23.29	27.28	9.26	38
	LSD 5% (14 df)	1.54	0.073	0.37[a] 0.076	0.806[a] 0.069	4.34	5.07	0.305	n.s.

[1] Seed after delinting (not cleaned seeds), [a] $P \geq 0.05 \leq 0.1$

The yield components such as number of bolls per plant and mean boll weight increased significantly ($P \leq 0.05$) with aeration and decreased with increasing salinity levels (Table 5.3.2.5). The aeration effect on HI was only significant at highest salinity levels compared to control (Graph 2 in Appendix). Similarly the harvest index (lint yield/AGDB) also increased significantly with aeration and decreased with increasing salinity levels (Table 5.3.2.3). However, effect of salinity and aeration treatments on the root: shoot ratio were not significantly different in the experiment (Table 5.3.2.3). Fruit set percent of cotton in the experiment was significantly lowest at salinity of 14 and 20 dS m^{-1} compared to control and 8 dS m^{-1}, and aeration increased fruit set, but not significantly, compared to non-aerated control (Table 5.3.2.4).

5.3.2.5 Leaf gas exchange and leaf temperature

Leaf gas exchange measured in terms of leaf net photosynthesis and transpiration rate did not differ significantly due to salinity and aeration treatments in the experiment. However, stomatal conductance was reduced significantly ($p \leq 0.05$) with increasing salinity and increased with aeration treatments (Table 5.3.2.6). Likewise, RUEi estimated from gas exchange data indicated that the effects of salinity and aeration treatments on the RUEi were not significantly different. Crop water stress index over the season increased with increasing salinity levels and decreased with the aeration. A similar trend was evident for leaf temperature (Table 5.3.2.6).

5.3.2.6 Leaf physiology

Leaf weight ratio (LWR) increased with increasing salinity and decreased with aeration treatment (Table 5.3.2.5). Relative water content (RWC) of the leaf tissue did not differ significantly with salinity but increased significantly with aeration treatment (Table 5.3.2.6). Likewise, predawn leaf water potential (LWP) decreased significantly with increasing salinity levels but increased with the aeration treatment (Table 5.3.2.5). The effect of treatments on specific leaf area (SLA) was not significant. However, SLA was higher for aeration compared to control and for salinity at 8 dS m^{-1}followed by 14 dS m^{-1} compared to control and the highest salinity (Table 5.3.2.6). A significant interaction effect due to aeration and salinity was observed on the osmolality of xylem sap. Aeration significaly increased the xylem sap osmolality at highest salinity level only (Graph 3 in appendix). However, the effect of aeration and salinity independently did not have significant effect on the osmolality of the xylem sap on cotton (Table 5.3.2.5).

5.3.2.7 Plant water relation and WUE

Season long applied water to cotton decreased significantly ($P \leq 0.05$) with increasing salinity levels and increased with aeration (Table 5.3.2.4). Similarly the WUE_{sl} for lint and biomass increased significantly ($P \leq 0.05$) with aeration compared to the control and decreased due to salinity at 14 and 20 dS m^{-1} compared to control and 8 dS m^{-1} in the experiment (Table 5.3.2.4). WUE_i increased with aeration, however, there was no trend of salinity effect on WUE_i (Table 5.3.2.4). Carbon discrimination (Δ‰) is considered as a surrogate of transpiration efficiency. The carbon discrimination of leaf, stem and root tissues did not differ significantly due to salinity and aeration treatments (Table 5.3.2.5).

5.3.2.8 Membrane properties of the leaf tissues

Electrolyte leakage (EL) of the leaf tissue increased significantly ($P \leq 0.05$) with increasing salinity levels but the relative leakage ratio (RLR) was only greater at 20 dS m^{-1} compared to other salinity levels. RLR and EL of cotton leaf decreased with aeration compared with the control, but not significantly so (Table 5.3.2.6).

Table 5.3.2.5 Boll properties, soil respiration, leaf water potentials and stem diameter of cotton in relation to salinity levels and aeration treatments in a heavy clay soil, 2003.

Factor	Level	Bolls (#)	Mean boll wt (g)	Soil respiration ($g\ CO_2\ m^{-2}\ h^{-1}$)	Carbon discrimination (Δ‰)			Leaf wt ratio	Osmolality of xylem sap (m mol kg^{-1})	LWP (-kPa)	Stem diameter (mm)
					Root	Stem	Leaf				
Salinity EC_e (dSm^{-1})	2	16.69	5.79	1.32	19.32	19.81	20.1	0.18	65.40	1580	10.67
	8	14.87	5.74	0.94	19.03	19.98	19.87	0.19	82.67	1710	10.43
	14	10.38	5.31	0.63	19.09	19.79	20.49	0.21	67.50	1846	9.13
	20	9.33	5.07	0.41	18.37	19.62	19.95	0.22	81.17	1868	9.05
	LSD 5% (14 df)	3.10	0.51	0.30	0.77[a]	n.s.	n.s.	n.s.	13.98	79.6	0.79
Aeration	Aeration	13.91	5.67	0.86	19.07	19.78	20.23	0.19	75.67	1703	10.15
	Control	11.72	5.29	0.79	18.84	19.81	19.97	0.21	72.25	1801	9.49
	LSD 5% (14 df)	2.19[a]	0.36	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	56.3	0.56
	SxA (LSD) P value	-	-	-	-	-	-	-	19.77 0.049	-	-

[a] $P \geq 0.05 \leq 0.1$

Table 5.3.2.6 Leaf membrane properties, relative water content, specific leaf area, gas exchange, crop water stress, and radiation use efficiency as affected by salinity levels and aeration treatments in a heavy clay soil, 2003.

Factor	Levels	Membrane leakage		RWC[3] (%)	SLA[4] ($cm^2\ g^{-1}$)	Leaf photosynthesis (μ mol $m^{-2}\ s^{-1}$)	Stomatal conductance (mol $m^{-2}\ s^{-1}$)	Transpiration rate (m mol $m^{-2}\ s^{-1}$)	RUE_i[5]	CWSI[6] (0-1 scale)	Leaf temperature (°C)
		RLR[1] (%)	EL[2] (%)								
Salinity EC_e (dS m^{-1})	2	7.2	15.3	79	175	14.36	0.11	3.52	10.18	0.24	30.61
	8	6.2	18.0	77	194	14.56	0.10	3.20	9.25	0.33	31.30
	14	10.3	21.8	80	184	14.81	0.10	3.13	10.47	0.33	30.98
	20	18.5	34.2	81	174	13.21	0.09	3.19	8.45	0.39	31.91
	LSD 5% (14 df)	7.94	5.42	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.095	0.68
Aeration	Aeration	9.5	21.2	80	186	15.03	0.11	3.21	9.92	0.28	30.84
	Control	11.6	23.4	78	177	13.40	0.10	3.31	9.25	0.36	31.56
	LSD 5% (14 df)	n.s.	n.s.	2.35	n.s.	1.33	n.s.	n.s.	n.s.	0.067	0.48

[1]Relative leakage ratio (%) of leaf membrane, [2] Electrolyte leakage ratio (%) of the leaf membrane, [3] Relative water content (%) of leaf tissue [4] Specific leaf area [5] RUEi was determined by (A/E) = Rate of net leaf photosynthesis/ rate of transpiration, [6] Crop water stress index in 0-1 scale.

5.3.2.9 Root properties

Root weight decreased significantly with increasing salinity. Aeration increased root weight of cotton. Root: shoot ratio was not greatly affected by salinity treatments but aeration reduced the ratio (Table 5.3.2.3). Taproot length due to salinity did not differ significantly. However, longer tap roots were noticed in the aerated treatment compared with the control (Table 5.3.2.3). Root diameter did not vary but the RLD increased with aeration and decreased with increase in the salinity levels. Soil respiration decreased significantly ($P \leq 0.05$) with increasing salinity levels and aeration increased soil respiration by 9% compared to the control treatment (Table 5.3.2.5).

5.3.2.10 Salt accumulation and partitioning

Sodium and chloride concentration in the leaf, stem and root tissues increased significantly ($P \leq 0.05$) with increase in salinity. However, effect of aeration was not significant for Na^+ and Cl^- concentration on the leaf, stem and root tissues in this experiment. Concentration of Ca^{2+} in the leaf, stem and root tissue did not differ significantly with salinity and aeration either. K^+ concentration, in the leaf and stem did not differ significantly due to salinity levels, however, K^+ decreased with aeration in both leaf and stem tissue. Root K^+ concentration though did not vary with respect to aeration but decreased significantly with increasing salinity levels. In the root tissue K^+:Na^+ ratio decreased significantly ($P \leq 0.05$) with increasing salinity levels and increased with aeration compared to the control.

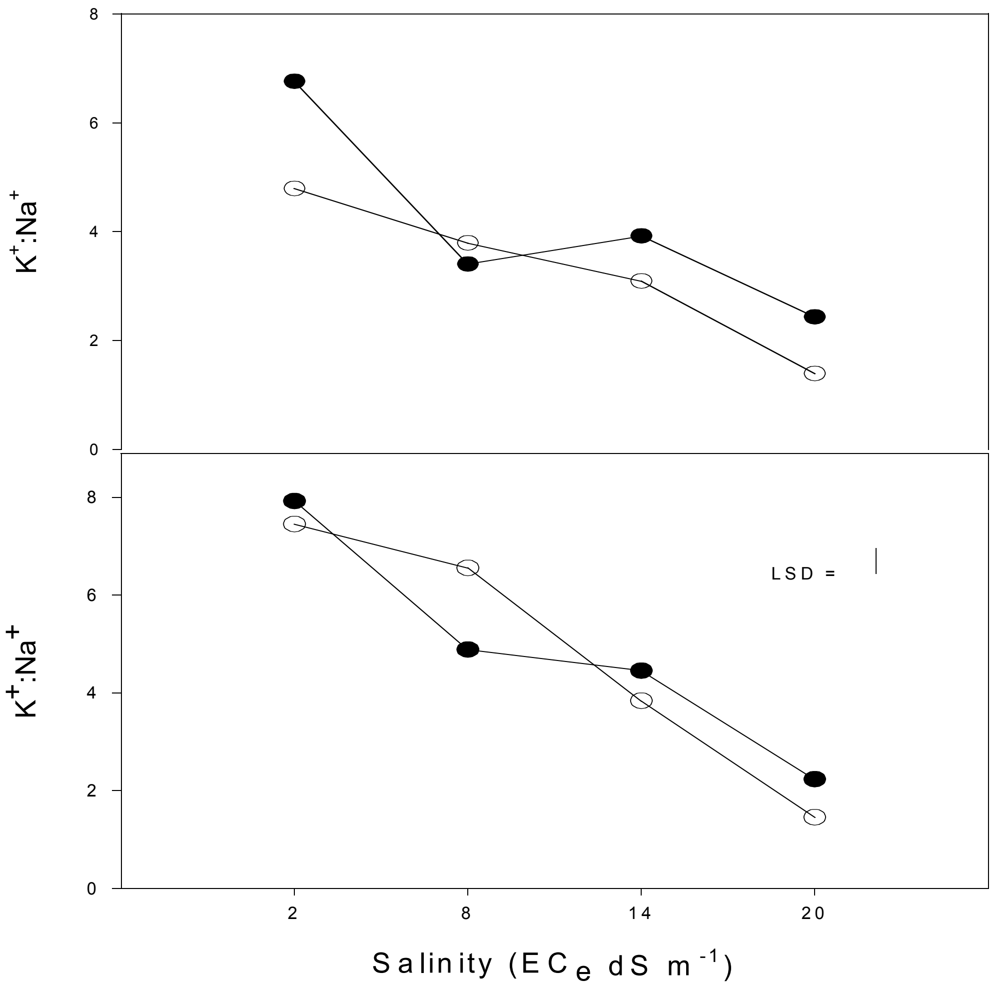

Figure 5.3.2.4 Potassium to sodium ratio in the leaf (bottom graph) and stem (top graph) tissue in a range of salinity levels with and without aeration in heavy clay soil.

In conclusion, lint yield of cotton decreased progressively with increase in soil salinity. Soil aeration increased yield across all salinity treatments, somewhat more so at higher salinity. Averaged over the salinity treatments, aeration increased cotton lint yield by 26 percent compared with the non-aerated treatment.

Table 5.3.2.7 Concentration of ions in leaf, stem and root tissues of cotton as affected by soil salinity and aeration in a heavy clay soil, 2003.

Factor	Level	Leaf salt concentration					Root salt concentration					Stem salt concentration				
		Na^+ (g 100g^{-1})	Cl^- (mg kg^{-1})	K^+ (g 100 g^{-1})	$K^+:Na^+$	Ca 2+	Na^+ (g 100g^{-1})	Cl^- (mg kg^{-1})	K^+ (g 100 g^{-1})	$K^+:Na^+$	Ca 2+	Na^+ (g 100g^{-1})	Cl^- (mg kg^{-1})	K^+ (g 100 g^{-1})	$K^+:Na^+$	Ca 2+
Salinity	2	0.181	2.20	1.32	7.68	3.94	0.210	0.43	1.01	5.11	0.33	0.228	0.65	1.21	5.77	0.72
EC_e (dS m^{-1})	6	0.240	2.48	1.31	5.71	3.17	0.355	0.55	0.76	2.22	0.38	0.332	0.84	1.04	3.59	0.65
	14	0.355	3.34	1.42	4.13	3.86	0.368	0.78	0.89	2.84	0.45	0.349	0.74	1.15	3.50	0.63
	20	0.774	4.36	1.31	1.83	3.40	0.479	0.89	0.64	1.48	0.47	0.610	1.27	1.08	1.90	0.74
	LSD	0.135	0.92	n.s.	1.85	0.68[1]	0.129	0.305	0.161	1.42	n. s.	0.129	0.43	n.s.	2.06	n.s.
Aeration	Aeration	0.398	3.02	1.31	4.82	3.54	0.339	0.72	0.83	2.96	0.43	0.396	0.813	1.04	3.26	0.65
	Control	0.377	3.18	1.37	4.86	3.65	0.367	0.60	0.82	2.87	0.40	0.363	0.950	1.21	4.12	0.72
	LSD	n.s.	n.s	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.11 0.00	n.s.	n.s.
	SxA LSD P value			0.22 0.04										0.22 0.03		

[1] $P \geq 0.0\ 5 \leq 0.1$

5.3.3 Soybean Experiment

5.3.3.1 Environmental parameters and applied water to the crop

The daily mean air temperature measured outside the screen house ranged from 11.7 to 23.2°C and there was a gradual decrease in temperature over the crop period. The relative humidity ranged from 40 to 80%. Solar radiation inside the screen house averaged 9.2 MJ m^{-2} d^{-1}, with a minimum of 2.6 to a maximum of 12.5 MJ $m^{-2}d^{-1}$. Season mean rhizosphere O_2 concentration decreased with increasing salinity treatment and increased with aeration compared with the control. In general, rhizosphere O_2 concentration was observed highest at night and lowest at midday. Season mean rhizospheric O_2 concentration measured from the 14 dS m^{-1} treatment showed that aeration maintained relatively higher O_2 concentration in the rhizosphere (mean = 5.95, range = 0.016 - 8.508 ppm) at 25.9 °C (range 21.4 – 32.6 °C) compared to the control (mean = 0.941, range = 0.003 – 2.601 ppm) at 30.6 °C (range = 19.8 – 24.4 °C).

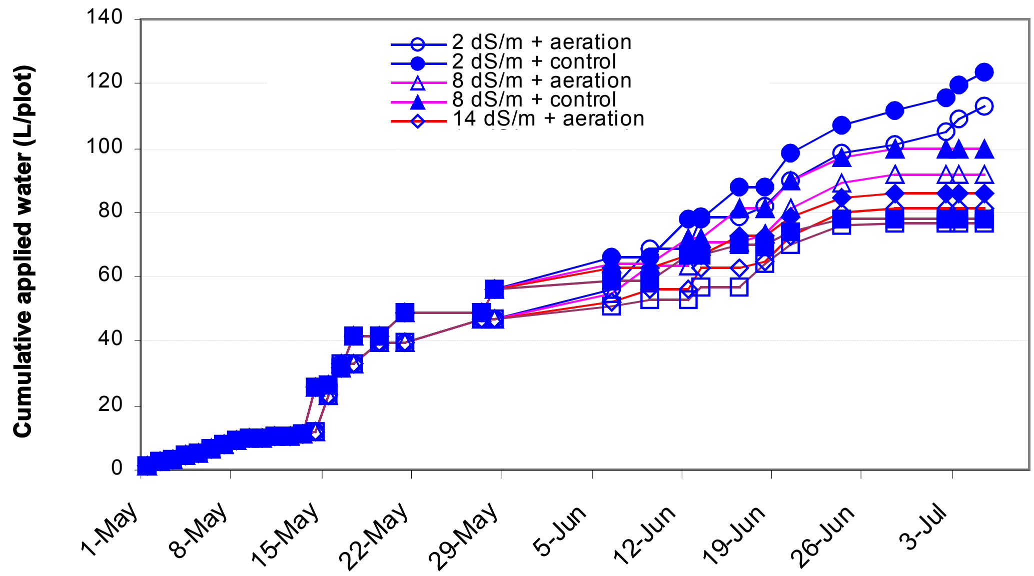

Figure 5.3.3.1 Cumulative water applied (litre) over the crop season for different salinity and aeration treatment combinations for vegetable soybean.

Data on water applied to the crop over the crop season for different treatments are presented in Figure 5.3.3.1 and showed that the quantity of water applied decreased with increasing salinity. Soil water content over the season varied between 35 to 50 mm H_2O per 100 mm soil in the experiment except towards the end of crop harvest (Figure 5.3.3.2). Pots at higher salinity, especially those non-aerated, recorded high soil moisture above field capacity and, therefore, remained saturated for most of the time.

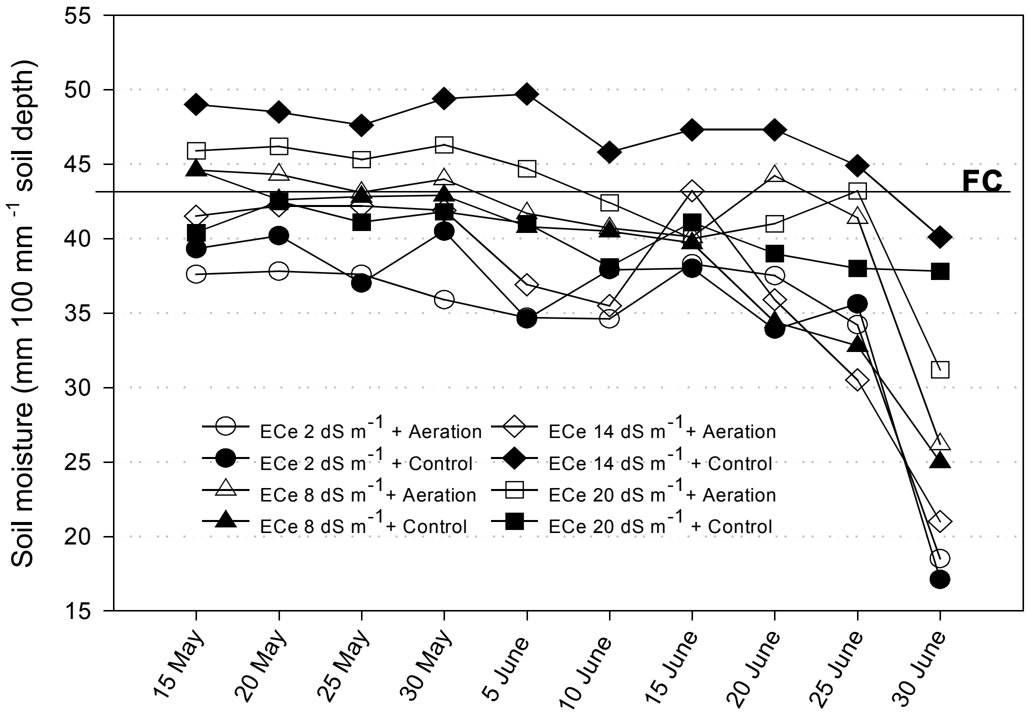

Figure 5.3.3.2 Changes on soil moisture over the crop season with respect to soil salinity and aeration for vegetable soybean in a heavy clay soil (the solid line indicates the field capacity (FC).

5.3.3.2 Plant growth characteristics

A significant effect of salinity and aeration was observed for plant height and stem diameter at harvest. They both decreased with increasing salinity while aeration significantly ($P \leq 0.05$) increased plant height (Table 5.3.3.1) and stem diameter (Table

5.3.3.2) compared with the control. The effect of aeration on stem diameter was greater at the higher salinity levels (Figure 5.3.3.3).

Table 5.3.3.1 Leaf and stem characteristics of vegetable soybean as affected by aeration and soil salinity in a heavy clay soil.

Factor	Level	Plant height (cm)	Nodes ($plant^{-1}$)	Leaves ($plant^{-1}$)	Leaf size (cm^2)	Leaf area (m^2 $plant^{-1}$)	Chlorophyll (SPAD units)	LI[1] (%)
Salinity	2	72.4	11.98	11.25	254.83	0.286	37.7	62.4
EC_e	8	62.9	11.30	10.33	250.99	0.253	37.9	60.2
(dS m^{-1})	14	53.3	10.35	8.25	213.20	0.177	38.3	55.6
	20	55.4	10.24	9.33	240.5	0.224	38.5	56.6
	LSD 5% (14 df)	7.12	0.78	n.s.	n.s.	0.055	n.s.	5.10
Aeration	Aeration	64.9	11.08	9.83	247.41	0.244	38.1	60.0
	Control	60.1	10.86	9.75	232.38	0.226	38.2	57.4
	LSD 5% (14 df)	5.05[a] 0.06	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

[1] Light interception (%) by the canopy, [a] $P \geq 0.05 \leq 0.1$

Likewise, the number of nodes, the number of leaves and total leaf area per plant decreased significantly ($P \leq 0.05$) with increasing salinity, however, the effect of aeration on these parameters was not significant (Table 5.3.3.1). Likewise, total leaf area and unit leaf area did not significantly differ between aeration and control, although greater leaf size and total leaf area per plant was evident for the aerated treatment (Table 5.3.3.1). The canopy light interception averaged over the crop duration was significantly less ($P \leq 0.05$) as salinity increased, and increased, but not significantly so, with aeration compared with the control (Table 5.3.3.1).

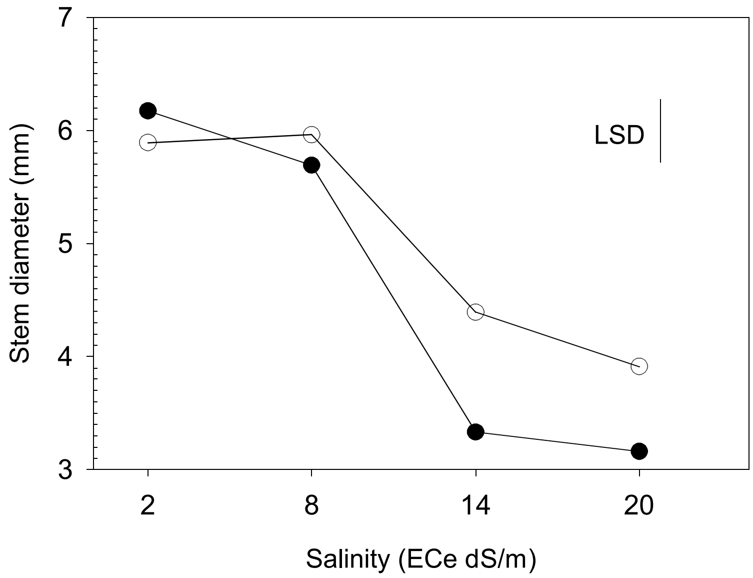

Figure 5.3.3.3 Change in stem diameter of vegetable soybean with respect to salinity levels with (open circle) and without aeration (closed circle) in a heavy clay soil.

5.3.3.3 Leaf characteristics

Aeration significantly reduced SLA compared to the control and in general SLA was lowest at 8 dS m^{-1} compared to lower and higher salinities (Table 5.3.3.3).

Table 5.3.3.2 Dry matter accumulation and partitioning for vegetable soybean as affected by aeration and soil salinity in a heavy clay soil.

Factor	Levels	Dry weight[1] (g $plant^{-1}$)					Root: shoot ratio	Stem diameter (mm)	Soil respiration (g CO_2 m^{-2} h^{-1})
		Root	Stem	Leaf	AGDB[2]	Total biomass			
Salinity EC_e ($dS\ m^{-1}$)	2	0.97	6.53	8.48	15.01	15.99	0.065	6.03	0.99
	8	0.90	5.85	8.15	14.00	14.90	0.065	5.83	0.57
	14	0.75	5.34	7.11	10.97	11.72	0.069	5.34	0.66
	20	0.71	5.23	6.71	10.24	10.96	0.070	5.23	0.54
	LSD 5% (14 df)	0.17	0.82	1.32	1.80	2.06	n.s.	0.38	0.30
Aeration	Aeration	0.86	5.33	7.98	13.31	14.71	0.065	5.76	0.76
	Control	0.81	4.56	7.24	11.80	12.61	0.070	5.46	0.61
	LSD 5% (14 df)	n.s.	0.58	n.s.	1.39	1.46	n.s.	0.28	n.s.

[1] The crop was harvested once over at 67 days after seeding without growing for the full season, [2] AGDB = above-ground dry biomass

5.3.3.4 Yield and dry matter partitioning

The root, stem, leaf, above ground, and total biomass decreased significantly ($P \leq 0.05$) with increasing salinity. Aeration increased root, stem, leaf, above ground, and total biomass of vegetable soybean compared to the non-aerated control. Although the root: shoot ratio showed an increasing trend with increasing salinity, the difference between the treatments was too small to be significant (Table 5.3.3.2).

Table 5.3.3.3 Leaf electrolyte leakage (EL), relative water content (RWC), specific leaf area (SLA) and gas exchange properties, and crop water stress index (CWSI) for vegetable soybean as affected by aeration and soil salinity in a heavy clay soil.

Factor	Levels	EL (%)	RWC (%)	SLA (cm^2 g^{-1})	Leaf photosynthesis (μ mol m^{-2} s^{-1})	SC (mol m^{-2} s^{-1})	Transpiration rate (m mol m^{-2} s^{-1})	CWSI (0-1 scale)	Leaf temperature (°C)
Salinity EC_e (dS m^{-1})	2	18.7	74.3	255.2	13.21	0.155	2.86	0.250	30.8
	8	30.4	71.2	209.7	14.08	0.148	2.69	0.370	31.7
	14	44.1	75.1	271.1	11.95	0.143	2.57	0.358	31.1
	20	67.1	72.2	251.5	11.32	0.156	2.75	0.365	31.6
	LSD 5% (14 df)	19.13	n.s.	41.86	0.67	n.s.	n.s.	n.s.	n.s.
Aeration	Aeration	44.7	69.7	231.2	12.77	0.155	2.76	0.323	31.2
	Control	35.4	76.7	262.6	12.51	0.146	2.69	0.349	31.3
	LSD 5% (14 df)	n.s.	7.54[a]	29.59	n.s.	n.s.	n.s.	n.s.	n.s.

[a] P ≥ 0.05 ≤ 0.1

5.3.3.5 Membrane properties of the leaf tissues

Leaf disc electrolyte leakage (EL) increased significantly ($P \leq 0.05$) with increasing salinity (Table 5.3.3.3). The aerated treatment reduced EL compared with the control by 21 percent, but this difference was not statistically significant. The relative water content in the leaf tissue did not vary significantly with respect to salinity, however, RWC increased with aeration compared to that of the control (Table 5.3.3.3).

5.3.3.6 Leaf gas exchange properties, and leaf temperature

The net leaf photosynthesis was significantly ($P \leq 0.05$) higher at ECe 8 dS m^{-1} followed by the control (2 dS m^{-1}) and then decreased significantly with further increase in salinity. The positive effect of aeration on leaf net photosynthesis was only evident at 8 dS m^{-1} (14.71 vs. 13.44 µmol CO_2 m^{-2} s^{-1}, LSD (14df) = 0.95). The effects of salinity or aeration were not significant for transpiration rate, stomatal conductance, crop water stress index or leaf temperature (Table 5.3.3.3). Soil respiration increased with aeration compared to the control, and decreased significantly ($P \leq 0.05$) with increasing salinity (Table 5.3.3.2).

Table 5.3.3.4 Applied water, water use efficiency (WUE_i-instantaneous and WUE_{sl}-season long) and accumulated sap flow (for a five day period) of vegetable soybean as affected by aeration and soil salinity treatments in a heavy clay soil.

Factor	Levels	Applied water (L $plant^{-1}$)	Accumulated flow (g $plant^{-1}$)	WUE_i	WUE_{sl}
Salinity EC_e (dS m^{-1})	2	4.92	559.6	4.803	3.25
	8	3.99	479.1	5.621	3.75
	14	3.48	359.0	5.027	3.39
	20	3.22	318.5	4.568	3.47
	LSD 5% (14 df)	0.23	No replication	n.s.	n.s.
Aeration	Aeration	3.77	492.1	4.908	3.81
	Control	4.04	366.0	5.102	3.12
	LSD 5% (14 df)	0.16	No replication	n.s.	0.47[a]

[a] $P \geq 0.05 \leq 0.1$

5.3.3.7 Plant water relation, water use and water use efficiency

The leaf relative water content did not differ significantly with respect to salinity or aeration treatments (Table 5.3.3.3). Water use declined significantly in response to increased salinity. WUE estimated as WUE_i did not vary significantly in response to salinity or aeration treatments (Table 5.3.3.4). A significant ($P \leq 0.08$) effect of aeration, however, was revealed for biomass WUE_{sl} such that aeration increased WUE of biomass compared to the control, but the WUE_{sl} did not differ in response to salinity treatments (Table 5.3.3.4). Quantification of plant transpiration rate by sap flow system showed that aerated plants achieved higher rates compared with the control (Figure 5.3.3.5) especially at 8 and 14 dS m^{-1}(5.3.3.4).

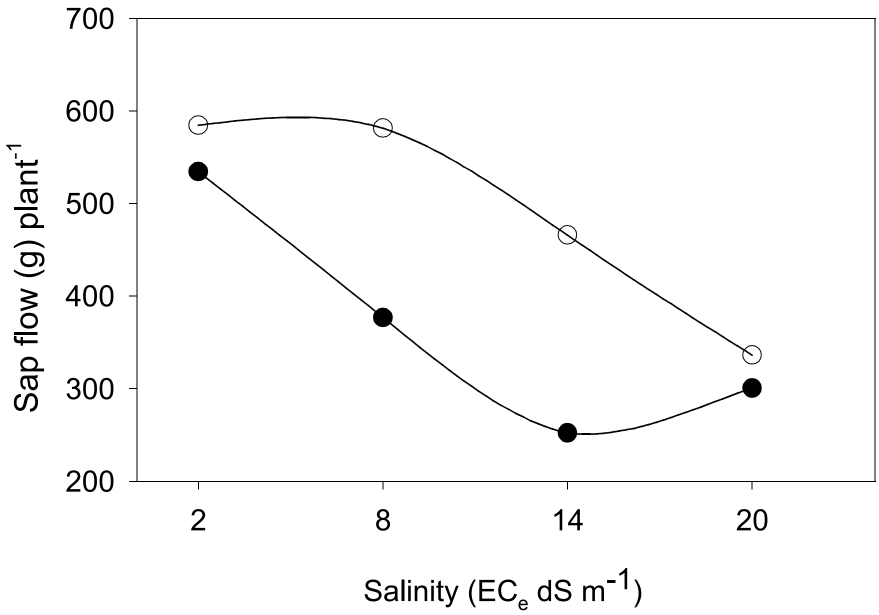

Figure 5.3.3.4 Cumulative sap flow over a five day period for vegetable soybean in different salinity levels with (open circles) and without aeration (closed circles) in a heavy clay soil.

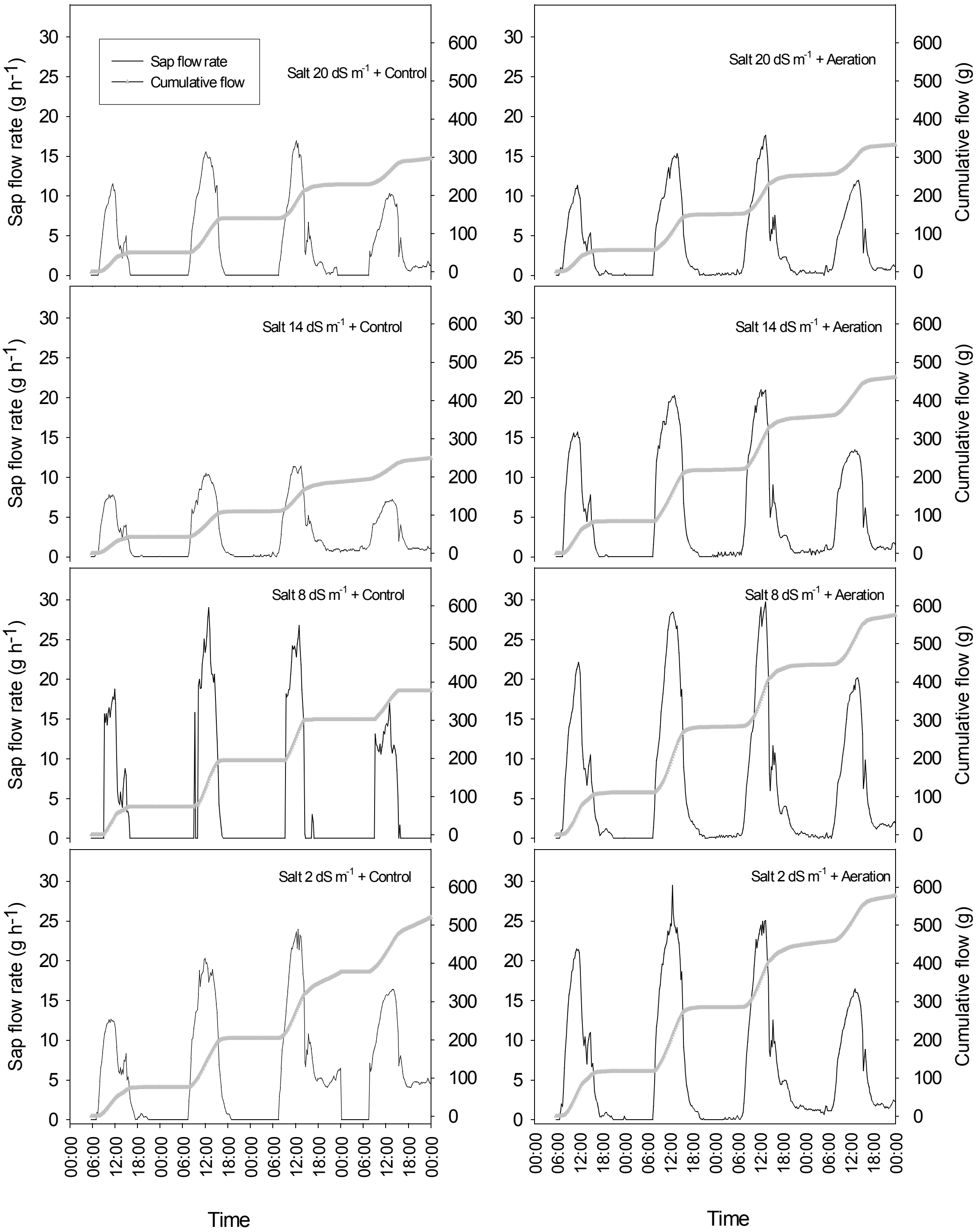

Figure 5.3.3.5 Stem sap flow of vegetable soybean measured over five days, showing the sap flow rate (thin lines) and accumulated flow (thick grey lines) over four soil salinity levels without (left) and with aeration (right) in heavy clay soil.

5.3.3.8 Leaf salt analysis

Both the aeration and salinity affected leaf, stem and root tissue concentrations of Na^+, Cl^-, Ca^{2+} and K^+ concentration and the K^+: Na^+ ratio (Table 5.3.3.5). Leaf Na^+ decreased with aeration compared with the control irrespective of salinity levels. The leaf Na^+ was higher for the highest level of salinity treatment compared to the lower salinity treatments. The aeration showed lower leaf tissue Na^+ concentrations by 25% compared with the control (Table 5.3.3.5). Similarly, tissue Cl^- increased markedly with increasing salinity and the highest was recorded at 20 dS m^{-1}. Concentration of Cl^- was lower in the aerated treatment at all salinity levels. Significantly higher Ca^{2+} leaf tissue concentrations were evident with increased salinity. The effect of aeration on Ca^{2+} was also evident such that higher Ca^{2+} was recorded in the control compared to the aeration (Table 5.3.3.5). Although differences in K^+ concentrations in leaf tissue were not significant, higher K^+ was recorded in aerated compared to control. The K^+:Na^+ ratio was greater at 6 dS m^{-1} compared to 2 dS m^{-1} and then decreased progressively with increase in salinity. Leaf tissue K^+ of the aerated plants were 22% higher compared with the control and, and increasing salinity reduced the K^+ in the leaf.

The Na^+ in the leaf tissues was found on average to be only 2.54% that of the Na^+ of the root tissues. Root Na^+ increased with increase in salinity. Concentration of Cl^- was lower in root than leaf tissue. Likewise Ca^{2+} in the root was significantly lower compared to that in the leaf. Its concentration increased slightly with increasing salt levels but difference due to aeration was negligible. Unlike leaves, the K^+:Na^+ ratio was very low in root tissues, and it showed a decreasing pattern with increasing salinity. However, there was no difference due to aeration. The pattern of salt concentrations in the stem was similar to that of leaf samples, but the concentrations were a little higher for Na^+ and K^+, and lower for Cl^-, Ca^{2+}, and the K^+: Na^+ ratio (Table 5.3.3.5).

Table 5.3.3.5 Ion concentrations and ratios as affected by soil salinity and aeration for tomato in a heavy clay soil

Factor	Level	Leaf salt concentration and ratios					Root salt concentration and ratios					Stem salt concentration and ratios				
		Na^+ (%)	Cl^- (mg kg^{-1})	K^+ (%)	K^+:Na^+	Ca^{2+} (%)	Na^+ (%)	Cl^- (mg kg^{-1})	K^+ (%)	K^+:Na^+	Ca^{2+} (%)	Na^+ (%)	Cl^- (mg kg^{-1})	K^+ (%)	K^+:Na^+	Ca^{2+} (%)
Salinity EC_e (dS m^{-1})	2	0.018	1.19	1.46	85.6	2.44	0.401	0.695	0.928	2.32	0.32	0.023	0.719	1.93	84.0	1.12
	8	0.012	1.99	1.42	118.4	2.51	0.629	1.075	0.717	1.14	0.33	020	1.424	2.34	124.0	1.63
	14	0.015	3.39	1.43	98.5	2.70	0.874	1.393	0.570	0.65	0.36	0.099	2.587	1.92	25.9	1.59
	20	0.025	3.67	1.40	60.5	2.72	0.912	1.468	0.509	0.56	0.41	0.154	3.060	2.22	30.0	1.89
	SD (n=8)	0.006	1.19	0.08	26.03	0.16	0.222	0.329	0.173	0.752	0.041	0.089	1.067	0.277	48.44	0.324
Aeration	Aeration	0.015	2.25	1.45	99.8	2.49	0.694	1.134	0.687	1.16	0.35	0.033	1.675	2.13	80.9	1.51
	Control	0.020	2.88	1.39	81.7	2.69	0.714	1.184	0.675	1.18	0.36	0.115	2.220	2.07	51.1	1.62
	SD (n=8)	0.006	1.19	0.08	26.03	0.16	0.222	0.329	0.173	0.752	0.041	0.08	1.067	0.277	48.44	0.324

5.4 DISCUSSION

The results of the current experiments indicated that aeration of the rhizosphere provides significant benefits across all levels of salinity trialled for tomato, cotton and vegetable soybean. Plant growth measured as height decreased consistently with increasing salinity but increased with aeration in all species. Plant height was significantly correlated with biomass for tomato (r = 0.673***, n = 45), cotton (0.869***, n = 24) and soybean (r = 0.733***, n = 24). The leaf properties of number, size and area responded positively to aeration for tomato and cotton but not for vegetable soybean. However, soybean leaf weight per plant increased significantly with aeration.

Significant correlations between biomass yield and leaf weight, on tomato (r = 0.863*** n = 45), soybean (r = 0.937***, n = 24) and leaf number for cotton (r = 0.812***, n = 24) were also observed. Leaf growth and development are sensitive to salinity (Lopez *et al*., 2002) and lack of O_2 induced by waterlogging in the rhizosphere (Barrett-Lennard, 2003). Such positive effects on leaf growth due to aeration at higher salinity levels is indicative that O_2 in the rhizosphere was deficient in the control (mean O_2 concentration 5.95 vs. 0.941 mg L^{-1} in 14 dS m-^{1} treatment with and without aeration respectively) that limited root respiration in the heavy clay soil under saline conditions. Reduction of leaf area and dry weight in tomato at higher salinity was also observed by Rudich and Luchinsky (1986) to be not due to a reduction in number of leaves but due to reduction of leaf size, corresponding to a greater SLA. However, in this thesis research increasing salinity reduced leaf area, number, and size in tomato, although the effect on leaf size for cotton and soybean was not significant. In contrary the salinity effect on SLA was not significant on tomato and cotton, however, SLA decreased significantly with 8 dS m^{-1} significant in tomato and cotton, although SLA decreased at 8 dS m^{-1} compared to other salinity levels in soybean. This stimulatory effect of salinity at 8 dS m^{-1} particularly in the soybean needs further research attention.

Leaf growth is very sensitive to salinity, and the response is instantaneous. Reduced leaf growth in saline soil is due to a reduction in cell turgidity or cell wall rheological properties, caused by a decrease in the leaf water potential (Munns, 2002)**.** Higher leaf water potential observed with the aeration treatment suggests that aeration could have a marked effect in maintaining positive plant water relations in saline soil, and contribute towards leaf growth and development.

The tomato plants in the experiment were pruned to a single stem and the leaf area index for the crop was kept low compared to non-pruned plants. Aeration consistently increased canopy light interception in vegetable soybean and cotton where leaf area was not manipulated manually. A positive correlation between yield and season-long canopy light interception was recorded in both soybean (r = 0.642**, n = 24) and cotton (r = 0.793**, n = 24). The reduction in leaf area and dry weight brought about by salinity and low O_2 resulted in low fruit yield as leaf dry weight is related to fruit yield in many crops (Sainju and Singh, 1997).

The stem was found to be very sensitive to salinity and hypoxia irrespective of the species. In the three species, stem diameter invariably decreased with increasing salinity and increased with aeration. A significant and positive correlation between the biomass yield and stem diameter were also noted for vegetable soybean (r = 0.854***, n = 24), and lint yield and stem diameter for cotton (r = 0.85***, n = 24). A significant liner relationship (r^2 = 0.9478**, n = 8) between stem diameter and biomass at harvest in soybean (Figure 5.4.1) suggests that stem diameter could be a surrogate of plant response to O_2 concentration in the root zone of the crop. The results of Tang and

Kozlowski (1982) who showed that the rate of diameter growth is reduced by prolonged flooding in most flood-intolerant species are in agreement with this finding.

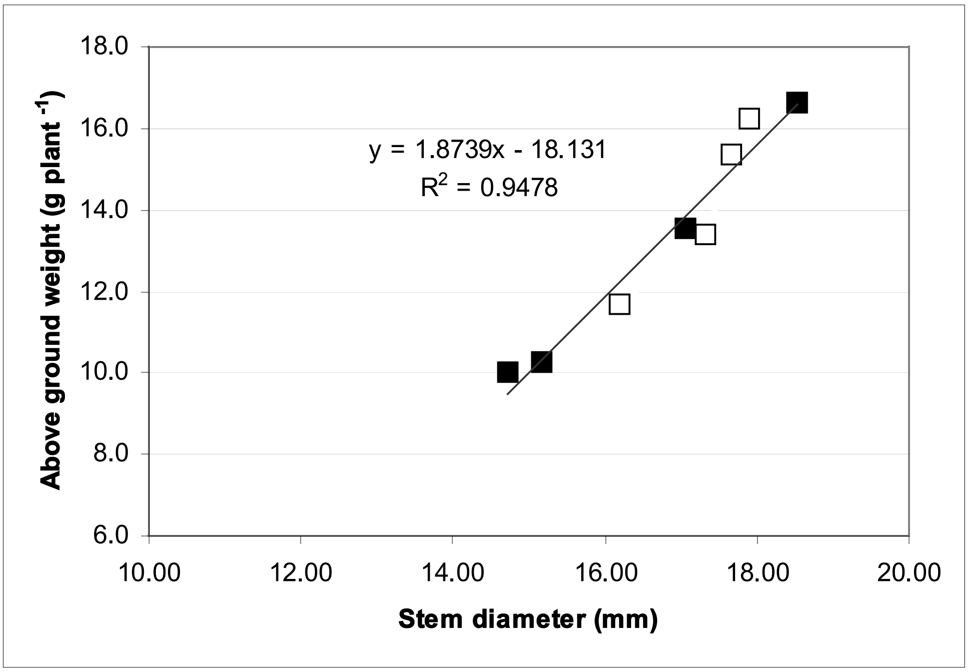

Figure 5.4.1 Relationship between stem diameter and biomass over a range of salinity levels with aeration (□ open square box symbols) and without aeration (■ filled square box symbols) in vegetable soybean.

Aeration and salinity were found to markedly affect the reproductive performance of tomato. Flowering was delayed significantly by higher salinity, but the delay by aeration was not significant (Table 5.3.1.3). More fruits were harvested in less saline treatments. Sharaf and Hobson (1986) reported an enhanced earliness due to the shorter time period required from ovule fertilization to fruit ripening in saline compared with non-salinized conditions. So it appears that salinity delayed maturity by later flowering, but the post flowering effect of salinity is to hasten the maturity of fruits. Villa-Castorena *et al.* (2003) also observed decreased plant relative growth (RGR) rate up to the pod formation stage and thereafter, maximum RGR in Chile pepper. Greater fruit yield in the less saline treatments was more dependent on the size of the fruit rather than the number of flowers and fruit set *per se*. Pollen fertility of salt-treated tomato plants has been found to be similar to that of the control (Adams and Ho, 1992). The implication from the work of Johnson *et al*. (1992) is that such reductions in fruit size were related to lowered water potential that constrained the rate of fruit expansion. The reduction in fruit size due to salinity is variety specific. In general, the larger the fruit size, the more important is its reduction in size by salinity (Cruz *et al*., 1990). The variety used in these experiments has a large fruit and, therefore, the reduction in fruit size in response to salinity and lack of O_2 was likewise large.

Although the effect of aeration and salinity on cotton maturity was not prominent, the effect of salinity on cotton reproductive performance in terms of number of fruiting forms was profound. Number and size of bolls were reduced with salinity and increased with aeration. Reduction of boll size and number in saline and waterlogged soil is common for many cotton varieties as reported by Flowers (2004). Soybean was harvested at 67 das, i.e., before pod formation; hence the reproductive performance with respect to aeration could not be assessed for this species.

In general biomass reduction due to salinity in tomato was 54% as salinity increased from 2-10 dS m^{-1}, and 32% and 53% for soybean and cotton respectively as salinity increased from 2-20 dS m^{-1}. Aeration on the other hand, increased biomass yield by 33%, 21.4% and 12.8% for tomato, soybean and cotton, respectively, suggesting a more notable aeration response in sensitive compared to moderately tolerant and tolerant species (Figure 5.4.2).

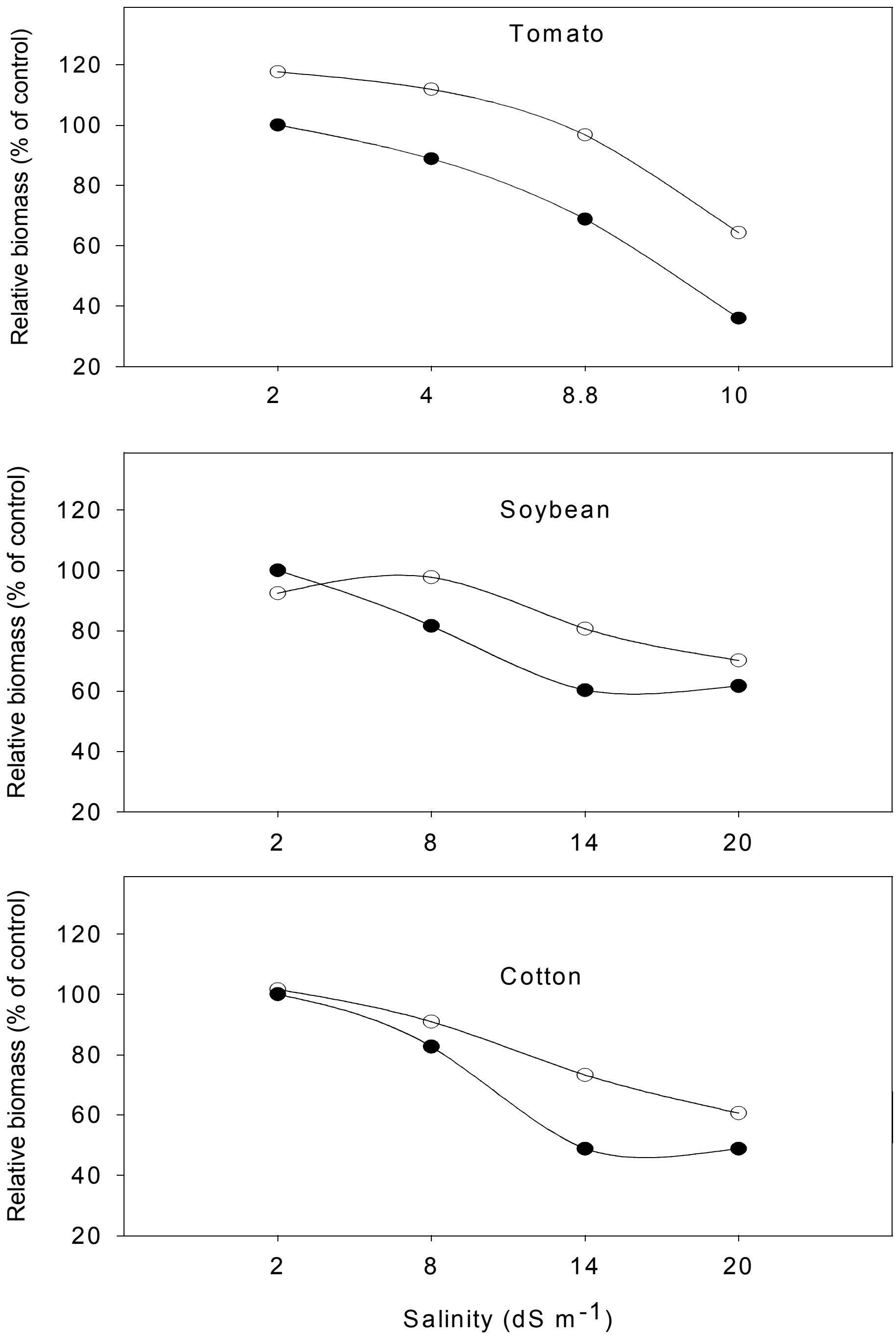

Figure 5.4.2 Relative biomass yield as % of control treatment (2 dS m^{-1} without aeration) at different salinity levels with (open circle) and without aeration (closed circle) for sensitive (tomato), moderately tolerant (vegetable soybean) and tolerant (cotton) crop species.

The rate of photosynthesis is generally reduced under salt stress (Cuartero and Fernadez-Munoz, 1990), as was observed in soybean but photosynthesis in tomato and cotton did not vary with salinity or aeration. In tomato, growth declined more rapidly and at lower concentration of Na^+ in the leaf than did photosynthesis Yeo and Flowers (1989) in Alarcon *et al*. (1994) and growth declines more than photosynthesis in long-term studies (Seemann and Critchley, 1985), and tomato is sink, rather than source limited with respect to carbon assimilation (Hocking and Steer, 1994). Taken together, this implies that the tomato can withstand a certain loss in photosynthetic rate with little effect on growth and fruiting. The lack of significant response for photosynthesis caused by salinity and reduced aeration in the current trials is in agreement with the earlier findings. The higher yield for the aerated and low salinity treatments may have been possible without an increase in the leaf photosynthesis simply by maintaining a higher leaf area under lower salinity and aeration treatments.

Salinity and reduced aeration showed profound effects on the total and component biomass of all species. In spite of greater concentration of salt on the roots, root growth appeared to be less affected by salt than shoot growth and so the root/shoot dry weight ratio was greater at greater salinity. The rise in the root/shoot dry weight ratio for the three species under salt stress must be accompanied by changes in the allocation of assimilates between root and shoot. Although increased salinity resulted in a decrease in HI, aeration increased HI for tomato and cotton (Tables 5.3.1.4 and 5.3.2.3). Perez-Alfocea *et al.* (1996) showed that in salt-treated plants there was a greater proportion of assimilate directed to the root compared to assimilate to the shoot than in control plants. Root diameter increased as a response to increasing salinity and to aeration in all three species. Earlier work by Kafkafi and Brenstein (1996) is in agreement with these findings.

Generally there is a strong inverse linear relationship between salinity and plant water use (Pessarakli and Tucker, 1988) and a linear relationship between aeration and plant water use (Bhattarai and Midmore, 2004; Bhattarai *et al*., 2005b)**.** No significant differences were recorded for instantaneous transpiration rate, stomatal conductance and WUE_i with respect to salinity and aeration in the tested species, except for cotton where aeration increased WUE_i and stomatal conductance. However, plants grown on heavy clay soil recorded decreased water use with increasing salinity (all species) and aeration resulted in an increased water use in tomato and cotton but not in soybean. As the stomatal conductance and leaf transpiration rate did not differ significantly, it is possible that the higher stem sap flow rate with aeration was related to greater leaf area per plant in tomato.

Similarly, an association between higher leaf area and plant water use was also observed in cotton across salinity and aeration treatment. In soybean, a small decrease in water use with aeration compared to the control, especially at lower salinity levels (2 and 8 dS m^{-1}) yet with a higher dry weight with less water (Figure 5.4.3) is an interesting observation, which needs further study. Plants with their root system in a medium with heterogeneous salt concentration, such as occurs in the field, preferentially develop more roots and absorb more water in the less saline part of the medium (McCully, 1999). However, in these pot experiments soil salt distribution was uniform. Pessarakli and Tucker (1988) suggested decreased root permeability in cotton and bean, and Rodriguez *et al.* (1997) suggested reduced root hydraulic conductance as being responsible for reduction in uptake of water in saline environment.

The high sap flow in the aeration treatments under saline environments may be conditioned by an increase in the root hydraulic conductance. However, the aeration effect on moderating the root hydraulic conductivity in saline soil is not well understood. The WUE_{sl} in these experiments showed that WUE declined with increasing salinity and increased with aeration. Farquhar *et al.* (1989) suggested carbon discrimination as a surrogate of season long WUE in many crops, and it has been utilized in a breeding program (Richards *et al*., 2002) for the selection of water use efficient germplasm. A number of studies reported that carbon isotope discrimination decreases with increase in salinity (Poss *et al*., 2000; Vaughan *et al*., 2002 and Kutuk *et al*., 2004). The trials on tomato leaf and cotton root samples (not the leaf and stem) analysed for the carbon discrimination were in agreement with those earlier findings. Aeration effects on Δ‰ under saline soil environments are not previously reported, and also noted not significantly different in these trials. Further study to establish the relationship between WUE_{sl} and Δ‰ for oxygenated saline soil would provide insight to determine the efficacy of oxygation towards improving water use efficiency in saline soils for different crops.

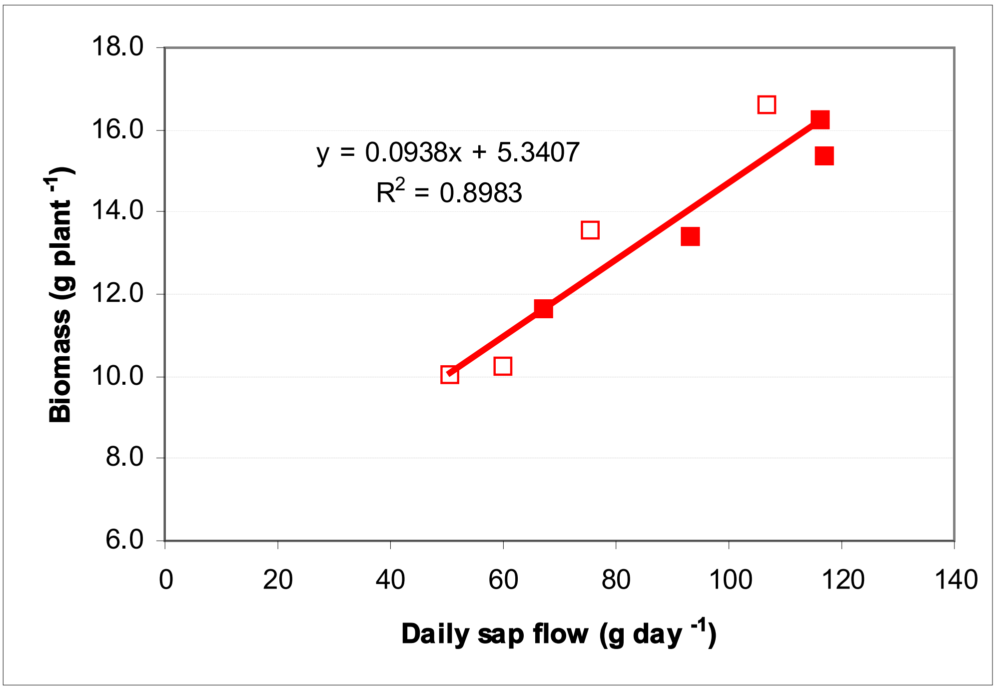

Figure 5.4.3 Relationship between daily transpiration and biomass yield of vegetable soybean in saline soil with (□) and without (■) aeration treatments.

In general Na^+ increased and Ca^{2+} and K^+ decreased slightly with increasing salinity in all three species. Leaf tissues of tomato, soybean and cotton accumulated more Na^+ with increase in salinity and less Na^+ in response to aeration (except for cotton) compared to the control. Letey (1961) reported a decrease in Na^+ uptake with aeration of the rhizosphere. Accumulation of Na^+ salt in the leaves is species-specific (Storey and Walker, 1987), however, most of the glycophytes maintain a low concentration of sodium in the leaves and excrete this element on the leaf surface (Rudich and Luchinsky, 1986). Moreover, there is an inhibition of Na^+ transport to the leaves, which results in a gradient of Na^+ concentration from roots to leaves. The accumulation of Na^+ in the leaves occurs at the expenses of K^+, Ca^{2+} and Mg^{++}. The ratio between the ion content of leaves under saline conditions and the corresponding values in the control plant is referred to as ion regulation index. The ion regulation index in term of K^+: Na^+, Ca^{2+}: Na^+ and Mg^{++}: Na^+ decreased with increasing salinity and increased with aeration compared with the control (Tables 5.3.1.6, 5.3.2.7). Rengel (1992) also used these ratios as the indicator of the salt stress in tomato and reported that these ratios are better indicators than the Na^+ concentration alone for the leaf tissue samples to determine the salt tolerance in plant. These data on ion regulation, as reflected by the higher K^+: Na^+ ratio, suggest that aeration improves plant tolerance to salinity in saline environments.

The ability of the plant to regulate shoot ion composition relies, in part, on selective uptake and transport processes in the root. Cell membranes are the major sites for controlling active solute flux (Kafkafi and Bernstein, 1996). Salinity and hypoxia cause a decrease in root membrane fluidity, which is extremely important for the control of selective plant uptake of ions. The efficiency of ion regulation by the plant root has a direct effect on the root and leaf membrane. The results with tomato indicate that with aeration, the root membrane became less damaged at higher salinities, conferring greater regulation of salts. Reduced electrolyte leakage and relative leakage ratio, measures of the membrane integrity in leaves, showed that aeration decreased and salinity increased leakage ratio (Tables 5.3.1.6, 5.3.2.6, 5.3.3.3).

In summary, aeration under saline soil environments particularly influenced growth, development and reproductive performance of the three species (sensitive, moderately tolerant and tolerant) in a heavy clay soil. An increase in the leaf biomass and greater light interception for cotton and soybean, and increases in fruit number and size (for tomato) were observed due to aeration which all contributed toward greater yield. In general aeration effects in saline heavy clay soil were mediated through greater root activity, as observed by general increase in root weight, root length density, and an enhanced soil respiration. Improved root metabolic activities and respiration in response to aeration drove greater uptake of water as observed by a significant increase in the sap flow rate and accumulated flow due to aeration. The increased transpiration was supported by wider conducting tissue (Plate 5.3.1- size of conducting tissue increased from 100 µm to 150 µm with aeration at 8.8 dS m^{-1}) and an increase in the stem diameter. The increased sap flow to leaves contributed to a less negative LWP, decreased CWSI, and maintained leaf turgor, facilitated leaf growth, and contributed to canopy and therefore, greater light interception. Enhanced membrane permeability conferred by aeration contributed towards greater exclusion of salts. Therefore, less salts entered leaves in spite of increased sap flow and water use by the plants, because the leaf membranes were more selective and less leaky as showed by lower RLR in the aerated treatment.

Reduced Na^+ content in the leaf samples and increased ion regulation index were evident in the aerated treatments compared with the control, showing that greater tolerance was conferred by aeration treatments in saline soil and tolerance to hypoxia was conferred in the saline soils. Increasing salinity and hypoxia reduced water uptake by plants as measured by sap flow. Improved root permeability (expressed as hydraulic conductance of the root system) could be an explanation for the increased water uptake with aeration. Although the permeability of the tomato roots seems to be constant during short periods of salinization (Clarkson, *et al*. 2000), a strong correlation between root hydraulic conductance was observed with long exposure in high NaCl concentration (Rodriguez *et al.,* 1997)**.** Further studies are required to determine whether the increase in water flow through the root system is due to changes in the water potential gradient across the root system, to changes in hydraulic conductance produced by modifications of the root structure, or to both reasons.

5.5 CONCLUSION

Reduced aeration due to salinity and sodicity of clay soil has serious consequences for plant production. Plant uptake of sodium from the soil increases significantly when O_2 deficiency occurs in the rhizosphere. Oxygation can provide supplementary O_2 to the active root mass of SDI crops and, therefore, improve plant performance in saline heavy clay soils. Aeration in saline soil stimulated plant growth mediated through enhanced root functioning, and greater water uptake but minimized salt ingress. Crop yield increased significantly irrespective of the species, though the effect was greater in sensitive (tomato 33% increase), followed by moderately tolerant (soybean 21%) and tolerant (cotton 13%) species. In general, the crop performance declined with increase in salinity, but in soybean increasing salinity from 2 to 8 dS m^{-1} with aeration augmented root activities, sap flow and greater biomass accumulation. The behaviour of salts in terms of the movement and uptake by plants will be different in the field soils compared to that of the pot soils. The lateral and vertical movement of salt in the pot soil are greatly impeded as opposed to the field conditions where a dynamic salt movement occurs in response to change in water table, soil moisture, and greater root spread. These preliminary results from glasshouse environments appear to be very promising in terms of benefit in crop yield and biomass. Therefore, field scale verification of oxygation for commercial application to harness the productive use of saline water and saline soil is recommended. Further experiments and rigorous controlled environment studies are also warranted to elucidate the mechanisms for oxygation benefits.

6
General Conclusions and Future Research

Furrow irrigation, the conventional method for cotton, incurs significant loss of irrigation water and, therefore, has very poor irrigation efficiency. SDI could potentially be utilized for cotton irrigation on heavy clay soils, and help make best use of scarce irrigation water. The paucity of information on the performance of cotton, and on soil water movement and water balances on heavy clay soils, in relation to SDI application rates, prompted the current research on heavy clay soil with cotton. The results of the two-year field experiments comprising various SDI irrigation application rates, in comparison to conventional furrow, highlight the opportunities for the use of SDI on heavy clay for cotton production. This was underpinned by a significant improvement in the irrigation efficiency and reduction in the environmental hazards such as runoff and deep drainage associated with furrow irrigation.

It is clear that SDI should be of interest to growers of cotton on heavy soils as an alternative to furrow irrigation. Through precise manipulation of the irrigation rates with SDI, it would be possible to manipulate crop maturity and temporal and spatial soil water content in the soil profile. The data suggest that SDI cotton on heavy clay soil can adapt to less than traditionally believed optimal levels of irrigation without severe loss of lint yield. A 25% reduction of computed crop water requirements based on ETc and delivered by SDI produced as much lint yield as did crops supplied with full crop evapo-transpiration requirements. A 75% supply of the daily ETc with SDI was more efficient than higher rates in terms of maintaining a high yield, a favourable control of the balance between vegetative and reproductive growth and improving the efficiency of water use by the crop. Reducing the level of irrigation to 50% ETc significantly enhanced crop earliness, and resulted in reductions in water, fertiliser and pesticide applications to the crop. These all have significant bearing when planning crop rotation, weed control and disease management. It also widened the window for integration of a winter crop in cotton-based cropping systems.

Controlling the subsurface and surface water content to reduce deep drainage and runoff loss was also effective by reducing the rate of irrigation supplied to the cotton crop with SDI to 75% ETc. Higher irrigation rates in SDI and furrow irrigation resulted in runoff on the heavy clay soil. Maintenance of a dry surface as observed in 50 and 75% ETc could also reduce significant surface evaporative loss of water and should increase the interception and store of seasonal rain.

However, in terms of WUE, while between SDI treatments those with lower rates of application led to higher lint WUE_{sl}, largely because of their higher harvest index, SDI did not invariably show greater lint WUE_{sl} than the furrow treatment. Indeed, while in the first year lint WUE_{sl} with furrow irrigation was considerably less than that of SDI treatments, in the second year when furrow irrigation practice was refined it was equally as high as the highest SDI treatment. It is clear that improved management of furrow irrigation can considerably enhance lint WUE_{sl}.

The drier treatments exhibited greater heat stress as measured by their greater CWSI, despite their smaller canopy and perhaps because of their lower water use. The greater CWSI of drier SDI treatments was related to lower rates of photosynthesis, and lower instantaneous RUEi and WUE_i.

The results presented here could benefit the irrigation, particularly cotton, industries especially those on heavy clay soils making them more efficient users of irrigation water. Further research work on timing of irrigation (day or night?), pulsing (how frequent?), start of first irrigation (early stress required or harmful?) would help further improve water use efficiency and stimulate a greater understanding of physiology of cotton grown with SDI. Further studies on the details of soil moisture and root distribution as related to the top growth, on the development of sound plant + soil + environment based irrigation scheduling, and on overcoming midday depression of photosynthesis evident with high temperature would further help improve the performance of SDI crops on heavy clay soils.

SDI offers great potential for improving WUE, saving on water input, and also minimizing the negative environmental impacts due to run off and deep drainage, which are often very high with conventional furrow irrigation. In spite of the advocated benefits, adoption of SDI technology is relatively slow even though there are already pressures on industries to opt for water-saving irrigation methods. While reviewing the data on cotton response to SDI on heavy clay soils, it was theorized that with drip irrigation as water exists from the emitter it purges the soil surrounding the emitter of soil air (and O_2). Such lack of O_2 could cause hypoxia and set a limitation to the effective root functioning and growth, leading to lack of yield increase, or even yield reduction at irrigation rates above those computed to satisfy 75% of ETc. In order to overcome such hypoxia that may be associated with SDI, different methods for delivering O_2 directly to the root zone - Oxygation - were developed and tested in a range of model crops at different soil water contents. The results of the oxygation experiments suggested that aerating the rhizosphere of tomato, soybean and cotton in a heavy clay soil significantly increased yield compared to non-aerated controls, irrespective of soil water content. The increase in yields were associated with enhanced root function (evidenced by higher soil respiration and root mass) and various associated effects through enhanced canopy transpiration, leading to higher rates of photosynthesis, and more and heavier fruits, pods and bolls in tomato, vegetable soybean and cotton respectively. Aeration increased root weight and length whenever measured and promoted greater total soil respiration. Water use efficiency, expressed as the ratio of photosynthesis to transpiration, and of yield to total water use, was greater in aeration treatments. The experiment on soybean revealed that soil microbial population, especially bacteria population, did not alter in number with respect to aeration practices. The research suggests that, provided the supply of aerated water can be maintained along long stretches of SDI tape, aeration of root zones in heavy clay soils will significantly improve yield and WUE of tomato, vegetable soybean and cotton. It is also expected that these responses would hold true in other similar crops.

Oxygation of the rhizosphere shows tremendous promise for the unlocking of yield potential of irrigated crops and will further optimize the SDI system. It is considered that the benefits achieved with oxygation through SDI delivery will have tremendous impacts as SDI is the only (current) irrigation method to harness the benefit of rhizosphere aeration to crops. In order to achieve the full advantage of oxygation, further research is still required to investigate the effect of oxygation across soil types, soil water contents as well as different crops. The effects of oxygation on the details of soil processes, soil microbial community, and intricate plant response are still not well understood. Research on model crops over a range of soil O_2 levels delivered through SDI to the rhizosphere is called for to determine optimum O_2 levels for different soil types and moisture contents, in relation to environmental variables. Equally important is modelling of the oxygation system, to improve design and to broaden the application. The future is very promising but a sizable amount of cross-disciplinary research work is still required. It is possible that oxygation will be a future focus and direction of innovative irrigation worldwide, in light of reduced allocation of irrigation water for agriculture, but the need to produce still more food.

Besides irrigation-induced reduction of the O_2 diffusion and content in the rhizosphere, other soil physical, chemical and biological processes can limit O_2 diffusion from the atmosphere to the root zone and reduce availability of O_2 to the rhizosphere. Subsurface constraints associated with compaction, sodicity, and salinity are a few of many such phenomena. Salinity and sodicity in a heavy clay soil greatly reduce the porosity, induce waterlogging and impair O_2 diffusion to rhizosphere.

Aeration under saline soil environments influenced growth, development and reproductive performance of three species (tomato – sensitive to salinity; vegetable soybean – moderately tolerant; and cotton – tolerant species) on a heavy clay soil. Increases in the leaf biomass, greater light interception, and increase in fruit number and size were variously observed across the species in response to aeration which all contributed toward greater yield. In general the benefits of aeration on saline heavy clay soil were mediated through greater root activity, as observed by a general increase in root weight, root length density, and an enhanced soil respiration in all tested species (in tomato soil respiration was not measured). Improved root metabolic activities and respiration due to aeration drove greater uptake of water as observed by a significant increase in the sap flow rate and accumulated transpiration. The increased transpiration was possibly supported by bigger conducting tissue and an increase in the stem diameter observed in the crops. The increased sap flow through to leaves contributed to a more favourable LWP for tissue expansion, a decreased CWSI, greater leaf turgor, facilitated leaf growth that contributed to bigger canopies and therefore, greater light interception. Aerated plants showed greater membrane permeability of the leaf tissues (measured by low electrolyte leakage and RLR) suggesting that greater exclusion of the salt by roots was operating. The evidence that the aeration conferred greater salt exclusion was related to the low salt concentration in the leaf tissue with aeration compared to the control.

Reduced Na^+ concentration in the leaf samples and increased ion regulation index recorded for the aerated treatments compared with the control indicated that greater tolerance was conferred by aeration treatments in hypoxic and/or saline soil. Increasing salinity and hypoxia reduced water uptake by plants. Improved root permeability (expressed as hydraulic conductance of the root system) could be an explanation for the increased water uptake with aeration. Further studies are required to determine whether the increase in water flow through the root system is due to changes in the water potential gradient across the root system, to changes in hydraulic conductance produced by modifications of the root structure, or to both reasons.

Salinity is one of the most important environmental threats worldwide. While combating salinity is a prime objective for agricultural research, learning to live with salinity is a short or medium term option, and in this light the productive use of saline land appears possible employing oxygation for it has been shown to promote salt exclusion by the roots. Although these early results are promising, future research is still required to understand in greater detail the physiological, biochemical and molecular basis for such an effect. This effect needs to be quantified in a range of soil types and crops across the range of anticipated biotic and abiotic environmental parameters characteristic of production systems. It is very important to remember that a large body of ground/irrigation water in many parts of the world is saline and using saline water for irrigation is a common practice in those areas. However, it is not known whether the aeration of saline irrigation water offers the same advantage in terms of salt exclusion as was observed with aeration of saline soils. The long-term salinity and aeration effects on the soil physical, chemical, biological processes and plant response within the myriad of other environmental variables need to be considered in the future research. The potential use of oxygation in other soil environments, which are hostile in terms of O_2 concentration in the rhizosphere, such as land fills and compacted soil should also be considered for the future application of oxygation.

Oxygation has tremendous potential to change the face of irrigation systems of the horticultural as well as broad-acre crops worldwide and most particularly contribute towards greater productivity and savings of irrigation water by enhanced WUE, minimizing the negative environmental impacts of irrigation and enhancing productive use of saline land/water for crop production. The oxygation research both in non saline and saline heavy clay soils reported in this thesis were carried out on three different crops as the pot experiments. It is generally assumed that the oxygen movement, both lateral and vertical, in the soil is greatly restricted in the pot environment compared to that of the more open and porous field environment. Therefore, the extrapolation of the experiment results must be carried out with caution then employing the oxygation technology for the commercial application. Field scale verification of oxygation, in different soil types at various soil moisture levels, for different crops is needed to establish the benefit of oxygation for plant production as well as developing the cost and benefit of oxygation for commercial application of this technology.

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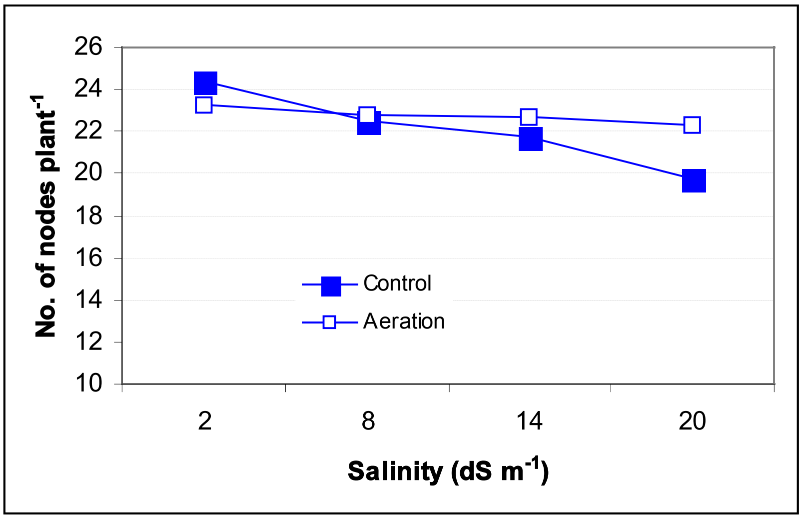
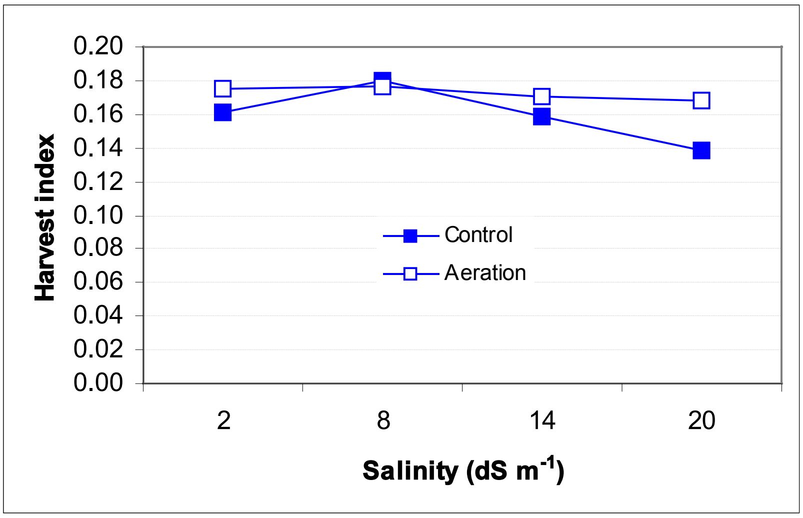
APPENDIX:

I. Weather data over the period of experiments from Rockhampton, QLD, 2002-2004.

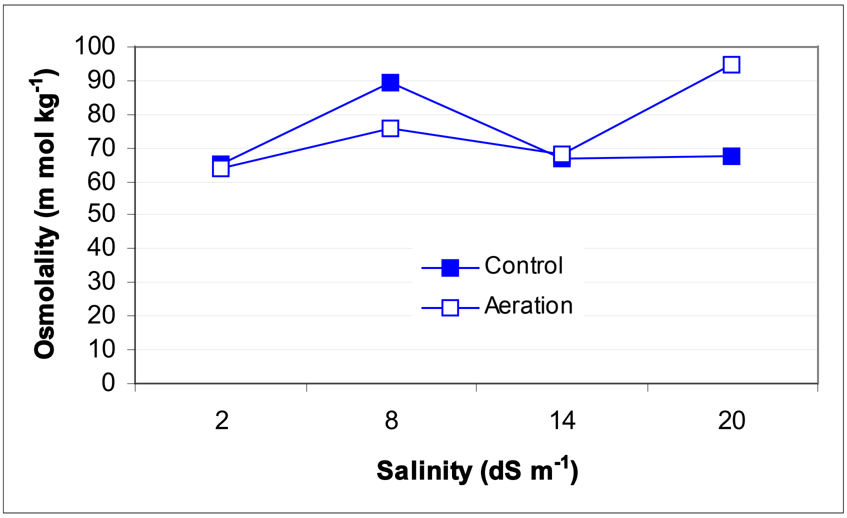
YEAR	Month	Rain (mm)	Wind (M/s)	Light (Wm^{-2})	Amb T (ºC)	Radiation (MJ $m^{-2}d^{-1}$)	Net radiation (67% of outside)
2002	January	51.6	1.4	275.2	28.0	23.8	15.9
	February	34 .2	1.3	240.1	27.9	20.7	13.9
	March	30.2	1.4	252.6	25.5	21.8	14.6
	April	10.4	1.4	204.5	23.7	17.7	11.8
	May	9.0	1.1	163.9	19.8	14.2	9.5
	June	149.0	1.1	138.1	17.2	11.9	8.0
	July	0.6	0.9	166.2	15.6	14.4	9.6
	August	69.6	1.1	178.7	17.4	15.4	10.3
	September	3.2	1.2	246.9	21.1	21.3	14.3
	October	1.0	1.3	286.6	23.9	24.8	16.6
	November	68.0	1.2	308.1	24.5	26.6	17.8
	December	70.0	1.5	309.6	26.5	26.8	17.9
Average		41.4	1.2	230.9	22.6	19.9	13.4
2003	January	2.6	1.5	288.1	26.6	24.9	16.7
	February	447.8	1.2	199.5	26.0	17.2	11.5
	March	3.6	1.1	221.2	25.0	19.1	12.8
	April	49.2	1.0	202.1	23.2	17.5	11.7
	May	23.2	1.0	162.0	20.3	14.0	9.4
	June	28.2	0.6	138.7	18.5	12.0	8.0
	July	12.8	0.9	158.2	16.6	13.7	9.2
	August	23.4	1.0	184.9	18.5	16.0	10.7
	September	18.8	1.2	253.8	21.6	21.9	14.7
	October	129.4	1.3	264.4	23.6	22.8	15.3
	November	15.2	1.3	290.8	24.3	25.1	16.8
	December	120.2	1.2	258.8	26.2	22.4	15.0
Average		72.9	1.1	218.7	22.5	18.9	12.7
2004	January	164.2	1.1	256.3	27.6	22.1	14.8
	February	80.8	0.8	239.7	27.4	20.7	13.9
	March	83.0	1.3	234.0	25.6	20.2	13.5
	April	16.0	1.2	194.4	23.5	16.8	11.3
	May	0.6	0.6	172.9	20.0	14.9	10.0
	June	7.6	0.9	153.6	17.4	13.3	8.9
	July	0.4	0.6	111.0	18.8	9.6	6.4
Average		50.3	1.0	206.2	23.5	17.8	11.9



Graph 1: Number of nodes on cotton as affected by aeration in a range of salinity levels.



Graph 2: Harvest Index of cotton as affected by aeration at different salinity levels.



Graph 3: Cotton xylem sap osmolality as affected by aeration at different salinity levels.