University of Southern Queensland

Quantifying the Role of Irrigation Uniformity on Lettuce Production and Profitability in the Lockyer Valley, Queensland

A dissertation submitted by

Amjed Hussain

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ABSTRACT

Water is a major input resource for irrigated agriculture and has a leading role amongst the factors responsible for infield yield variability. The uniformity of irrigation applications is commonly reported to be a key determinant of crop yields and profitability. However, improvements in irrigation application uniformity do not always improve yields or economic returns and there is some debate over the benefits of implementing site specific irrigation management under different environmental and climatic conditions.

Catch can tests to evaluate irrigation uniformity are labour intensive and time consuming. Hence, they are commonly conducted on only small areas which lead to uncertainties over field scale spatial variations. While soil-water and crop sensing technology has enhanced irrigation research, these technologies are not currently used to evaluate commercial irrigation performance. Hence, the objectives of this research were to: (a) quantify the spatial yield and quality variability in an irrigated crop under specific irrigation design, management and environmental conditions, (b) evaluate the potential to use proximal or remote sensors for crop and soil-water measurements as part of irrigation performance evaluations, (c) identify variations in the seasonal patterns of irrigated water application and the resultant impact on soil-water and crop responses, and (d) evaluate the agronomic and economic benefits of improving the irrigation uniformity for a range of environmental conditions.

A preliminary trial was conducted to evaluate the effect of non-uniform sprinkler irrigation applications on lettuce grown under commercial conditions in the Lockyer Valley, Queensland. A three-fold variation in the depth of water applied at specific locations in the field was measured within individual irrigation events even though selected sprinkler grids within the field were found to have a coefficient of uniformity (CU) greater than 80%. Substantial variations in sprinkler operating pressure (303 to 372 kPa) and discharge (0.07 to 0.14 l s^{-1}) across the field were also measured suggesting that the variation in applied depths across the field may have been larger than measured within the grids. The variation in sprinkler pressure and flow rate was due to differences in sprinkler elevation, position along the laterals, pipe leakage and nozzle wear. However, the depth of irrigation water applied at

specific locations in the field was not correlated with lettuce head size because head size was not very variable suggesting that a range of other factors including the presence of in-season rainfall and over-irrigation may also influence crop growth under commercial conditions.

Two trials (autumn and winter crops) were subsequently conducted to evaluate the potential to use proximal plant and soil-water measurement systems to obtain spatial data for irrigation performance evaluations. Three sprinkler irrigation grids with different application uniformities were established within each trial plot. These trials were also used to determine the variation in uniformity of irrigation applications during the season and the consequential effect on soil moisture, lettuce growth and yield.

Thermal infrared (for the calculation of crop water stress index) measurements of the lettuce plants were generally poorly correlated with both water applications (autumn trial $R^2 < 0.1$; winter trial $R^2 < 0.54$) and canopy area (autumn trial $R^2 < 0.02$; winter trial $R^2 < 0.28$). There were also no correlations between the multispectral reflectance measurements (used to calculate the normalised difference vegetation index) and water application. Measurements of lettuce canopy area and head size derived from photographs taken by a camera mounted perpendicularly (either 1.15 m or 10 m) above the ground surface were found to be well correlated ($R^2 = 0.35$ to 0.92) with physically measured canopy area and head size measurements. The correlations generally improved throughout the season suggesting that this method may potentially be suitable for evaluating field scale spatial yield variability in lettuce crops.

The evaluation of sprinkler irrigation uniformity using traditional catch can analyses is resource prohibitive and commonly results in only small grids being used to infer whole field performance. Measurements of apparent soil electrical conductivity (EC_a) using electromagnetic (EM) sensors have been used to measure spatial variability in soil moisture but no detailed studies have been taken to evaluate the potential to use these sensors for measuring sprinkler irrigation uniformity. Apparent soil electrical conductivity (ECa) measurements were found to be not suitable for evaluating the uniformity of individual sprinkler irrigation applications where either the volumes applied are small or the uniformity of the application is relatively high (e.g. Christensen's coefficient of uniformity (CU) > 75%). However, ECa measurements may be useful to identify cumulative non-uniformities in irrigation applications later in the season where the spatial pattern of water application is consistent throughout the season and the uniformity of the application is poor (e.g. CU < 70%). A similar relationship was found between soil tension (soil matric potential) and water application measurements with correlation generally higher in low uniformity grids later in the season.

Substantial variations were found in the uniformity of individual irrigation applications throughout the season (e.g. CU ranged from 69 to 89% for a high uniformity grid). Similarly, the uniformity measured by catch cans at different grid locations in the same field during the same event was also found to vary widely (e.g. CU ranged from 61 to 85%). Hence, uniformity measurements taken using a limited number of grids over a single irrigation event may not adequately reflect the performance of the irrigation system over the whole season. The frequency distribution plots of the irrigation application depths were generally found to be normally distributed when the CU was greater than 75%. However, low uniformity applications (e.g. CU < 60%) were often multi-modal and generally positively skewed towards the low application depths.

The effect of irrigation water application on crop growth and yield was evaluated in both trials. Variations in water application during the mid to late growing period were found to affect lettuce head development and marketability more than canopy size. There was also a substantial loss in marketability due to the depth of water application at specific locations within the grids. The proportion of marketable heads ranged from less than 20% to more than 70% within the low and high water application areas, respectively, of the low irrigation uniformity grids. The wide variation in the proportion of marketable heads with water application across each of the grids and trials confirms that many factors other than water (e.g. disease, fertility) may influence marketability. These factors were also responsible for the high degree of scatter in the plots relating total seasonal water (irrigation and effective rainfall) applied and yield. Both polynomial (i.e. quadratic) and exponential (i.e. plateau) functions were fitted to the data and there was no difference between the correlation

for each form of equation. Hence, both forms were used in the subsequent economic analysis to evaluate the benefits of irrigation uniformity improvements.

The economic analysis demonstrated that where the existing irrigation uniformity is low, returns can generally be increased with improvements in irrigation uniformity. However, the magnitude of the benefit is dependent on the season, nature of the crop production response and the total water applied. The benefits of system improvements are maximised when the crop has a quadratic production function and appropriate irrigation scheduling is used. However, where the crop has an exponential production function or inappropriate scheduling is used then the gains may be small or negative. Similarly, in-season rainfall reduces the marginal benefit of irrigation system improvement with negligible increase in returns when effective rainfall meets 50% or more of the crop water requirements. The incentive for irrigation system improvement is greatest when water is limited and unable to be purchased. Periods of low product price would be expected to encourage irrigation uniformity improvements as non-uniform systems have a higher-break even price and require increased management (e.g. scheduling) to remain viable. These results may be used by both industry and growers to develop appropriate investment strategies to improve the performance of irrigation systems.

CERTIFICATE OF DISSERTATION

I certify that the ideas, experimental work, results, analyses and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

Signature of candidate Date

Endorsement

Signature of Principal Supervisor Date

Signature of Associate Supervisor Date

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PUBLICATIONS ARISING FROM THIS RESEARCH

HUSSAIN, A. and Raine, S.R. (2008). A preliminary evaluation of the potential to use electromagnetic induction to assess sprinkler irrigation performance in horticultural crops. First Global Workshop on Digital Soil Sensing and Mapping, Sydney, 5-8th February.

HUSSAIN, A., Raine, S.R. and Henderson, C.W. (2008). Preliminary evaluation of relationships between irrigation non-uniformity and crop responses in lettuce. National Conference, Irrigation Australia Limited, Melbourne, 20-22nd May.

HUSSAIN, A., Raine, S.R., Henderson, C.W. and Jensen, T. (2008). Evaluation of a proximal vision data acquisition system for measuring spatial variability in lettuce growth. National Conference, Agronomy Society of Australia, Adelaide, 21-25th September.

HUSSAIN, A. (2009). Digital imagery tracks lettuce growth. Precision Ag News. Southern Precision Agriculture Association. Vol 5, No 2, pp: 9-10.

HUSSAIN, A., Raine, S.R. and Smith. R. (2009). The economics of sprinkler irrigation uniformity for lettuce production with variable rainfall. CIGR International Symposium, Australian Society for Engineering in Agriculture, Brisbane, 13-16 September.

HUSSAIN, A., and Raine, S.R. (2010). Can electromagnetic induction be used to evaluate sprinkler irrigation uniformity for a shallow rooted crop? Paper accepted for presentation to 19th World Congress of Soil Science, Brisbane, 1-6 August.

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Chapter 1. Introduction

1.1 Background

Irrigated agriculture is a significant contributor to the Australian economy. The irrigation industry is the major water user in Australia consuming up to 75% of all water diverted for use (Fairweather *et al*. 2003; Goyne and McIntyre 2002). During 2007-08, 39,637 agricultural establishments irrigated 1.85 million hectares (Mha) and applied 6,285 GL of water at an average of 3.4 ML/ha (ABS 2009). The gross value from irrigated agriculture was $7.25 billion in 1996-97 (Fairweather *et al*. 2003) and increased to $9.1 billion in 2004-05 (ABS 2006). This represents about 23% of the total gross value of agricultural production in Australia. The agriculture industry consumed largest volume of water 12,191 gigalitre (GL) representing 65% of consumption in Australia. The water users within the agricultural sector are livestock, pasture, grains and other agriculture (4,374 GL), dairy farming (2,276 GL), cotton (1,821 GL), vegetables, fruit and grapes (1,820 GL), sugar (1,269) and rice (631 GL) (ABS 2006).

Major sources of irrigation water in Australia include surface water and ground water. Irrigation water is transported through more than 24,000 km of channels, pipes and waterways to the farm gate (ANCID 2005). Farmers use a variety of irrigation techniques to apply water to their crops and pastures. Common systems include surface (i.e. furrow, basin, or border check), drip or trickle, and sprinkler (i.e. micro sprinklers, travelling guns, booms, centre pivots, lateral moves and solid set systems) (ABS 2006). Surface irrigation is the major form of application, irrigating 1.5 Mha while sprinkler is used to irrigate about 0.7 Mha and drip or trickle is used on 0.21 Mha (ABS 2006). The design and management of each irrigation system will affect the spatial uniformity of water application and efficiency within irrigated fields.

Spatial and temporal yield variability within fields has been recognised for centuries (Zhang *et al*. 2002). For example, there is typically a ten fold winegrape yield variation across vineyards in any given year (Bramley and Hamilton 2004). Spatial and temporal yield variability has also been reported in cotton (Elms *et al*.

2001; Meredith 1996; Wilkerson and Hart 1996), corn (Chen *et al*. 2004; Kravchenko and Bullock 2000; Stone *et al*. 1985), wheat (Ciha 1984; Jin and Jiang 2002; Kelly *et al*. 2004), soybean (Cox *et al*. 2003; Kravchenko and Bullock 2000), sorghum (Chen *et al*. 2004; Machado *et al*. 2002a) and vegetables (Barber and Raine 2002).

The spatial factors responsible for yield variability include field topography, fertiliser uniformity, irrigation uniformity, genetic variation, plant health, soil hydraulic and nutrient properties, microclimate differences as well as pest and disease infestation (Zhang *et al*. 2002). Climatic factors such as rainfall, temperature and radiation also vary temporally (Zhang *et al*. 2002). Water commonly has a leading role among the factors responsible for spatial and temporal yield variability and is a major input resource for precision management (Sadler *et al*. 2000b; Warrick and Gardner 1983). However, many of the infield spatial variability studies have involved rainfed crops and it seems likely that non-uniform applications of irrigation water may be hard to detect against a background variation introduced by edaphic and micro-climatic factors.

Yield variability within surface-irrigated fields has been related to the spatial variability of available soil-water due to non-uniform irrigations (Palmer 2005). The only form of water which can be beneficially utilised by crops is the soil-water (Zhang *et al.* 1994), and soil-water relations have been shown to explain more than 50% of infield soybean yield variability (Irmark *et al.* 2002). Hence, temporal and spatial management of soil-water can significantly increase water use efficiency (Jin *et al.* 1999). However, there is also some uncertainty over the benefits of implementing site specific irrigation management under different environmental and climatic conditions (Smith and Raine 2000) and improvements in irrigation application system uniformity do not always produce yield or economic benefits (Rezende *et al.* 2000). There are other factors which can also limit yield and economic return such as soil type, fertiliser application, crop variety and environment. Locally in Queensland, there is some debate over the benefits of improved spatial irrigation uniformity for the production of lettuce (Henderson, C 2006, pers. comm., 10 April).

There is also no doubt that the use of remote sensing has enhanced our research capabilities but these technologies are not widely used to evaluate irrigation performance and commercial growers are reluctant to use these technologies. This may be due to a failure to identify the magnitude of the potential benefits, difficulties in identifying appropriate technologies or an inability to integrate the data into commercial crop management systems. Hence, there is a need to answer some simple questions including:

- Is there significant temporal and spatial yield variability within lettuce crops?
- Which tools are appropriate to monitor spatial and temporal variation in irrigated crop behaviour within fields?
- How does irrigation application uniformity, scheduling and other factors influence yield variability?
- How is the optimum application uniformity for an irrigation system affected by the crop, irrigation management and environmental conditions?

1.2 Research hypotheses and aim

The aim of this research work was to identify strategies for optimising the design and management of overhead irrigation application systems. The overarching hypothesis of this research is that irrigated crop production responses and profitability can be increased (and environmental impacts minimised) by the adoption of irrigation design and management practices which optimise the uniformity of irrigation applications. This research is based on the following component hypotheses:

- There is a significant variability in crop production responses within existing irrigation management units (e.g. fields), a substantial and manageable part of which is related to water application.
- Proximal and remote sensing tools can be used to effectively map spatial variability in crop and soil-water responses to irrigation applications.
- There is substantial in-season variation in the pattern and performance of irrigation application which influence field scale crop responses.
- The optimal irrigation uniformity will be a function of the crop (e.g. water sensitivity, price) and environmental (e.g. rainfall) conditions.

1.3 Structure of dissertation

This dissertation comprises ten chapters (Figure 1.1). The literature review (Chapter 2) provides an overview of the factors responsible for spatial and temporal yield variability and particularly the role of water in this variability. Previous research into the techniques used to evaluate infield variability, strategies to optimise irrigation application and crop yield and the economic benefits associated with optimising irrigation uniformity are discussed.

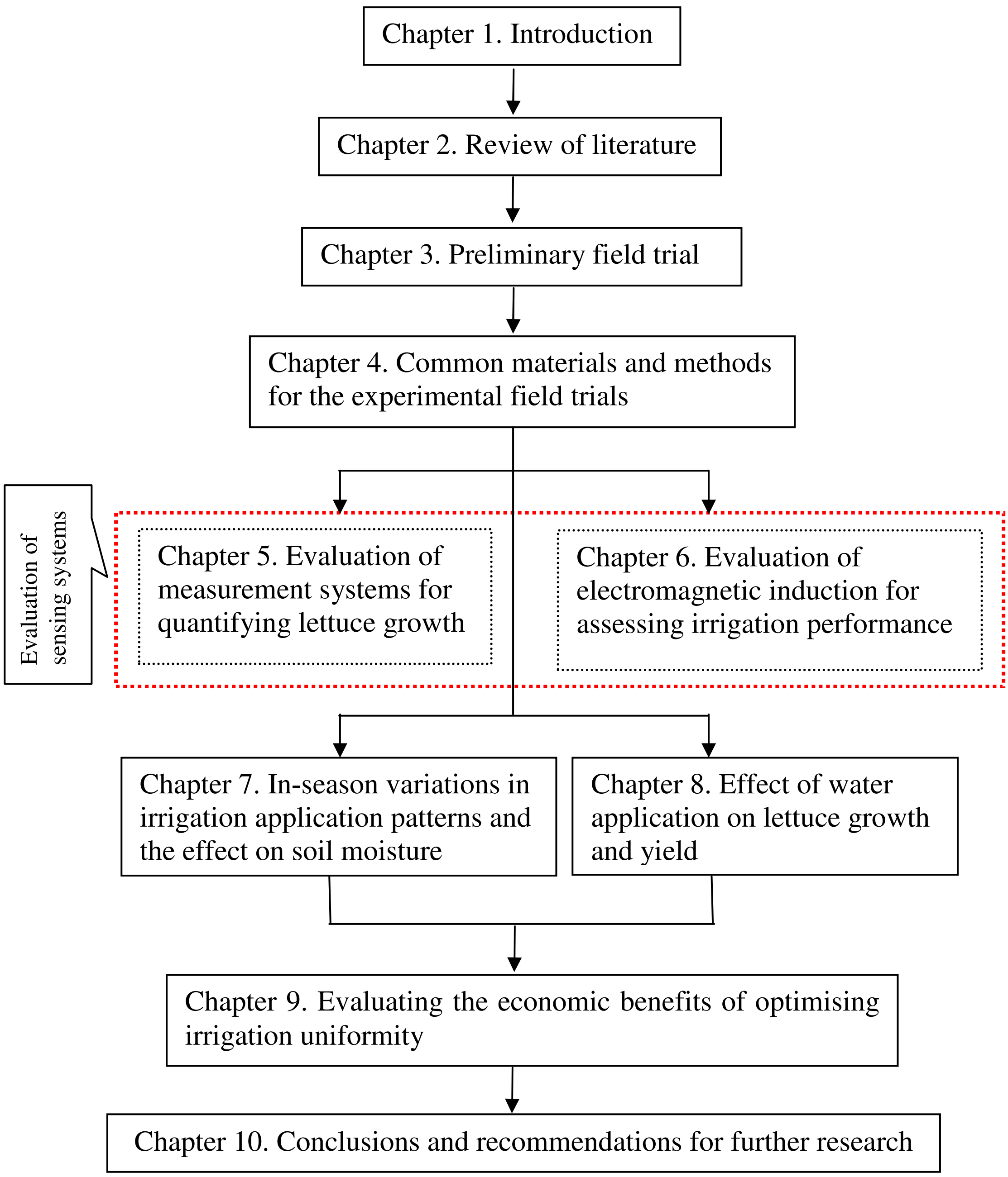


Figure 1.1 Structure of dissertation

Chapter 3 reports on a preliminary evaluation of the impact of irrigation uniformity on the infield yield variability for a commercial lettuce crop. This trial highlighted the need to (a) evaluate the potential to use alternative measurements for more rapid spatial determination of plant growth and irrigation uniformity, (b) conduct trials under more controlled conditions to better understand the role of irrigation uniformity on commercial crop production systems and (c) evaluate the economic benefits of irrigation system improvement. The common materials and methods used to conduct the subsequent trials are detailed in Chapter 4.

Chapters 5 and 6 provide an evaluation of crop and soil remote measurement systems. Chapter 5 evaluates the potential of various proximal sensors to measure lettuce growth. Chapter 6 evaluates the potential to use electromagnetic measurement of soil apparent electrical conductivity (ECa) for assessing irrigation uniformity. Chapter 7 reports on the spatial and temporal variation in irrigation applications over two growing seasons and identifies the relationships between water applications and soil moisture. The effect of irrigation application uniformity on lettuce crop growth and its relationship with yield are presented in Chapter 8. The implications of in-season rainfall are discussed and the crop production functions used in the subsequent analysis are presented.

Chapter 9 uses the irrigation performance and empirical crop production relationships identified in the field trials to evaluate the effect of spatial and temporal variation in water application on yield. The economic impact of irrigation uniformity is evaluated under different in-season rainfall scenarios. The major conclusions and recommendations for further research are presented in Chapter 10.

Chapter 2. Review of literature

This chapter provides an introduction (Section 2.1) to spatial and temporal yield variability for different crops, the factors affecting this variability, and the role of water in variability The tools to evaluate the spatial and temporal water and yield variability are also reviewed (Chapter 2.1.3) The effect of non-uniform irrigation application on growth and yield is investigated (Chapter 2.2) and recent approaches to identifying optimal irrigation uniformity under a range of crop, irrigation system and environmental conditions are discussed (Chapter 2.4).

2.1 Infield crop variability

2.1.1 Variations over space and time

A wide range of variability in both irrigation water application and yield is commonly observed in many crops (Bucks and Hunsaker 1987; Zhang *et al*. 2002). For example, Dagan (2002) reported that between 2 and 12 ML/ha of water were applied by a wide variety of citrus growers operating under commercial conditions (i.e. different soil types and crop ages) in the central Burnett region and that the yield ranged from 0 to 56 t/ha (Figure 2.1). Similar results were also found for grapes, stone and prone fruit and pastures in the Murray Darling Basin (Bramley and Hamilton 2004).

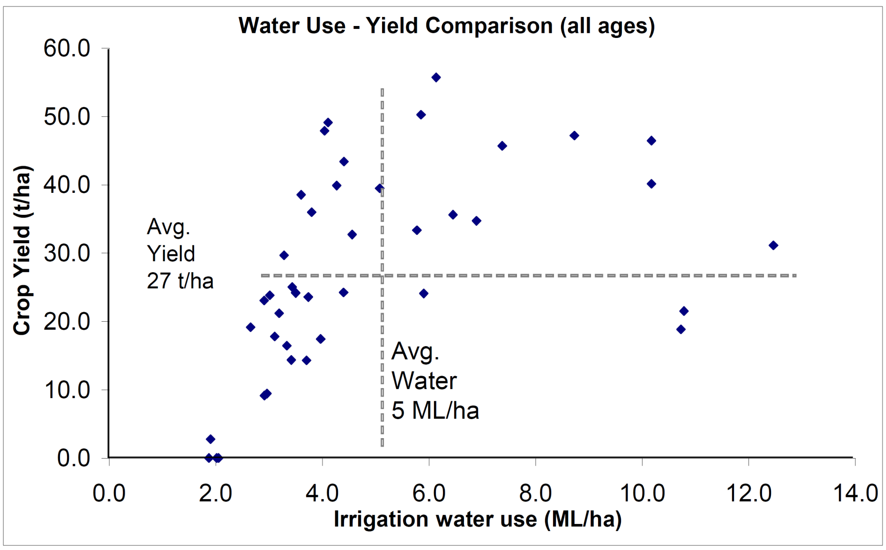


Figure 2.1 Citrus yield and irrigation water use comparison (Dagan 2002)

Yield mapping (Figure 2.2) has also shown substantial infield spatial variability for irrigated grapes (Bramley and Hamilton 2004), cotton (Raine and Foley 2002), wheat (Plant *et al*. 1999) and corn (Heerman *et al*. 2000; Sadler *et al*. 2000a). Whelan and McBratney (2000) found that the coefficients of variation for wheat yield within fields ranged from 13 to 83% while for sorghum the range was from 12 to 44%. Significant inter-year yield variability has also been found (Blackmore *et al*. 2003; Colvin *et al*. 1997; Marchetti *et al*. 1998) for rainfed crops (Figure 2.3). A substantial temporal variability in rainfed corn and soybean yield was also reported by Chang *et al*. (2000). This suggests that yield variability is a multi-attribute variable and that there is a need to identify interactions with other environmental and management factors to identify optimal irrigation management practices.

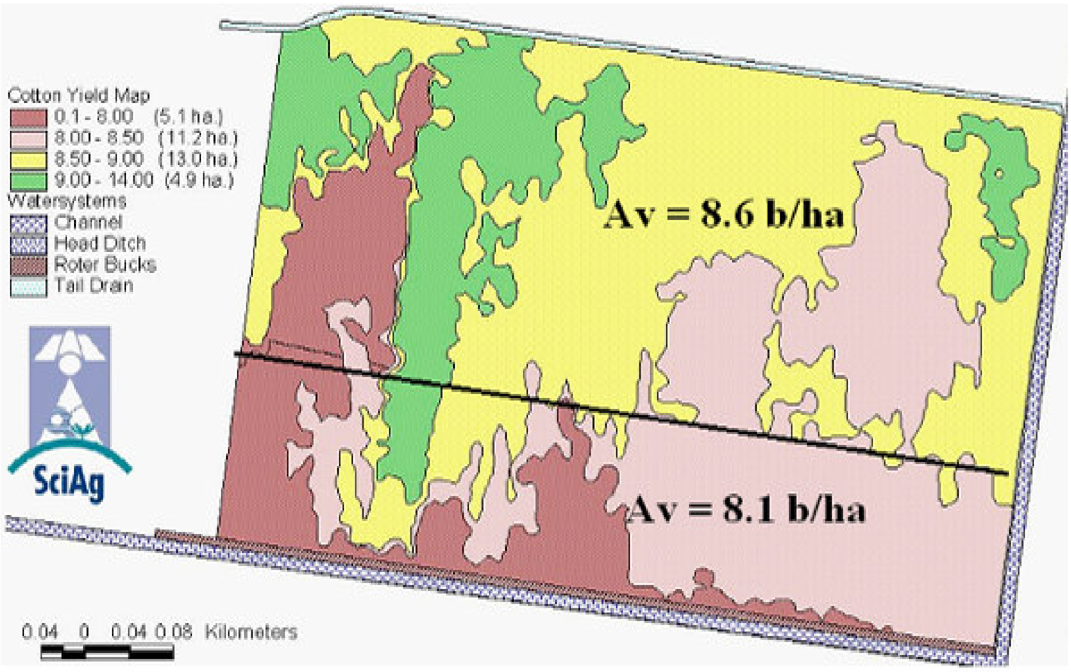


Figure 2.2 Infield variation in surface irrigated cotton yield (Raine and Foley 2002)

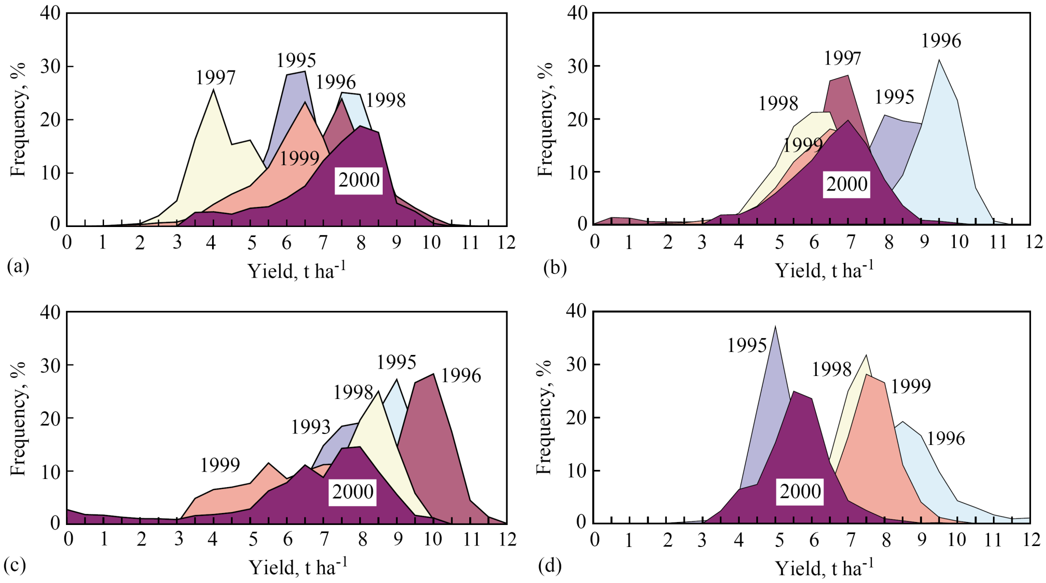


Figure 2.3 Six-year yield histograms for four fields of (a) winter barley (b) winter wheat (c) winter wheat and seed rape and (d) winter wheat (Blackmore *et al*. 2003)

2.1.2 Factors affecting variability

2.1.2.1 Climate and topography

Climatic factors such as rainfall, length of growing season, and temperature have been found to affect crop yield. Up to 67% of corn yield variability between years has been explained by climatic factors (Huggins and Alderfer 1995). The amount of rainfall clearly affects the relative year to year yield (Figure 2.4) (Wong and Asseng 2006). However, the yield response (Figure 2.4) is not intuitive with some areas producing higher yields in dry years than in wet years (possibly due to better drainage). Similarly, while larger patterns at the field scale are likely to be related to soil differences, there are many smaller scale differences in the spatial patterns between years which suggest there may be an interaction between the rainfall and micro-topography or agronomic factors.

In deeper alluvial soils, temperature is a major factor affecting cotton production (Bange 2002). Morphological and physiological effects of low temperatures during germination, emergence, and early seedling growth can also affect lint yield (Bauer and Bradow 1996; Kittock *et al*. 1987). Cathey and Meredith (1988) found that late cotton sowing reduced micronaire and lint yield, but did not affect fibre length, strength or elongation. Increasing rainfall has been found to increase corn yield and decrease variance while increasing temperature reduced corn yield and increase variance (Chen *et al*. 2004).

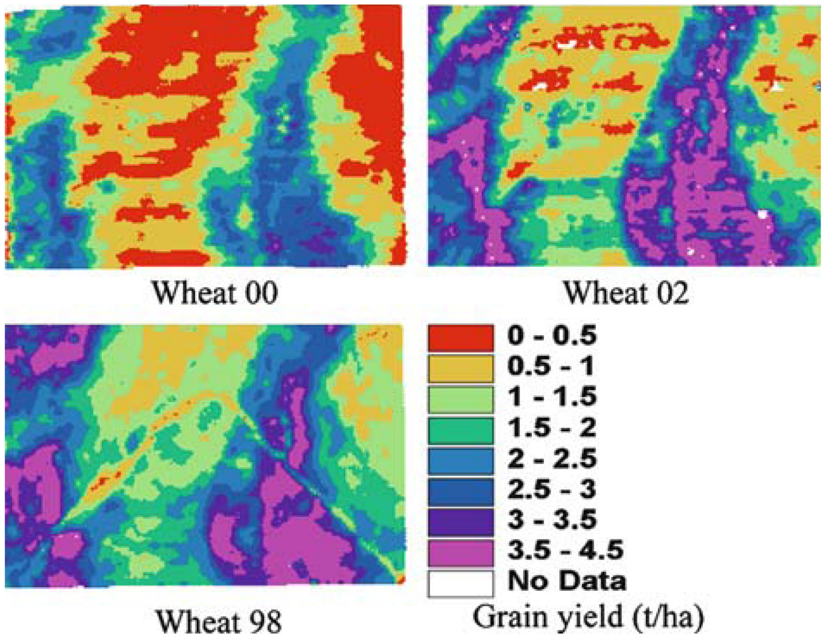


Figure 2.4 Wheat yield monitor data (kriged at 5m intervals) showing spatial patterns in wet (2000 & 2002) & dry years (1998) (Wong & Asseng 2006).

Yang *et al*. (1998) reported that topographic parameters could explain 13 to 35% of the yield variability in wheat fields. However, Miller *et al*. (1988) found no correlation between slope and wheat yield. Higher soybean yields have been found on lower slopes while yield was highly variable on moderate and high slopes during moderate to dry weather (Kravchenko *et al*. 2000). Similarly, higher corn grain yields were recorded on landscape positions that received overland flow water from higher areas (Stone *et al*. 1985). Kaspar *et al*. (2003) found that in four years with less than normal growing season precipitation, corn yield was negatively correlated with relative elevation, slope, and curvature. However, in two years with greater than normal precipitation, yield was positively correlated with relative elevation and slope. The efficiency of applied nutrients has also been found to be higher in years with average precipitation than in years with above-average precipitation, and much higher than in dry years (Chloupek *et al*. 2004). Hence, water redistribution in complex landscapes need to be quantified in order to determine field productivity (Halvorson and Doll 1991).

Machado *et al*. (2002b) found higher corn grain yields at high elevations while lower grain yield at low elevations under a low energy precision application system. Increased corn yield variability has also been observed on steeper slopes (Graveel *et al*. 1989). Intra-annual differences in rainfall had the largest affect on corn grain yield at locations where the surface slope was large (Timlin *et al*. 1998). While topographic attributes may explain some of the spatial variability in crop yield, soil-water displays more random spatial variability and its dynamic nature makes it difficult to predict in both space and time (Green and Erskine 2004).

2.1.2.2 Soils

Jaynes *et al*. (2003) suggests that soil moisture may be the dominant factor determining yield behavior within fields and is likely that soil type plays dominant role in water holding capacity (Michael 1999) and affects crop yield. However, there is also a range of physical (Schwab *et al*. 1993) and chemical (McCann *et al*. 1997) properties of the soil which can affect the moisture content in the soil. Areas with high clay content typically have high soil moisture contents and have been found to have higher yield in soybean fields, suggesting clay could be used as a basis for site-specific soil management (Cox *et al*. 2003). Similarly, soils with high clay and silt fractions produced greater sorghum yield than low clay soil under an 80% evapotranspiration (ETo) treatment (Machado *et al*. 2002a). However, Bruce *et al*. 1990 reported a 3 to 18% decrease of soybean yield with increases in clay content. Winter wheat growth and yield has also been strongly correlated with surface (0-30 cm) soil data (e.g. texture, pH and organic matter) (Vrindts *et al*. 2003).

Topographic features are highly correlated with soil properties, moisture content (Ovalles and Collins 1986; Sinai *et al*. 1981), water holding capacity of the soil (Hanna *et al*. 1982) and with yield (Ciha 1984). Topographic attributes explained 10 to 62% of the variation in measured soil physical properties, suggesting that knowledge of soil properties and landscape features together are important for aiding the implementation of site-specific crop management (Iqbal *et al*. 2005). For example, foot slopes and back slopes were found to contain an average of 40 mm more available soil water than soils on the top of the hill and shoulders (Hanna *et al*. 1982). Kravchenko and Bullock (2000) consistently observed higher corn and soybean yield at lower landscape positions and that soil properties and topographic positions explained about 40% of yield variability. Winter wheat yield components were found to be significantly affected by different soil, slope positions and cultivars (Ciha 1984). However, Ebeid *et al*. (1995) found that areas at higher elevations had larger soybean yields due to more plant available water being held by the higher clay levels in the eroded soils.

Soil properties have been found to affect surface irrigation uniformity and crop yields (Bucks and Hunsaker 1987; Sadler *et al*. 2000b). Soil compaction has also been found (Daniells 1989; Hodgson 1982) to increase waterlogging and reduce cotton yields by reducing infiltration under irrigation. In white beans, soil compaction reduced aeration and water availability and reduced the growth and yield while growth and yield was better in clay loam than sandy loam soil possibly due to better moisture holding capacity, nutrients and organic matter content (Tu and Tan 1991). McGarry (1994) found that soil structural degradation (i.e. compaction and shear stresses) reduced green boll numbers in cotton by up to 50% and lint by 35%. Cotton seedling emergence was reduced from 58 to 10% when surface crust strength increased from 0.25 to 1.20 g cm^{-2} in a sandy loam soil but deep tillage alleviated the effect (Agrawal 1994). In some soils, it may be feasible to overcome soil problems and boost yields by irrigating more frequently and by adding extra nitrogen. However, this strategy did not work on compacted Vertisols (Roth and Call 1991).

2.1.2.3 Nutrients

Soil nutrients have a large influence on the spatial variability of crop yield (Jin and Jiang 2002). Nutrients such as manganese, nitrate, phosphorus and boron were found to be responsible for variation in infield corn yields from 8.4 to 13.8 t/ha (Coelho *et al*. 1998).

Nitrogen limits yield and is the most commonly applied fertiliser. Hence, there has been a substantial amount of research into the nitrogen requirement of crops and the potential to use precision agriculture to variably apply nitrogen in response to spatially differing needs (Ersahin 2001; Schmidt *et al*. 2002). For example, Kelly *et al*. (2004) found that there was a >60% likelihood that plant-available nitrogen was yield-limiting for 17%, 23%, and 26% of a dryland field sown to sorghum, wheat or barley, respectively.

Spatial management of nitrogen can reduce overall nitrogen application while maintaining profitability (Bongiovanni and Lowenberg-Deboer 2004). Spatially variable nitrogen application was found to produce a 5% efficiency advantage over fixed rate applications in wheat when the coefficient of variation (CV) for nitrogen was 32%, and produced a 10% advantage when the CV was 48% (Cassman and Plant 1992). Spatially variable nitrogen applications have also been found to increase production and net revenue for both cotton (Yu *et al*. 2003) and irrigated corn (Snyder *et al*. 1998). Soil moisture can also assist in the uptake of the nutrients but it is difficult to separate interactions between them. Moore and Tyndale-Biscoe (1999) found that a large proportion of the variability in crop yield could be explained by differing soil moisture holding capacity and that the benefits of spatially variable nitrogen management (when the fertiliser was applied at the beginning of the season) were modest for wheat.

Variable rate nitrogen applications to a potato crop did not reduce the level of nitrogen loss from the field when compared with conventional nitrogen application (Watkins and Lu 1998). However, variable rate water application was found to reduce nitrogen losses by 50% when compared with uniform water application, and areas of the field with low productivity were found to have the greatest potential to benefit from variable rate water application (Watkins and Lu 1998).

2.1.2.4 Water

Temporal and spatial management of soil-water can significantly affect water use efficiency (Jin *et al*. 1999). Spatial variations in soil-water relations may also be an important factor in causing spatial variation in crop yield (Sadler *et al*. 2000b) with increasing soil-water deficit reducing crop growth (Figure 2.5). Hence, an understanding of the spatial variability in soil-water content and availability for plant uptake is required to maximise crop production and minimise environmental impacts.

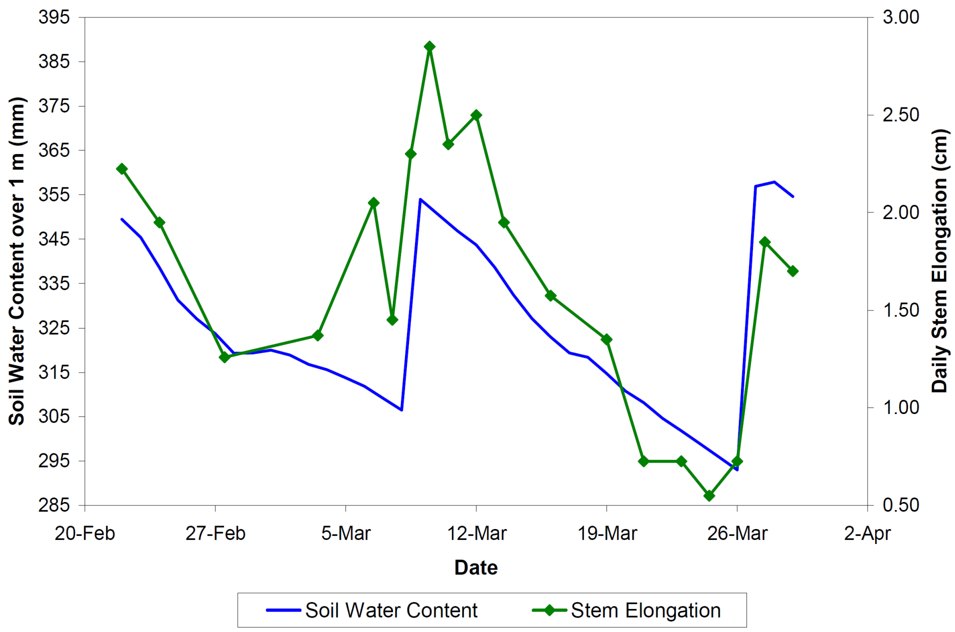
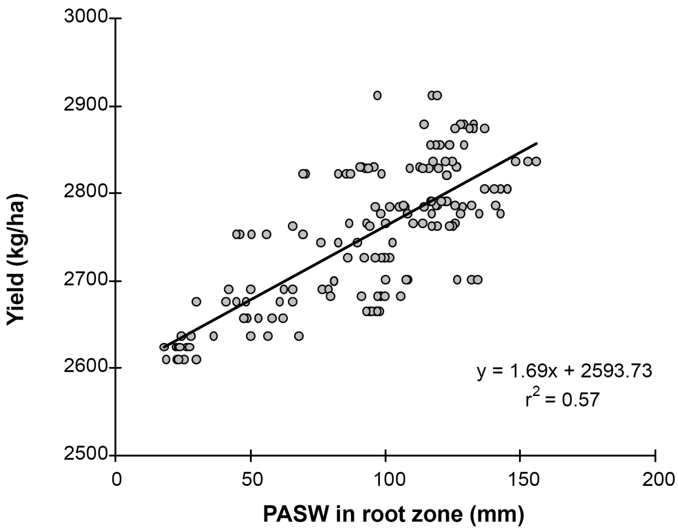


Figure 2.5 Sugarcane daily stem elongation relative to soil water content (Baillie 2004)

Factors which influence the spatial and temporal patterns of soil-water availability include irrigation application (Reichardt *et al*. 2001), redistribution of water over the soil surface (Kachanoski and Jong 1988), infiltration (Blaine *et al*. 1988), soil-water holding capacity (Leeper *et al*. 1974) and plant uptake (O'Grady *et al*. 2002). The pattern of soil-water uptake is closely related with the efficient management of water, fertiliser and other production inputs (Bucks and Hunsaker 1987).

Cavero *et al*. (2001) from a simulation study on maize reported that 50-70% yield variability could be due to difference of water availability in soil but soil fertility can also contribute in this variability. Similarly, the relationship between plant available soil-water and soybean yield (Figure 2.6) was found to explain more than 50% of yield variability (Irmark *et al*. 2002). However, in an irrigated potato crop, half of the observed variability (R^2 = 0.47) in water content was explained by a temporally stable spatial pattern where the yield was higher in the drier areas, and highly variable and frequently low in the wetted areas (Starr 2005).

(a)



(b)

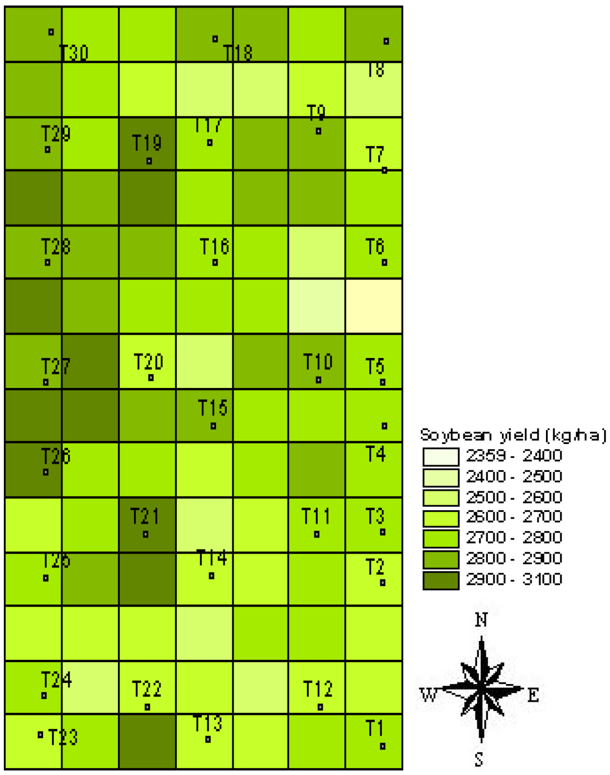


Figure 2.6 (a) Relationship between plant available soil water and soybean yield and (b) average soybean yield (kg ha^{-1}) for 98 grid cells (each 50 × 50 m). 'T' denotes the position of TDR tubes (Irmark *et al.* 2002)

Variations in seasonal water applications, water use, and seasonal average soil-water contents were found to account for 35% of the variability in wheat yield (Hunsaker and Bucks 1987). Coefficients of variation for a corn-soybean-wheat rotation were as high as 45% in years with low precipitation compared to 14% in years with higher precipitation (Kravchenko *et al.* 2005). Similarly, no spatial correlation was observed between corn yield, soil-water content and nitrate nitrogen, while a highly significant negative temporal correlation was observed between yield and soil-water content (Figure 2.7) (Marchetti *et al.* 1998).

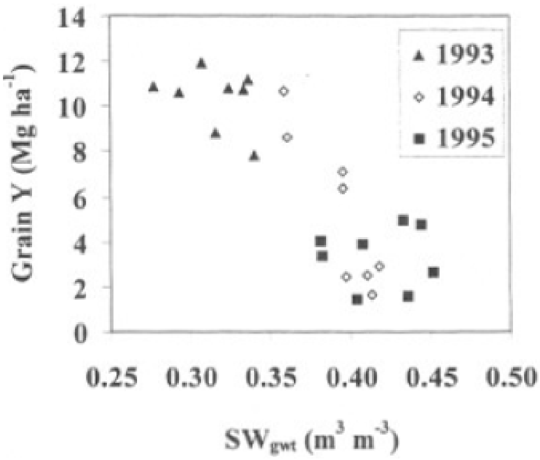


Fig 2.7 Relationship between corn grain yield and soil water content (Marchetti *et al.* 1998)

The above discussion (Section 2.1.2) highlights that many factors contribute to yield variability. However, the level of contribution can vary depending on the environment, soil type and characteristics, water, nutrients, topography and crop type.

2.1.3 Methods of measuring infield variability

The ability to identify spatial and temporal variability is affected by the measurement techniques and sampling strategy adopted. Data to assess infield variability can be collected by discrete physical sampling, continuous sampling or remote sensing (Plant 2001; Sabins 1996; Sadler *et al.* 2000b).

2.1.3.1 Discrete physical sampling

Discrete physical sampling is the traditional method of measuring field data. In this method, the data is collected at representative points (selected on either a random or grid basis) across the entire field. For example, soil cores can be extracted for sampling or plant tissue samples taken for subsequent laboratory analysis (Plant

2001). A random discrete sampling technique is often appropriate for many spatial variability studies (Miller *et al*. 1988). However, this technique may be expensive due to labour, sample analysis costs or time requirements and it may not identify all spatial variability in the field where relatively small numbers of samples are collected (Plant 2001; Senay *et al*. 1998).

Grid based sampling to capture meaningful variations may also be expensive and alternative methods of measuring infield variation (e.g. soil or yield mapping, aerial photography) are useful to target discrete samples in areas requiring characterisation (Sadler *et al*. 1998). However, grid sampling has the risk of interacting with periodic phenomenas such as regularly spaced drains (Plant 2001). Maps based on soil colour from aerial photographs and the farmer's past management experience have also been used to develop sampling strategies for variable rate input applications (Fleming *et al*. 2000).

2.1.3.2 Continuous sampling and proximal sensing

Continuous sampling strategies use either contact or proximal sensors. Examples include on-the-go yield monitoring (Plant 2001), soil moisture or salinity measurement using electromagnetic induction (Al-karadsheh *et al*. 2002; Taylor *et al*. 2003) and measuring crop stress by using thermography (Sadler *et al*. 2000b; Stockle and Dugas 1992).

Yield monitors

Yield monitors provide valuable information for identifying infield spatial variability. Yield data is commonly collected using yield monitors on harvesters. Yield maps have been used to visualise spatial patterns of corn yield (Birrell *et al*. 1996; Schepers *et al*. 2004; Stafford *et al*. 1991).

More reliable yield maps can be obtained by combining multi-year yield maps for the same field (Moore and Wolcott 2000). Multi-year yield maps provide an insight into determining potential management zones, and to identify where yield is low or fluctuating (Diker *et al*. 2004). Yield maps have also been used to select suitable soil sampling intervals and as a basis for selecting management zones (Bourennane *et al*. 2004). However, yield maps provide an indication of past management practices and may not be useful in making future decisions when temporal (i.e. year to year) variability is greater than spatial variation (Eghball and Varvel 1997).

Whichever yield monitoring sensors are used, synthesis of the yield map should consider errors inherent in the yield measurement process (Plant 2001). Errors in yield mapping include: incorrect swath width, the time lag of crop passing through the harvester, crop surges, losses from the harvester, GPS errors and sensor inaccuracy (Blackmore and Marshall 1996). For example, a radiometric yield sensor on a combine harvester produced a 1% grain flow error when a 8 t/ha wheat or barley crop was harvested (Blackmore *et al*. 2003).

Electromagnetic induction

EM38 measures soil electrical conductivity using two coils, one act as a transmitter and the other as a receiver (Figure 2.8). A small current is making to flow in the soil by the transmitting coil for primary electromagnetic field and secondary electromagnetic field is measured by the receiving coil. The ratio of these two signals is used to measure ECa. The higher the soil moisture content the higher will be the value of ECa.

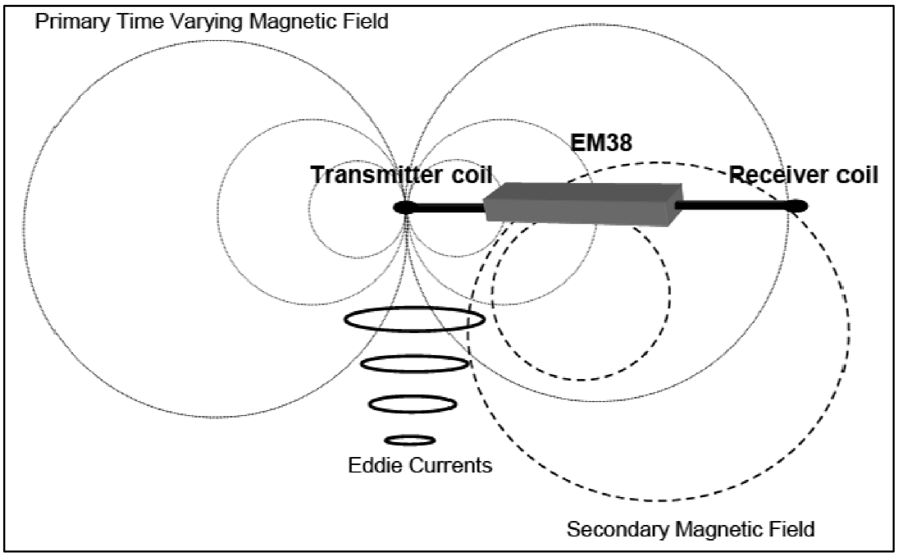


Figure 2.8 The principle of operation of EM38 (Geonics Ltd, Mississauga, Ontario Canada)

Conventional soil sampling methods may be appropriate for the identification of soil differences at specific locations in the field but are unable to demarcate soil boundaries for precision farming. However, electromagnetic induction (EMI) scanning at or near soil-water field capacity has the potential to measure spatial differences in soil physical properties (Earl *et al*. 2003; Hong *et al*. 2002). EMI sensors measure the apparent soil electrical conductivity (ECa) without direct contact between the sensor and the soil. These sensors provide fast, non-destructive measurements of soil ECa and soil-water content and could be used to provide the spatial information required to target the application of production inputs (e.g. water and fertiliser) using variable rate application technology (Figure 2.9) (Al-Karadsheh *et al.* 2002; Plant 2001; Taylor *et al*. 2003).

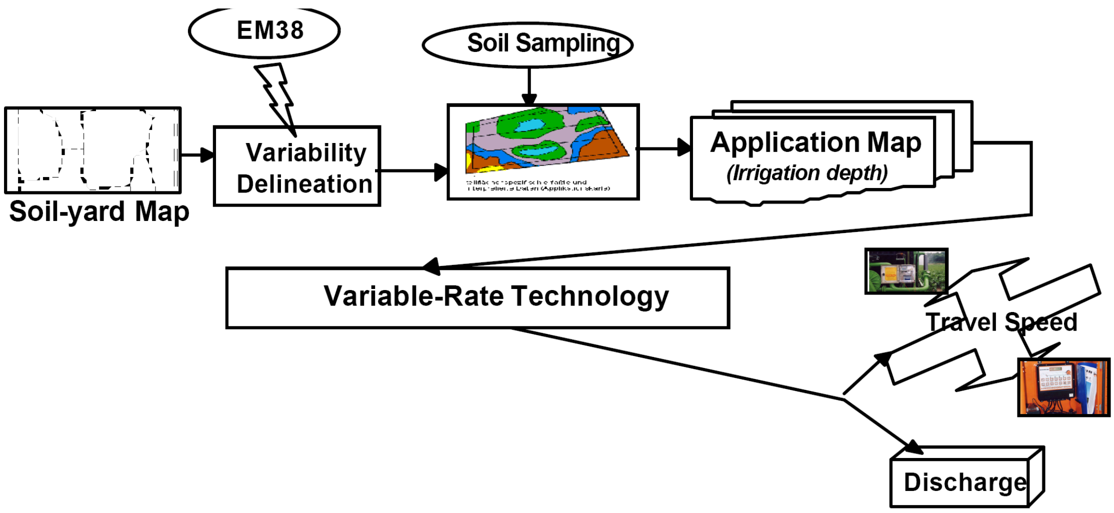


Figure 2.9 Strategy for precision irrigation (Al-Karadsheh *et al.* 2002)

EMI measurements are only useful if directly related to soil or crop features of interest. Strong correlations between ECa and soil-water content have been observed (Figure 2.10) suggesting that ECa measurements may potentially be used for irrigation scheduling (Moore *et al*. 2005; Morgan *et al*. 2000). However, Twombly *et al*. (2004) found only a weak negative correlation between ECa and soil moisture and little direct correlation between ECa and other soil properties. Hanson *et al.* (2000) found a linear relationship between ECa and soil moisture in a saline soil but suggested that specific field calibration was needed for the data to be of use.

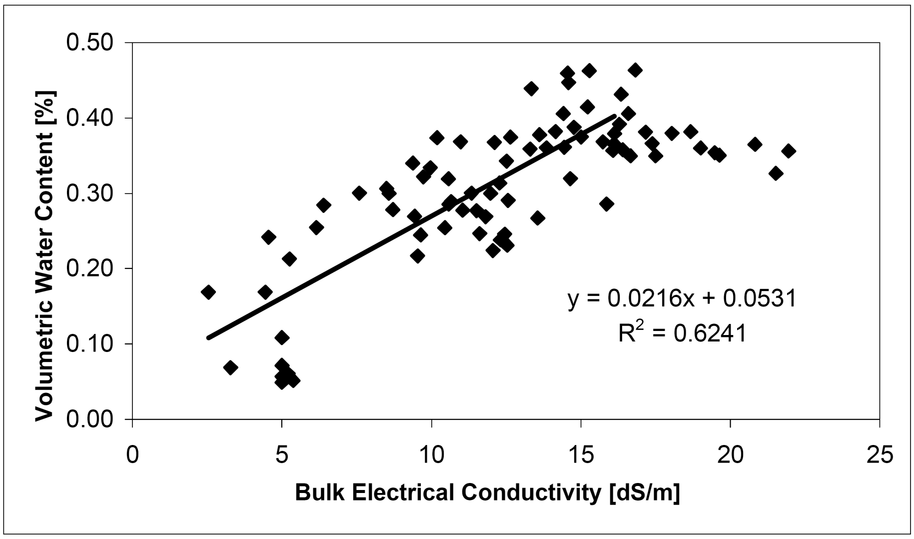
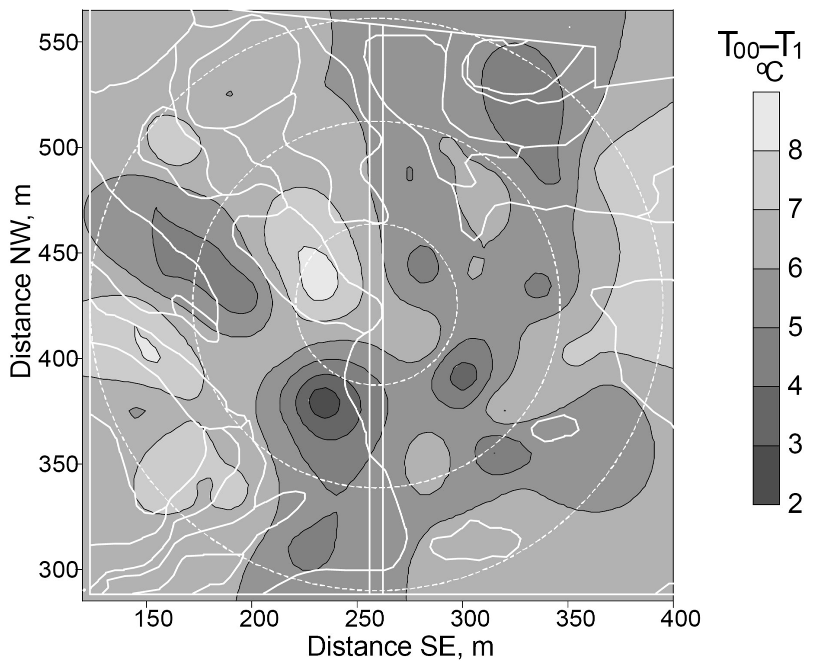


Figure 2.10 Linear response of EM38 to volumetric water content (Morgan *et al.* 2000)

EMI is unable to directly measure specific soil nutrient contents. However, where ECa is shown to be correlated with other soil properties (e.g. soil moisture content, soil texture, cation exchange capacity) ECa differences can be used to infer changes in soil nutrient concentrations (Heiniger *et al*. 2003). ECa has also been found to be positively correlated to the previous year's yield (Bramley 2003; Lund *et al*. 1998) and has been used to identify infield soil variations with over 85% accuracy (Anderson-Cook *et al*. 2002).

Proximal thermography

Crop water stress indices have been widely used for irrigation scheduling purposes (Alves and Pereira 2000; Idso 1982; Jackson *et al*. 1981; Moran *et al*. 1994; Reginato 1983). Infrared thermometer (IRT) measurements of canopy temperature have been used to calculate crop water stress indices (CWSI) (Jackson *et al*. 1981). These measurements have been used to track the development of water stress and provide a reasonable indication of irrigation needs in cotton (Jackson and Ezra 1985; Stockle and Dugas 1992). Soil-water content and canopy air temperature differences have also been found to vary significantly over short distances in corn (Sadler *et al*. 2000b). Arrays of infrared thermometers mounted on a centre pivot in corn have been used to obtain real time measurements (Figure 2.11) (Sadler *et al*. 2002) and may be useful in the management of water and nitrogen application (Camp *et al*. 1998).



Figurre 2.11 Contour map showing differences between mean canopy temperature for dry (0%) and wet plots (150%) of irrigation base rate in corn (Sadler *et al*. 2002)

Although crop water stress indices can provide a useful indication of the need for irrigation, they are less well suited to estimate the amount of irrigation water that is required (Jones 1999; McHugh *et al*. 2008; Stockle and Dugas 1992). The technique can be used as a readily portable system for spot measurements in crops and as a check for routinely measured moisture-based irrigation scheduling (Jones 1999). However, the resolution of IRT has been insufficient to detect small differences between well irrigated crops of cotton, tomato and grass, and the use of IRT to calculate the CWSI or estimate transpiration may not improve efficiency of high frequency irrigation systems such as drip (Ben-Asher *et al*. 1992).

2.1.3.3 Remote sensing

The term remote sensing commonly refers to the methods that employ electromagnetic energy (i.e. light, heat and radio waves) as the means of detecting and measuring target characteristics (Figure 2.12) (SURA 2005). Remote sensing is distinguished from proximal sensing in that remotely sensed data is normally obtained using platforms (e.g. aeroplanes or satellites) that are located well away from the crop. Remotely sensed data collected either by satellite or aircraft can provide low cost, spatially distributed data on plant growth and development (Moran *et al*. 1997; Plant *et al*. 2000). Remote sensing offers a chance to increase quantity and quality of survey data and may be closely correlated with yield data (Figure 2.13) (Lobell *et al*. 2005).

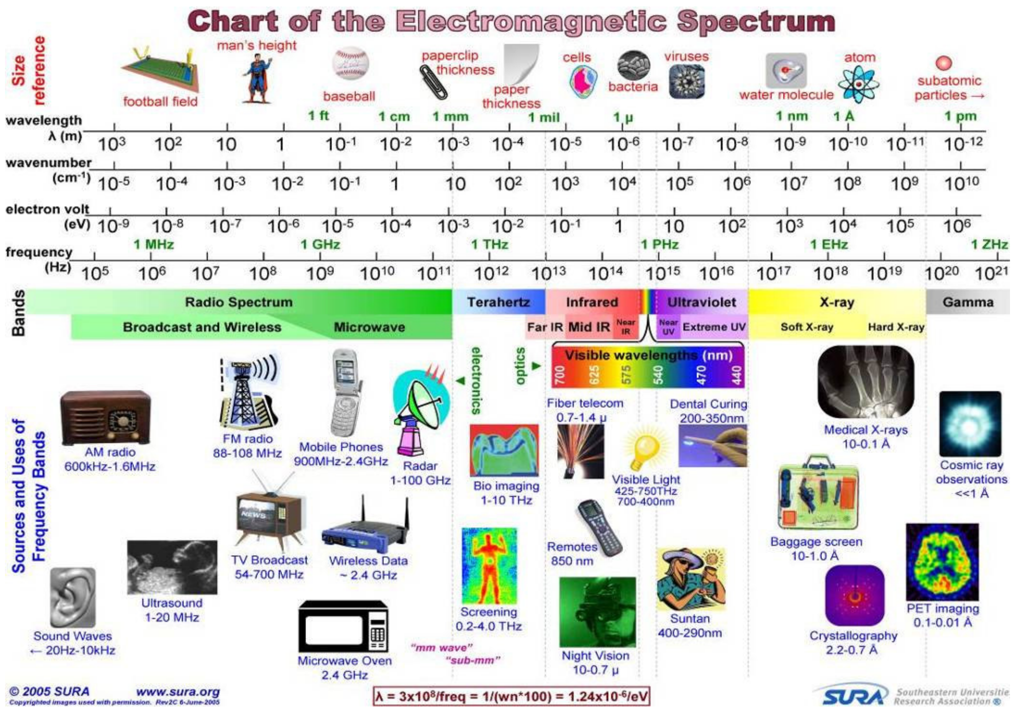


Figure 2.12 Range of frequencies of electromagnetic radiation (SURA 2005)

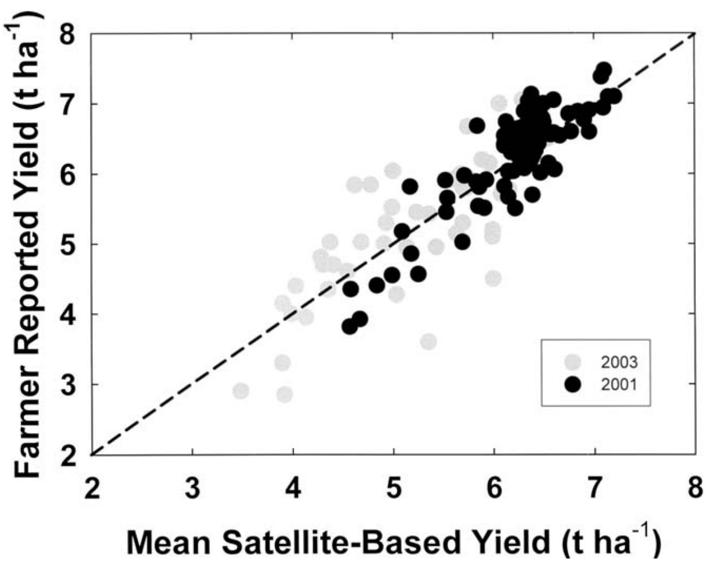


Figure 2.13 Measured and satellite based yield comparison for wheat (Lobell *et al*. 2005)

Reflectance (i.e. the combination of plant canopy and soil surface reflectance) is affected more by ground cover than by plant density or yield (Maas 1997). The normalised difference vegetation index (NDVI) is the most common crop canopy index used in remote sensing (Hall *et al*. 2002; Tucker 1979). NDVI integrated over time has been shown to be well correlated with cotton lint yield and nitrogen stress (Plant *et al*. 2000) as well as crop water stress (Bajwa and Vories 2006). A remote sensing package called the “Agricultural Irrigation Imaging System” uses red, near infrared and thermal infrared measurements to create field images of the crop and has been proposed to assist with irrigation scheduling to increase water use efficiency (Colaizzi *et al*. 2003).

Most research work in remote sensing for agriculture has focused on estimating crop biomass (Bedford *et al*. 1993), nutrient deficiencies and water stress (Penuelas *et al*. 1993), but little effort has been directed at how this information can be used for determining yields (Machado *et al*. 2002b). Theoretical modelling and field studies have shown that cotton canopies can be accurately measured in the red and infrared wavebands (Maas 1998). Aircraft and satellite scanning systems commonly use a single sensor and obtain two dimensional spatial data with nearly negligible time lag. However, significant delay in the delivery of results may occur (Sadler *et al*. 2002). Current satellite based sensors may provide the resolution, timeliness and quality required for many precision crop management operations. In particular, images from aircraft based sensors have a potentially unique role in monitoring seasonally variable crop/soil conditions and time-specific and time-critical crop management (Moran *et al*. 1997). Until recently, for the spatial resolution required in precision farming (10-100 m), satellite data has been of limited usefulness and aircraft platforms has been preferred (Sadler *et al*. 1998).

Aerial photography has also been used to study crop growth and stress (Sadler *et al*. 1998). Aerial photography is the original form of remote sensing and is still widely used (Sabins 1996). Aerial images have been used to assess spatial variability in plant available soil water and soybean yield (Clay *et al*. 2002; Irmak *et al*. 2002), crop nitrogen status (Blackmer *et al*. 1996) and cotton yield (Vellidis *et al*. 2004). Aerial photography itself can not be used to identify the factors responsible for yield variability (Clay *et al*. 2002). Similarly, while the photographs clearly show the resulting yield patterns, these images can not provide the magnitude of variability unless correlated to field measured parameters (Vellidis *et al*. 2004). Magri *et al*. (2005) concluded that aerial image data was correlated to soil organic matter content and in some cases to yield in a maize crop but was not well correlated with other soil fertility indicators.

2.1.4 Analysis techniques for evaluating variability

Characterisation of spatial and temporal variability is important to evaluate the effects of management strategies. The coefficient of variation has been used (Kravchenko *et al*. 2005) to identify significant differences in the infield spatial yield variability of crops due to the effect of management topography or weather. Variograms and trend surfaces of yield data over space and time have also helped to understand the factors responsible for yield variability (Ambuel *et al*. 1994). Variograms using spherical models were found to be more appropriate than Gaussian, exponential, or linear models for spatial studies of soil moisture, nitrogen and herbicide (Chancellor and Goronea 1994). Large and small-scale variations have also been identified using median polishing techniques and variograms (Bakhsh *et al*. 2000).

The primary causes of spatial yield variability have been identified using correlation analysis, classification and regression trees (Plant *et al*. 1999). Huggins and Alderfer (1995) used a multiple regression analysis to evaluate the effect of climate and site properties on crop yield. Heermann *et al*. (2000) used an autoregression spatial model (which is similar to a linear regression model, but corrects for spatial relationships between the observations) to evaluate relationships between yield, water application, weeds, rootworm, soil texture, nutrients, organic matter and pH. The correlations are critical to identify yield variability but interactions between the yield parameters are also important.

Semi-variogram and cross semi-variogram analyses have been used to study the spatial variability of soil properties, corn quality and yield (Miao *et al*. 2006). Quality and yield maps were generated from point data using kriging, co-kriging, inverse distance weighting or radial basis functions available in the geostatistical analysis module of ArcGIS (Miao *et al*. 2006). Schepers *et al*. (2004) applied spatial autocorrelation using variogram models, block kriging and cross validation to study the spatial structure of landscape attributes in irrigated corn. Sadler *et al*. (1998) used co-kriging of yield with semi-variograms to study remotely sensed temperature data. Cross semi-variograms have also proven to be useful relating wheat yield and soil properties on a complex hill slope (Miller *et al*. 1988).

Classical statistical techniques are often inadequate to account for spatial correlations between yield and inputs. For example, regression analysis was found to be inadequate to identify the spatial correlation of soil properties and wheat yield on a complex hill slope (Miller *et al*. 1988). Hence, spatial analysis techniques (e.g. geostatistics, fractal analysis, advanced series analysis) have also been used to study the spatial behaviour of inputs, crop growth and yield (Sadler *et al*. 2000a). Geostatistics, using semi-variogram analysis, was originally designed for use in mining geology, but has been successfully used to study spatial variability in crops (Vauclin *et al*. 1983; Vieira *et al*. 1981). Geostatistical analysis was found (Miller *et al*. 1988) to be more appropriate than simple correlation or multiple regressions for studying the relationships between soil, topography and yield. However, geostatistical results would be expected to apply best within regions very similar to those in which they were obtained (Sadler *et al*. 2000a).

Fractal analysis has also been used to quantify temporal yield variability. Temporal variability greatly influences how spatial variability is expressed in a given field (Eghball and Varvel 1997). Fractal dimension (i.e. slopes of the regression lines of log semi-variogram vs. log lag year) has been found to be small for crops/fields exhibiting little short term variation but large in crops/fields exhibiting large short term variation (Eghball and Power 1995). Multifractal and joint multifactal analysis has also been used to study yield/topography relationships (Kravchenko *et al*. 2000).

Standard or crisp clustering analysis is a more natural indicator of spatio-temporal patterns than correlation and regression analyses for crop rotations (Perez-Quezada *et al*. 2003). However, growth analysis is season dependent and appears more informative in a drought year than in a relatively wet year (Machado *et al*. 2002b). Non-hierarchal cluster analysis was used to study spatial and temporal behaviour of corn over a six year period and reduced the temporal yield data from 224 plots into five contiguous clusters across the field (Jaynes *et al*. 2003).

Temporal analysis of the difference between individual and spatial average values, and Spearman's rank correlation has also been used to reduce a large measurement network to a few representative locations. However, Spearman's rank correlation is questionable if differences between measured values are smaller than experimental uncertainties (Vachaud *et al*. 1985). The general conclusion from the above discussion is that simple statistical approaches including coefficient of variation, correlation analysis, variograms and trend surfaces can be used to adequately identify in-field spatial variability.

2.2 Irrigation systems

Irrigation systems play an important role in efficiently applying water to crops. No single irrigation system and management practice will be appropriate for all growers in all the environments (Raine and Foley 2001). Hence, a wide variety of irrigation systems are commonly used depending on the crops and the environment. The main application systems used for irrigation of horticultural crops in Queensland (Figure 2.14) are microspray (36.6%), drip/trickle (25.3%), solid set (12.4%) and handshift sprinklers (10.2%). A key performance indicator for irrigation application systems is their ability to apply the desired quantity of water uniformly over the irrigated area.

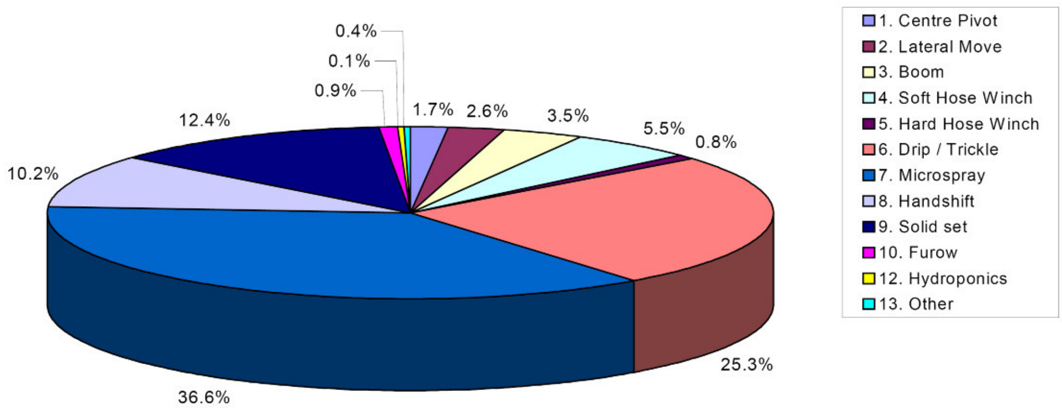


Figure 2.14. Irrigation application systems in the Queensland horticultural industry (Barraclough & Co. 1999)

2.2.1 Uniformity of irrigation applications

Irrigation systems have a major effect on the agronomic and economic variability of crop production mainly due to non-uniform water application. Irrigation application uniformity varies between application systems (Table 2.1). Higher uniformity can usually be expected from overhead sprinkler or micro-irrigation systems. However, water application losses are inevitable with all irrigation systems. For example, major losses under sprinkler systems may be due to evaporation, deep drainage, surface runoff, water leakage from laterals, pipe friction, operating pressures (Hanke *et al*. 2004), faulty or worn sprinkler nozzles (Li and Kawano 1998; Louie and Selker 2000) and spray drift.

Table. 2.1 Irrigation systems and potential whole field distribution uniformities (Burt 1995)

Irrigation system	Potential field DU (%)
Permanent under tree sprinkler	94
Linear move	92
Orchard drip	90
Sloping furrows	89
Level furrows	87
Border strip	85
Row crop drip	90
Hand move sprinkler (w alt. sets)	85
Hand move sprinkler (w/o alt. sets)	75

The most commonly used parameters to evaluate the uniformity of sprinkler systems are Christiansen's (1942) coefficient of uniformity (CU) and distribution uniformity (DU) (Smajstrla *et al*. 1997; Tarjuelo *et al*. 1999; Walker and Skogerboe 1987):

$$CU = (1 - \frac{Average\ deviation\ from\ average\ depth\ of\ application}{Overall\ average\ depth\ of\ application})100$$

$$DU = (\frac{Average\ low\ quarter\ depth\ of\ application}{Overall\ average\ depth\ of\ application})100$$

Low uniformity may be associated with a range of problems but most commonly is due to inappropriate sprinkler selection, sprinkler and lateral spacings, pressure differences along the laterals or operating the system under inappropriate conditions (e.g. high wind) (Raine 1999). Low uniformity may also be attributed to worn emitters and blockages. Martin-Benito *et al*. (1992) demonstrated that sprinkler uniformity (a) decreased as the wind speed increased, (b) was higher with triangular sprinkler layouts compared to square or rectangle sprinkler layouts and (c) improved with the use of two nozzles instead of one on each sprinkler. Dechmi *et al*. (2003) also found high variability between the uniformity and water applied to consecutive irrigation events due to differences in wind speed (Figure 2.15). To achieve high uniformity, it is generally recommended that sprinklers should be spaced at approximately 60% of the wetted diameter but that the spacing should be reduced to 30% of the wetted diameter for wind speeds of >16 km/hr (Jensen 1983). The sprinkler spacing to wetted diameter ratio for fixed plate, low drift nozzle sprinklers used on centre pivot and linear move irrigation machines should not exceed 0.20 in order to achieve a CU > 90% (Clark *et al*. 2003). The water pressure in sprinkler irrigation systems has a significant role in the uniformity of application (Hanke *et al*. 2004; Mateos 1998). Operating pressures of greater than 400 kPa in solid set systems have higher operating costs and produce small-size droplets subject to evaporation and drift. Therefore, the sprinklers should be operated to the designed pressure and adequate maintenance also required for a consistently uniform pressure and flow rate.

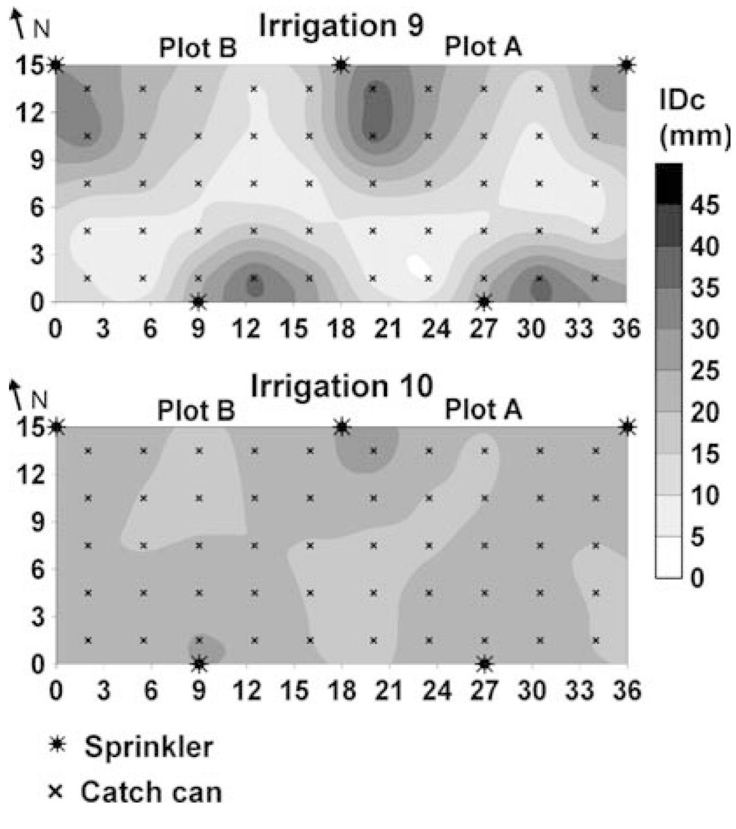


Figure 2.15 Contour map of irrigation depths for two consecutive irrigations applied at (a) 5.3 ms^{-1} and (b) 1.2 ms^{-1} wind speed (Dechmi *et al.* 2003)

2.2.2 Variation in irrigation application and uniformity during the crop season

Sprinkler irrigation performance has been found to vary from irrigation to irrigation during the season. For example, a large variability in both water application and uniformity was observed throughout the season for a solid set sprinkler system irrigating corn (Martinez *et al*. 2003) (Table 2.2). Similarly, the water distribution uniformity for hand moved sprinklers operating under different sprinkler pressures and wind speeds varied from 63.4 to 91.9% during a sugar beet and bean season (Topak *et al*. 2005). There is also significant difference in the variations in uniformity measured in different locations within the field (Mateos 2006). Day-time irrigations of a solid set irrigation system had a mean Christiansen coefficient of uniformity that was 5 to 7% lower than for night-time irrigations (Cavero *et al*. 2008). The spatial variability of water application under a sprinkler system has been found to be higher than the spatial variability of infiltrated water (Mateos *et al*. 1997).

Table 2.2 Irrigation distribution and uniformity for corn (Martinez *et al*. 2003)

Irrigation date	Experimental Plot 1			Experimental Plot 2		
	Water application depth (mm)	Distribution uniformity (DU) (%)	Coefficient of Uniformity (UC) (%)	Water application depth (mm)	Distribution uniformity (DU) (%)	Coefficient of Uniformity (UC) (%)
30/06/01	26.0	65.6	79.6	19.6	72.7	81.7
02/07/01	11.8	72.1	81.9	10.1	76.7	87.0
06/07/01	44.0	58.7	72.4	41.3	78.8	85.6
13/07/01	44.9	63.5	77.8	42.4	73.1	83.0
20/07/01	47.1	68.6	78.0	45.9	59.0	72.6
27/07/01	43.5	76.6	83.8	41.8	71.4	81.2
03/08/01	34.5	66.9	76.5	32.2	63.9	75.7
10/08/01	52.9	60.1	73.9	52.6	64.4	80.2
17/08/01	38.5	59.1	71.0	35.1	53.6	71.0
24/08/01	29.4	57.7	70.6	27.1	53.0	68.5
31/08/01	26.0	56.3	70.1	24.0	52.5	70.7

2.2.3 Effect of non-uniform irrigation application on crop yield

Soil-water availability is a major determinant of crop yield and is often correlated with the uniformity of irrigation applications. Uneven watering has been found to affect crop growth for a range of crops including corn (Heermann *et al*. 2000), citrus (Figure 2.16) (Dagan 2002), cotton (Dalton *et al*. 2001; Milroy and Tennakoon 2002), maize (Dechmi *et al*. 2003), sugarcane (Baillie 2004), sugarbeet (Ucan and Gencoglan 2004), cauliflower (Figure 2.17) and lettuce (Barber and Raine 2002).

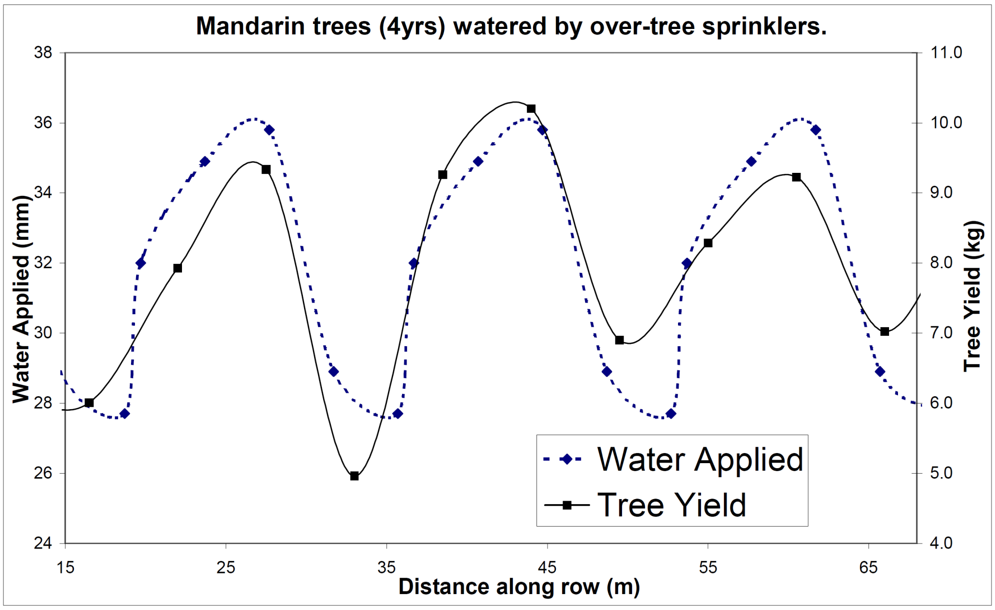


Figure 2.16 Yield variation caused by uneven sprinkler watering of mandarin trees (Dagan 2002)

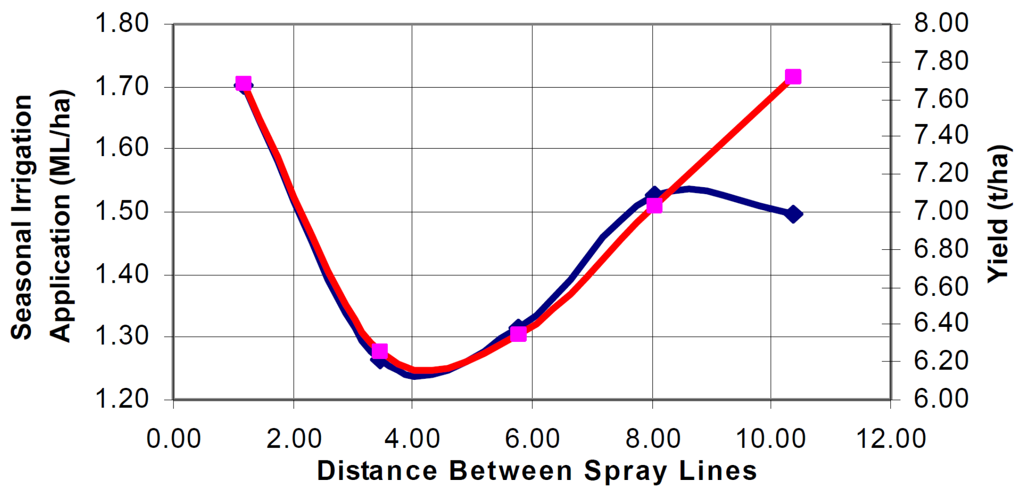


Figure 2.17 Variation in irrigation application and cauliflower yield between sprinkler irrigation laterals (Barber and Raine 2002)

As the uniformity of water application decreases there is an increasing range of water and fertigation volumes applied within the irrigated area (Figure 2.18) (Li and Rao 2003) and a consequent reduction in overall yield. For example, Baillie (2004) reported that sugarcane yield decreased by 8% for every 10% reduction in CU under a travelling gun irrigation system in the Bundaberg region of Queensland (Figure 2.19). Hence, it is generally accepted that increasing the uniformity of the irrigation will increase the total yield achieved. However, improvements in irrigation application system uniformity often require additional investment on capital infrastructure or operating costs (Raine 1999) and do not always produce yield or economic benefits. For example, Rezende *et al.* (2000) findings demonstrate the inbuilt mechanisms of plants and their resilience to stress and reported that improving CU from 58% to 86% increased bean yield from 1501 to 2759 kg ha^{-1} but increasing the CU further to 94% reduced the yield to 2333 kg ha^{-1}. In this case, Rezende *et al.* (2000) suggested that vegetative growth was more affected by irrigation uniformity than grain yield.

(a)

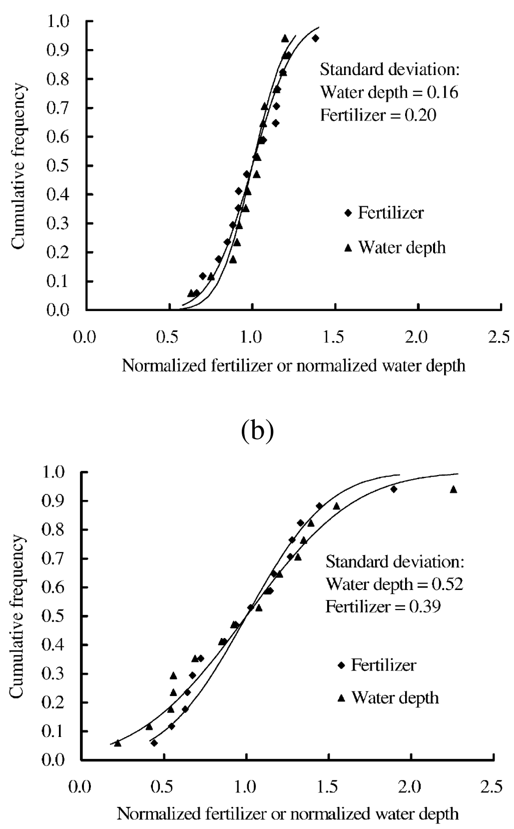


Figure 2.18 Cumulative frequency distributions for fertiliser and water application when the CU is (a) 88% and (b) 59% (Li and Rao 2003)

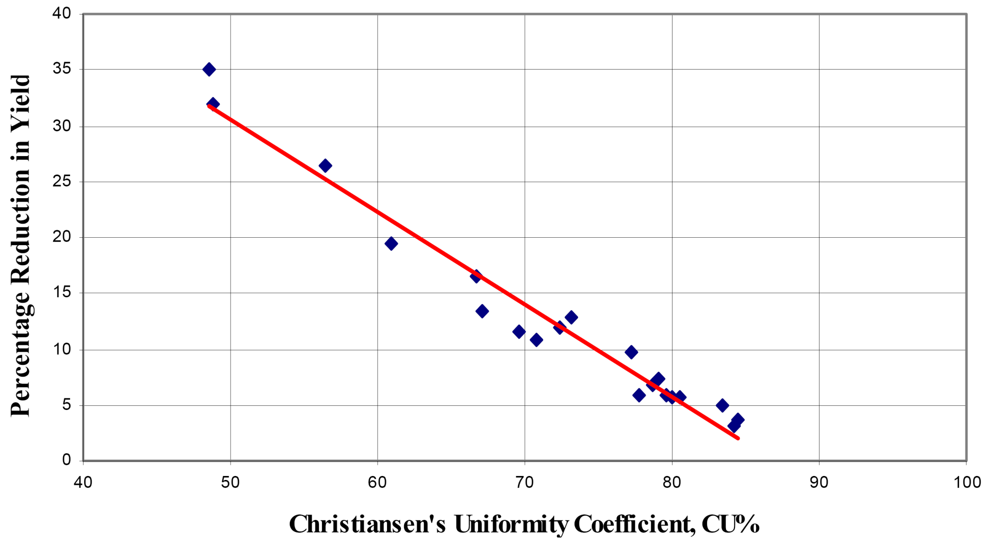


Figure 2.19 Reduction in sugarcane yield due to non-uniformity of travelling gun (Baillie 2004)

2.2.4 Effect of in-season rainfall

The effect on yield of non-uniform applications is also a function of the total irrigation water applied and rainfall. Optimal irrigation management not only requires the appropriate knowledge of the irrigation system but also needs environmental knowledge as some of the crop water requirement may be met by the rainfall. Mateos *et al.* (1997) applied 260 and 400 mm of water at a CU of 80% and 52% and concluded that cotton yield under these conditions was not affected by either the uniformity or the amount of water applied. However, Stern and Bresler (1983) found that for an irrigation system applying a CU of 85%, a seasonal irrigation application of 200 mm produced a 10% yield decrease while 400 mm produced a yield decrease of only 2%. Hence, the impact of non-uniform irrigation application appears to be dependent on the crop response to water, underlying environmental (e.g. soil, topography) variation, seasonal climatic characteristics and the irrigation management (e.g. volume and timing of water applied).

The effect of irrigation non-uniformity on yield variability may be minimised by in-season rainfall. Significant amounts of frequent rainfall during the season will likely fill the soil profile uniformly across the field. Hence, irrigation uniformity will be more important in drier areas and where the crop is sensitive to water stress. Rainfall distribution and intensity affected spatial and temporal patterns of millet yield

(Rockstrom *et al*. 1999). Chen *et al*. (2004) concluded that more rainfall caused corn yield to increase while also decreasing yield variability across the field. Under centre pivot irrigation, higher rainfall in 1999 reduced the spatial variation in corn grain yield when compared to 1998 (Machado *et al.* 2002b). The presence of rainfall has been found to increase sugarcane stalk growth (Figure 2.20) under surface irrigation (Attard *et al.* 2003).

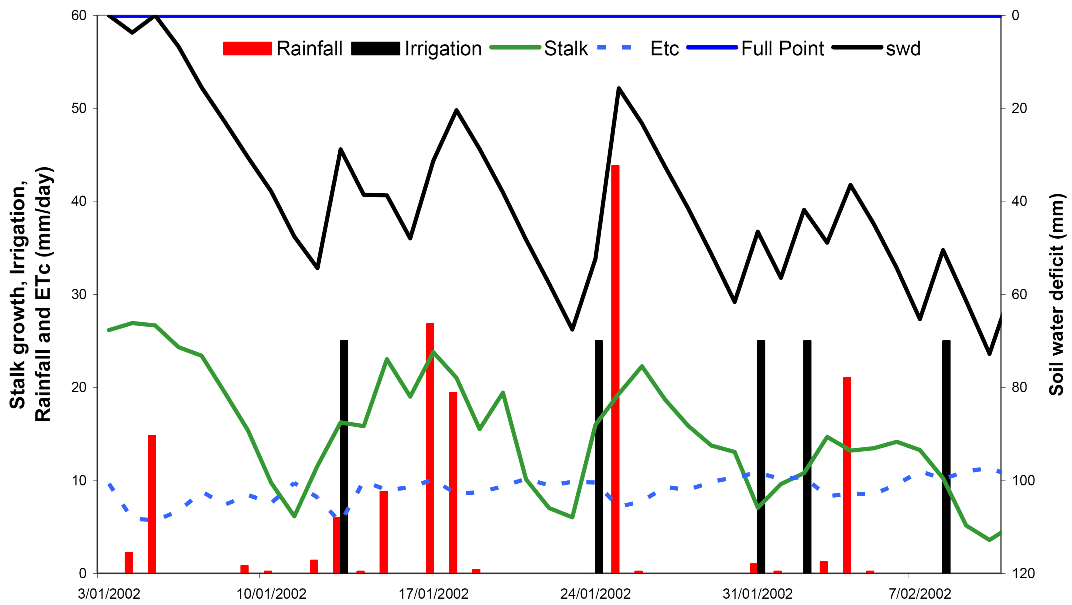


Figure 2.20 Sugarcane stalk growth in the Burdekin (Attard *et al.* 2003)

2.3 Lettuce production in Southern Queensland

Vegetables are a major contributor to irrigated agricultural production in Australia consuming 455 GL of water (ABS 2006). The lettuce (*Lactuca sativa*) industry is one of the largest vegetable production industries with a gross value of approximately $174 million (AUSVEG 2007). Approximately 7,559 ha of lettuce is planted annually producing an average of 23.7 tones/ha (Figure 2.21). In Queensland, the lettuce is primarily produced in the Lockyer Valley, southern highlands and eastern Darling Downs (Heisswolf *et al.* 1997). A wide variety of lettuce are produced including crisphead (iceberg), romaine (cos), looseleaf and butter head. Lettuce is grown on a wide range of soil types ranging from light sandy to heavy clay loams (Dimsey and Vujovic 2005). Lettuce are generally established using transplants with 3-4 rows per bed and a plant population of about 60,000 plants/ha (Napier 2004).

Solid set sprinkler irrigation systems are commonly used by lettuce growers in Australia (Barraclough and Co 1999). Lettuce is a shallow rooted crop and 85% of water uptake occurs from <20 cm of soil profile (Heisswolf *et al*. 1997). The lettuce crop is susceptible to water stress and uniform distribution of irrigation water is necessary to ensure the areas are not over or under irrigated. However, very little information is available on the spatial variability (i.e. uniformity) of irrigation application and its impact on lettuce growth and economic returns.

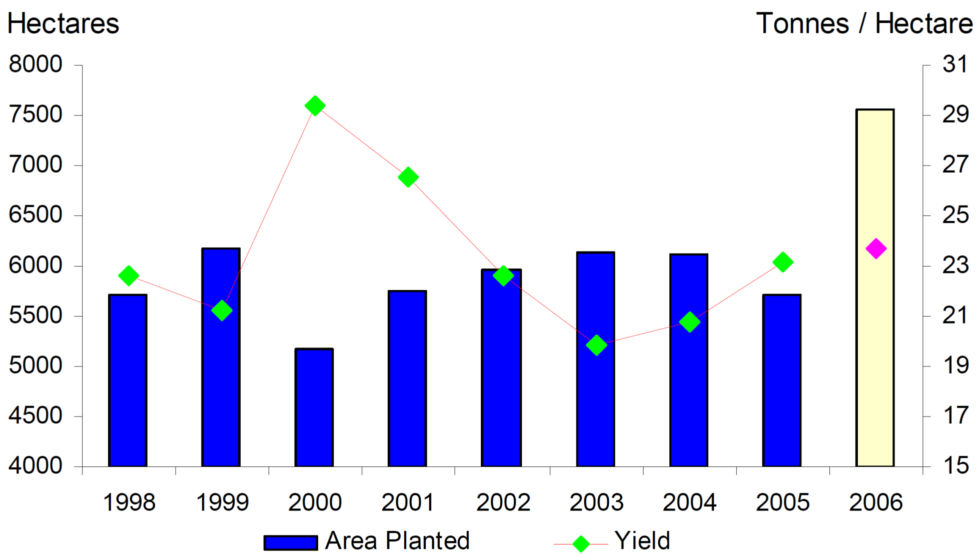


Figure 2.21 Lettuce area planted and yield in Australia 2007 (AUSVEG 2007)

2.4 Optimising irrigation uniformity

2.4.1 Differences between crops

The effect of irrigation uniformity on crop growth and yield is a function of the crop response to water stress. For example, horticultural crops are often more sensitive to water stress than broadacre crops (e.g. cotton, wheat and sorghum). Cotton yield was not affected either by uniformity or by the amount of water applied (Mateos *et al*. 1997). Similarly, Li and Rao (2001) observed that sprinkler irrigation uniformity was not related to wheat yield. However, a sprinkler system with CU of 86% produced a higher bean grain yield than CU of 58, 66 and 94% (Rezende *et al*. 2000).

Increasing irrigation uniformity and reducing the applied volumes increased production in an alfalfa crop irrigated by solid set sprinklers (Montazar and Sadeghi 2008). Corn yield are only marginally affected between CU = 90 and 100% while CU = 75% causes a reduction in yield and an increase in nitrogen leaching (Pang *et al.* 1997). Yields of onion appear to be more related to irrigation method than application efficiency (Figure 2.22) (Al-Jamal *et al.* 2001).

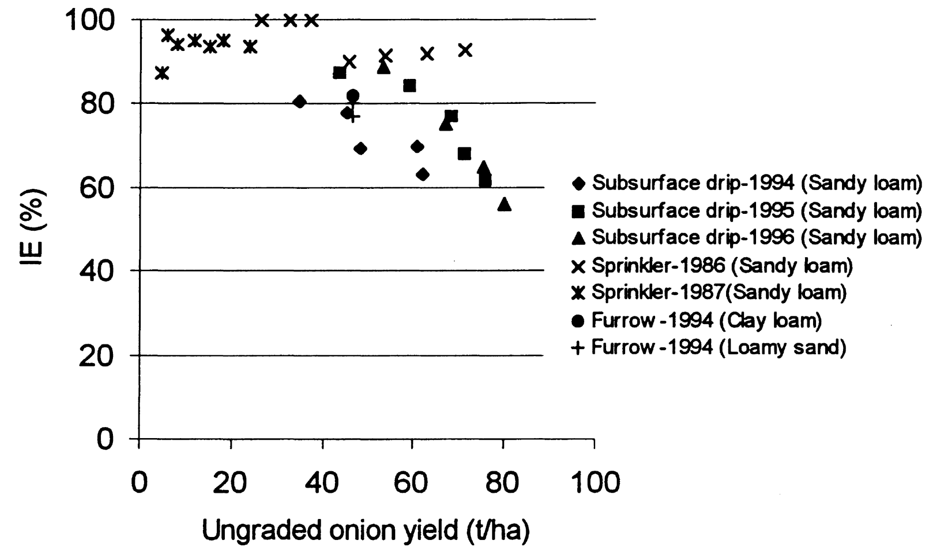


Figure 2.22 Relationships between irrigation efficiency and onion yield for different irrigation systems and soils (Al-Jamal *et al.* 2001)

2.4.2 Effect of irrigation performance on economic returns

The decision to improve the uniformity of an existing commercial irrigation system will be a function of the economic benefits associated with the system conversion. The costs and benefits are commonly evaluated by a gross margin analysis. In this analysis, the optimal performance maximises the net return rather than the crop yield. For example, Alvarez *et al.* (2004) evaluated the gross marginal benefit (Table 2.3) of improving irrigation uniformity for four crops (barley, garlic, maize and onion) under solid set sprinkler irrigation. The crop response functions generally plateau with increasing water application (Figure 2.23) but a small yield penalty was imposed for excessive water application. Hence, the gross margin was generally smaller with low uniformity systems for the same volume of water application. The optimum level of water application also decreased with increasing uniformity (Table 2.3).

Table 2.3 Gross margin (€/ha) under different irrigation uniformities (Alvarez *et al.* 2004)

Crop	CU (%)	Optimum depth (mm)	Gross margin (€/ha)	Water economic profitability (€/m³)	ET_a/ET_m
Barley	75	0.0	254.3	—	0.43
	80	0.0	254.3	—	0.43
	85	0.0	254.3	—	0.43
	90	271.5	282.5	0.10	0.82
Garlic	75	570.2	2345.1	0.41	0.94
	80	521.8	2478.0	0.47	0.95
	85	470.3	2599.3	0.55	0.96
	90	427.1	2703.2	0.63	0.98
Maize	75	623.6	477.6	0.08	0.90
	80	592.8	532.7	0.09	0.92
	85	577.5	574.6	0.10	0.94
	90	542.4	700.2	0.13	0.96
Onion	75	789.6	2072.1	0.26	0.95
	80	749.7	2207.3	0.29	0.96
	85	674.3	2302.5	0.34	0.97
	90	599.8	2474.2	0.41	0.98

(a) (b)

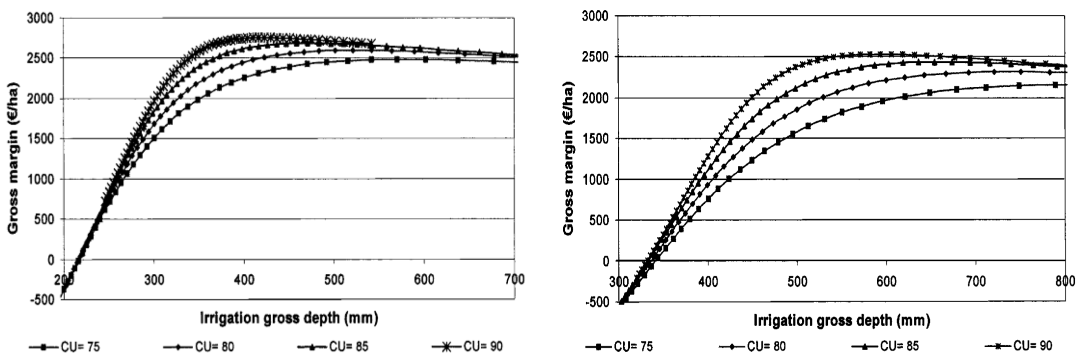


Figure 2.23 Relationships between irrigation application uniformity and gross margin for (a) garlic and (b) onion crop (Alvarez *et al.* 2004)

Brennan (2008) evaluated the interaction of water application and irrigation uniformity on the economic returns of lettuce (Figure 2.24). This work suggests that there are economic benefits associated with improving irrigation uniformity. However, depending on the crop responses to water, data presented by Brennan

(2008) suggests that a sensible risk management strategy to obtain the same gross margins involves increasing the volume of water applied. This raises uncertainty over the identification of optimal irrigation uniformity targets for irrigation design and has implications for the success of irrigation extension programmes focused primarily on system performance improvements.

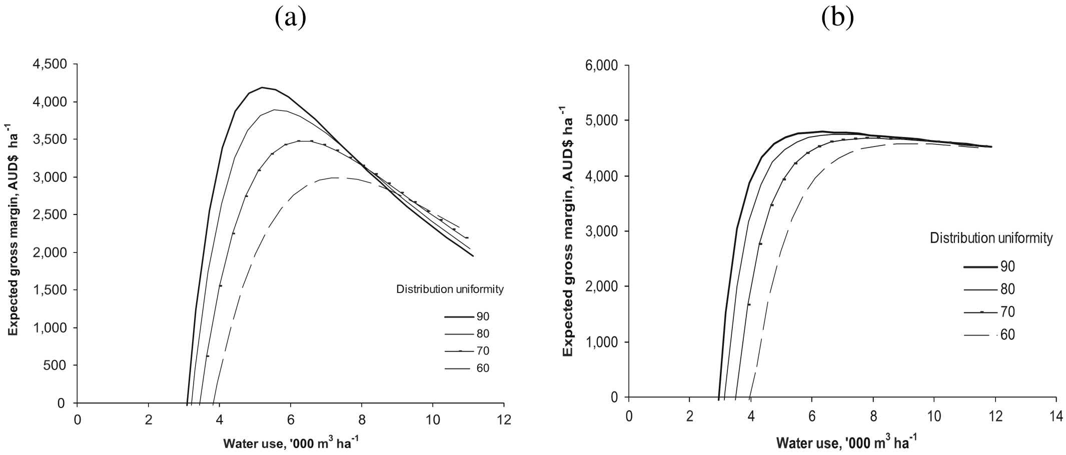


Figure 2.24 Effect of water application and irrigation uniformity on economic returns of lettuce using (a) declining and (b) plateau yield functions (Brennan 2008)

2.5 Conclusions and specific objectives for this project

The main conclusions drawn from this review are:

- There is often significant temporal and spatial yield variability in crops within irrigated fields.
- Physical measurements of irrigation performance and crop responses at large scale are time consuming and resource intensive. However, there are a range of proximal and remote sensing options which could be used to evaluate irrigation and crop responses.
- There are a wide range of factors influencing yield variability but it would appear that soil-water and irrigation application (timing, volume and spatial uniformity) are major contributors of infield yield variability.
- Significant non-uniformity in irrigation application often exists which may affect yield, particularly if in-season rain does not occur and/or if application volumes are yield limiting.

- Maximising profitability will require the identification of the optimal irrigation uniformity for the crop, irrigation management and environmental conditions.

However, it is not clear how these factors quantitatively interact to affect irrigation design and management options for high value horticultural crops. Hence, the specific objectives of this research are to:

1. Quantify the spatial yield/quality variability in an irrigated horticultural crop under specific irrigation design, management and environmental conditions (Chapter 3).
2. Evaluate the potential to use proximal and remote sensors for spatial crop (Chapter 5) and soil-water (Chapter 6) measurements as part of irrigation performance evaluations.
3. Identify variations in the seasonal pattern of water application and the resultant effect on soil-water (Chapter 7) and crop growth response (Chapter 8).
4. Evaluate the agronomic and economic benefits of improving the irrigation uniformity for a range of environmental conditions (Chapter 9).

Chapter 3. Preliminary evaluation of the relationships between irrigation application uniformity and yield for a commercial lettuce farm

3.1 Introduction

The literature review (Chapter 2) identified that the uniformity of irrigation applications is a key determinant of crop yield and profitability. However, the optimal level of uniformity is also a function of a range of factors including in-season rainfall, soil, irrigation scheduling practice and crop sensitivity and returns. Barber and Raine (2002) identified that the design of solid set sprinkler irrigation systems in the Lockyer Valley, Queensland, resulted in low application uniformity. However, after five years of local extension programme promoting the benefits of improved irrigation system design there is little evidence that growers in this area are adopting more uniform irrigation application systems. There is also some debate over the benefits of improved irrigation uniformity for the commercial production of lettuce in this area (Henderson, C 2006, pers. comm., 10 April). Hence, a preliminary trial was conducted to evaluate the effect of non-uniform irrigation applications on lettuce growth under commercial conditions. Lettuce was chosen as it is a major crop in the region, has a short growing season and was expected to be sensitive to irrigated water applications.

3.2 Methodology

This preliminary trial was conducted on a commercial lettuce farm in the Lockyer Valley, Queensland. Lettuce (cv. Iceberg) had already been planted on raised beds with four rows per bed. The crop was transplanted on the 12/4/06 and managed according to commercial practices by the grower. A solid set sprinkler irrigation system was used and the sprinklers were arranged in a 9 × 13.5 m triangular pattern (Figure 3.1). The timing of irrigation applications throughout the season were determined by the grower using visual observations of the crop and soil. Approximately 25 mm was normally applied in each irrigation event. The potential evapotranspiration (ETo) ranged from 2.9 to 5.3 mm/day and there were only two rainfall events (5 and 8 mm each) during the growing season. Irrigation performance

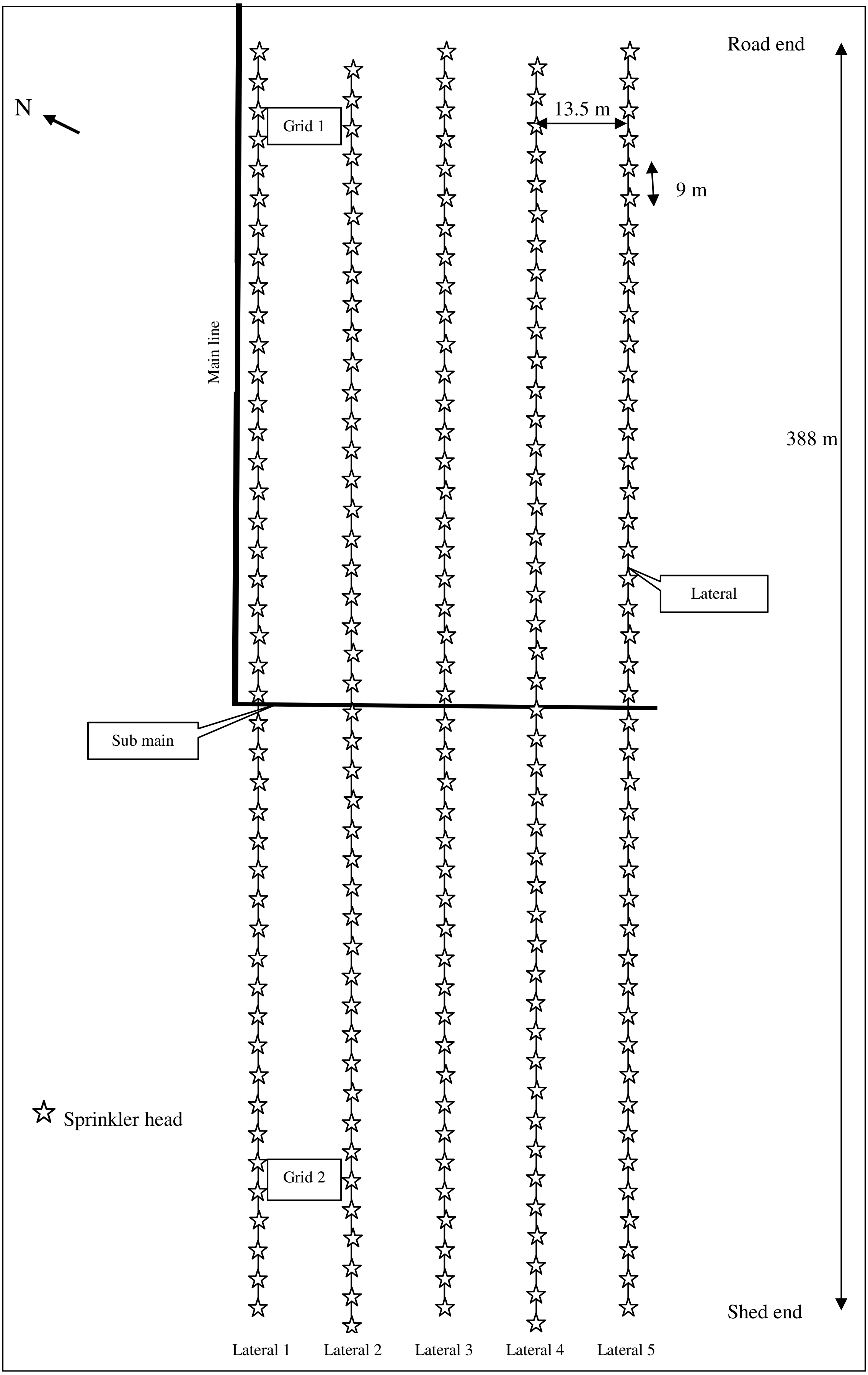


Figure 3.1 Schematic layout of the preliminary trial site (not to scale)

was measured on two irrigation dates (29/5/06 & 8/6/06) late in the season. The operating pressure and discharge rate of selected sprinklers were measured. Two catch can grids (9 × 13.5 m) were established between two laterals at each end of the field (approximately 320 m apart). The catch can data was used to identify the minimum, maximum and average depth of applied water and to calculate the uniformity of the applications. The diameters of four lettuce heads around each can in each grid were physically measured on the 8/6/06 (Figure 3.2).

Figure 3.2 Physical measurement of lettuce head diameter

3.3 Results and discussion

Substantial variations in sprinkler operating pressure (Figure 3.3) and discharge (Table 3.1) were observed both along laterals and between adjacent laterals. The highest pressure was found immediately adjacent to the sub-main and generally decreased with increasing distance along the sub-main and lateral. The pressure was also affected by field topography with lower pressures measured at the shed end of the field (approximately 1 m higher than at the road end). Sprinkler discharge varied from 0.07 to 0.14 L s^{-1}. However, differences in discharge were poorly related to location along the lateral (Table 3.1) suggesting that nozzle wear and/or leakage may have been the dominant factor affecting sprinkler discharge in this system.

The coefficient of uniformity of irrigation applications for the two measured grids was greater than 80% (Table 3.2). However, the range of point measured (i.e. catch can) water applications ranged from 16 to 54.5 mm (target = 25 mm) for the

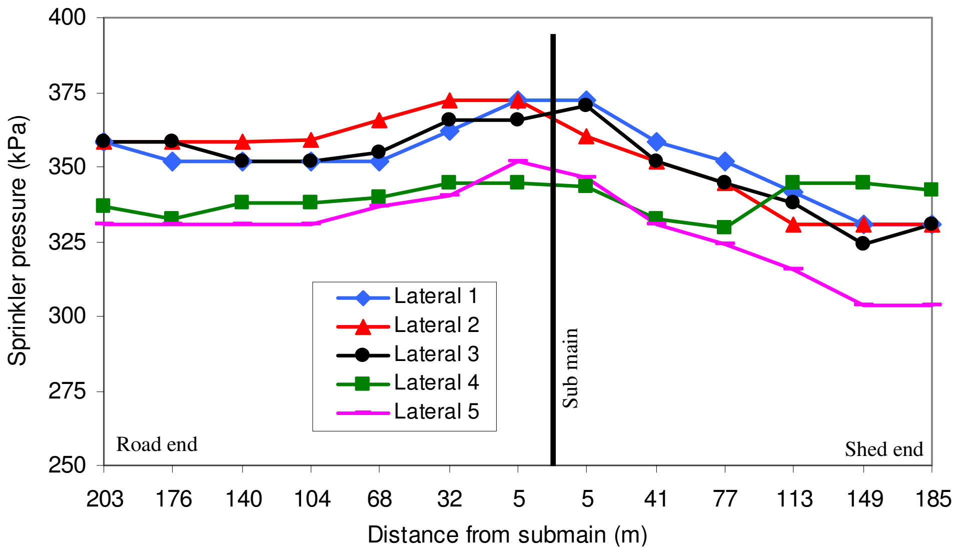


Figure 3.3 Sprinkler operating pressure measured on the 18/5/06

Table 3.1 Selected sprinkler discharge rates (L s^{-1}) on the 18/5/06

Sprinkler number	**Lateral number**				
	L1	**L2**	**L3**	**L4**	**L5**
Road end					
1	0.13	0.13	0.12	0.13	0.14
4	-	0.07	-	-	-
7	-	0.13	-	-	-
10	-	0.11	-	-	-
13	-	0.11	-	-	-
16	-	0.14	-	-	-
19	-	0.11	-	-	-
23	-	0.11	-	-	-
27	-	0.10	-	-	-
31	-	0.12	-	-	-
35	-	0.10	-	-	-
39	-	0.10	-	-	-
44	-	-	-	0.10	0.11
Shed end					

irrigation on the 29/5/06 and 5.3 to 15.9 mm (target = 9 mm) on the 8/6/06. The patterns of water application were similar between grids with more water generally being applied close to the sprinklers (Figures 3.4 and 3.5). While the depth of water applied at each point in both irrigations was reasonably well correlated for the shed end grid (R^2 = 0.73), it was not well correlated (R^2 = 0.21) for the road end grid.

This suggests that while the general pattern of water application may be consistent between irrigations, small changes in the pattern (possibly due to wind or operating conditions) may have a substantial effect on the depth of water applied to particular plants.

Table 3.2 Performance of the irrigation application measured using catch can grids

Irrigation		Coefficient of uniformity (CU) (%)	Distribution uniformity (DU) (%)	Application depths (mm)	
				Mean	Range
29/5/06	Road end	87	82	25.2	18.6-39.8
	Shed end	83	75	26.7	16.0-54.5
8/6/06	Road end	89	83	8.4	5.3-11.8
	Shed end	83	76	9.6	6.1-15.9

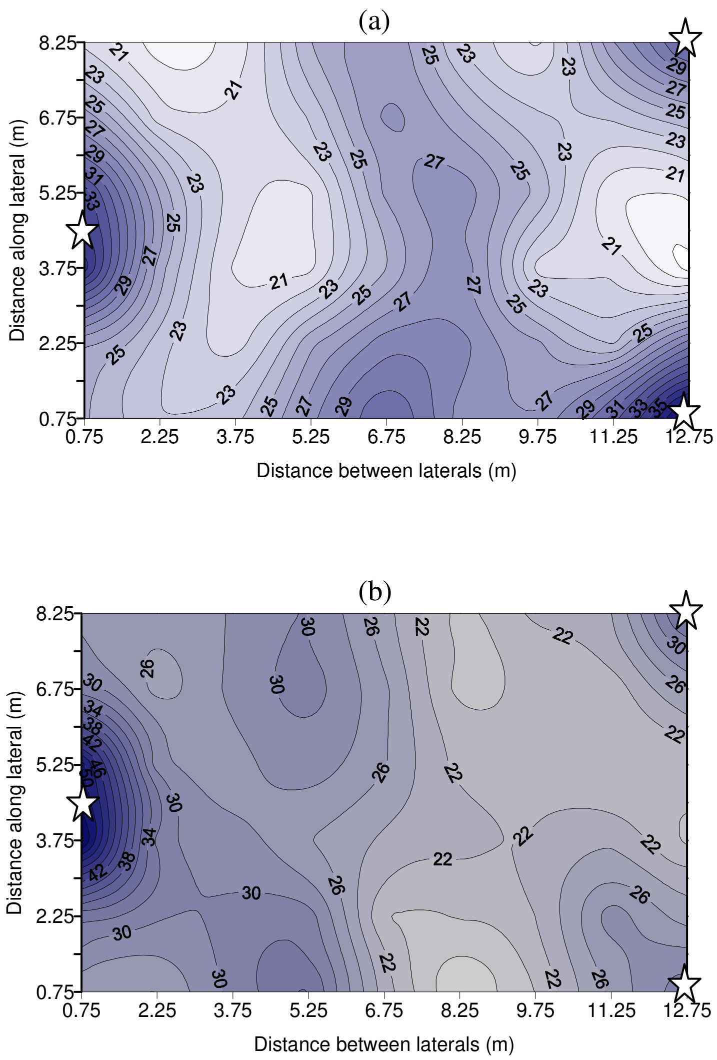


Figure 3.4 Pattern of water application (mm) for (a) road end and (b) shed end grid measured on the 29/5/06

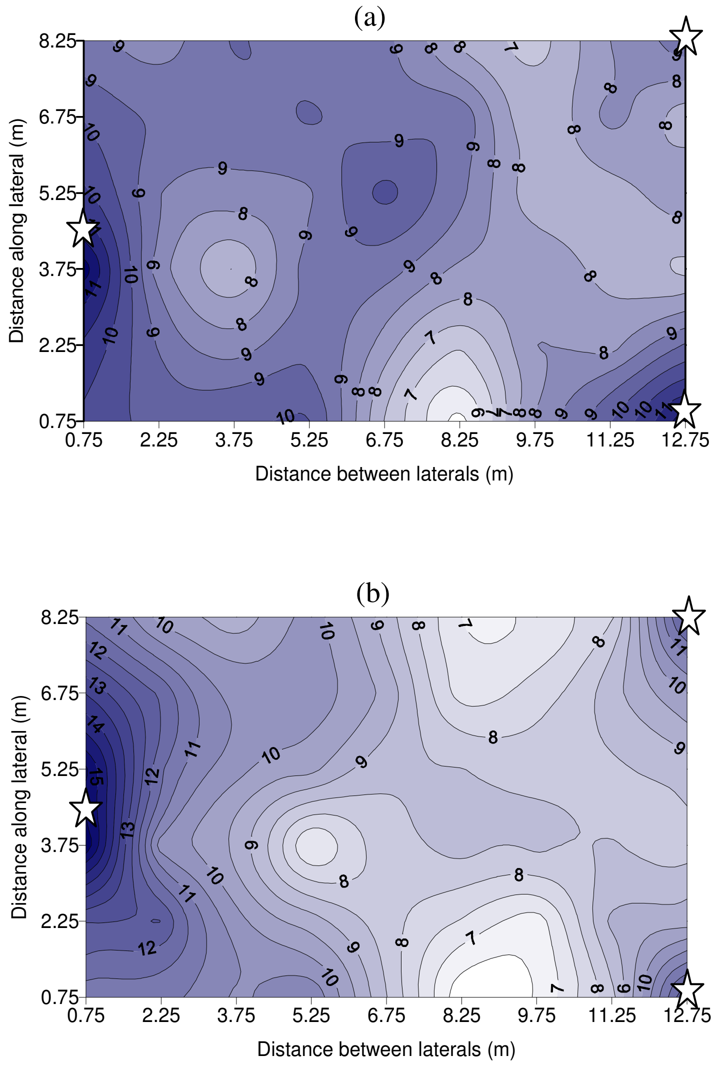


Figure 3.5 Pattern of water application (mm) for (a) road end and (b) shed end grid measured on the 8/6/06

There were substantial variations in the size of lettuce heads measured within the grids (Figure 3.6). However, there was no significant relationship (R^2 = 0.1) found between the normalised water application measured by the catch cans and the average lettuce head size around each catch can. This is contrary to the findings of earlier work (e.g. Barber and Raine 2002) and suggests that a range of factors may have influenced crop growth and reduced the impact of irrigation non-uniformity. Possible factors which may have masked this relationship include the:

- Shape of the specific lettuce variety/cultivar crop production function and the sensitivity of the harvested component to differences in water application within the ranges applied;

- Irrigation management practices (including the frequency and volume of applications) leading to over and under irrigation;
- Inconsistent patterns within grids of irrigation application throughout the season due to either management (e.g. pressure) or environmental (e.g. wind speed/direction) variables;
- Non-uniform fertiliser application and management practices;
- Presence of genetic variation within the crop population; and
- Occurrence of in-season or pre-season stored rainfall (including number of events, timing and volumes applied).

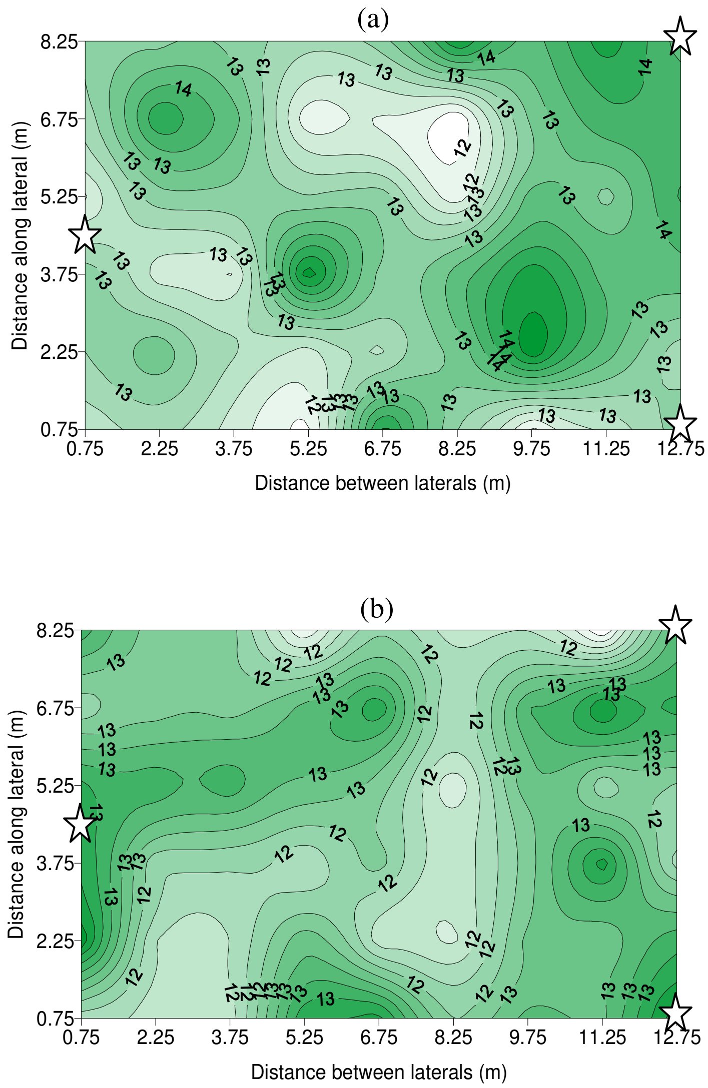


Figure 3.6 Variability of the lettuce head diameter (cm) for (a) road end and (b) shed end grid

Hence, to understand the importance of irrigation uniformity on production and returns at the field scale it is necessary to understand the role of these and other factors in crop growth and the economic returns associated with irrigation system improvements. As it is difficult to separate the role of these factors under commercial operating conditions, the next phase of this research will need to be investigated under more controlled trial conditions.

These trials also reinforced both the labour and time intensive nature of individual plant growth measurements and catch can trials (Section 2.1.3.1). This restricts irrigation performance evaluations to grid samples which can only be conducted in small areas of the field. Extrapolating this grid data to whole field performance is difficult due to the variations in sprinkler pressure and discharge across the field. Hence, there is a need to also evaluate sensing technologies to more rapidly measure the uniformity of irrigation applications and crop growth responses at the field scale.

3.4 Conclusions

The uniformity of the commercial irrigation applications measured on two sprinkler grids using catch cans was high but a three-fold variation in the volume of water applied at specific locations was measured within individual irrigation events. Substantial variations in sprinkler operating pressure and discharge across the field were also measured. However, the volume of irrigated water application measured within the grids was not correlated to lettuce head size suggesting that a range of other factors also influence crop growth. The labour and time intensive nature of individual plant and catch can grid measurements restricts the ability to adequately evaluate irrigation performance and crop responses at field scales. Hence, there is a need to (a) evaluate the potential to use alternative measurements for more rapid assessment of plant growth and irrigation uniformity at larger spatial scale, (b) conduct field trials under more controlled conditions to better understand the role of irrigation uniformity on crop production and (c) evaluate the economic benefits of irrigation uniformity improvement under commercial conditions.

Chapter 4. Common materials and methods for the experimental field trials

4.1 Introduction

The literature review (chapter 2) highlighted that many factors influence the optimal uniformity of the application system. However, the preliminary evaluation of the relationship between irrigation uniformity and lettuce growth (Chapter 3) showed that crop yield can be quite uniform even when irrigation is not uniform. Hence, there is a need to better understand the factors influencing spatial yield variability and to identify technologies which enable these measurements to be conducted more readily. To better understand these relationships, two field trials were conducted. The data from these trials was used to evaluate the potential to use proximal plant (Chapter 5) and soil-water (Chapter 6) measurement systems to obtain spatial data for irrigation performance evaluations. These trials were also used to determine (a) the variation in uniformity of irrigation applications during the season and the consequential effect on soil moisture distribution (Chapter 7) and (b) the effect of irrigation application on crop growth and yield (Chapter 8). This chapter provides details on the common materials and methods used in these field trials. In particular, it describes the trial site, irrigation application system and crop agronomic management practices.

4.2 Trial site

The two trials were conducted on the Department of Primary Industries and Fisheries Gatton Research Station, Queensland (Appendix 4.1). The research station is located approximately 90 km west of Brisbane and 8 km east of Gatton (27^{o}33' S, 152^{o}20' E). The trial plots were approximately 1000 m^2 in size and located approximately 150 m from the Lockyer Creek in the North-West corner of the research station (Figure 4.1). The trial plots had been used for vegetable production trials over a period of more than 40 years. Surface drainage at the site was from the creek towards the highway end of the plots on a grade of approximately 1:1000. The soil at the site (Figure 4.2) is a moderately self-mulching Black Vertisol (Isbell 2002). The first (autumn) cropping trial was conducted between April and June 2007. The second (winter) trial was conducted between August and October 2007 and was located approximately 20 m to the east of the autumn trial plot.

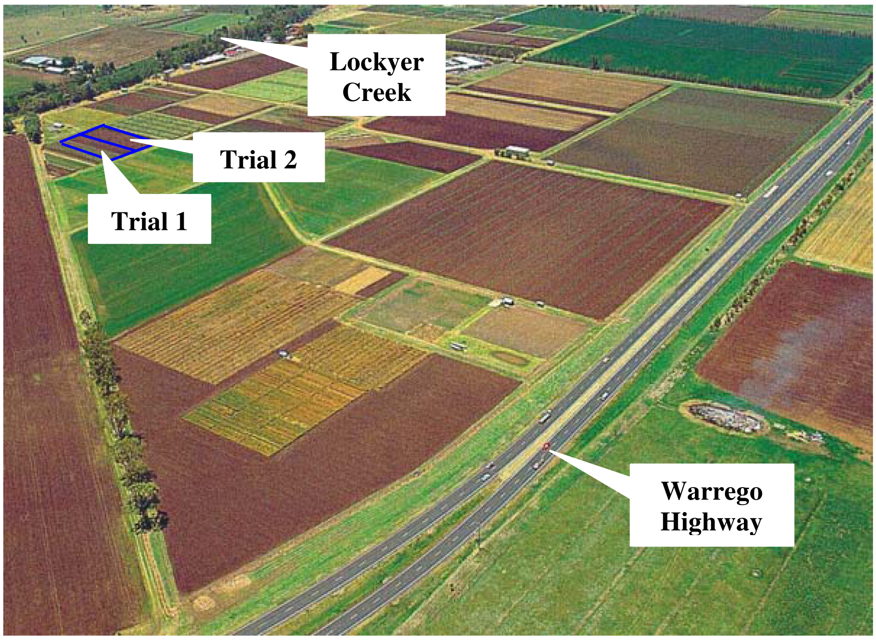


Figure 4.1 Aerial view of Gatton Research Station showing the trial site location

Figure 4.2 Soil at the trial site

4.3 Climate and weather

The climate at the research station is sub-tropical with long, hot summers and short, mild to cold winters. The average annual rainfall is 783 mm with a large variation in annual rainfall distribution (Table 4.1). A weather station (Environdata, WeatherMaster 2000) (Figure 4.3) recording wind speed, wind direction, humidity, solar radiation, rainfall, maximum and minimum temperatures was installed at the trial site before the start of the autumn trial and remained there until after the winter trial was harvested. Data was recorded at 10 minute intervals.

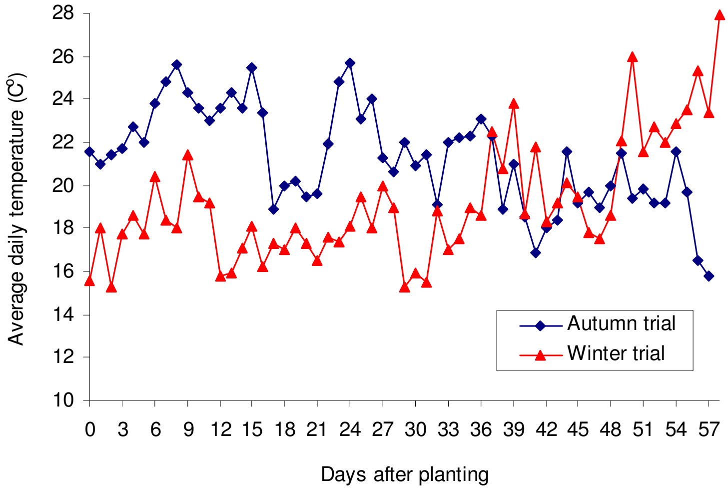
Table 4.1 Long term average monthly rainfall (mm) for Gatton Research Station, Lockyer Valley, Queensland (1968 to 2009) (Bureau of Meteorology 2009)

Mean rainfall (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
	110.8	100.4	65.0	53.9	60.3	34.0	37.1	26.7	31.5	67.3	96.5	100.8	782.7

Figure 4.3 Weather station installed near the trial site

The average daily temperature, solar radiation and evapotranspiration is presented in Figure 4.4 for both trials. Daily weather data for both irrigation trials is provided in Appendix 4.2. A total of 54.6 mm of rainfall was measured during the autumn trial (Figure 4.5a) with the main rainfall event (35.8 mm on the 6/6/07) occurring after harvest had started. No other substantial rainfall was recorded with only minor (≤ 5 mm) events occurring during the main growing period. In contrast, a total of 109.8 mm of rainfall was recorded during the winter trial (Figure 4.5b) with the majority of this rainfall occurring during the main growing period (20/8/07 to 6/9/07).

(a)



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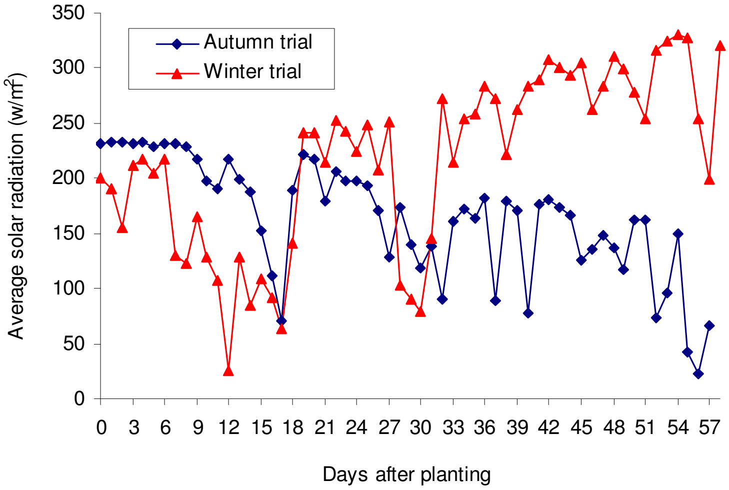

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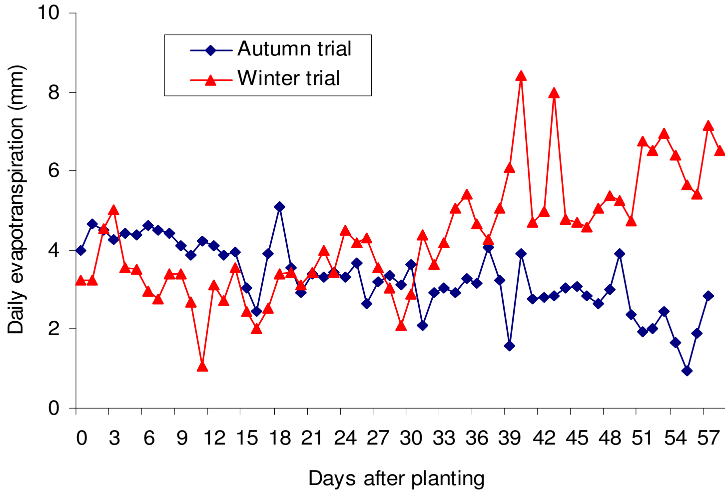
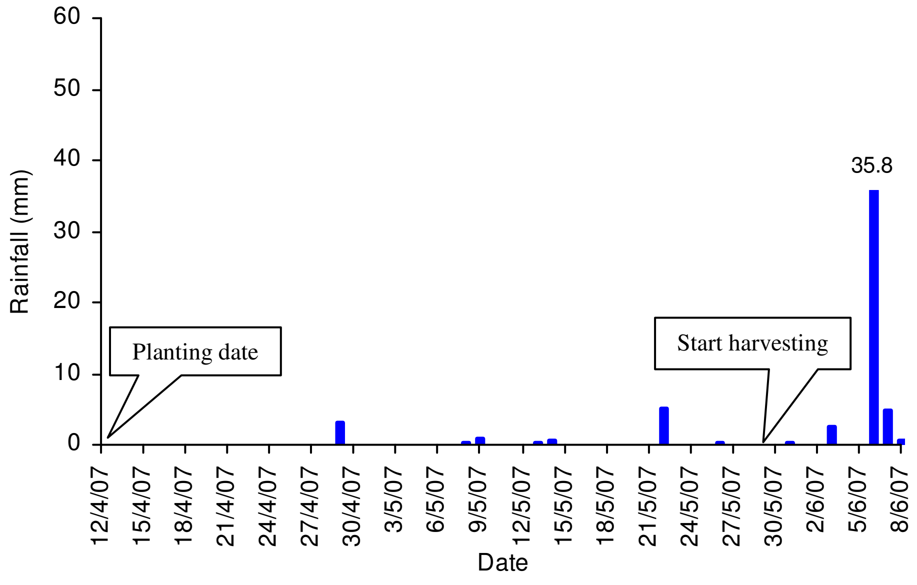


Figure 4.4 Autumn and winter trial average daily (a) temperature (C°) (b) solar radiation (W/m^2) and (c) evapotranspiration (ETo) in 2007 at Gatton Research Station QLD

(a)



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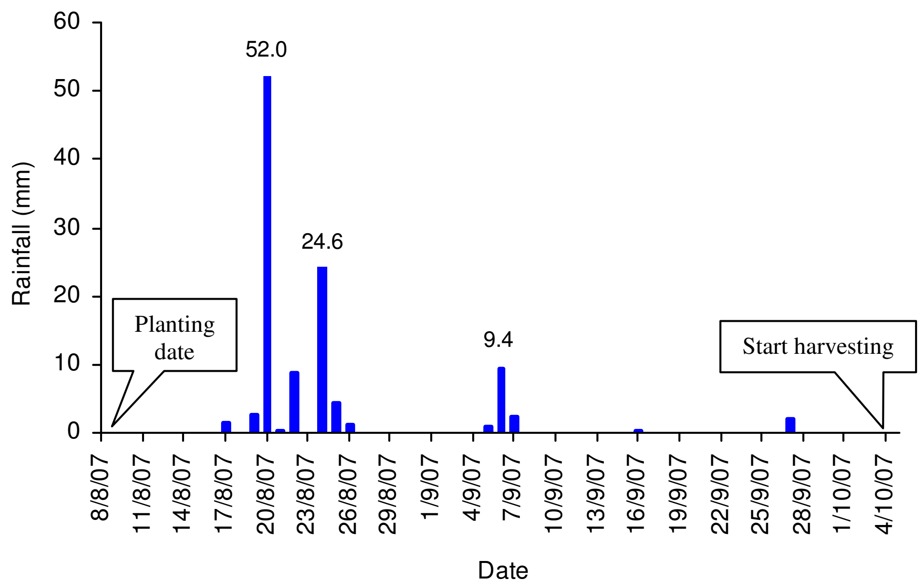


Figure 4.5 Rainfall during the (a) autumn and (b) winter trial

There was a substantial variation in both average wind speed and direction measured during the irrigation events in each trial (Table 4.2). The average wind speed during individual irrigation events varied from 2.9 to 9.0 km/h in the autumn trial and from 3.4 to 10.7 km/h in the winter trial. Average wind direction in the autumn trial was generally from the East or South-East with two events from the South-West (Table

4.2). However, average wind direction during the early part of the winter trial was predominantly from the South-West but tended South-East to South later in the season.

Table 4.2 Wind speed and direction during each irrigation event

Catch can date	Average wind speed (km/h)	Average wind direction (degree)[a]
Autumn trial		
13/4/07	6.6	106.9
15/4/07	6.0	137.6
20/4/07	7.2	118.9
26/4/07	8.1	109.3
2/5/07	5.1	239.4
8/5/07	7.9	88.9
14/5/07	2.9	190.2
18/5/07	4.3	259.2
25/5/07	3.5	97.9
30/5/07	9.0	240.2
Winter trial		
9/8/07	4.6	265.3
11/8/07	8.2	230.8
15/8/07	10.5	79.7
18/8/07	10.1	230.6
1/9/07	4.9	108.5
13/9/07	7.9	264.2
19/9/07	3.4	157.1
25/9/07	4.4	114.4
29/9/07	10.7	184.3
3/10/07	6.0	99.6

a = where zero degree is north

4.4 Crop establishment and agronomic management

The trial sites were 92 × 11 m in size and cultivated into seven beds (1.3 m wide) separated by 0.3 m furrows. Three rows of five week old Iceberg lettuce (cv. Titanic) were transplanted (Figure 4.6a) onto each bed on the 12/4/07 for the autumn trial. Four week old Iceberg (cv. Raider) lettuce was transplanted on the 8/8/07 in the winter trial. In both trials, the crop was transplanted into dry soil beds and irrigated after planting to ensure establishment. During the autumn trial, fertiliser was applied on the 24/4/07 and 17/5/07 (Figure 4.6b) while crop insect spray was applied on the 10/5/07 and 16/5/07 using a boom spray rig (Figure 4.6c). In the winter trial, fertiliser was applied on the 31/8/07 and 12/9/07 while insect spray was applied on the 30/8/07, 10/9/07, 21/9/07 and 27/9/07. Fertiliser application details are given in Appendix. 4.3. The detail of insect and pest attack on harvested crop is shown in Appendix 8.1. Manual hoeing for weed control was also conducted during both trials.

(a) (b) (c)

Figure 4.6 (a) Lettuce transplanting (b) fertiliser spreading and (c) insect spray in operation

4.5 Irrigation application system

4.5.1 General

Both trials were irrigated using a solid set irrigation system with ISS Rainspray sprinkler heads fitted with 1.98 mm nozzles on 0.6 m risers. The sprinklers typically operated at 335-370 kPa and had a 360^0 rotation angle. The sprinklers were arranged in a square pattern with 9 m spacings along the laterals and an 11 m lateral spacing (Figure 4.7). The water supply pump was nearly 500 m from the trial site and the pressure was normally 380-410 kPa at the inlet to the trial. A flow meter was installed in the sub-main at the inlet to the trial site to monitor the volume of water applied in each irrigation. A single pre-plant and ten in-crop irrigations were applied in each trial.

Figure 4.7 Irrigation system layout for the Poor-2 grid (winter trial)

4.5.2 Modification of sprinkler system for trials

Sprinkler pressure reducers and changing the sprinkler heads to R2000 rotators (Nelson, Australia) were used in order to create a range of water distribution uniformities in each trial.

Autumn trial

In the autumn trial, the first four in-crop irrigations were applied using the standard sprinkler irrigation system in order to establish the transplants. For subsequent irrigations, the uniformity of sprinkler application was deliberately reduced in one grid (Poor-1 grid, 9-18 m from the sub-main) by fitting Nelson pressure reducers (138 and 172 kPa) (Figure 4.8a) on three out of the four sprinklers. In a second grid (Control grid, 36-45 m from the sub-main), all sprinklers were unchanged with typical operating pressures of 335-370 kPa. Several options were implemented to change the distribution uniformity of a third grid (Poor-2 grid, 63-72 m from sub-main). These included changing the sprinkler nozzles on the 7/5/07 and replacing the sprinkler heads with Nelson rotators (Model R 2000) on the 15/5/07 (Figure 4.8b). The layout of the Control and the Poor-1 grids are shown in Figure 4.9.

(a) (b)

Figure 4.8 (a) Nelson reducer and (b) Rotator fitted on riser

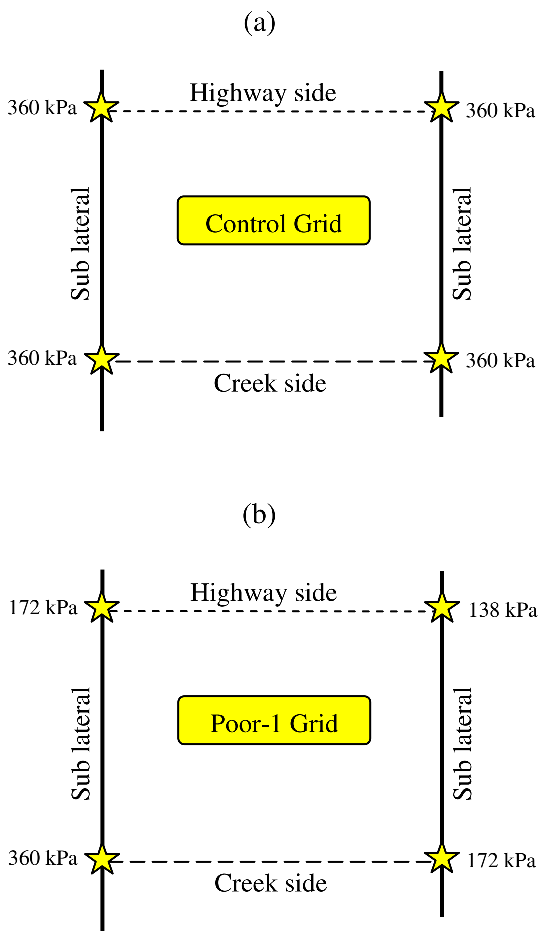


Figure 4.9 Layout of the (a) Control and (b) Poor-1 grid showing the operating pressure of each sprinkler (autumn trial)

Winter trial

In the winter trial, the pressure reducers were introduced in two out of the three measured grids (termed the Poor-1 and the Poor-2 grids). There was no modification of pressure within the third grid (Control grid). In order to improve the performance of the irrigation system all old sprinklers were replaced with new ISS Rainsprays after the first in-crop irrigation (9/8/07). The first three in-crop irrigations were applied to establish transplants. After the third irrigation (15/8/07), the sprinkler pressures in the Poor-1 (9-18 m from the sub-main) and the Poor-2 grids (72-81 m from sub-main) were deliberately reduced at three sprinklers to 138 or 172 kPa using Nelson pressure reducers. One sprinkler within each Poor grid was left unchanged at 360 kPa pressure. To increase spatial variability, the pressure of one of the 172 kPa sprinklers was reduced to 103 kPa after the fourth irrigation (18/8/07) in both the Poor grids (Figure 4.10). To further reduce the uniformity worn sprinkler heads and nozzles were installed in both Poor grids after the fifth irrigation (1/9/07). The sprinkler pressure and heads in the Control grid (36-45 m from the sub-main) were not changed at any time.

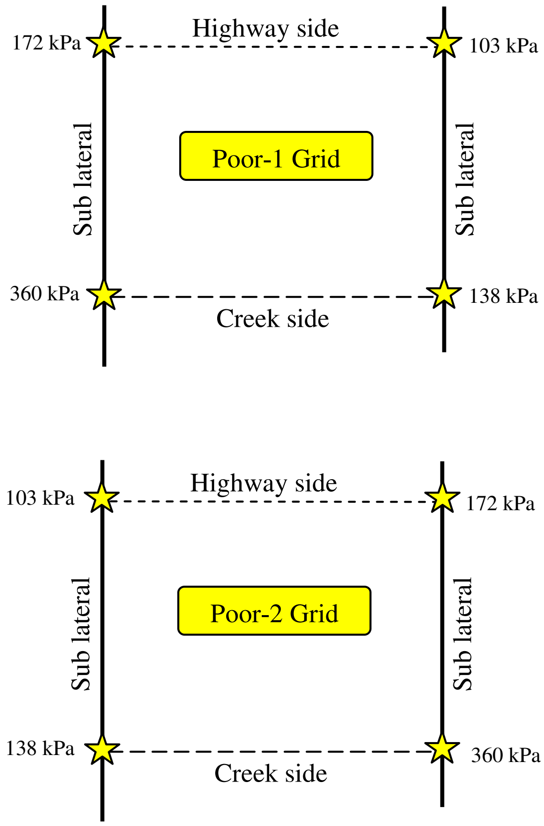


Figure 4.10 Layout of the poor grids showing the operating pressure of each sprinkler (winter trial)

4.5.3 Performance measurements

Measurements of sprinkler pressure, discharge rate and water distribution are commonly used to evaluate the performance of sprinkler irrigation systems. The operating pressure of each corner sprinkler of the grids was measured during each irrigation. A digital pressure meter (DPI 705, Druck, UK) was used to measure the pressure at a valve introduced into the riser pipe below the sprinkler head (Figure 4.11a). Sprinkler discharge was measured by mounting one end of a plastic pipe over the sprinkler nozzle while keeping the other end in a bucket of known volume and measuring the time to fill by stopwatch (Smajstrla *et al*. 1997) (Figure 4.11b). The uniformity of the irrigation application was measured by using catch cans (diameter =

110 mm) arranged in a grid with a catchment spacing of 1.5 × 1.56 m (Figure 4.12). The cans were mounted on 45 cm long (5 mm thick) plastic sticks. Irrigations were conducted in the evenings and the catch can data collected the following morning by using measuring cylinders.

(a) (b)

Figure 4.11 Measurement of sprinkler (a) pressure and (b) discharge

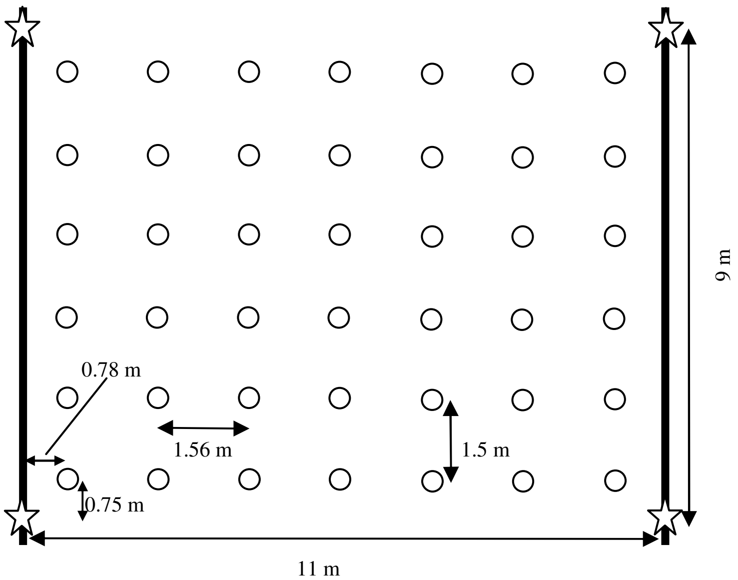


Figure 4.12 The catch cans arrangement in the grid to measure uniformity of application (not to scale)

4.6 Soil tension measurements and irrigation scheduling

Tensiometers (at 0.15 m depth) were installed in each grid next to the catch cans. In the autumn trial, the tensiometers were placed next to each catch can in the Poor-1 grid and next to every second catch can in the Poor-2 and Control grids (Figure 4.13a). However, in the winter trial, the tensiometers were installed next to each catch can in all grids. In both trials, soil tension (soil matric potential) was recorded at twenty-four hour intervals for the duration of the cropping season. Soil tension was measured using a SoilSpec tensiometer (Figure 4.13b) from the 17/4/07 in the autumn trial and after 8/8/07 in the winter trial. Irrigations were applied when the average tensiometer value in the Control grid approached 25 kPa (Heisswolf *et al.* 1997). The choice of 25 kPa measured at 15 cm depth (i.e. the middle of the active rooting depth for lettuce) is consistent with commercial practice locally and recommendations for management provided by Heisswolf *et al*. (1997).

(a) (b)

Figure 4.13 (a) Tensiometer installed next to each catch can and (b) soil tension measurement

4.7 Crop growth and harvest measurements

Lettuce canopy and head size were measured on plants on either side of each catch can using a measuring tape during each trial. The canopy diameter was measured in two dimensions at ~90° and averaged. The canopy area was calculated by multiplying the measured length and width of the projected foliage. Canopy size measurements were obtained on seven occasions (1/5/07, 7/5/07, 13/5/07, 16/5/07, 18/5/07, 22/5/07 and 24/5/07) and head size measurements were obtained on three occasions (22/5/07, 24/5/07 and 28/5/07) during the autumn trial. For the winter trial, canopy measurements were taken on ten occasions (14/8/07, 18/8/07, 23/8/07, 30/8/07, 7/9/07, 12/9/07 18/9/07, 24/9/07, 29/9/07 and 3/10/07) while head measurements were taken on three occasions (24/9/07, 29/9/07 and 3/10/07).

Six tagged lettuces were harvested around each catch can for the Poor-1 grid and from alternate catch cans for the Poor-2 and the Control grids for the autumn trial. The plants were sequentially harvested in the autumn trial on four occasions (29/5/07, 1/6/07, 5/6/07 and 8/6/07) as per local commercial practices and assessed using the Harvester's Tactile Assessment of head maturity test (Heisswolf *et al*. 1997). For the winter trial, lettuces in the Poor-1 and Control grids were harvested only on the 4/10/07 and on the 5/10/07 for the Poor-2 grid (Figure 4.14). Measurements of lettuce fresh weight, head weight and diameter were obtained. General lettuce appearance parameters (e.g. colour, shape, maturity and major defects including insect and disease attack and bolting) were also recorded along with minor defects (e.g. physical and pest damage, physical disorder and temporary injury) which were used to categorise the lettuce heads as either marketable or non-marketable. Minimum lettuce marketable head weight reflected marketable demands and was 500 grams for the autumn trial and 400 grams for the winter trial.

Figure 4.14 Lettuce harvested on the 5/10/07 from the Poor-2 grid (winter trial)

Chapter 5. Evaluation of measurement systems for quantifying lettuce growth

5.1 Introduction

Plant growth and yield monitoring plays an important role in precision agriculture (Plant 2001) and may be used to improve the targeting of inputs (e.g. water and fertiliser) and reduce production costs. The measurement of spatial growth or yield variability is also an important precursor to the determination of strategies for the optimal design and management of irrigation systems. To adequately evaluate the spatial variability of crop production at the field scale it is necessary to obtain measurements of plant growth and yield across the field. However, discrete physical measurement of individual lettuce plants is both labour and time intensive (Chapter 3). The field spatial variability can be measured by proximal or remote sensing techniques (Chapter 2.1.3).

Aerial photography has been used to study crop growth (Irmark *et al*. 2002) and assess the spatial variability of crop yields (Vellidis *et al*. 2004). However, proximal sensing using inexpensive digital cameras has also recently been investigated. For example, Caton (2004) compared camera measurements with physical sampling in rice and observed that the correlations were weak for the first 14 and 21 days after planting but improved at 28 days after planting. Similarly, significant correlations have been found between photo-derived projected foliage areas and cabbage growth (Yang *et al*. 2007) and wheat yield (Jensen *et al*. 2007). Stereo-imaging has also been used to measure canopy area in soybean (Biskup *et al*. 2007) and aerial digital videography used to measure spatial variability in sorghum yield (Yang and Anderson 1999). Thermal infrared thermometers have also been used to measure canopy temperature and calculate crop water stress indices (Chapter 2.1.3.2). Multispectral (normally the infrared and visible red spectrum) measurements have also been used to identify crop canopy growth which is most commonly expressed as the normalised difference vegetation index (NDVI) (Chapter 2.1.3.3). Hence, this chapter reports on the potential to measure lettuce growth using vision, infrared and multispectral sensors.

5.2 Methodology

5.2.1 Proximal vision measurement

Proximal vision measurements of the lettuce plants in both the autumn and the winter trials (Chapter 4) were obtained using an Olympus (3.2 megapixel) C-360 Zoom (Olympus Corporation, Tokyo) camera mounted perpendicularly 1.15 m above the ground surface (Figure 5.1a). The diameter of two tagged plants on either side of each catch can in the Poor grids was physically measured throughout the season using a tape to enable the calculation of the projected canopy area and head size (Chapter 4.7). Measurements of photographs and lettuce canopy area in the Poor-1 grid were taken during the autumn trial on six occasions 19, 25, 31, 36, 40 and 42 days after transplanting (DAT) and head size (diameter) on three occasions (40, 42, 46 DAT). The canopy area measurements were taken on ten occasions during the winter trial (6, 10, 15, 22, 30, 35, 41, 47, 52, 56 DAT) and head size on two occasions (52, 56 DAT). A customised programme developed in Microsoft Visual Studio was used to calculate the number of green pixels for each plant in the photograph. This software was able to "automatically" identify individual plants and calculate the foliage area (based on pixel resolution of 0.51 mm) early in the season when there was no overlap of the individual plant canopies. Manual identification of the plants was necessary later in the season due to the canopy overlap between adjacent plants (Figure 5.1b). The software was also able to identify the number of pixels for the lettuce head by manual identification and calculate the diameter of the lettuce head (Figure 5.1c). Automatic identification of the head was based on a shape algorithm. The software automatically created an Excel worksheet providing the pixel number for canopy and head diameter and the canopy area and head size based on the known pixel size.

5.2.2 Aerial photogrammetry

Digital aerial photographs were obtained for both trials with the assistance of the Department of Primary Industries Queensland staff. During the autumn trial, aerial photographs were taken on two occasions using a 5.0 megapixel Kodak CX7525 (Eastman Kodak Company, Rochester, New York) camera suspended from a balloon above the crop (Figure 5.2a). The height of the balloon above the ground was approximately 40 m and each photo included all seven beds of the Poor-1 grid

(Figure 5.2b). The software used to calculate the number of green pixels in the proximal (1.15 m) photograph (Chapter 5.2.1) was also used to process these aerial photographs.

(a)

(b)

(c)

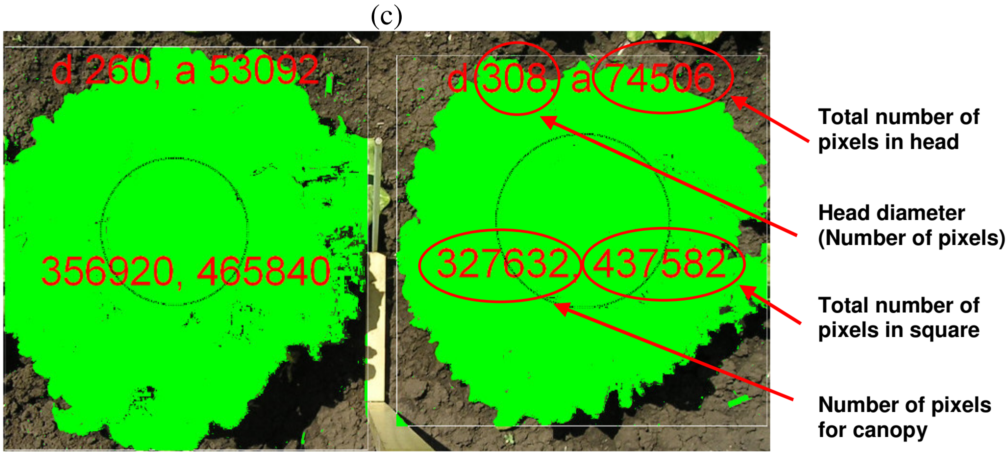


Figure 5.1 (a) Photograph acquisition at 1.15 m height and example (b) photograph taken on 52 DAT (winter trial) (c) green pixel identification for lettuce canopy and head size measurement

(a)

(b)

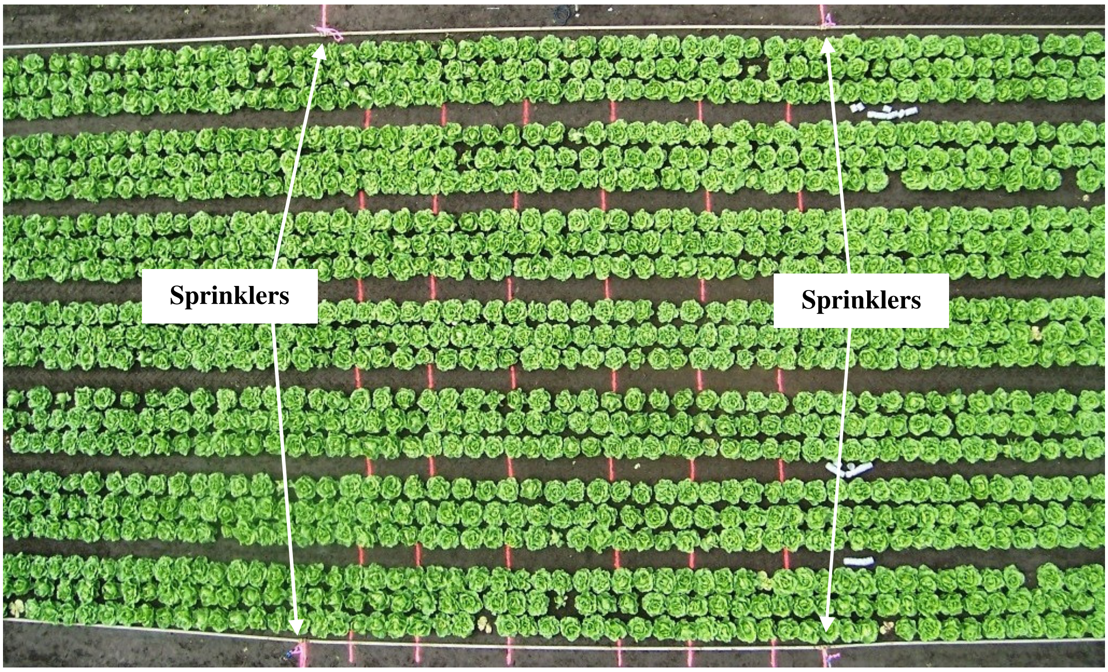


Figure 5.2 (a) Aerial photograph acquisition by balloon and (b) example photograph of the Poor-1 grid in the autumn trial (lines in the furrows indicate the position of catch cans)

Deflection of the camera due to wind made it difficult to obtain accurate photographs of the plot using the balloon platform. Similarly, fluctuation in camera height above the crop due to balloon movement also required rectification and the re-calculation of the pixel dimensions for each photograph. Therefore for the winter trial, the camera was mounted on a vertical mast and offset boom attached to the back of a vehicle (Figure 5.3). The dimensions of the mast and offset boom were adjustable but the mast was maintained at a height of 10 m above the crop and the camera was positioned 3.2 m within the crop boundary. This system did not photograph all of the seven beds in one single frame. Hence, photographs were taken along both sides of the plot to obtain data for all seven plant beds in the trial (Figure 5.4). These photographs were acquired on four occasions (22, 41, 47 and 52 DAT) for both the Poor-1 and Poor-2 grids and the green pixel area calculated using the Microsoft Visual Studio (Chapter 5.2.1) software.

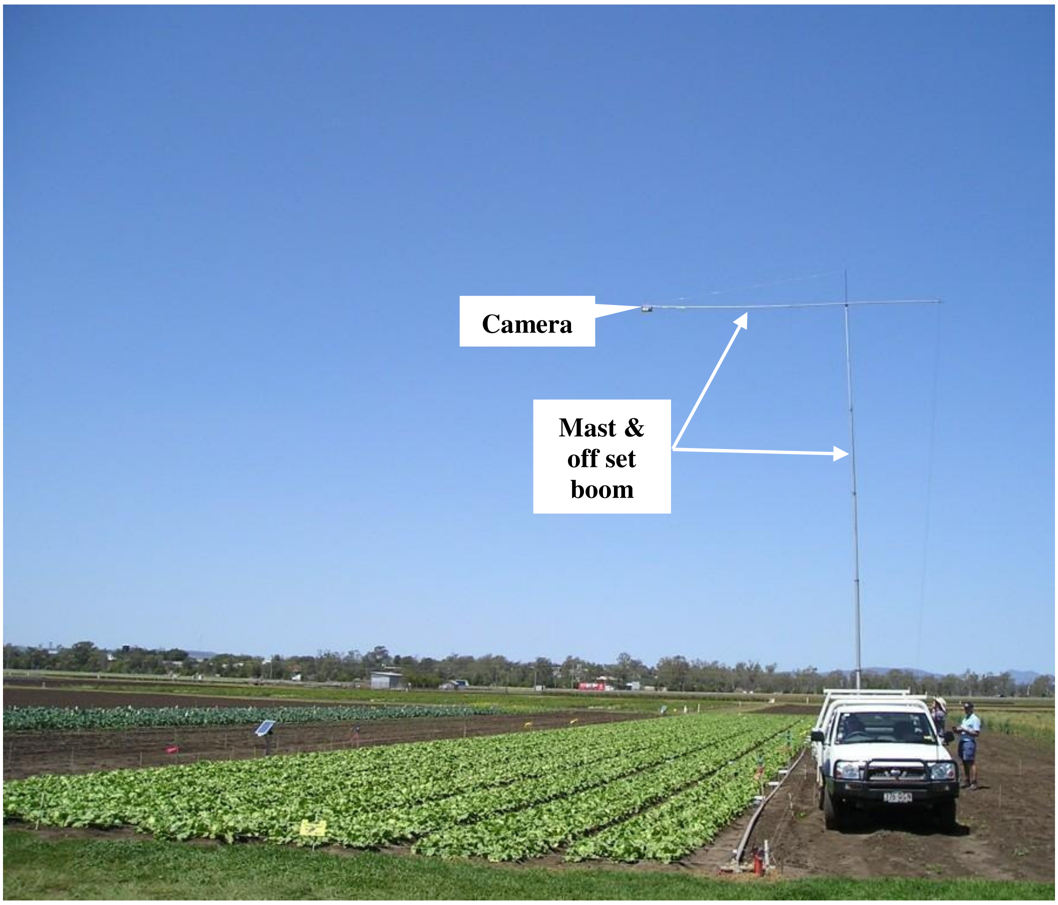


Figure 5.3 Photograph acquisition using mast and offset boom

Figure 5.4 Example photograph using mast and offset boom platform of the Poor-1 grid (winter trial)

5.2.3 Proximal canopy temperature measurement

An infrared thermometer (Model 510B AG Multimeter, Everest Interscience Inc. Tucson AZ) (Figure 5.5) was used to measure the canopy temperature and calculate the crop water stress index (CWSI) based on the approach discussed by Idso 1982 and Jackson *et al*. 1981. Thermal sensing of the crop was undertaken only after the plant canopy had developed enough to avoid problems with soil in the field of view. Measurements were taken from a height of 0.6 m above the crop on two plants either side of the catch can in the middle of the crop. The measurements were taken on eight occasions (33, 35, 36, 39, 40, 41, 42 and 43 DAT) from the Poor-1 grid during the autumn trial. For the winter trial, measurements were taken on three occasions (47, 51 and 54 DAT). The CWSI values were correlated with the volume of water applied at each catch can in the previous irrigation.

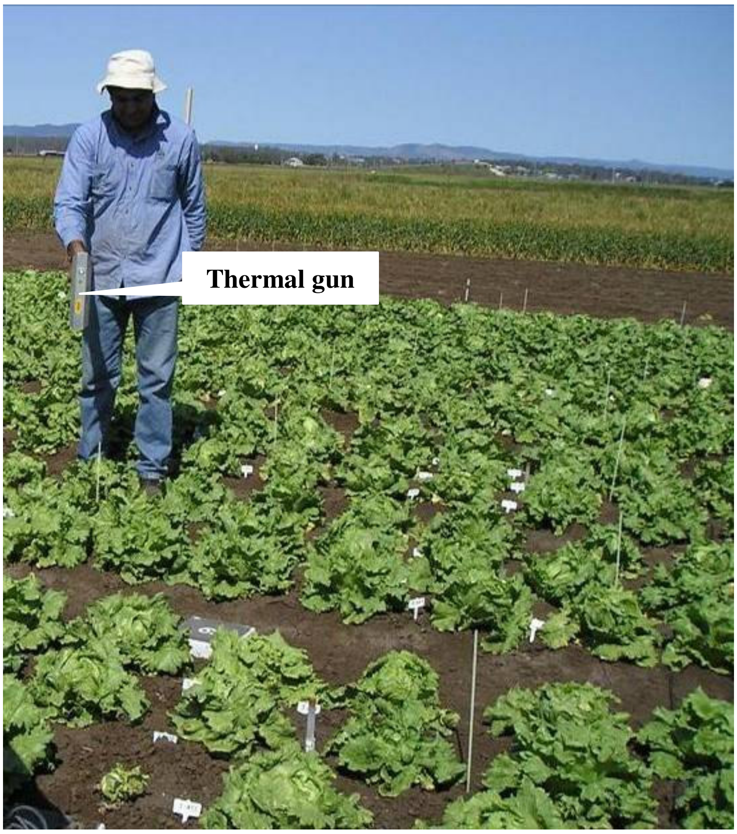


Figure 5.5 Thermal imagery of individual lettuce plants

5.2.4 Proximal multi spectral canopy measurement

Normalised difference vegetation index (NDVI) (Jackson *et al*. 1983; Tucker 1979; Tucker *et al*. 1991) was measured from multispectral canopy reflection using a GreenSeeker Model 500 series (GreenSeeker, NTech, CA). The emission wavelengths for these sensors are 770 nm (near infrared) and 656 nm (red) and the field of view (FOV) is 600 (±100 mm) × 15 (±5.0 mm). A global positioning system (Garmin, Australia) was also attached to obtain positioned data (Figure 5.6). Data was collected on two occasions (47 and 56 DAT) for both the Poor grids in the winter trial. Point based measurements were taken next to the catch cans by placing the NDVI sensor approximately 900 mm above the crop. The NDVI values were compared with the total seasonal water application at each can.

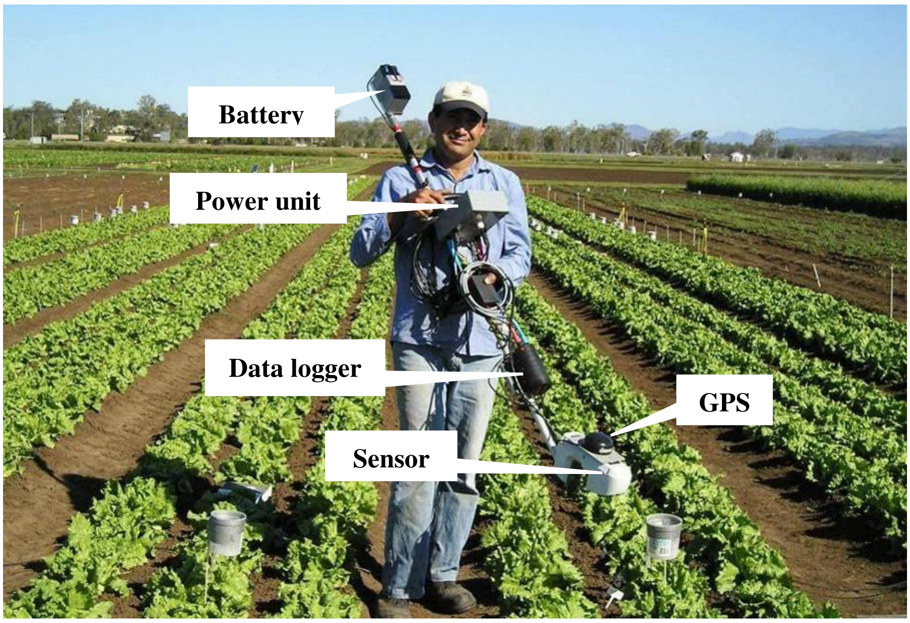


Figure 5.6 Customised Greenseeker Model 500 series

5.3 Results and discussion

5.3.1 Proximal vision measurement

The physical and photo-derived measurements of the canopy area were significantly correlated to each other in both growing seasons (Table 5.1). For the autumn trial, the coefficients of determination (i.e. R^2) for the manually detected canopy area decreased from 0.6 at 16 DAT to 0.33 at 42 DAT due to increasing canopy overlap. However, the coefficients between the physical and photo-derived head size in the autumn trial increased with DAT reaching 0.76 at 46 DAT. For the winter trial, these correlations ranged from 0.35 to 0.74 for periods up to 15 DAT but ranged from 0.73 to 0.89 for measurements taken later in the season (e.g. Appendix 5.1). One reason for the low correlations observed early in the winter trial may be the difficulty in taking accurate physical measurements due to the asymmetrical shape of the canopy during this period. The small leaf size relative to the pixel resolution early in the season may also have contributed. However, the overlap of canopy leaves between adjacent plants later in the season also leads to inaccuracies in both the physical and photo-derived measures. In the winter trial, the automatic software detection of the individual plants early in the season generally produced slightly lower correlations than the manual detection of plants up to 15 DAT but there were no substantial differences at 22 and 30 DAT. It was not possible to use automatic detection after 30 DAT as the software was unable to identify individual plants due to canopy overlap. Significant (P < 0.05) correlations (R^2 = 0.83-0.92) between physical and photo-derived measurements of lettuce head diameter were also observed (Table 5.1) in the winter trial suggesting that this approach may be suitable for lettuce yield monitoring, possibly as part of a real-time digital video acquisition system.

Table 5.1 Coefficients of determination (P < 0.05) for linear relationships between physical and photograph derived canopy area (and head size) measurements obtained from photographs taken at 1.15 m height

Autumn trial		Winter trial				
DAT	Poor-1 grid	DAT	Poor-1 grid	Poor-2 grid	Poor-1 grid	Poor-2 grid
	Manual detection of individual plants		Manual detection of individual plants		Automatic detection of individual plants	
19	0.60	6	0.49	0.35	0.35	0.37
25	0.50	10	0.60	0.58	0.45	0.52
31	0.52	15	0.73	0.74	0.63	0.70
36	0.47	22	0.85	0.89	0.72	0.89
40	0.43 0.52[a]	30	0.84	0.89	0.84	0.89
42	0.33 0.56[a]	35	0.73	0.86		
46	0.76[a]	41	0.81	0.89		
		47	0.75	0.89		
		52	0.80 0.83[a]	0.86 0.92[a]		
		56	0.87 0.90[a]	0.89 0.92[a]		

a = Coefficients of determination for head size measurements

5.3.2 Aerial photogrammetry

There were fewer green pixels for each lettuce in the photograph taken from the balloon during the autumn trial compared to the 1.15 m photograph (Figure 5.7). The linear relationship between the physical and photograph derived canopy area measurements were poor (R^2 ~ 0.25) due to lower image resolution and parallax errors. Hence, while balloon photographs have the advantage of covering relatively large areas of crop in a single image this platform was not considered appropriate for measuring infield spatial variability in lettuce at the resolution required.

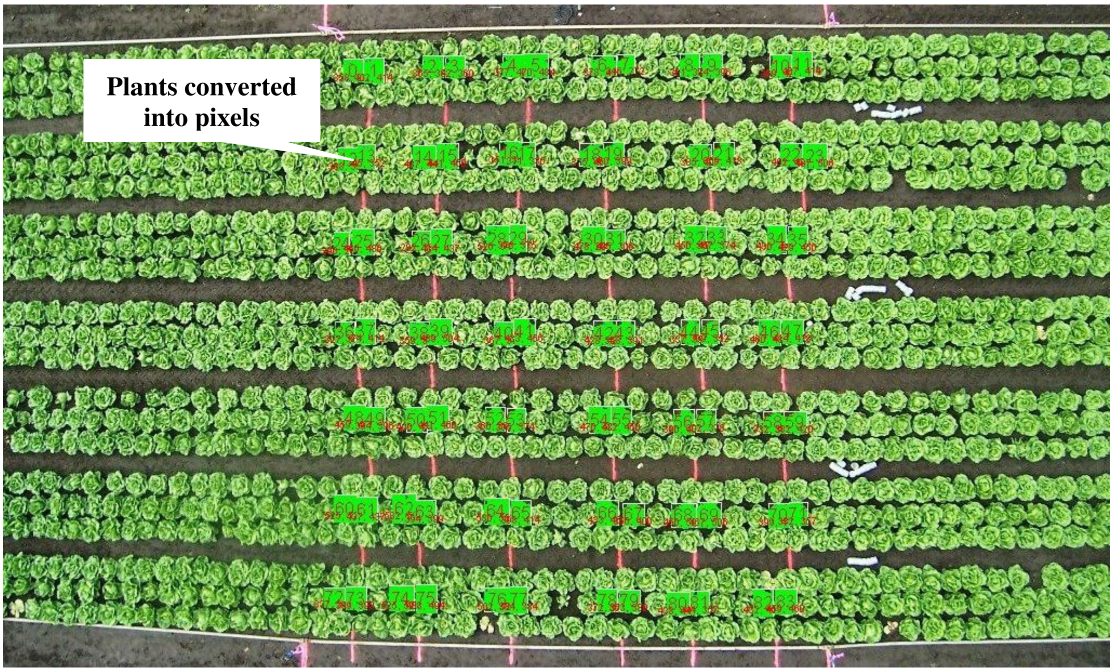


Figure 5.7 Example photograph taken from balloon platform showing image processing overlay to determine the green pixel area of individual lettuce plants (autumn trial)

As expected, the use of 10 metre mast and offset boom in the winter trial increased the image resolution (Figure 5.8) and resulted in the better delineation of individual lettuces compared to the balloon photograph. However, the pixel size (6.19 × 6.19 mm) was larger than the pixel size for the 1.15 m proximal images. Coefficients of determination (R^2) between the physically measured and 10 m photograph derived canopy area ranged from 0.50-0.82 (Table 5.2). These coefficients were typically 0.1 to 0.2 lower than those obtained using measurements derived from the 1.15 m photographs, presumably due to the lower resolution (larger pixel size) associated with the 10 m photographs and possibly due to parallax errors in the images. They were, however, substantially better than the correlation obtained for the balloon platform and are high enough to suggest that there is the potential to use this platform for yield mapping of lettuce crops.

Figure 5.8 Example photograph taken from 10 m mast and offset boom platform showing image processing overlay to determine the green pixel area of individual lettuce plants (winter trial)

Table 5.2 Coefficients of determination for linear relationships between physical and photograph derived canopy area measurements obtained from photographs taken from 10 m mast and offset boom (winter trial)

DAT	Poor-1 grid	Poor-2 grid
	Manual detection of individual plants	
22	0.64	0.68
41	0.69	0.79
47	0.50	0.72
52	0.70	0.82

5.3.3 Crop water stress index

The CWSI values measured during the autumn trial were generally very low (i.e. zero) indicating no water stress to the plants while in the winter trial these values ranged from 0.24-0.83 and 0.3-0.59 (i.e. substantial differences in crop stress) for the Poor-1 and the Poor-2 grids, respectively. Example contour map of CWSI values on

47 DAT for the Poor-1 grid in the winter trial indicate similar patterns of CWSI with water application on 42 DAT (Figure 5.9). The CWSI was generally lower in areas of high water application (e.g. near sprinklers) and higher in areas of low water application (e.g. along the third to fifth beds). However, linear correlations between water applied and CWSI measurements were not significant ($P < 0.05$) during the autumn trial (Table 5.3). This may have been due to the late instigation of the low water application uniformity treatment, the presence of in-season rainfall or low temperature (Figure 4.4a) and solar radiation (Figure 4.4b) during this crop. However, significant ($P < 0.05$) correlations (explaining between 30 and 54% of the variation) between water application and CWSI were observed in the winter trial (Table 5.3). Measurements during the winter trial were taken after a period of little rainfall and when daily temperatures and solar radiations were higher than in the autumn trial. This would be expected to have increased crop water demand and hence more likely to exhibit crop stress in areas of low water application. It should also be noted that lettuce crops are shallow rooted (maximum of 60 cm) (Jackson and Stivers 1993; Kristensen 2006) with an active root zone of <30 cm. Lettuce are commercially irrigated more frequently than broad acre crops and this may explain why there were no strong CWSI and water interactions. Lettuce canopy area was poorly correlated with CWSI in both trials (Table 5.3) suggesting that the canopy size is not correlated with the water stress on individual days.

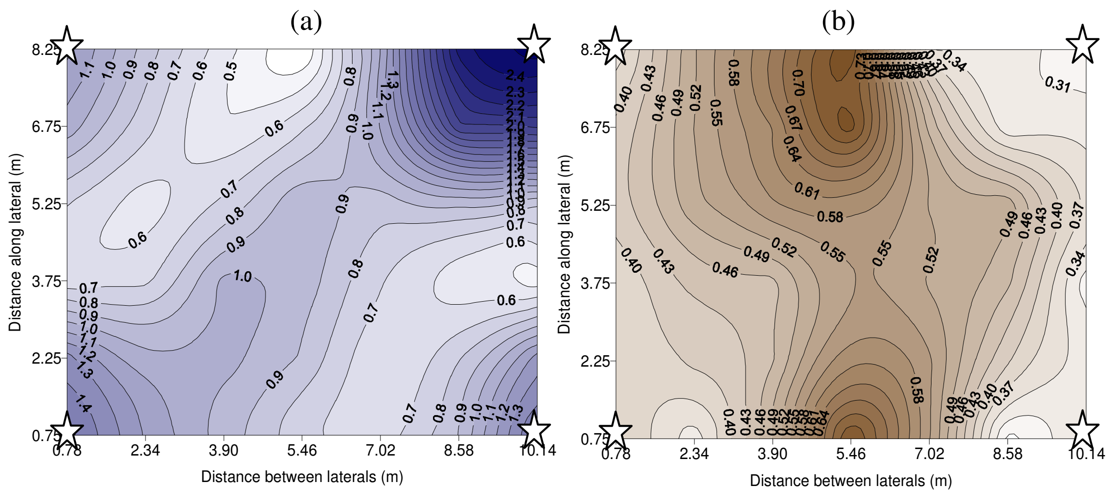


Figure 5.9 Spatial pattern of (a) normalised (to average) water application (42 DAT) and (b) CWSI (47 DAT) for the Poor-1 grid (winter trial). Stars indicate sprinklers

Table 5.3 Coefficients of determination for linear relationships between CWSI, water applied and lettuce canopy area

Autumn trial				Winter trial			
Measurement date (DAT)		Water applied vs. CWSI	CWSI vs. Canopy area	Measurement date (DAT)		Water applied vs. CWSI	CWSI vs. Canopy area
Catch can	CWSI			Catch can	CWSI		
32	33	0.00	0.02	42	47	0.31/0.28[b]	0.00/0.04[b]
	35	0.01		48	51	0.53/0.49[b]	0.23/0.09[b]
36	36	0.02	0.00	52	54	0.54/0.45[b]	0.28/0.06[b]
	39	0.09					
40[a]	40	0.04	0.02				
	41	0.02					
	42	0.00					
43	43	0.01	0.00				

a = Rainfall event, b =Coefficients of determination for the Poor-2 grid

5.3.4 Normalised difference vegetation index

Example contour patterns of NDVI for the Poor grids during the winter trial are shown in Figure 5.10. The NDVI values are generally lower in the central beds where water application was low and higher near the sprinklers. The lowest NDVI values within the Poor-2 grid were associated with dying plants. However, there was no significant correlation (R^2 ~ 0.1) found between NDVI and water application suggesting that these measurements could not be used to evaluate spatial yield variability due to water application in lettuce crops.

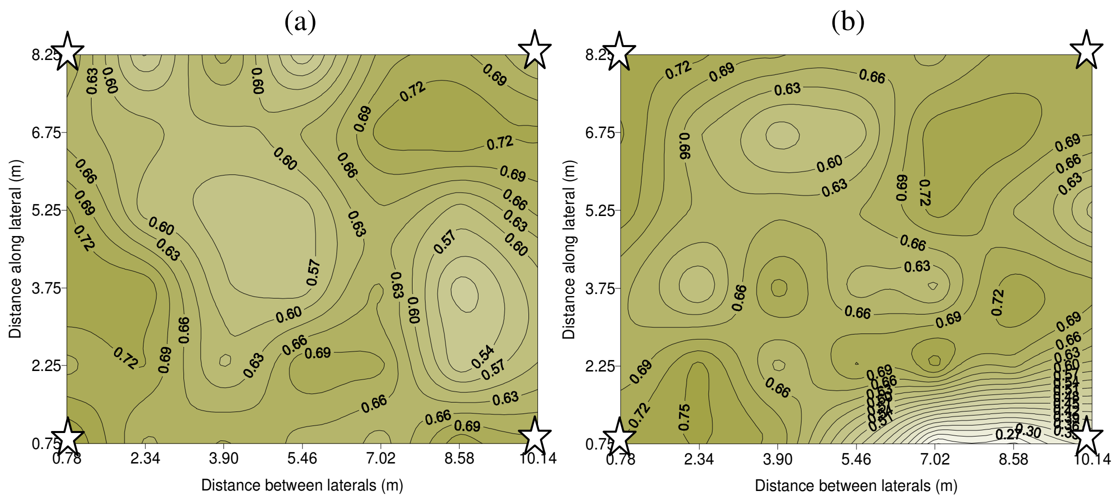


Figure 5.10 Contour patterns of NDVI for the (a) Poor-1 and (b) Poor-2 grids on the 56 DAT (winter trial). Stars indicate sprinklers

5.4 Conclusions

This work has demonstrated that thermal infrared measurements of canopy temperature (i.e. CWSI) and multispectral reflectance measurements of the canopy (i.e. NDVI) were poorly correlated with water application and lettuce growth most likely because of lack of water stress. However, there is potential to use proximal vision sensing (i.e. 1.15 m camera system) and low altitude (i.e. 10 m mast and offset boom platform) aerial photography for yield mapping and evaluating spatial variability of lettuce, particularly later in the season. Both of these platforms require further development work to be able to be used for routine measurement and analysis. Key areas of further development include:

- Need for additional validation on a wider range of field conditions and crop varieties.
- Refinement of the camera mounting to enable continuous measurement (including an assessment of errors due to fluctuation in platform height and movement speed across the field).
- Modification and refinement of the software to enable real-time acquisition and integration with GPS data to automatically produce field scale maps.

Because the photogrammetry methods require further improvement before they can be routinely implemented, this data and approach was not used in the following chapters.

Chapter 6. Evaluation of electromagnetic induction for assessing irrigation performance

6.1 Introduction

The uniformity of irrigation application is a key performance measure of any irrigation system. However, sprinkler irrigation uniformity measurements obtained using catch cans are time consuming (Chapter 3) and result in the evaluation of only small areas of the field. Irrigation applications directly affect soil moisture and hence, soil moisture measurements may potentially be able to be used to evaluate the irrigation system performance. Measurement of apparent (or bulk) soil electrical conductivity (ECa) using electromagnetic (EM) sensors has been used (Moore *et al.* 2005; Taylor *et al.* 2003) to monitor spatial variability in soil moisture for dryland crops. However, there are no studies reported in the literature evaluating the potential to use these sensors for measuring irrigation uniformity under sprinkler irrigation systems. Hence, this chapter reports a preliminary study conducted to evaluate the potential to use an EM sensor to evaluate irrigation uniformity.

6.2 Methodology

Apparent soil electrical conductivity (ECa) was measured throughout both the autumn and winter lettuce trials (Chapter 4) using an EM38 (Geonics Ltd. Mississauga, Ontario) (Figure 6.1). The EM38 is designed to measure ECa to a depth of 75 cm in horizontal mode and to a depth of 150 cm in vertical mode.

Autumn trial

To evaluate the effect of the irrigation submain and laterals on the ECa readings, ECa measurements in both horizontal and vertical mode were taken over the whole trial site before (28/3/07; 2 m interval) and after (4/4/07; 2 m interval) the sprinkler system was installed and again after the pre-plant irrigation (7/4/07; 10 m interval) (Appendix 6.1). ECa measurements were also taken before and after irrigations to evaluate the irrigation performance. Measurements were taken at each catch can location in the three grids where irrigation uniformity was monitored for the first four in-crop irrigations but in only the Poor-1 grid for the next three irrigations (Appendix

6.2). Some additional ECa measurements were also taken between the 5th, 6th and 7th irrigations. ECa measurements were not able to be collected after the seventh irrigation as it was not possible to place the instrument on the ground surface due to increasing plant size.

Figure 6.1 EM38 in operation placed on the soil surface (autumn trial)

Winter trial

ECa measurements were obtained by using the EM38 in horizontal mode during the winter season. ECa measurements were taken over the whole trial plot at the start, middle and end of the growing season (Appendix 6.3). EM data was collected at 2 m intervals before and after each irrigation during the trial. Measurements within the three treatment grids were taken next to each catch can. ECa measurements were taken at ground level for the 4th, 5th and 6th irrigations. However, EM meter was mounted on a wooden stand 35 cm above the beds (Figure 6.2) for measurements of the 7th and 10th irrigations.

Figure 6.2 Use of EM38 on wooden stand (winter trial)

6.3 Results and Discussion

6.3.1 Effect of irrigation system installation on ECa

There was no substantial difference in the pattern of ECa observed before and after the sprinkler system installation (Figures 6.3 and 6.4). There was also no difference in the before and after system installation patterns of ECa observed by using the EM38 in horizontal (Figure 6.3) and vertical (Figure 6.4) modes. Slight differences in the contour spacing after system installation (4/4/07) are most likely because this survey was conducted using 10 m grid intervals while the other surveys used a 2 m interval. ECa values were higher at >80 m along the lateral due to a change in soil properties. The ECa values were generally higher following the pre-plant irrigations with higher readings near the sprinklers presumably due to higher water application in these areas compared to the rest of the plots.

6.3.2 Correlations between irrigation application volumes and ECa

Example contour maps of water application and ECa within the Poor-1 grid in the autumn trial are presented here for an irrigation conducted before (Figure 6.5) and after (Figure 6.6) sprinkler modification. Higher water application and ECa values

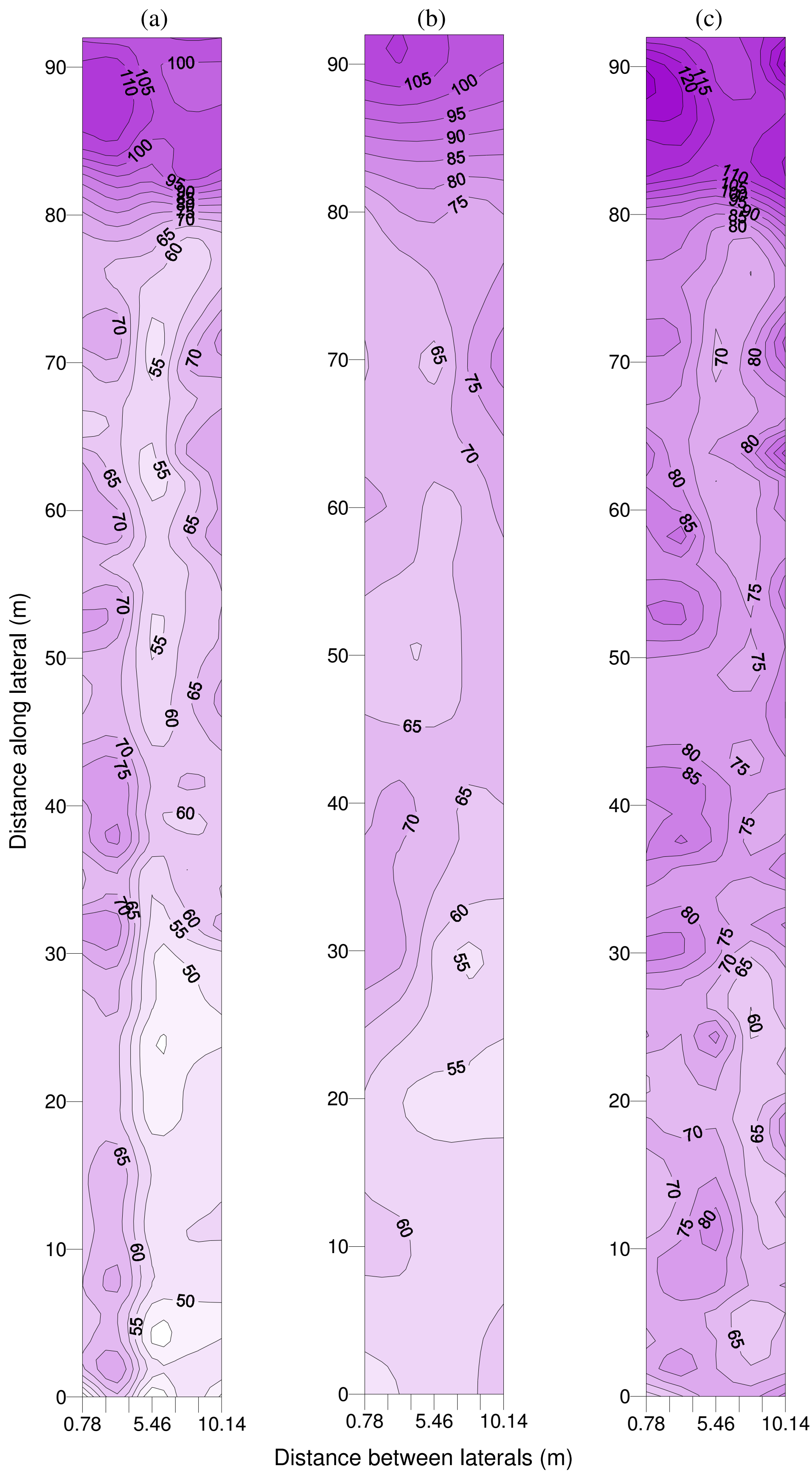


Figure 6.3 Horizontal mode ECa measured (a) before sprinkler system installation (28/3/07), (b) after sprinkler installation (4/4/07) and (c) after pre-plant irrigation (7/4/07) (autumn trial)

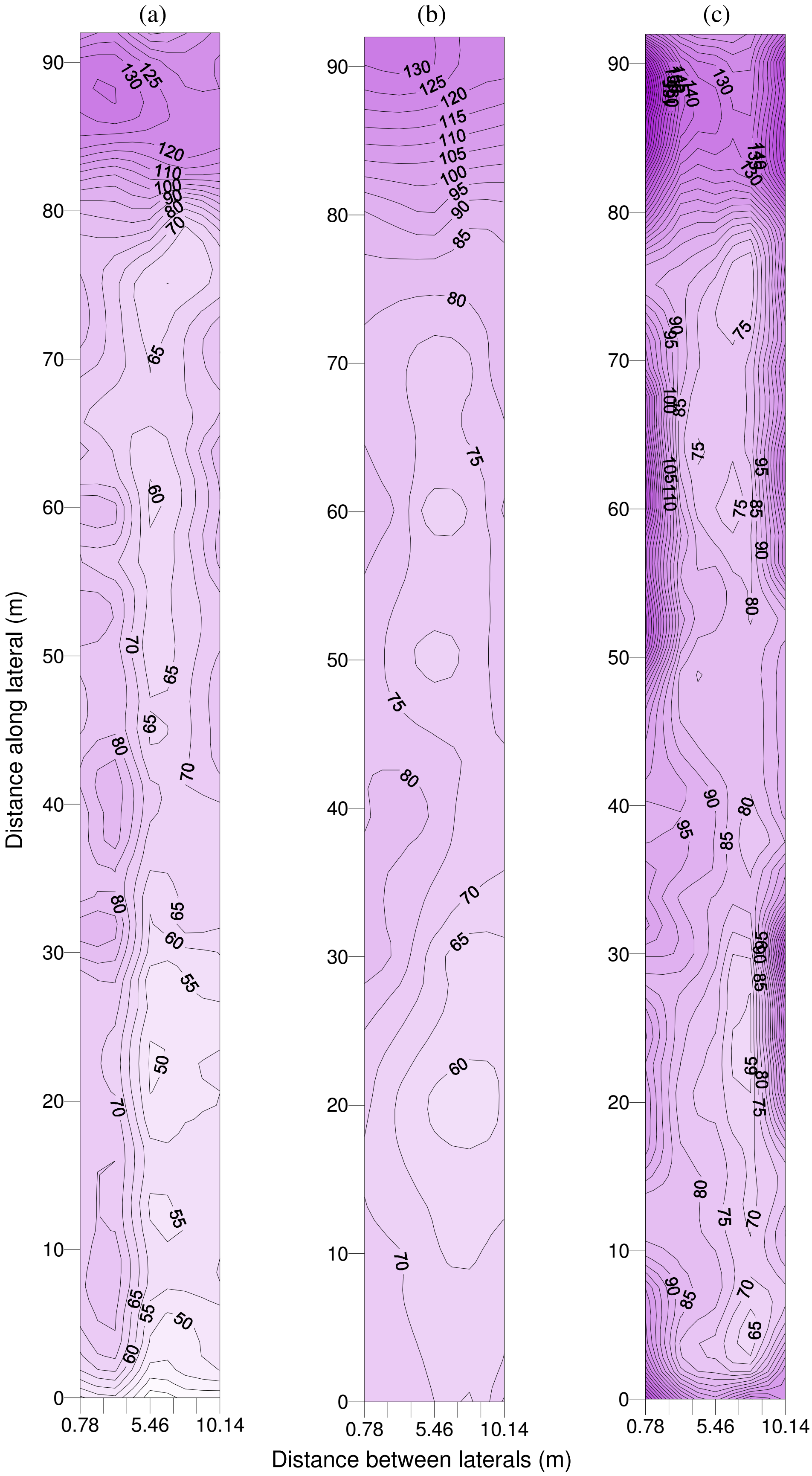


Figure 6.4 Vertical mode ECa measured (a) before sprinkler system installation (28/3/07), (b) after sprinkler installation (4/4/07) and (c) after pre-plant irrigation (7/4/07) (autumn trial)

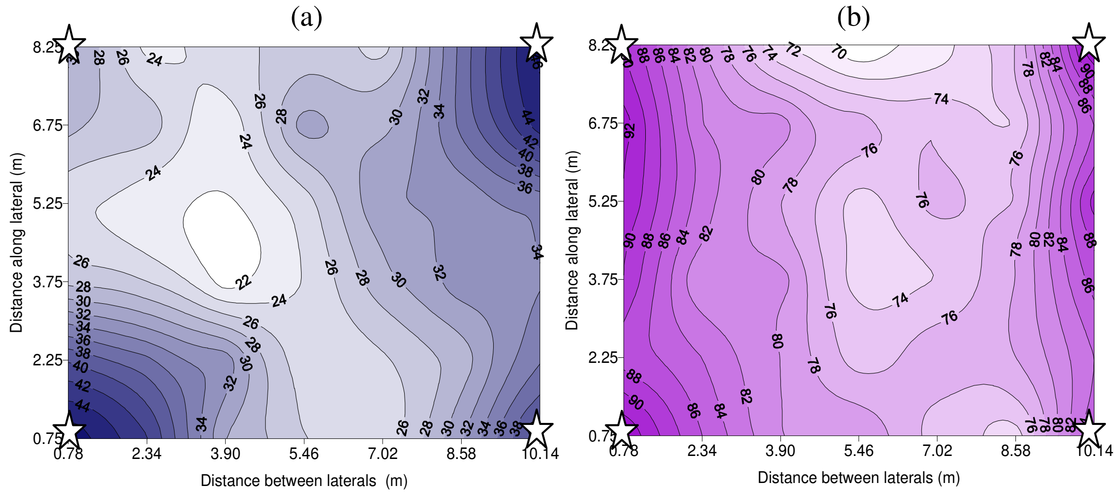


Figure 6.5 Pattern of (a) irrigation water application (mm) and (b) ECa (mS/m) (horizontal) on 13/4/07 in the Poor-1 grid (autumn trial)

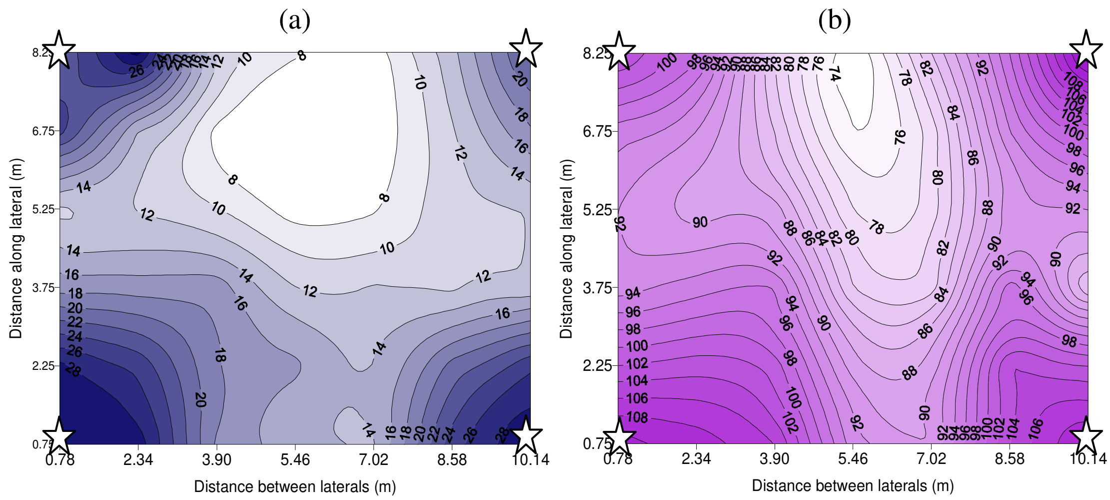


Figure 6.6 Pattern of (a) irrigation water application (mm) and (b) ECa (mS/m) (horizontal) on 8/5/07 in the Poor-1 grid (autumn trial)

were generally observed close to the sprinklers. The coefficients of determination (R^2) between the volume of irrigation water applied and the ECa measured after the irrigation application was generally low (i.e. $R^2 < 0.4$) for the first four measured irrigations in the autumn trial (Table 6.1). The large volumes of water applied, comparatively high sprinkler uniformity and relatively small volumes of water being used by the crop during this period acted to maintain a moist soil profile and produced only small differences in ECa across the plot (e.g. Figure 6.5). However, the correlation between water applied and ECa measured in horizontal mode progressively improved (up to $R^2 \sim 0.77$) (Table 6.1, Figure 6.6) after the sprinkler pressures were reduced on the 1/5/07 (Appendix 6.4). The increased correlation after the reduction in sprinkler performance reflects the greater range of irrigation volumes applied and increased differences in the soil moisture profiles across the plot. For the winter trial, no correlations were found between ECa and water applied (Table 6.3) due to the effect of in-season rainfall events which reduced differences in soil moisture content across the plots (Appendix 6.6).

The correlations between volumes of water applied and ECa measured in vertical mode (Table 6.2, Appendix 6.5) were generally lower compared to horizontal mode correlations (Table 6.1) presumably due to the greater influence of sub-soil moisture which was not greatly affected by the irrigation application or crop extraction. There was generally no difference in the correlations between water application and ECa when measured in horizontal mode (Table 6.1) irrespective of the period of time after irrigation that the EM readings were taken. However, the correlations between water applied and ECa measured in vertical mode generally increased with measurement time after irrigation for events measured later in the season (Table 6.2). The correlations increased after the reduction in sprinkler performance (1/5/07) due to the greater range of irrigation volumes applied and increased differences in the soil moisture profiles across the plot. It is also consistent with the ECa more accurately identifying progressive soil profile drying in areas where smaller irrigation volumes were applied. This suggests that EM measurements may be used to identify gross differences in soil moisture across sprinkler irrigated plots where the spatial differences in the volume of irrigation water application are large and consistent throughout the season.

The correlation between the volume of irrigation water applied and the difference in the ECa measured before and after irrigation was generally poor (Tables 6.1 to 6.3, Appendix 6.7). These correlations were also generally worse than the correlations between the water applications and the absolute ECa. This is consistent with the measurement errors associated with using the EM data in differential mode being greater than for single ECa measurements and suggests that differential ECa is not likely to be an appropriate substitute for traditional sprinkler irrigation performance evaluations. However, in both seasons the highest coefficients of determination (R^2 ~ 0.5) for the differential ECa data (Tables 6.1 to 6.3) occurred shortly after changing the sprinkler pressures. This was during a period when the soil moisture variations associated with the individual irrigation applications would be maximised. This suggests that differential ECa measurements are best able to identify the performance (i.e. non-uniformity) of individual irrigation events when either the spatial pattern or volume of water applied varies greatly between irrigations.

Table 6.1 Coefficients of determination for a log curve fitted between irrigation water applied, ECa measured (horizontal) after irrigations, and the difference in ECa measured before and after irrigations (autumn trial)

<table>
<tr><th>Catch can date</th><th>No. of irrigation after transplant</th><th>ECa measured date</th><th>Correlations between depth of water applied and ECa (R^2)</th><th>Correlations between depth of water applied and ΔECa (R^2)</th></tr>
<tr><td rowspan="2">13/4/07</td><td rowspan="2">Ist</td><td>13/4/07</td><td>0.17 (± 0.08)</td><td></td></tr>
<tr><td>14/4/07</td><td>0.12 (± 0.08)</td><td rowspan="2">0.11 (± 0.11)</td></tr>
<tr><td rowspan="2">15/4/07</td><td rowspan="2">2nd</td><td>15/4/07</td><td>0.30 (± 0.03)</td></tr>
<tr><td>19/4/07</td><td>0.37 (± 0.16)</td><td rowspan="2">0.24 (± 0.26)</td></tr>
<tr><td rowspan="2">20/4/07</td><td rowspan="2">3rd</td><td>20/4/07</td><td>0.36 (± 0.11)</td></tr>
<tr><td>25/4/07</td><td>0.31 (± 0.12)</td><td rowspan="2">0.12 (± 0.12)</td></tr>
<tr><td rowspan="2">26/4/07</td><td rowspan="2">4th</td><td>26/4/07</td><td>0.22 (± 0.18)</td></tr>
<tr><td>1/5/07</td><td>0.47</td><td rowspan="2">0.26</td></tr>
<tr><td rowspan="3">2/5/07</td><td rowspan="3">5th</td><td>2/5/07</td><td>0.56</td></tr>
<tr><td>6/5/07</td><td>0.60</td><td></td></tr>
<tr><td>7/5/07</td><td>0.57</td><td rowspan="2">0.56</td></tr>
<tr><td rowspan="5">8/5/07</td><td rowspan="5">6th</td><td>8/5/07</td><td>0.74</td></tr>
<tr><td>9/5/07</td><td>0.77</td><td></td></tr>
<tr><td>10/5/07</td><td>0.74</td><td></td></tr>
<tr><td>12/5/07</td><td>0.70</td><td></td></tr>
<tr><td>13/5/07</td><td>0.75</td><td rowspan="2">0.28</td></tr>
<tr><td rowspan="3">14/5/07</td><td rowspan="3">7th</td><td>14/5/07</td><td>0.60</td></tr>
<tr><td>15/5/07</td><td>0.65</td><td></td></tr>
<tr><td>17/5/07</td><td>0.61</td><td></td></tr>
</table>

Table 6.2 Coefficients of determination for a log curve fitted between irrigation water applied, ECa measured (vertical) after irrigations, and the difference in ECa measured before and after irrigations (autumn trial)

<table>
<tr><th>Catch can date</th><th>No. of irrigation after transplant</th><th>ECa measured date</th><th>Correlations between depth of water applied and ECa (R^2)</th><th>Correlations between depth of water applied and ΔECa (R^2)</th></tr>
<tr><td rowspan="2">13/4/07</td><td rowspan="2">Ist</td><td>13/4/07</td><td>0.17(±0.12)</td><td></td></tr>
<tr><td>14/4/07</td><td>0.17(±0.17)</td><td rowspan="2">0.04 (± 0.03)</td></tr>
<tr><td rowspan="2">15/4/07</td><td rowspan="2">2nd</td><td>15/4/07</td><td>0.09(±0.07)</td></tr>
<tr><td>19/4/07</td><td>0.14(±0.21)</td><td rowspan="2">0.11 (± 0.05)</td></tr>
<tr><td rowspan="2">20/4/07</td><td rowspan="2">3rd</td><td>20/4/07</td><td>0.19(±0.03)</td></tr>
<tr><td>25/4/07</td><td>0.39(±0.08)</td><td rowspan="2">0.06 (± 0.05)</td></tr>
<tr><td rowspan="2">26/4/07</td><td rowspan="2">4th</td><td>26/4/07</td><td>0.14(±0.09)</td></tr>
<tr><td>1/5/07</td><td>0.48</td><td rowspan="2">0.01</td></tr>
<tr><td rowspan="3">2/5/07</td><td rowspan="3">5th</td><td>2/5/07</td><td>0.28</td></tr>
<tr><td>6/5/07</td><td>0.58</td><td></td></tr>
<tr><td>7/5/07</td><td>0.64</td><td rowspan="2">0.13</td></tr>
<tr><td rowspan="5">8/5/07</td><td rowspan="5">6th</td><td>8/5/07</td><td>0.32</td></tr>
<tr><td>9/5/07</td><td>0.32</td><td></td></tr>
<tr><td>10/5/07</td><td>0.54</td><td></td></tr>
<tr><td>12/5/07</td><td>0.51</td><td></td></tr>
<tr><td>13/5/07</td><td>0.55</td><td rowspan="2">0.01</td></tr>
<tr><td rowspan="3">14/5/07</td><td rowspan="3">7th</td><td>14/5/07</td><td>0.08</td></tr>
<tr><td>15/5/07</td><td>0.06</td><td></td></tr>
<tr><td>17/5/07</td><td>0.46</td><td></td></tr>
</table>

Table 6.3 Coefficients of determination for a log curve fitted between irrigation water applied, ECa measured (horizontal) after irrigations, and the difference in ECa measured before and after irrigations (winter trial)

<table>
<tr><th rowspan="2">Catch can date</th><th rowspan="2">No. of irrigation after transplant</th><th rowspan="2">ECa measured date</th><th colspan="3">Correlations between depth of water applied and ECa (R^2)</th><th colspan="3">Correlations between depth of water applied and ΔECa (R^2)</th></tr>
<tr><th>Poor-1 grid</th><th>Poor-2 grid</th><th>Control grid</th><th>Poor- 1 grid</th><th>Poor-2 grid</th><th>Control grid</th></tr>
<tr><td rowspan="2">18/8/07</td><td rowspan="2">4th</td><td>17/8/07[a]</td><td></td><td></td><td></td><td rowspan="2">0.00</td><td rowspan="2">0.03</td><td rowspan="2">0.09</td></tr>
<tr><td>18/8/07[a]</td><td>0.02</td><td>0.00</td><td>0.10</td></tr>
<tr><td rowspan="2">1/9/07</td><td rowspan="2">5th</td><td>31/8/07[a]</td><td></td><td></td><td></td><td rowspan="2">0.26</td><td rowspan="2">0.53</td><td rowspan="2">0.38</td></tr>
<tr><td>1/9/07[a]</td><td>0.02</td><td>0.01</td><td>0.06</td></tr>
<tr><td rowspan="2">13/9/07</td><td rowspan="2">6th</td><td>12/9/07[a]</td><td></td><td></td><td></td><td rowspan="2">0.55</td><td rowspan="2">0.45</td><td rowspan="2">0.16</td></tr>
<tr><td>13/9/07[a]</td><td>0.01</td><td>0.00</td><td>0.06</td></tr>
<tr><td rowspan="2">19/9/07</td><td rowspan="2">7th</td><td>17/9/07[b]</td><td></td><td></td><td></td><td rowspan="2">0.20</td><td rowspan="2">0.24</td><td rowspan="2">0.02</td></tr>
<tr><td>19/9/07[b]</td><td>0.00</td><td>0.14</td><td>0.00</td></tr>
<tr><td rowspan="2">3/10/07</td><td rowspan="2">10th</td><td>1/10/07[b]</td><td></td><td></td><td></td><td rowspan="2">0.22</td><td rowspan="2">0.56</td><td rowspan="2">0.05</td></tr>
<tr><td>3/10/07[b]</td><td>0.15</td><td>0.72</td><td>0.05</td></tr>
</table>

a = ECa readings taken on the ground, b = ECa readings taken elevated

6.3.3 Correlations between ECa and soil tension and plant growth

ECa measurements were taken at the same time as soil tension (soil matric potential) measurements during both growing seasons. Correlations between soil tension and ECa were generally low (Table 6.4 and 6.5) but improved marginally for later irrigations due to the larger differences in soil moisture across the plots (Appendix 6.8). These correlations were weaker for vertical mode ECa compared to horizontal mode. This demonstrates that ECa approach doesn't appear to be useful to evaluate ECa and soil tension interactions. Plant canopy area was not correlated with ECa values during either trial but ECa values measured later in the season were marginally correlated (R^2 ~ 0.4) with lettuce head diameter (data not shown).

Table 6.4 Coefficients of determination for a linear relationship between soil tension and ECa (autumn trial)

Catch can date	No. of irrigation after transplant	Soil tension & ECa measurement date	Correlation between ECa and soil tension (R^2)	
			Horizontal mode	Vertical mode
15/4/07	2nd	19/4/07	0.07±0.11	0.01±0.01
20/4/07	3rd	20/4/07	0.02±0.03	0.06±0.03
		25/4/07	0.25±0.09	0.15±0.10
26/4/07	4th	26/4/07	0.05±0.04	0.14±0.10
		1/5/07	0.11	0.02
2/5/07	5th	2/5/07	0.07	0.09
		6/5/07	0.04	0.15
		7/5/07	0.01	0.11
8/5/07	6th	8/5/07	0.18	0.07
		9/5/07	0.17	0.03
		10/5/07	0.12	0.08
		12/5/07	0.14	0.07
		13/5/07	0.14	0.08
14/5/07	7th	14/5/07	0.21	0.04
		15/5/07	0.15	0.02
		17/5/07	0.18	0.16

Table 6.5 Coefficients of determination for a linear relationship between soil tension and horizontal mode ECa (winter trial)

Catch can date	No. of irrigation after transplant	Soil tension & ECa measurement date	Correlation between ECa and soil tension (R^2)		
			Poor-1 grid	Poor-2 grid	Control grid
15/8/07	3rd	17/8/07	0.01	0.04	0.30
18/8/07	4th	18/8/07	0.03	0.00	0.36
		31/8/07	0.01	0.17	0.01
1/9/07	5th	1/9/07	0.00	0.14	0.07
		12/9/07	0.01	0.16	0.03
13/9/07	6th	13/9/07	0.00	0.01	0.02
		17/9/07	0.07	0.40	0.03
19/9/07	7th	19/9/07	0.00	0.15	0.02
		1/10/07	0.03	0.24	0.00
3/10/07	10th	3/10/07	0.28	0.42	0.01

6.4 Conclusions

Electromagnetic induction does not appear to be suitable for evaluating the uniformity of individual sprinkler irrigation applications in shallow rooted crops or where the uniformity of the irrigation is comparatively high. There was no difference between using either the ECa measurements or the difference in ECa measured pre-irrigation and post-irrigation. However, this work suggests that electromagnetic sensing may be useful (in horizontal mode) to identify cumulative non-uniformities in sprinkler irrigation applications later in the season where the uniformity of application is poor (e.g. CU < 70%) and the application patterns are consistent throughout the season. In these cases, ECa values and patterns were similar irrespective of when irrigation occurred relative to the EM measurement. ECa measurements are also not able to be used to map lettuce growth. Given these limitations, electromagnetic sensing was not used in the subsequent evaluations of irrigation performance (Chapter 7) in this research.

Chapter 7. In-season variations in irrigation application patterns and the effect on soil moisture

7.1 Introduction

The uniformity of irrigation applications affects the amount of water applied to the soil and potentially crop stress at particular locations within the field. For a sprinkler irrigation system, the pattern of application is a function of both the system characteristics (e.g. sprinkler head design, spacing, height and nozzle size) and the operating conditions (e.g. operating pressure, wind speed and direction). Thus, both the pattern of irrigation application and the measure of uniformity would be expected to vary throughout the season (Chapter 3). However, irrigation performance evaluations are commonly conducted over only a single irrigation event with little regard for variation throughout the season. The presence of in-season rainfall could also be expected to reduce the impact of variations in soil moisture created by irrigation non-uniformity (Chapter 2.2.4). Hence, there is uncertainty regarding the size and nature of variation in irrigation application patterns throughout a season and the impact of this variation on soil moisture and consequently crop responses. This chapter reports on measurements conducted to assess the in-season variation in application system uniformity and the resultant changes in soil moisture patterns.

7.2 Variations in sprinkler pressure and flow rate

Three sprinkler grids (Control, Poor-1 and Poor-2) with different levels of application uniformity were established and monitored in both the autumn and winter trials (Chapter 4). The system operating pressure after the first four irrigations of the autumn trial varied between 361 and 387 kPa (Appendix 7.1). The operating pressures of individual sprinklers in the Poor-1 grid were modified after the first four in-crop irrigations by the installation of pressure reducers (Chapter 4.5.2). Where 138 and 172 kPa pressure reducers were fitted in the autumn trial, the measured sprinkler operating pressure ranged from 137 to 164 kPa and 186 to 208 kPa, respectively. Fitting the 138 and 172 kPa pressure reducers reduced the average sprinkler discharge rate from 4.8 L/min to 3.0 and 3.1 L/min, respectively (Table 7.1). Three sizes of pressure reducers (103, 138 and 172 kPa) were installed under three of the four poor grid sprinklers during the winter trial. In this trial, the average pressure measured for the individual sprinklers ranged from 118 to 355 kPa and the flow rates ranged from 2.6 to 4.6 L/min (Table 7.1, Appendix 7.1).

Table 7.1 Nominal and measured sprinkler pressure and flow rate for the Poor grids

Nominal pressure (kPa)	Autumn trial		Winter trial	
	Measured pressure (kPa)	Measured flow rate (L/min)	Measured Pressure (kPa)	Measured flow rate (L/min)
360	382 (± 26)	4.8 (± 0.3)	355 (± 16)	4.6 (± 0.3)
172	210 (± 28)	3.1 (± 0.2)	187 (± 9)	3.2 (± 0.2)
138	150 (± 10)	3.0 (± 0.1)	158 (± 16)	3.1 (± 0.1)
103	NA	NA	118 (± 4)	2.6 (± 0.1)

NA = Not applicable. Figures in brackets are standard deviation

7.3 Seasonal variations in irrigation performance

7.3.1 Application volume and uniformity

Autumn trial

A total of 261.9 mm (including rainfall) was applied on average to the Control grid. The potential evapotranspiration (ETo) for the season was 178.0 mm calculated on a daily basis using the weather data (Chapter 4.3) and the Penman-Monteith equation (Allen *et al*. 1998). The irrigation and rainfall applied exceed the ETo as irrigation volumes were not adjusted in response to measured parameters. This was consistent with local commercial practice. Individual irrigation applications to the Control grid varied from 9.7 to 28.8 mm/irrigation. There was no significant difference ($P < 0.05$) in the average depth of water applied to each of the measured grids for the first five irrigations (Table 7.2). However, the installation of the pressure reducers (on the 1/5/07) resulted in a substantial decrease in the average depth of applied water to the Poor-1 grid compared with the Control grid. There was no significant difference in water application between the Poor-2 and Control grids throughout the season.

The Christiansen's coefficient of uniformity (CU) (Christiansen 1942) varied between 76 and 89% for the Control grid for the autumn trial (Table 7.2). The CU in the Poor-1 grid ranged from 73 to 86% before sprinkler modification but ranged from 53 to 70% after the individual sprinkler pressures were reduced (Table 7.2). The CU of the Poor-2 grid was above 79% before sprinkler modification but then ranged from 66 to 82% after modification. The distribution uniformity (DU) (Smajstrla *et* *al*. 1997; Tarjuelo *et al*. 1999; Walker and Skogerboe 1987) followed the same trend as CU (Table 7.2). The catch can data for each grid and irrigation event is presented in Appendix 7.2.

Table 7.2 Irrigation application and uniformity for the autumn trial

Catch can date	Average water applied (mm)			Coefficient of uniformity (CU) (%)			Distribution uniformity (DU) (%)		
	Poor-1 grid	Poor-2 grid	Control grid	Poor-1 grid	Poor-2 grid	Control grid	Poor-1 grid	Poor-2 grid	Control grid
5/4/07	19.5(±5.2)	18.7(±4.0)	18.7(±4.2)	77.7	82.2	81.6	69.6	75.9	74.7
13/4/07	30.6(±7.0)	33.1(±5.8)	28.8(±5.1)	81.5	86.2	86.1	76.6	82.0	79.8
15/4/07	24.5(±4.2)	25.1(±4.3)	23.4(±3.7)	86.1	85.8	87.4	80.8	77.6	80.8
20/4/07	16.7(±5.7)	17.3(±3.4)	16.1(±4.9)	73.5	84.4	78.2	60.5	77.3	71.3
26/4/07	18.5(±6.1)	18.6(±3.7)	17.0(±2.5)	73.1	84.9	79.2	64.6	79.2	73.6
2/5/07[a]	15.6(±6.2)	20.8(±4.5)	20.7(±4.1)	66.5	81.7	84.1	56.0	75.8	74.1
8/5/07[b,c]	16.3(±7.2)	24.7(±6.3)	21.5(±5.2)	63.4	78.8	80.9	53.1	68.6	71.0
14/5/07	16.7(±7.0)	25.7(±4.8)	21.9(±3.1)	66.6	84.1	88.9	50.1	76.1	82.9
18/5/07[d]	7.8(±3.3)	10.0(±3.9)	9.7(±3.1)	64.6	66.9	76.0	51.6	51.2	64.9
25/5/07	14.0(±5.0)	16.8(±3.8)	17.0(±2.5)	70.3	82.0	88.9	63.1	74.0	84.7
30/5/07	7.3(±4.0)	10.9(±5.0)	10.6(±2.7)	53.4	66.0	80.4	44.3	47.1	70.9
Total	187.5	221.7	205.4						

Figures in brackets are standard deviations of the water applied within each grid
Shaded areas indicate data after sprinkler pressure or head changed
a = Introduced 172 kPa pressure reducers in the Poor-1 grid
b = Replaced one 172 kPa reducer with a 138 kPa reducer in the Poor-1 grid
c = Replaced old nozzles with new ones in the Poor-2 grid
d = Introduced Nelson rotators into the Poor-2 grid

Winter trial

A total of 293.3 mm was applied on average to the Control grid during the winter trial compared to the ETo of 233.0 mm. Individual irrigation applications to the Control grid varied from 10.9 to 23.9 mm/irrigation. There was no significant difference ($P < 0.05$) in the average depth of water applied to each of the measured grids for the first three irrigations (Table 7.3). The installation of the pressure reducers (on the 18/8/07) resulted in a substantial decrease in the average depth of applied water to each of the Poor grids compared with the Control grid. However, there was no significant decrease in uniformity compared to the Control grid until worn sprinkler heads were refitted to the Poor grids on the 13/9/07.

The CU for the Control grid varied between 69 and 88% throughout the season (Table 7.3). The CU for the Poor grids ranged from 61 to 86% before the sprinkler heads were modified (up to and including the 1/9/07). However, after sprinkler modification, the CU varied from 37 to 65% in the Poor-1 grid and from 46 to 64% in the Poor-2 grid. The DU followed the same trend in each case (Table 7.3). The catch can data for each grid and irrigation event is presented in Appendix 7.2.

Table 7.3 Irrigation application and uniformity for the winter trial

Catch can date	Average water applied (mm)			Coefficient of uniformity (CU) (%)			Distribution uniformity (DU) (%)		
	Poor-1 grid	Poor-2 grid	Control grid	Poor-1 grid	Poor-2 grid	Control grid	Poor-1 grid	Poor-2 grid	Control grid
9/8/07	24.8(±12.2)	18.3(±3.8)	18.3(±5.9)	61.1	84.9	76.6	52.3	77.4	72.0
11/8/07[a]	19.5(±4.0)	19.0(±3.5)	19.8(±3.8)	84.1	86.2	85.0	75.8	76.9	74.8
15/8/07	10.1(±3.5)	10.4(±3.4)	10.9(±4.0)	69.8	72.7	69.3	55.6	62.0	55.2
18/8/07[b]	13.9(±4.3)	14.7(±3.4)	19.2(±3.9)	75.4	82.6	84.9	63.9	70.9	72.3
1/9/07[c]	12.1(±3.0)	11.2(±3.7)	16.9(±3.2)	80.0	72.0	84.6	71.0	58.5	74.5
13/9/07[d]	13.4(±9.6)	13.2(±6.0)	19.2(±4.0)	48.1	63.7	82.8	32.4	52.1	70.6
19/9/07	15.4(±7.6)	14.9(±7.7)	23.9(±4.0)	65.1	58.3	88.0	55.9	47.2	85.7
25/9/07	16.0(±8.8)	14.4(±8.0)	23.1(±3.5)	59.4	55.0	88.4	50.9	44.9	83.4
29/9/07	6.1(±5.0)	6.7(±3.7)	10.9(±2.6)	37.0	55.2	80.5	21.6	39.4	67.4
3/10/07	13.6(±6.7)	12.9(±8.2)	21.5(±3.5)	62.0	46.1	87.3	54.6	36.7	78.6
Total	144.9	135.7	183.7						

Figures in brackets are standard deviations of the water applied within each grid
Shaded areas indicate data after system change
a = Replaced all old sprinklers with new ones for the whole trial
b = Introduced two 172 and one 138 kPa pressure reducers in each Poor grid
c = Replaced one 172 kPa reducer with a 103 kPa in each Poor grid
d = Replaced new sprinklers with worn sprinklers

7.3.2 Patterns of irrigation application

The pattern of irrigation application within each sprinkler grid varied considerably throughout the season both before and after introducing the pressure reducers (Appendix 7.3). Throughout the season in the Control grid, and prior to sprinkler modification in the Poor grids (i.e. when the uniformity was high), the spatial pattern of water application varied between irrigations primarily due to the effects of wind speed, wind direction and system operating pressure. For example (Figure 7.1), location 3.9 × 4.0 m in the Poor-1 grid received the smallest water application on the 13/4/07 while 4.25 × 8.25 m received the least water on the 15/4/07. However, following sprinkler modification (i.e. when uniformity measures were substantially lower), the application patterns were generally more consistent with large differences in application due to the over-riding impact of individual sprinkler radial leg patterns.

For example, in the Poor-1 grid (Figure 7.1), the last two catch cans (i.e. 6.75 and 8.25 m along lateral) on beds four and five (i.e. 5.46 and 7.02 m between laterals) always received less water than the rest of the grid. Similarly, areas around the sprinklers commonly received the highest water applications. Under these conditions the impact of wind speed and direction would be expected to have a relatively small effect on the pattern.

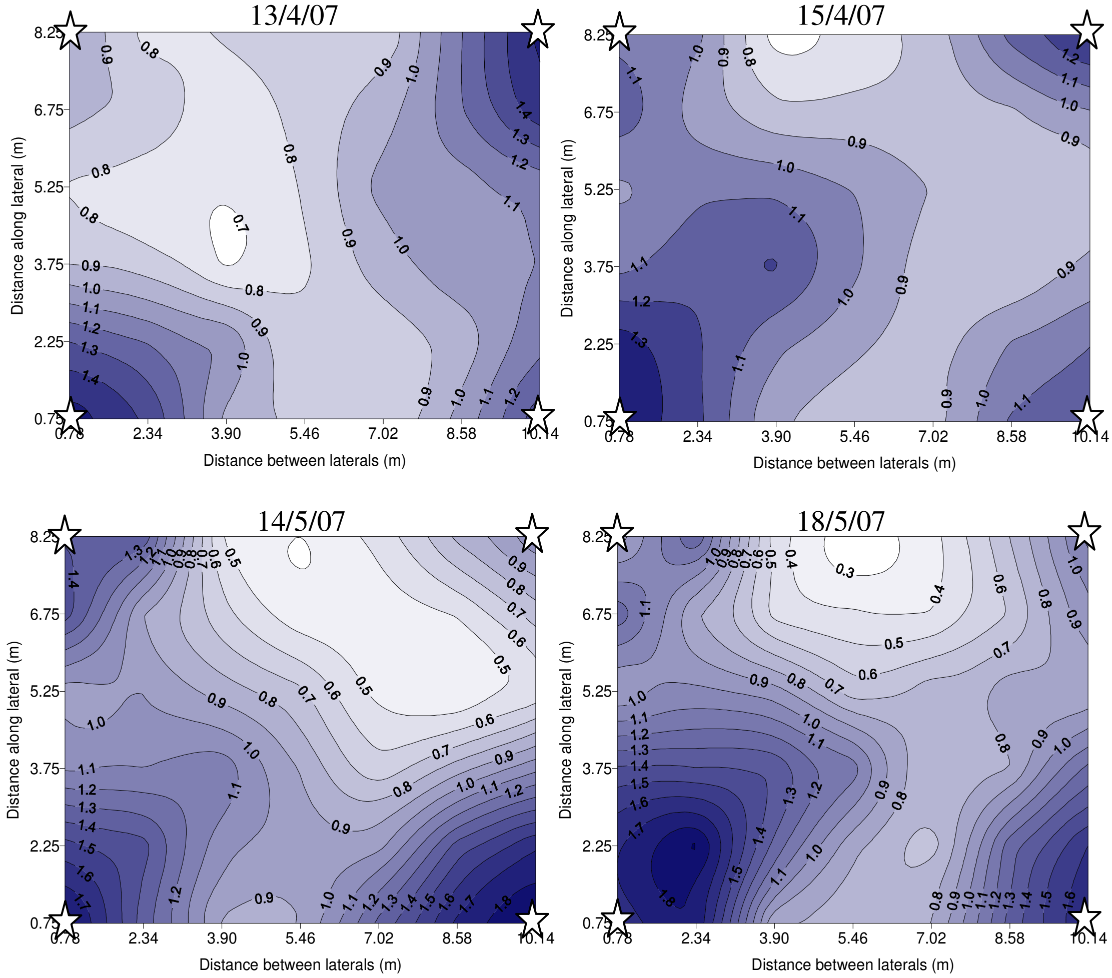


Figure 7.1 Normalised (to average) irrigation distribution in the Poor-1 grid before (13/4/07, 15/4/07) and after (14/5/07, 18/5/07) introducing pressure reducers in the autumn trial

Similar conclusions regarding sprinkler application patterns can be drawn for the winter trial (Appendix 7.3) with large variations in the pattern of application observed between irrigation events where the sprinkler uniformity was high (Figure 7.2). However, where the application uniformity was low (e.g. 19/9/07 and 29/9/07), the pattern tended to be more consistent for irrigation events and dominated by the sprinkler radial leg characteristics.

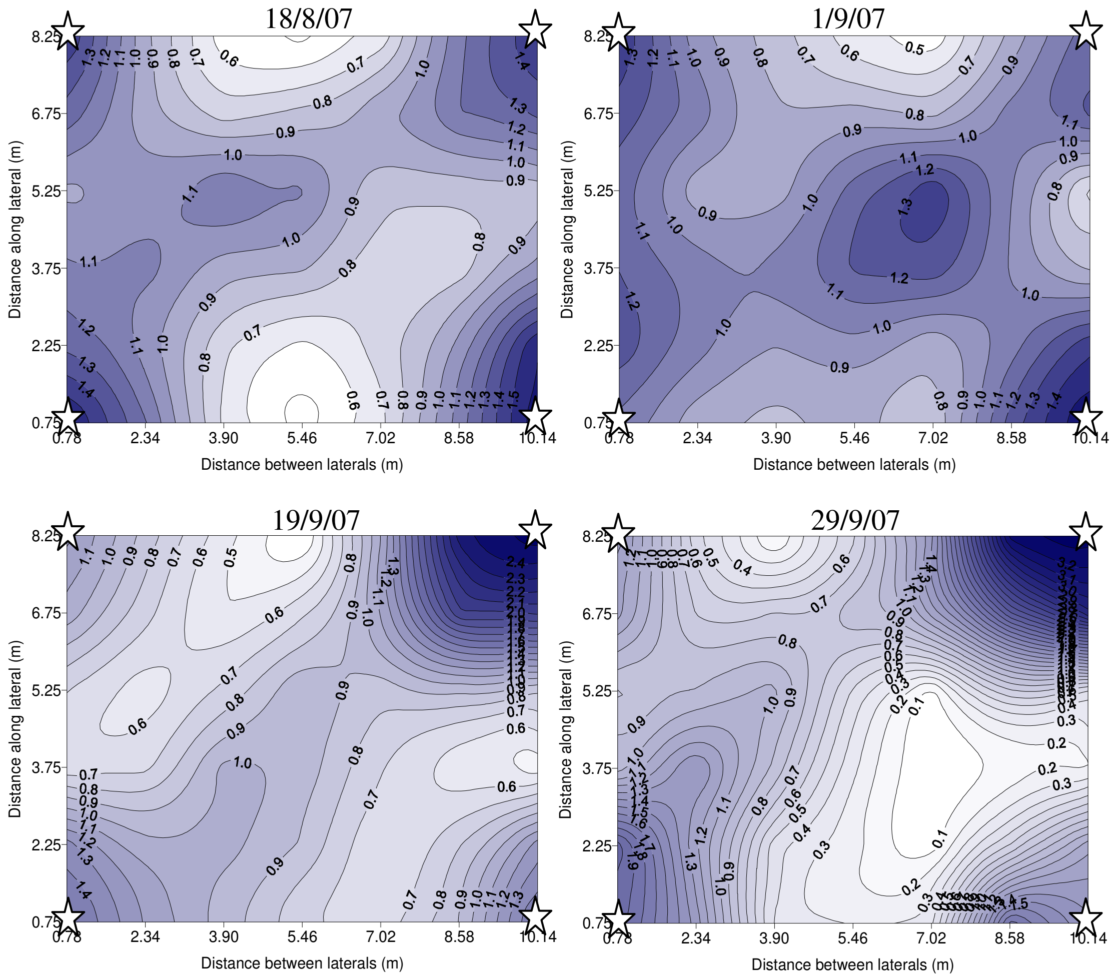


Figure 7.2 Normalised (to average) irrigation distribution in the Poor-1 grid before (18/8/07, 1/9/07) and after (19/9/07, 29/9/07) introducing pressure reducers in the winter trial

7.3.3 Frequency plots of application depth

The depth of water captured in the catch cans were normalised using the average water applied in each grid. Frequency plots of the normalised depth show a wide variation in the volumes applied from irrigation to irrigation both throughout the season and between the different grids (Figure 7.3 & 7.4). As expected there was a close inverse relationship between the CU and the range of irrigation depths applied within the grids. For example, the Control grid (i.e. high CU values) frequency plots were generally grouped in a narrow range around the average (Figure 7.3b) and these plots were often normally distributed. However, the variation in the depths applied within the Poor-1 (i.e. low CU) (Figure 7.3a) and Poor-2 grid (Appendix 7.4) was much greater. Where the CU was low (i.e. Poor-1 grid), the catch can depths were often multi-modal (e.g. 8/5/07, 14/5/07) and also likely to be positively skewed towards the lower application values (e.g. 25/5/07, 30/5/07).

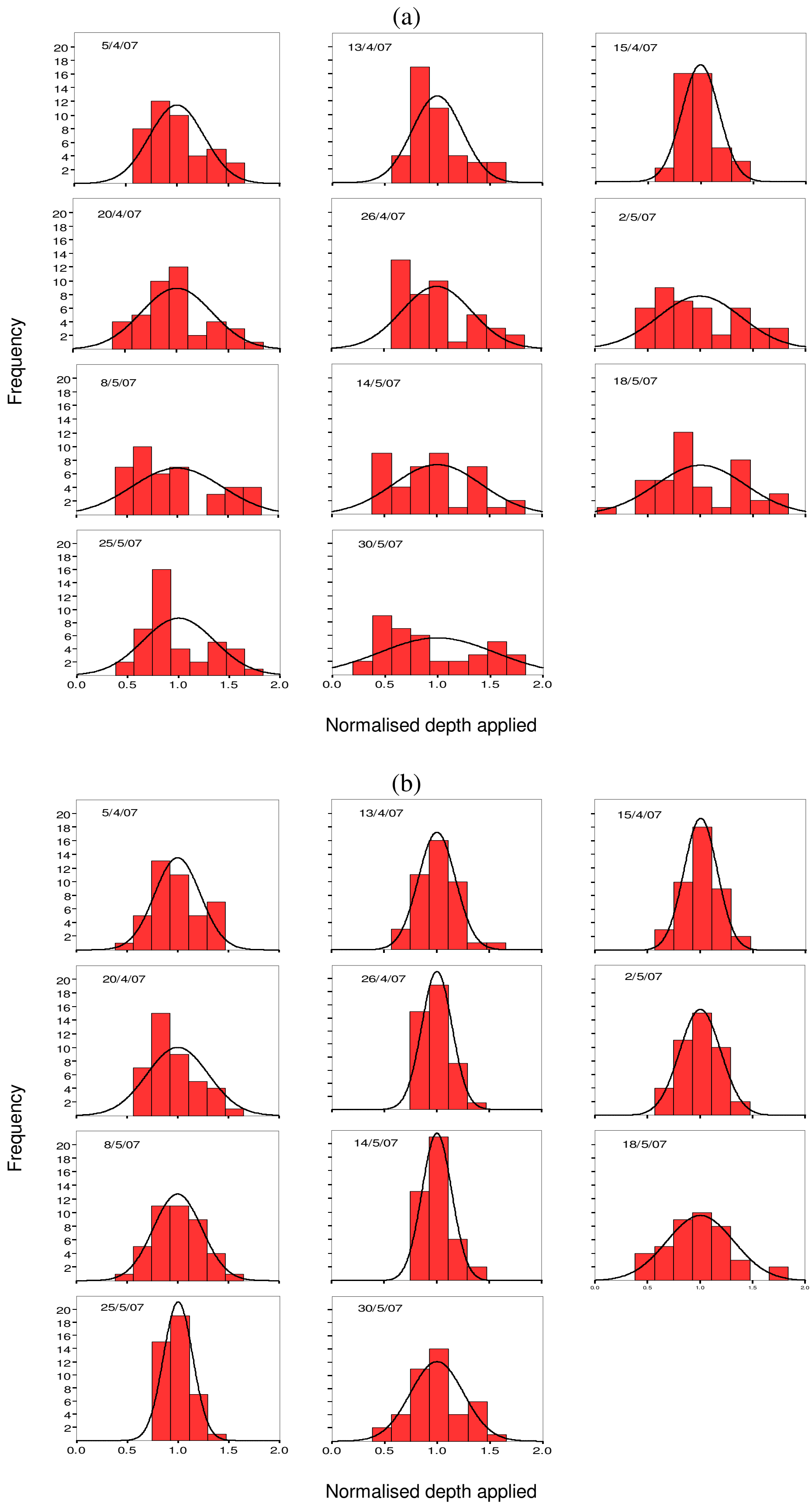
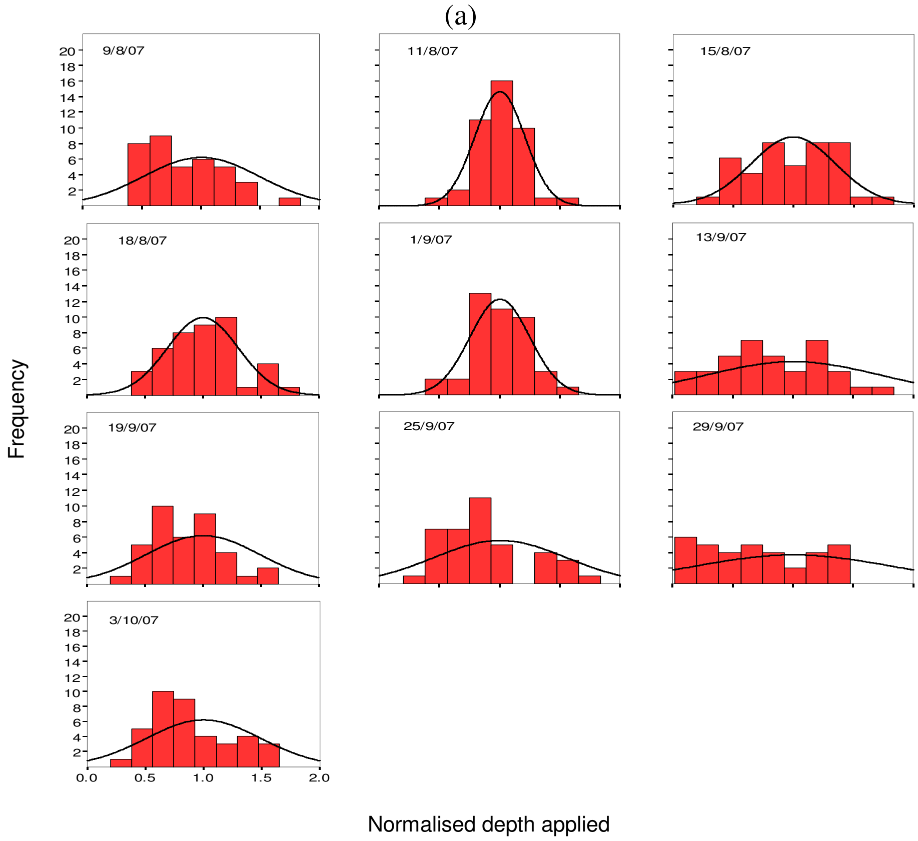


Figure 7.3 Frequency plots of the normalised depth of water applied in each irrigation to the (a) Poor-1 and (b) Control grids during the autumn trial. Solid line shows a normal distribution for comparison.

(a)



(b)

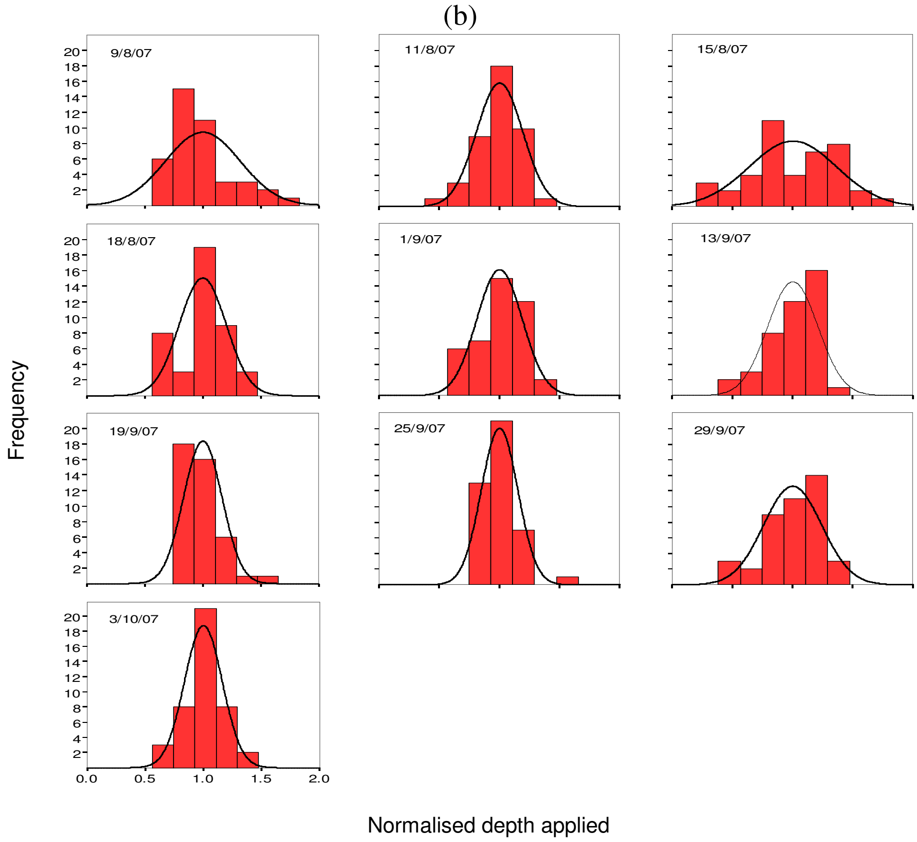


Figure 7.4 Frequency plots of the normalised depth of water applied in each irrigation to the (a) Poor-1 and (b) Control grids during the winter trial. Solid line shows a normal distribution for comparison

Frequency plots of total water applied in all the irrigations (Figure 7.5) show a similar pattern to the individual events. For the high uniformity Control grids, the water application was normally distributed while the lower uniformity Poor grids produced frequency plots skewed towards the lower application volumes.

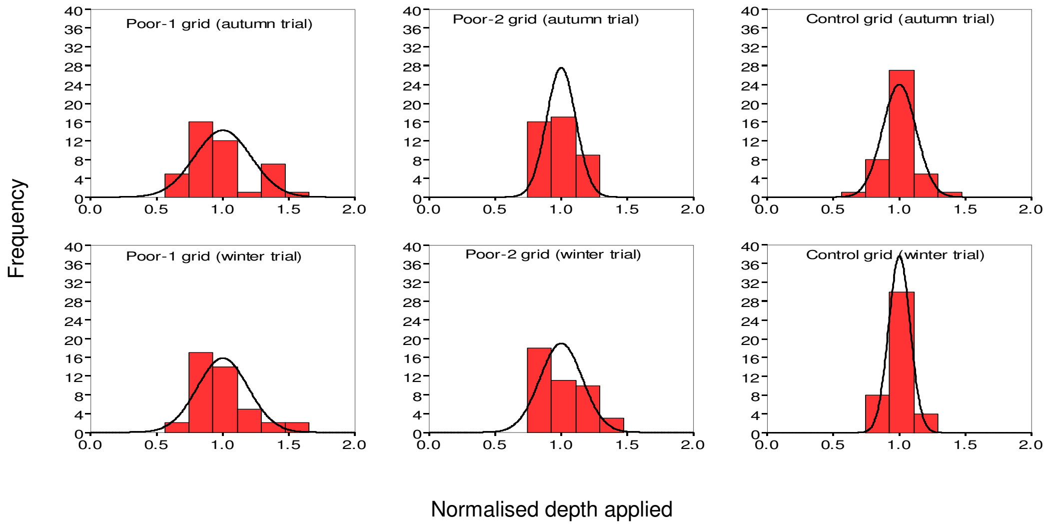


Figure 7.5 Frequency plots of the normalised total depth of water applied in all irrigations. Solid line shows a normal distribution for comparison

7.4 Effect of water application on soil tension

Daily soil tension (soil matric potential) measurements at 0.15 m depth were taken (Chapter 4.6) throughout both trials (Appendix 7.5). The application patterns were relatively consistent between irrigations after the pressure reducers were fitted and the low, medium and high water application areas were identified from the irrigation application contour plots (e.g. Figure 7.2). Examples of the soil tension variation within the high, medium and low water application areas for each grid are presented here.

7.4.1 Soil tension variability for low, medium and high water application areas

Autumn trial

As expected, soil tension (soil matric potential) varied throughout the season in response to the irrigation applications (Figure 7.6). In general, the higher the CU the smaller the variation between the high, medium and low water application areas.

There was also little difference in soil tension between these areas early in the autumn season when the crop water requirement and rooting depth of the plants were small. However, significant differences were observed later in the season (i.e. Control grid) as crop water demand increased and after the pressure reducers were fitted in the Poor-1 grid (Figure 7.6a). The soil tension before fitting the pressure reducers ranged between 4 to 23 kPa in the Poor-1 grid (Figure 7.6a) and increased after fitting the pressure reducers to maximum of 22, 55 and 93 kPa in the low, medium and high water application areas respectively. The soil tensions for the Poor-2 and Control grids were ≤41 kPa during the whole cropping season (Figure 7.6 b & c). However, there was typically a 10-20 kPa difference in the maximum soil tension observed between the low, medium and high water application areas of the Poor-2 and Control grids. Apart from the low water application area in the Poor-1 grid, all areas in all grids were re-wet to approximately 10 kPa by the irrigation events.

Winter trial

Rain (Figure 4.5) resulted in the being little difference in soil tension during the early part of the winter trial (Figure 7.7). Maximum soil tension was generally less than 20 kPa in all areas of all plots prior to the 7/9/07. However, after this period, differences started occurring with the maximum soil tension in the Poor-1 grid being 45, 75 and 89 kPa for the high, medium and low water application areas, respectively (Figure 7.7a). Relatively low irrigation uniformity for the Poor-2 grid on the 1/9/07 initiated differences in soil tension for the low, medium and high water application areas. In the Poor-2 grid, the maximum soil tension was 40, 64 and 81 kPa for the high, medium and low water application areas (Figure 7.7b). The maximum soil tensions in the Control grid were 34, 47 and 63 kPa for the high, medium and low application areas (Figure 7.7c) and consistent with higher crop water requirements during the later part of the season. It is interesting to note that the medium and low water application areas in the Poor grids did not reach field capacity (~ 10 kPa measured at 15 cm depth) but the high water application area did reach field capacity immediately after irrigation. However, all areas in the Control grid were re-wet back to field capacity after each irrigation.

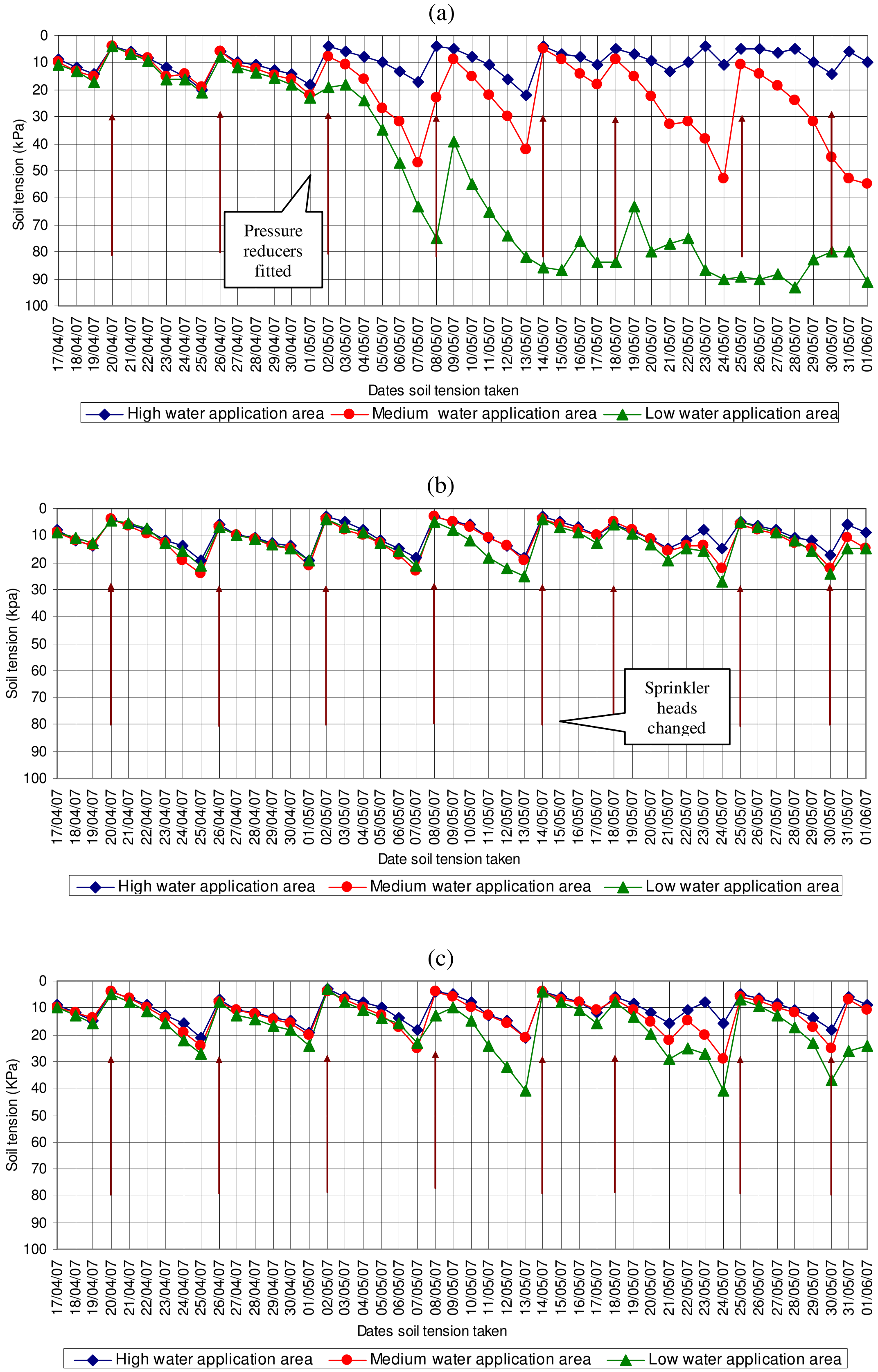


Figure 7.6 Soil tension variation in low, medium and high water application areas for the (a) Poor-1 (b) Poor-2 and (c) Control grids in the autumn trial. Arrows indicate irrigation events

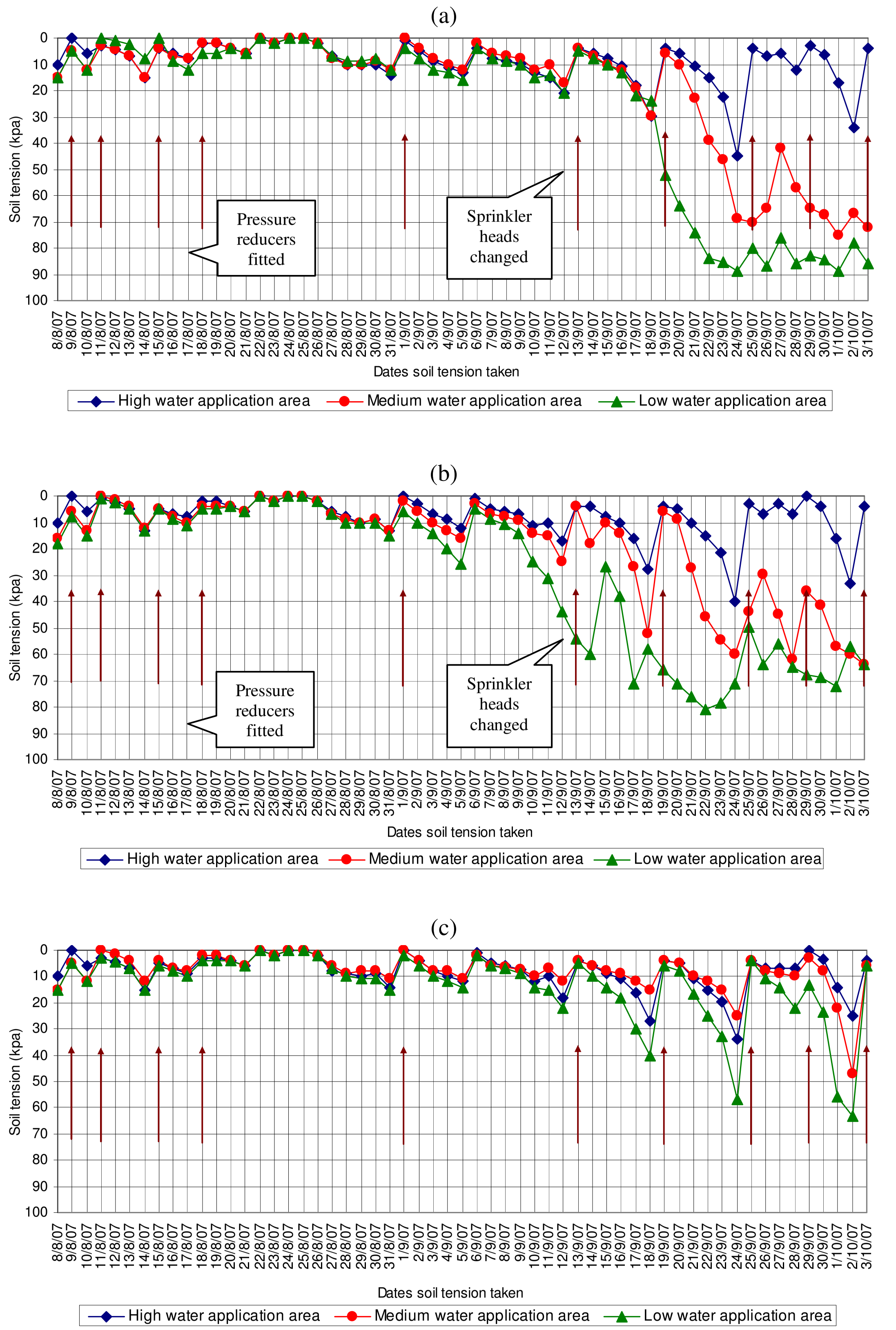


Figure 7.7 Soil tension variation in low, medium and high water application areas for the (a) Poor-1 (b) Poor-2 and (c) Control grids in the winter trial. Arrows indicate irrigation events

7.4.2 Relationships between water application and soil tension

Water application and soil tension

The irrigation water applied at each catch can was plotted against the soil tension (soil matric potential) measured on the second day after the irrigation event (Figure 7.8, Appendix 7.6). A power curve was found to best fit this data and the coefficients of determination (R^2) for these regressions for all irrigations are shown in Table 7.4. The choice of a power curve is also consistent with the non-linear relationship between soil water tension and the volumetric soil water content (Burt 1995). In the autumn trial, the coefficients of determination (R^2) were generally <0.5 in both the Control grid and in the Poor grids before modifying the pressures. However, the system modifications generally increased the R^2 with the maximum value of 0.85 recorded for the Poor-1 grid immediately after the system change. Higher irrigation uniformities in the Poor-2 and Control grids produced weaker correlations than in the Poor-1 grid. A similar pattern was also found for the winter trial (Table 7.4).

Table 7.4 Coefficients of determination for a power curve fitted between irrigation water applied and soil tension

Catch can date	Soil tension date	Coefficients of determination (R^2)		
		Poor-1 grid	Poor-2 grid	Control grid
Autumn trial				
15/4/07	17/4/07	0.33	0.16	0.23
20/4/07	21/4/07	0.41	0.00	0.63
26/4/07	27/4/07	0.51	0.16	0.08
2/5/07	3/5/07	0.85	0.44	0.55
8/5/07	9/5/07	0.73	0.15	0.29
14/5/07	15/5/07	0.72	0.01	0.10
18/5/07	19/5/07	0.60	0.58	0.29
25/5/07	26/5/07	0.59	0.04	0.10
Winter trial				
9/8/07	10/8/07	0.33	0.07	0.08
11/8/07	12/8/07	0.04	0.01	0.00
15/8/07	16/8/07	0.50	0.51	0.52
18/8/07	19/8/07	0.36	0.13	0.11
1/9/07	2/9/07	0.46	0.53	0.00
13/9/07	14/9/07	0.65	0.64	0.23
19/9/07	20/9/07	0.55	0.73	0.00
25/9/07	26/9/07	0.68	0.76	0.11
29/9/07	30/9/07	0.40	0.30	0.08

Shaded areas indicate data after system change

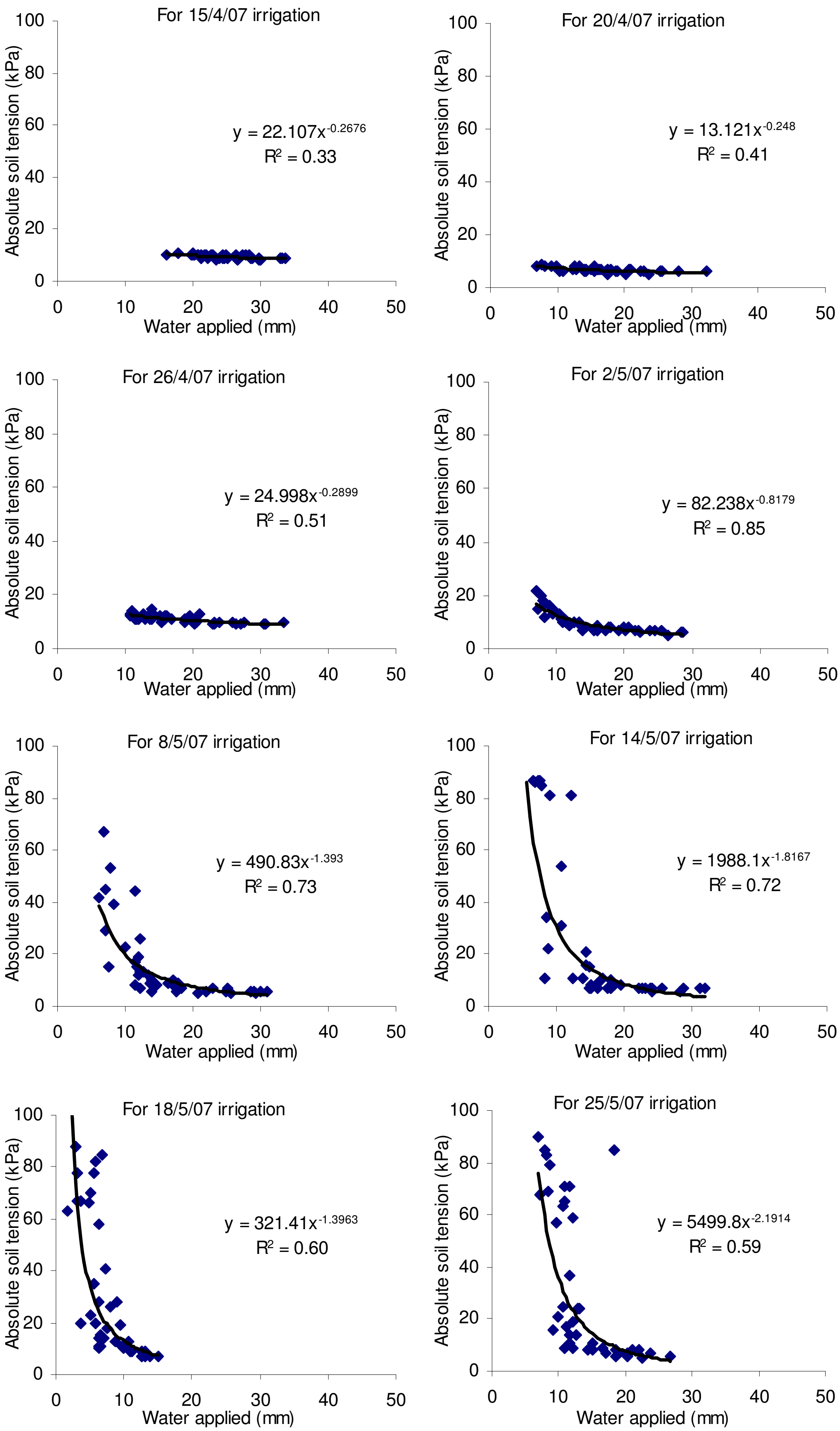


Figure 7.8 Effect of water application on soil tension in the Poor-1 grid (autumn trial) (each point represents a catch can and its associated tensiometer).

The correlations show (Figure 7.8) that early in the season (before modifying pressures) sufficient water was being applied in all areas of the grid to ensure the soil moisture was at field capacity after irrigation and hence, flat curves were produced. However, after fitting the pressure reducers (1/5/07) an increased variability in water application created areas within the grid which did not re-wet to field capacity (see also the soil tension curves, section 7.4.1). The increased spread in soil tension for values with low water application later in the season (Figure 7.8) reflect the soil tension measuring a cumulative effect while the water application at a point in any single event will vary with slight differences in spatial pattern of application (Section 7.3.2). There was little difference between the relationships measured late in the season for individual events (Figure 7.8) and the relationship identified when all data from the season was used (Figure 7.9).

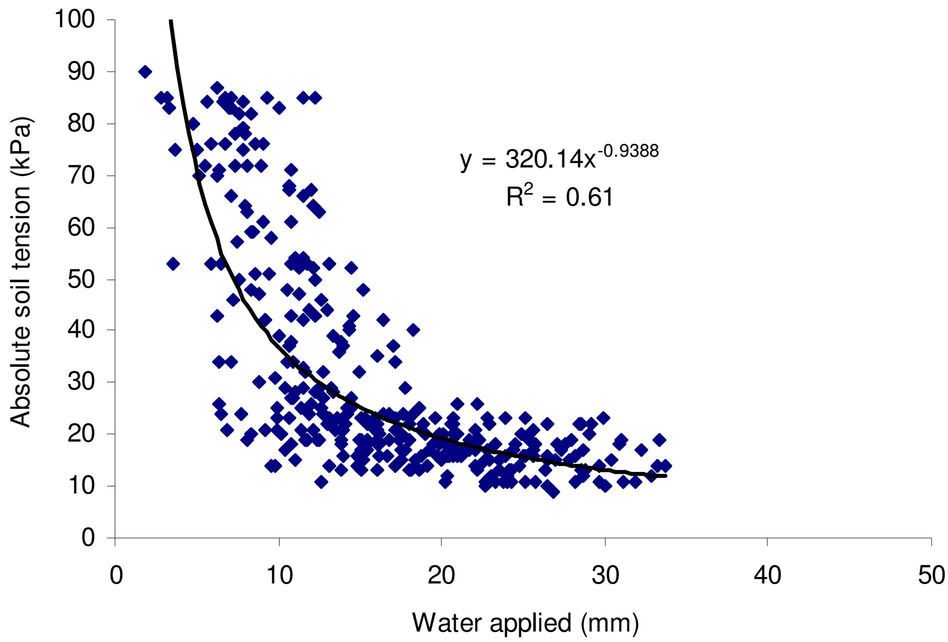


Figure 7.9 Water applied and soil tension for the Poor-1 grid, autumn trial (all data)

Water application and the change in soil tension from before and after the irrigation

The irrigation water applied and soil tension difference (the day before and after irrigation) were also compared (Figure 7.10). In this case, a log curve was found to best fit the data (Appendix 7.7) but the coefficients of determination for all

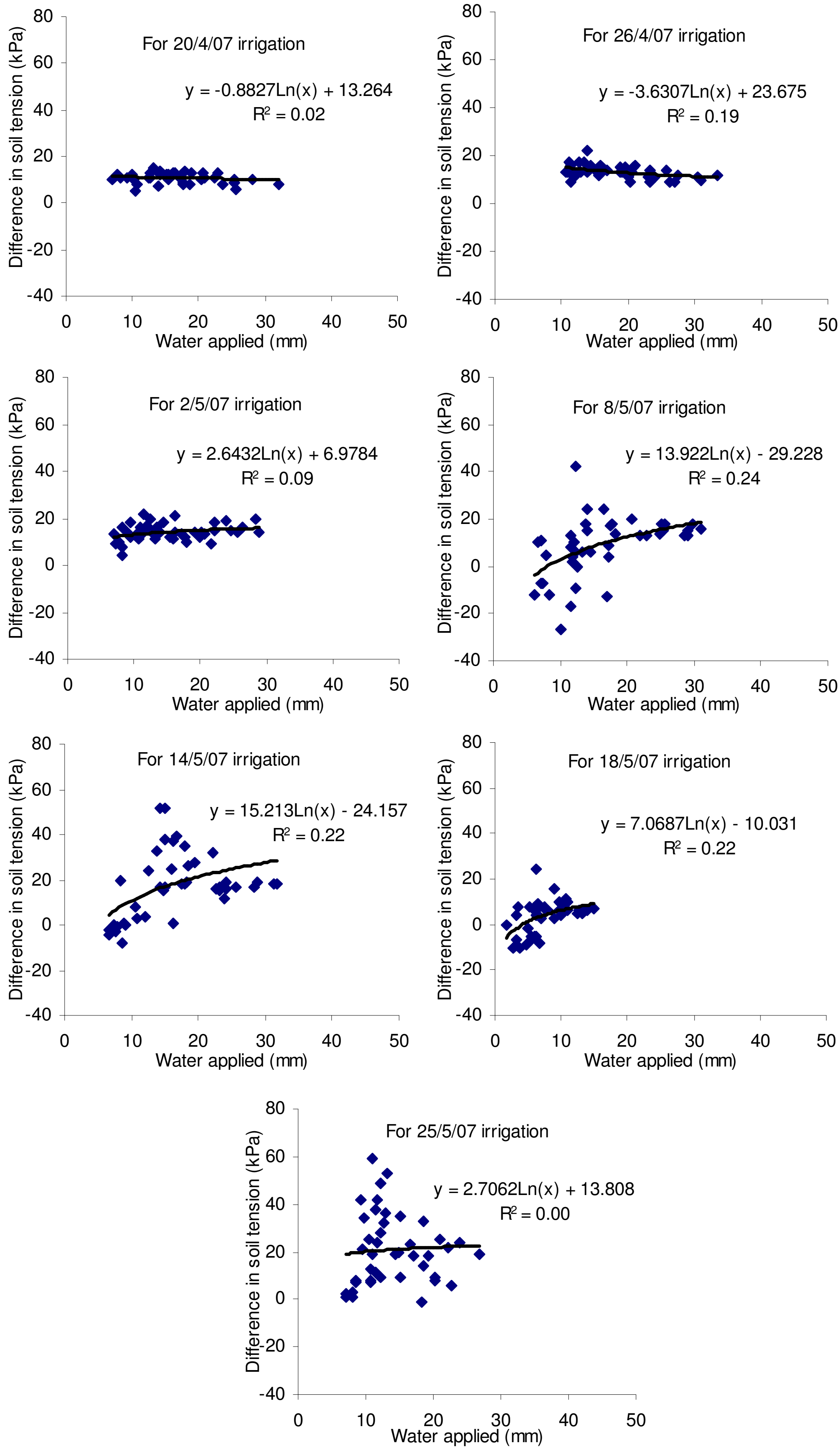


Figure 7.10 Effect of water application with difference in soil tension measured before and after irrigation for the Poor-1 grid (autumn trial)

irrigations (Table 7.5) were generally smaller than for the absolute soil tension relations (Table 7.4). As with the absolute soil tension measurement, there were slightly higher coefficients after the system had been modified to reduce application uniformity. Inconsistencies in the irrigation patterns (Appendix 7.3) are likely to be the main factors responsible for low coefficients. However it should be noted that this work was conducted on a heavy clay soil. The potential for lateral redistribution and high moisture holding capacity of the soil may also have influenced these relationships. Hence, it is possible that the effect of non-uniform irrigation applications may be more readily observed on sand textured soils. Rainfall events may also have affected the results with no relationship found for the 18/8/07 irrigation. The negative difference in soil tension later in the season in areas of low water application also suggests that more water is being extracted by the crop than was applied by the irrigation in these areas.

Table 7.5 Coefficients of determination for a log curve fitted between irrigation water applied and the difference in soil tension before and after irrigation

Catch can date	Coefficients of determination (R^2)		
	Poor-1 grid	Poor-2 grid	Control grid
Autumn trial			
20/4/07	0.02	0.01	0.09
26/4/07	0.19	0.14	0.15
2/5/07	0.09	0.04	0.06
8/5/07	0.24	0.01	0.21
14/5/07	0.22	0.04	0.14
18/5/07	0.22	0.54	0.01
25/5/07	0.00	0.28	0.01
Winter trial			
11/8/07	0.09	0.15	0.17
15/8/07	0.15	0.00	0.16
18/8/07	NR	NR	NR
1/9/07	0.53	0.26	0.04
13/9/07	0.44	0.19	0.06
19/9/07	0.45	0.62	0.02
25/9/07	0.30	0.23	0.07
29/9/07	0.08	0.06	0.01

Shaded areas indicate data after system change, NR = No relationship found

7.5 Conclusions

There were substantial variations in the uniformity of individual irrigation events throughout the season. The CU of the Control grids (without any induced system changes) varied from 76 to 89% and 69 to 88% in the autumn and winter trials, respectively. Similarly, there were also substantial variations in the performance measured by catch can grids at different locations in the same field in the same events. For example, the measured CU varied from 73 to 85% on the 26/4/07 and from 61 to 85% on the 9/8/07 prior to any system changes between the grids. These results confirm that it is not appropriate to only use a single catch can grid result on a single event to provide a measure of the irrigation performance over the whole field and season.

This work has shown that the pattern of irrigation application within the grid is affected by the sprinkler operating pressure, flow rate and environmental conditions and also possibly due to sprinkler head and nozzle wear. In general, the higher the irrigation uniformity, the less predictable pattern of water application. However, with low uniformity systems, the pattern appears to be dominated by the discharge from the individual sprinklers and less affected by the wind direction or speed.

The frequency of the application depths are more normally distributed as the uniformity increases. This suggests that while the spatial pattern of water application for specific irrigation events is difficult to predict, the frequency distribution of moderate to high uniformity irrigation applications will be normally distributed for both individual irrigation and the whole season at field scales.

Particularly with low uniformity irrigation systems, the depth of water application at particular locations within the field does impact on the resultant soil moisture tension (soil matric potential) and the potential to eventually cause plant water deficits and possibly affect production. This suggests that it should be possible to relate crop growth to application depths and identify crop production functions from this data.

Chapter 8. Effect of water application on lettuce growth and yield

8.1 Introduction

Effective irrigation management needs knowledge of the performance of the irrigation system and the contribution of other factors such as in-season rainfall, climate, soil fertility and genetics. Low irrigation uniformities have been found to result in spatial soil-water variations (Chapter 7) which can be expected to affect crop growth depending on the crop and environmental condition. However, little information is available on the effect of spatial and temporal variation in irrigation water application on lettuce growth and marketable yield. Significant yield and/or quality variation particularly in horticulture crops can reduce the marketable production and affect the net economic returns. Hence, to evaluate the economics of improved irrigation design and management there is a need to first identify the appropriate crop water production functions. In this chapter, data collected from the irrigated lettuce trials (Chapter 4) is used to determine crop water production functions for lettuce growing in the Lockyer Valley.

8.2 Methodology

Two irrigated lettuce trials were conducted (Chapter 4) with crop growth and harvest data collected as outlined in Chapter 4.7. The canopy (foliage) area of two tagged plants around each catch can (42 cans in each grid) was physically measured in the Poor-1 grid of the autumn trial and in both Poor grids during the winter trial. The canopy measurements in the autumn trial were taken between 19 and 42 days after transplant (DAT) while head measurements were taken until 46 DAT (one day before the start of harvesting). Measurements in the winter trial were taken from 6 to 56 DAT. Marketable heads (Appendix 8.1) were required to meet minimum quality characteristics and weigh at least 500 grams for the autumn trial and 400 grams for the winter trial. A Student's T-test was conducted using Microsoft Excel on the canopy measurements taken at each sampling time from each grid. Unless otherwise noted in the text, differences were significant at the $P < 0.05$ level.

8.3 Results and discussion

8.3.1 Lettuce growth and yield

The total growing days for both trials were similar at 57 and 58 days after transplanting. Due to varietal differences, the winter crop (Iceberg, cv. Raider) had a smaller canopy area throughout the growing season (Figure 8.1) than the autumn crop (Iceberg, cv. Titanic). The effect of individual plant genetic variability on final yield was evaluated by linear correlations between the first canopy area measurements and the subsequent canopy measurements. The strength of these relationships weakened as DAT increased (Figure 8.2) suggesting that the initial plant size (i.e. genetic variability) of the transplanted plants had no role in the final size of individual plants.

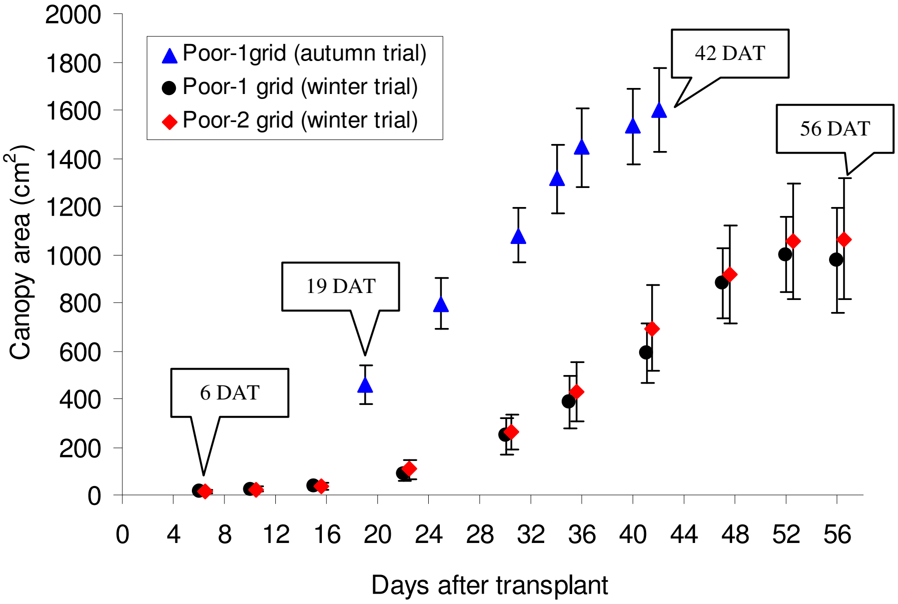


Figure 8.1 Change in standard deviation of average lettuce canopy during season (both trials)

The canopy area (Figure 8.1) increased significantly ($P < 0.05$) during the growing season with the coefficient of variation decreasing from 17.3% at 19 DAT to 11.0% on 42 DAT. During the final growth period of the autumn trial the average head diameter increased by an average of 0.43 cm per day (Table 8.1). There was a similar increase of 0.47 and 0.40 cm per day in the Poor-1 and Poor-2 grids for the winter trial (Table 8.1). There were no significant ($P < 0.05$) differences in head sizes between the grids with different irrigation uniformity. However, in the autumn trial, the lettuces in the Poor-1 grid tended to be smaller with a larger variance. All canopy area and head size measurements for both trials are presented in Appendix 8.2.

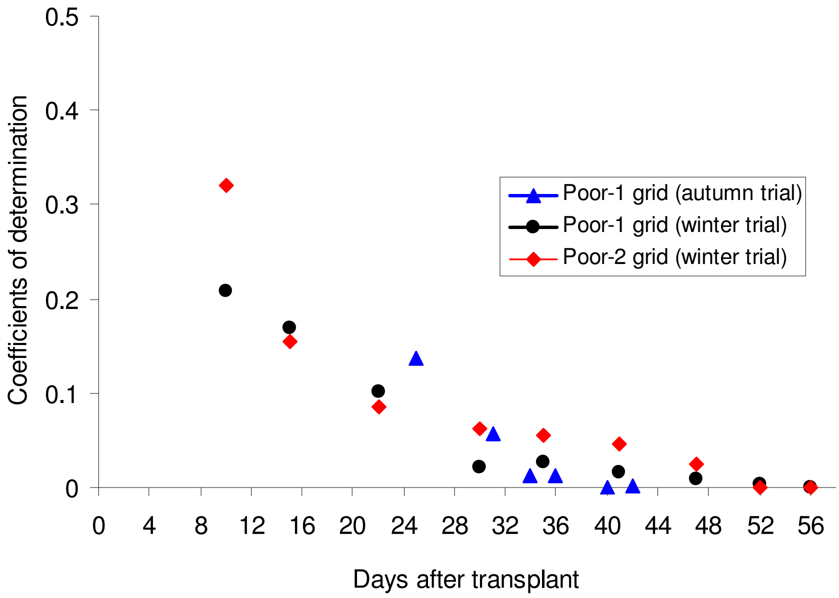


Figure 8.2 Coefficients of determination for a linear relationship between the canopy area on the first day of measurement and subsequent days of measurement

Table 8.1 Effect of irrigation uniformity on lettuce head diameter

Autumn trial				**Winter trial**			
DAT	**Head diameter (cm)**			**DAT**	**Head diameter (cm)**		
	Poor-1 grid	**Poor- 2 grid**	**Control grid**		**Poor-1 grid**	**Poor-2 grid**	**Control grid**
40	13.2(±3.8)			47	8.9(±1.9)	10.3(±1.9)	
42	14.7(±3.7)			52	12.1(±2.3)	13.7(±2.3)	
46	15.8(±3.4)	18.1(±3.2)	16.9(±2.8)	56	13.1(±1.9)	13.9(±2.2)	14.3(±2.2)
				57	11.5(±1.6)*		11.9(±1.6)*
				58		12.3(±1.6)*	

* Denotes harvested head diameter without wrapper leaves. Figures in brackets are standard deviation

Nearly 50% of the plants were harvested in the autumn trial on the 29/5/07 (first harvest) with decreasing numbers on the following days of sequential harvesting (Table 8.2, Appendix 8.3). Most marketable heads were harvested from the first three harvests suggesting that serial harvesting could be accomplished within a week with later harvesting creating problems such as bolting and hard heads. The highest marketable yield (71%) was found in the Control grid followed by the Poor-2 (58%)

and the Poor-1 (42%) grids confirming that applied water affects crop growth and that low irrigation application uniformities reduced marketability. In the winter trial, the Poor-1 grid produced the lowest marketable yield (50%) while the Control grid had a marketable yield of 73% (Table 8.3).

Table 8.2 Marketable lettuce heads for the autumn trial

Grids	Harvesting date	Harvested lettuce (No.)	Marketable lettuce (No.)	Marketable (%) of harvested
Poor-1 grid	29/5/07	112	59	53
	1/6/07	60	19	32
	5/6/07	49	23	47
	8/6/07	21	1	5
	Total	***242***	***102***	***42***
Poor-2 grid	29/5/07	62	50	81
	1/6/07	24	10	42
	5/6/07	31	11	35
	8/6/07	5	0	0
	Total	***122***	***71***	***58***
Control grid	29/5/07	60	51	85
	1/6/07	27	11	41
	5/6/07	31	24	77
	8/6/07	4	1	25
	Total	***122***	***87***	***71***

Table 8.3 Marketable lettuce heads for the winter trial

Grids	Harvesting date	Harvested lettuce (No.)	Marketable lettuce (No.)	Marketable (%) of harvested
Poor-1 grid	4/10/07	252	126	50
Poor-2 grid	5/10/07	251	201	80
Control grid	4/10/07	251	182	73

Strong linear relationships were observed between lettuce fresh weight and head weight (Figures 8.3a & 8.4a) and between marketable fresh and head weight (Figures 8.3b & 8.4b) in both seasons. The total fresh weight for the autumn trial varied from 29-71 t/ha and the maximum marketable head weight was 47 t/ha. For the winter trial, total fresh weight ranged from 23-48 t/ha with a maximum marketable head weight of 36 t/ha. Serial harvesting in the autumn trial produced a moderate but significant ($P < 0.05$) relationship ($R^2 = 0.42$) between total and marketable lettuce yield (Figure 8.3c). Single day harvesting in the winter trial resulted in a strong coefficient of determination ($R^2 = 0.87$) between the total and marketable head weight (Figure 8.4c).

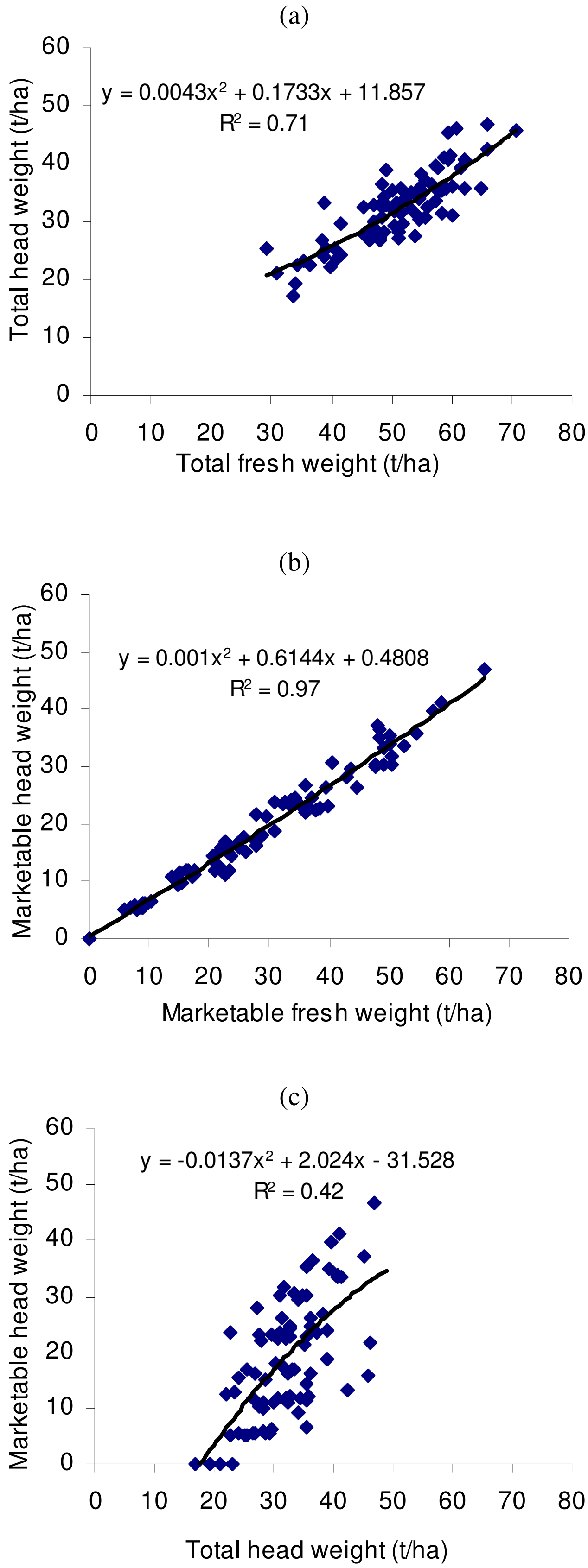


Figure 8.3 Relationships between (a) total and (b) marketable fresh weight and head weight and (c) total and marketable head weight (autumn trial)

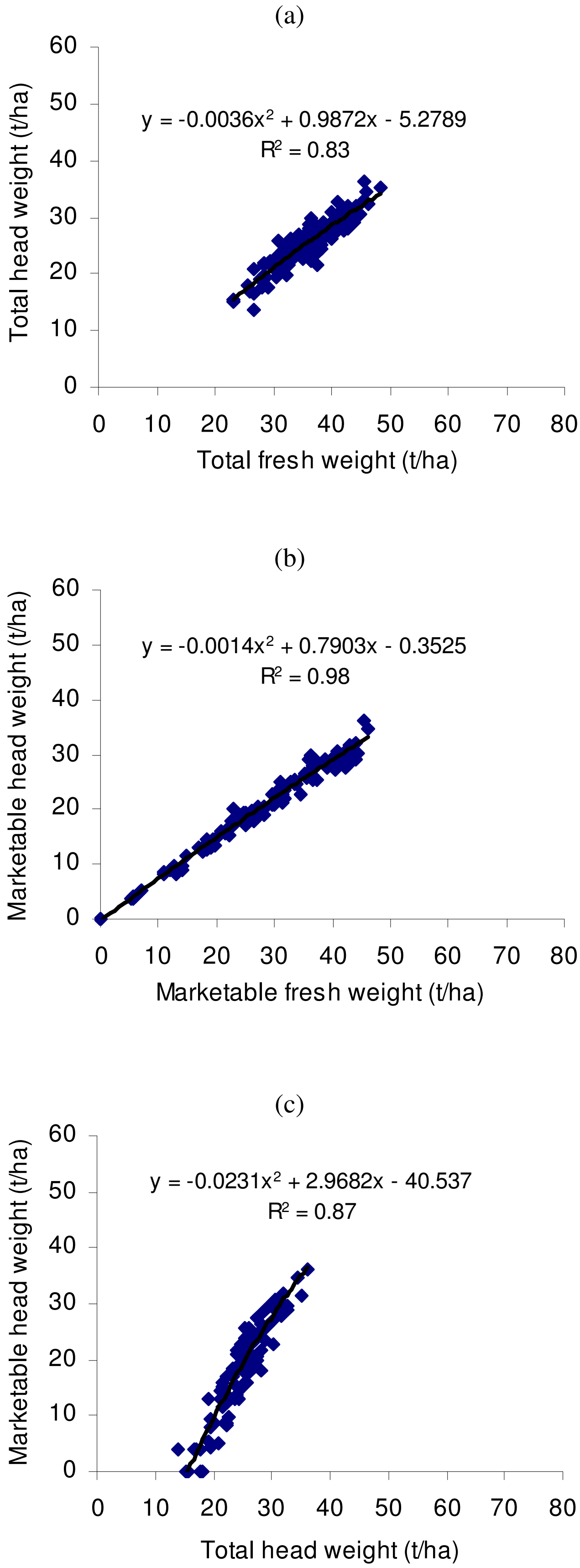


Figure 8.4 Relationships between (a) total and (b) marketable fresh weight and head weight and (c) total and marketable head weight (winter trial)

8.3.2 Effect of irrigation application on the spatial pattern of crop growth

Contour maps of cumulative water application (22/5/07), physically measured canopy area (24/5/07) and head diameter (28/5/07) for the Poor-1 grid (autumn trial) are shown as an example (Figure 8.5). Most water was applied close to the sprinklers in the poor uniformity grids and this was generally reflected in the crop growth patterns. Similarly, the contour patterns of the total harvested (up to 8/6/07) head size, head weight and marketable number of heads (Figure 8.6) show a spatial pattern similar to the irrigation water application pattern. Similar patterns were also found for the winter trial (Appendix 8.4) suggesting that there should be relationships between the water application and both crop growth and yield.

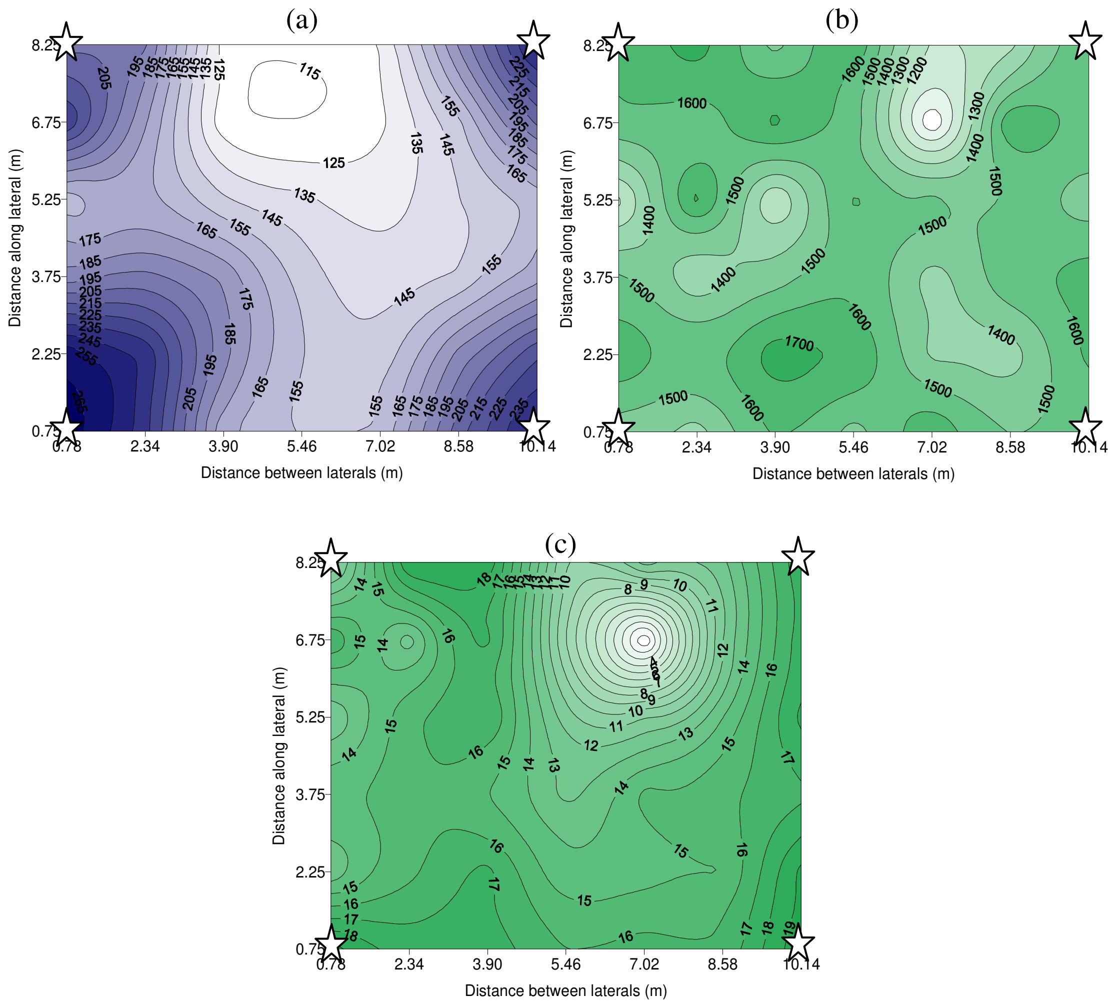


Figure 8.5 Spatial pattern of (a) cumulative water (mm) (22/5/07) (b) canopy area (cm^2) (24/5/07) and (c) head size (cm) (28/5/07) for the Poor-1 grid (autumn trial). Stars indicate sprinklers

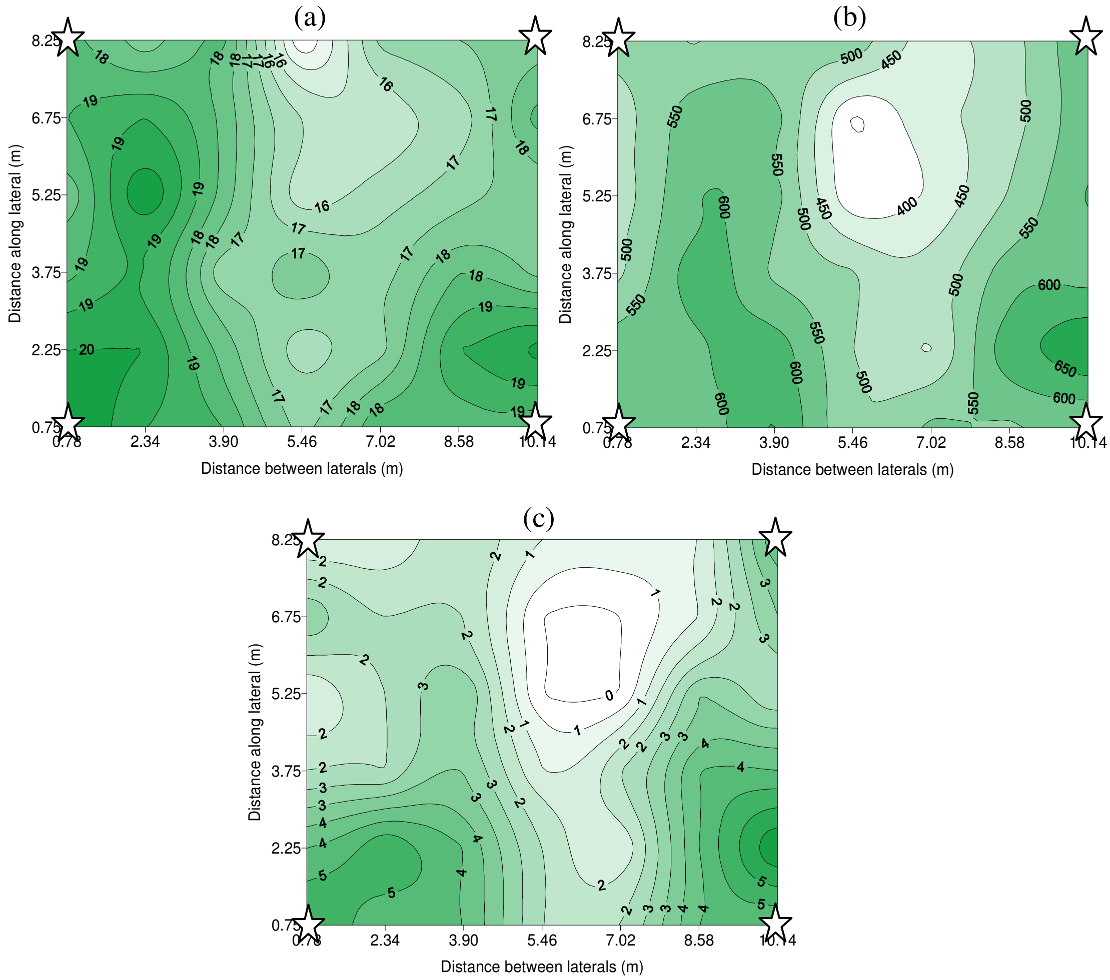


Figure 8.6 Spatial pattern of harvested lettuce (a) head size (cm) (b) head weight (gm) and (c) marketable heads for the Poor-1 grid (autumn trial). Stars indicate sprinklers

8.3.3 Relationships between water application and crop growth

Measurements of water applied (including all rainfall) at each catch can were correlated using polynomial curves (Appendix 8.5) to the growth of plants on either side of the catch cans. In general, the canopy area was not significantly ($P < 0.05$) correlated with cumulative water application (Figure 8.7, Table 8.4) suggesting that this measure may be influenced by factors (e.g. radiation, fertility) other than water application. However, water application was generally better related to head size (Table 8.4). In the winter season, the large number of in-season rainfall events (total = 109.8 mm applied) resulted in generally weak relationships (Table 8.5). However, later in the winter season the effect of the irrigation uniformity on growth was more evident with higher correlations observed in the low uniformity Poor-1 grid than in the Control grid as the range of applied water volumes increased.

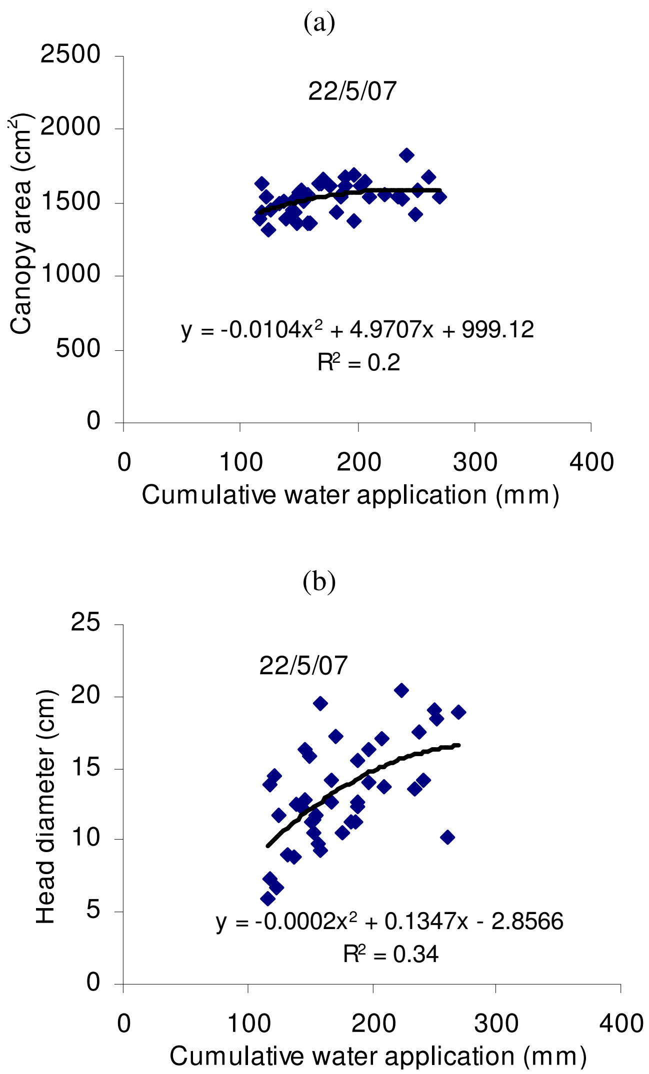


Figure 8.7 Effect of cumulative water application on (a) canopy area and (b) head size for the Poor-1 grid (autumn trial)

Table 8.4 Coefficients of determination for polynomial curves fitted between cumulative water application and lettuce growth (autumn trial)

Cumulative water measurement date	Plant measurement date	Coefficients of determination (R^2)			
		Poor-1 grid		Poor-2 grid	Control grid
		Canopy area	Head size	Head size	Head size
29/4/07	1/5/07	0.03			
2/5/07	7/5/07	0.00			
13/5/07	13/5/07	0.20			
14/5/07	16/5/07	0.04			
18/5/07	18/5/07	0.10			
22/5/07	22/5/07	0.20	0.34		
22/5/07	24/5/07	0.03	0.31		
26/5/07	28/5/07		0.26	0.07	0.23

Table 8.5 Coefficients of determination for polynomial curves fitted between cumulative water application and lettuce growth (winter trial)

Cumulative water measurement date	Plant measurement date	Coefficients of determination (R^2)					
		Poor-1 grid		Poor-2 grid		Control grid	
		Canopy area	Head size	Canopy area	Head size	Canopy area	Head size
11/8/07	14/8/07	0.07		0.09			
18/8/07	18/8/07	0.11		0.13			
22/8/07	23/8/07	0.13		0.19			
26/8/07	30/8/07	0.03		0.23			
7/9/07	7/9/07	0.19		0.20			
16/9/07	18/9/07	0.03		0.24			
19/9/07	24/9/07	0.06	0.17	0.07	0.06		
29/9/07	29/9/07	0.37	0.02	0.00	0.04		
3/10/07	3/10/07	0.40	0.35	0.02	0.01	0.21	0.19
3/10/07	4/10/07		0.31*				0.23*
3/10/07	5/10/07				0.11*		

* Denotes harvested plants without wrapper leaves

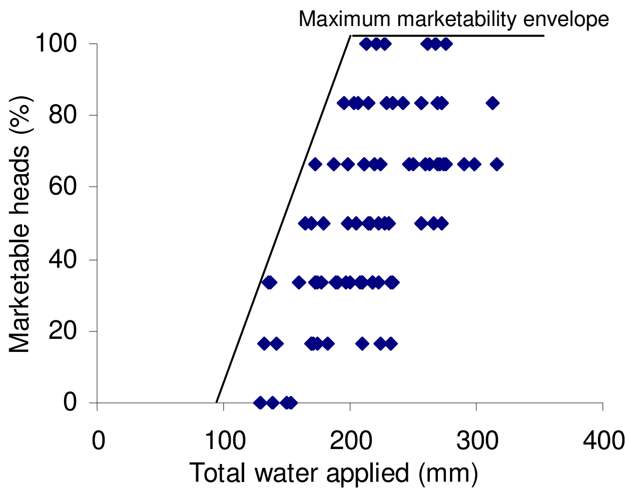
Logarithmic relationships between marketable head weight and the water applied during either (a) the whole season or (b) the last three weeks before harvest (critical period) were determined (Appendix 8.6). In both trials, the correlations were better (Table 8.6) for the Poor grids mainly due to a wider range of water application depths and more consistent pattern of irrigation applications. The correlations between the water applied in the last three weeks of the season were not greatly different to those obtained using the whole season water application (Table 8.6).

Table 8.6 Coefficients of determination for log curves relating the water applied either for the whole season or during the critical growth period with marketable head weight

Treatment	Whole season	Critical period
Autumn trial		
Poor-1 grid	0.50	0.51
Poor-2 grid	0.49	0.27
Control grid	0.16	0.11
Winter trial		
Poor-1 grid	0.30	0.34
Poor-2 grid	0.30	0.37
Control grid	0.02	0.00

Marketable heads for the autumn (≥ 500 gms) and winter (≥ 400 gms) trials were plotted against the total water application at each can during the season including rainfall. Marketable heads were maximised when approximately 200 and 250 mm of total water was applied in the autumn (Figure 8.8a) and winter (Figure 8.8b) trials, respectively. However, the wide variation in the marketable heads with water application confirms that many factors other than water (e.g. disease, fertility, genetic) may influence marketability.

(a)



(b)

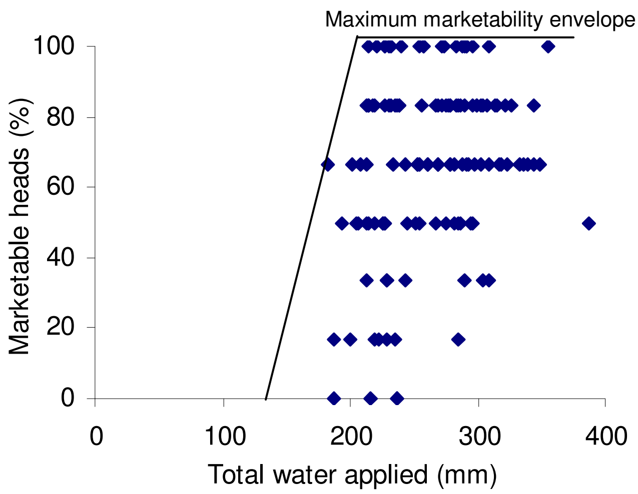


Figure 8.8 Effect of total water application on marketable heads for the (a) autumn and (b) winter trial

The effect of water application on lettuce canopy and head growth was found to be best demonstrated by evaluating five points (catch cans) from each of the high, medium and low water application areas within the Poor-1 grid. These points were selected by observing the irrigation application contours after fitting the pressure reducers and the application pattern was relatively consistent. In the autumn trial, there was no significant difference in canopy area between the areas (Table 8.7) but the standard deviation was higher in the low water application area. However, there was a significant difference in head size (Table 8.8) which resulted in a substantial reduction in the marketability. Similar results were found for the winter trial with significant differences in lettuce head size and marketability due to water application (Table 8.10). However, in the winter trial, the canopy areas of plots in the low water application area were smaller than in the other areas of the grid late in the season (Table 8.9).

Table 8.7 Canopy area of plants in the high, medium and low water application areas of the Poor-1 grid (autumn trial)

DAT	Canopy area (cm^2)		
	High water area	**Medium water area**	**Low water area**
19	466(±100)	481(±51)	446(±74)
25	810(±80)	802(±63)	771(±134)
31	1134(±83)	1084(±94)	1014(±68)
34	1337(±166)	1352(±129)	1274(±149)
36	1422(±124)	1507(±114)	1335(±193)
40	1596(±178)	1534(±155)	1428(±196)
42	1609(±153)	1646(±178)	1521(±276)

Figures in brackets are standard deviation

Table 8.8 Effect of water application on harvested lettuce in the high, medium and low water application areas of the Poor-1 grid (autumn trial)

Water application area	Lettuce fresh weight (g)	Lettuce head diameter (cm)	Lettuce head weight (g)	Marketable heads (%)
High	899 (±141)	19.2 (±2.1)	571 (±121)	73
Medium	827 (±152)	16.8 (±1.8)	473 (±103)	24
Low	741 (±140)	16.6 (±1.7)	443 (±96)	18

Figures in brackets are standard deviation

This data confirms that low water application reduces lettuce marketability, at least under the environmental conditions encountered and the range of water application depths applied. However, local lettuce growers report they have low levels of non-marketability despite their irrigation application systems often having low uniformities. This suggests that these growers may be compensating for low irrigation uniformity by applying higher irrigation volumes (at lower application efficiencies) generating excessive drainage or that there is substantial in-season rainfall in most seasons. It also suggests (as does Figure 8.7) that there is little (if any) yield penalty associated with over-irrigation. That might be the reason that there is always debate over the benefits of improved irrigation uniformity for the commercial production of lettuce in this area (Henderson, C 2006, pers. comm., 10 April)

Table 8.9 Canopy area of plants in the high, medium and low water application areas of the Poor-1 grid (winter trial)

DAT	Canopy area (cm^2)		
	High water area	Medium water area	Low water area
6	15(±6)	15(±5)	14(±9)
10	19(±8)	23(±8)	26(±9)
15	33(±11)	34(±9)	41(±13)
22	84(±19)	74(±20)	91(±25)
30	230(±71)	217(±44)	255(±69)
35	413(±119)	358(±70)	361(±67)
41	639(±112)	561(±93)	564(±107)
47	960(±144)	926(±116)	797(±96)
52	1101(±135)	1104(±99)	843(±95)
56	1161(±151)	1177(±143)	738(±123)

Figures in brackets are standard deviation

Table 8.10 Effect of water application on harvested lettuce in the high, medium and low water application areas of the Poor-1 grid (winter trial)

Water application area	Lettuce fresh weight (g)	Lettuce head diameter (cm)	Lettuce head weight (g)	Marketable heads (%)
High	685(±124)	12.8 (±1.3)	483 (±120)	73
Medium	644 (±104)	12.5 (±1.7)	451 (±91)	77
Low	486 (±145)	10.4 (±1.8)	329 (±114)	20

Figures in brackets are standard deviation

8.3.4 Relationships between water application and yield

The yield and water applied (irrigation and effective rainfall) data shows a high degree of scatter suggesting there is some uncertainty over whether the crop water production function plateaus or decreases at high water application. Hence, both declining and plateauing production functions were fitted to the data.

8.3.4.1 Polynomial (quadratic) production functions

The weather station data was used to calculate the potential evapotranspiration (ETo) using the Penman-Monteith equation (Allen *et al*. 1998). The seasonal ETo was 1.78 and 2.33 ML/ha for the autumn and winter trials, respectively. The lettuce head weights and water applied (expressed as a % of ETo) were then used to develop quadratic crop water production functions in the form:

$$Y = a * D_a^{\ 2} + b * D_a + c \qquad (8.1)$$

where:

Y = Yield (t/ha)
D_a = Depth of seasonal water application (% ETo)
a, b, c = Fitted constants

for the autumn (Figure 8.9) and winter (Figure 8.10) trials (Table 8.11). Total in-season water application in the autumn trial ranged from 51 to 140% of ETo while the total yield varied from 17 to 47 t/ha. In the winter trial, water applied ranged from 42 to 122% of ETo and yield from 14 to 36 t/ha. In both seasons, yield is maximised at approximately 100% of total seasonal ETo. These functions suggest that there was a larger marketable yield penalty for excessive water application in the winter than in the autumn trial.

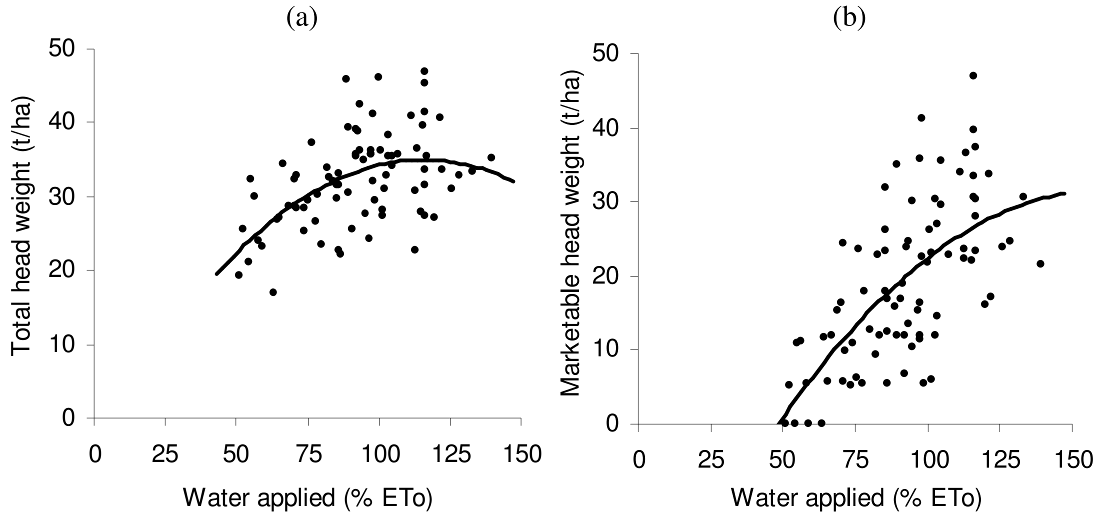


Figure 8.9 Quadratic crop water production functions for (a) total and (b) marketable lettuce yield (autumn trial)

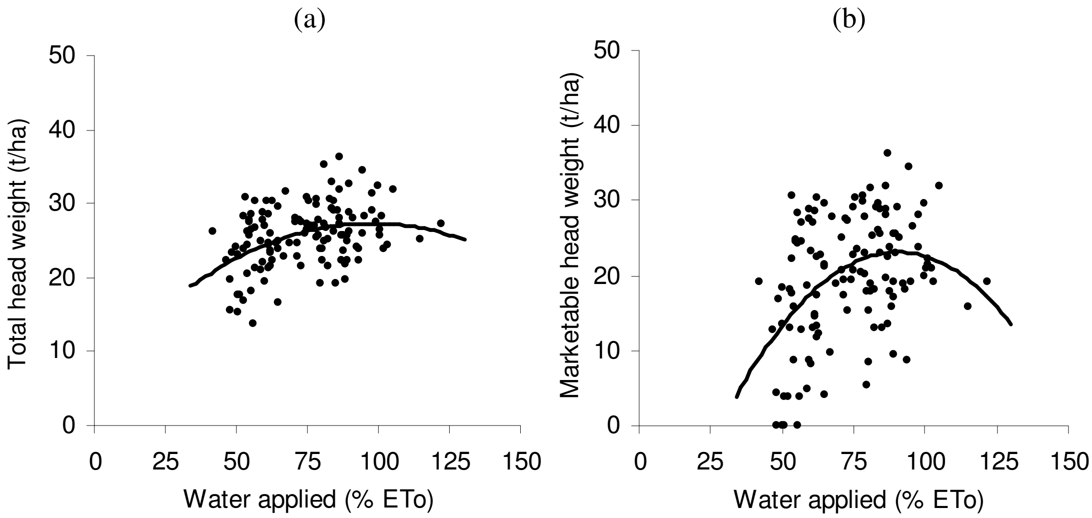


Figure 8.10 Quadratic crop water production functions for (a) total and (b) marketable lettuce yield (winter trial)

Table 8.11 Fitted parameters for the polynomial crop water production functions

Field trial	Yield function	*a*	*b*	*c*	R^2
Autumn	Total	-0.0029	0.6769	-4.1922	0.27
	Marketable	-0.0025	0.8007	-32.912	0.43
Winter	Total	-0.0021	0.4091	7.3672	0.15
	Marketable	-0.006	1.0914	-26.156	0.18

8.3.4.2 Exponential (plateau) production functions

An exponential (plateau) crop water production function in the form:

$$Y = a - b * exp(-c * D_a) + c \qquad (8.2)$$

where:

Y = Yield (t/ha)

D_a = Depth of seasonal water application (% ET_o)

a, b, c = Fitted constants

was also fitted to the autumn (Figure 8.11) and winter (Figure 8.12) yield and water application data (Table 8.12). The coefficients for this function are similar to the coefficients attained for the quadratic function (Section 8.3.4.1) and highlight the uncertainty over the exact nature of this relationship. While the autumn trial function suggests that marketable yield is still increasing across the range of water applied (Figure 8.11) the maximum marketable yield in the winter season was approached with approximately 75% ETo water applied (Figure 8.12).

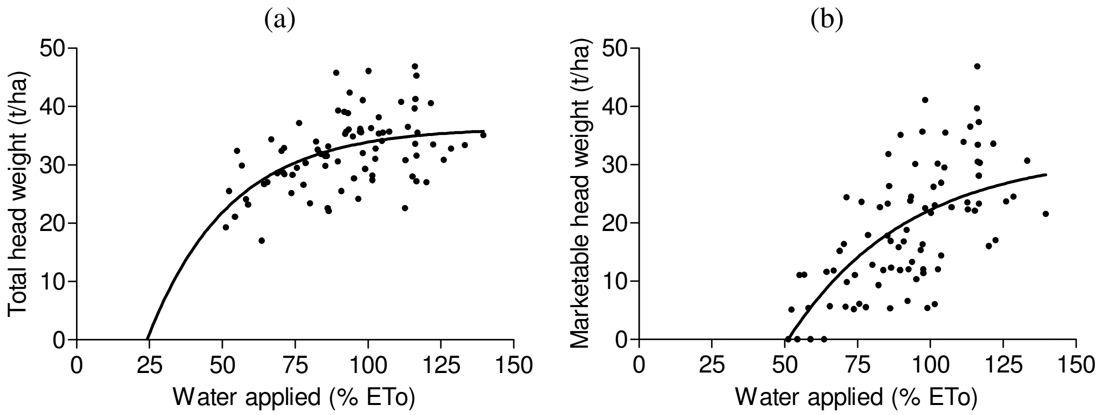


Figure 8.11 Exponential (plateau) crop water production functions for (a) total and (b) marketable lettuce yield (autumn trial)

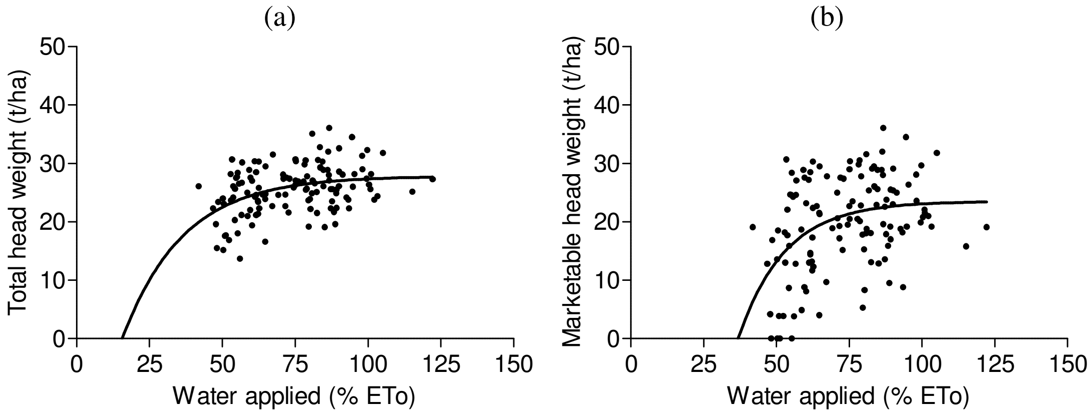


Figure 8.12 Exponential (plateau) crop water production functions for (a) total and (b) marketable lettuce yield (winter trial)

Table 8.12 Fitted parameters for the exponential crop water production functions

Field trial	Yield function	*a*	*b*	*c*	R^2
Autumn	Total	36.37	85.7	0.03543	0.26
	Marketable	32.0	111.2	0.02431	0.42
Winter	Total	27.83	59.3	0.04807	0.15
	Marketable	23.51	240.4	0.06296	0.17

8.4 Conclusions

There was no evidence that genetic variability between individual lettuce transplants affect crop size at the end of the season. Variations in the water application during the mid to late growing period affected lettuce head size more than canopy development. At the grid scale, irrigation application uniformities reduced the marketable yield. However, there was still substantial loss in marketable yield (~ 25%) even when the systems were operating above the industry accepted benchmark (CU = 75%) level. There was also substantial scatter in the water applied versus yield plots most likely due to a range of agronomic (e.g. genetic variations between plants, pest/disease) and environmental (e.g. spatial differences in nutrition, drainage, row position) influences. While increasing water application generally improved the yield there was uncertainty regarding the shape of the crop water production function for this crop. Hence, two different shaped crop water production functions were fitted to the data reflecting both the case when a yield penalty is imposed with excessive water application and when no penalty is imposed.

Chapter 9. Evaluating the economic benefits of optimising irrigation uniformity

9.1 Introduction

The shortage of water available for agriculture demands an increase in crop productivity through efficient irrigation management. The uniformity of irrigation applications plays a major role in irrigation production (Pereira *et al*. 2002). Higher uniformity gives lower in-field variability of crop yield (Dukes *et al.* 2006). However, growers with low uniformity irrigation systems often irrigate more frequently or apply greater depths particularly when water prices are low (Mantovani *et al*. 1995). This ensures that areas receiving lower applications are adequately irrigated and can contribute to the yield. However, this occurs at the expense of higher water use (Smith and Raine 2000) and fertiliser losses which may impact negatively on the environment (Clemmens 1991). Even with high uniformity application systems, inappropriate irrigation scheduling (e.g. volume and timing) can lead to substantial yield and economic losses (Alvarez *et al*. 2004). The effect of low application uniformity on crop yield is also affected by environmental conditions including soil properties and in-season rainfall (Mateos *et al*. 1997). However, the optimal irrigation uniformity and profitability will also be a function of the cost of the various inputs (e.g. water, fertiliser) (Romero *et al.* 2006) and the return for the crop (Alvarez *et al*. 2004). Hence, there is a need to incorporate both the physical crop responses and the economic costs and benefits in analyses to identify optimal irrigation uniformity. In this chapter, measured crop production functions are used to predict the yield and economic returns for different depths and uniformities of irrigation applications and for different depths of effective rainfall.

9.2 Methodology

The marketable yield production functions developed in Chapter 8 were used for the yield and economic analysis. Because of uncertainty over the yield response if excess water is applied, two different functions were applied to the data, to cover the cases (a) where a yield penalty is incurred (i.e. quadratic production function, Equation 8.1) and (b) where no yield penalty is incurred (i.e. an exponential plateau production function, Equation 8.2). Yield and economic benefits were calculated for total in-season water applications of 0.5 to 3.5 ML/ha and uniformities expressed as Christiansen's coefficient of uniformity (CU) ranging from 50 to 90%. The depths applied by sprinkler irrigation have been found to be normally distributed. Hence, for each of the cases considered, the irrigation depths within the field were assumed to be normally distributed about the seasonal mean application (I_μ). The standard deviations (σ) of applied depths for each irrigation uniformity and seasonal application were calculated from the CU (Warrick 1983):

$$\sigma = (1 - \frac{CU}{100})\frac{I_\mu}{0.798} \tag{9.1}$$

The individual irrigation depths (I_a) over the field were expressed as a standard score (Z_a) reflecting the number of standard deviations the particular depth was from the seasonal mean depth:

$$Z_a = \frac{I_a - I_\mu}{\sigma} \tag{9.2}$$

This standard score was then used to calculate the probability (P) of occurrence of depths in the range Z_a to Z_{a-1} (Bluman 1997):

$$P(Z_a \text{ to } Z_{a-1}) = P(< Z_a) - P(< Z_{a-1}) \tag{9.3}$$

The effect of in-season rainfall was evaluated by assuming that the seasonal mean irrigation depth (I_μ) was reduced by the magnitude of the effective rainfall (R) which was varied from 25 to 75% of the potential evapotranspiration (ETo) for the whole season. This effective rainfall was assumed to have fallen uniformly across the field. Hence, in this analysis, the total seasonal water application (D_a) at each location within the field was calculated as:

$$D_a = I_a + R \tag{9.4}$$

and the probably of occurrence was again determined using Equation 9.3 by substituting the total seasonal water application for the irrigation application. The depths applied (D_a) were then used to calculate the corresponding marketable yield using both the quadratic (i.e. declining) and exponential (i.e. plateau) production functions. The marketable yields for each location in the field were then aggregated to determine the total yield achieved at the field scale for each irrigation uniformity and seasonal mean water application.

The production and marketing costs were obtained from industry sources (Henderson, C 2007, pers. comm., 10 October) and adjusted to 2007 prices. Gross margins were calculated using the marketable yields, assuming 12 lettuces per carton, $12 per carton gross return and that the agronomic input costs (Table 9.1) were the same for each irrigation system irrespective of application uniformity. The lifetime (15 year) capital and maintenance costs were estimated at $8000/ha (Australian dollars) for an irrigation system with CU of 50% and were assumed to increase by $2000/ha for each 10% increase in CU. The net economic return was calculated as the gross margin less the amortised capital and maintenance cost of the irrigation system and assuming two crops were grown each year. Additional analyses were conducted to evaluate: (a) the effect of irrigation system uniformity and seasonal depth of applications on the product price required to break-even, and (b) the sensitivity of net returns to the product price.

Table 9.1 Production and marketing costs used in the gross margin analysis (2007 prices)

Production and marketing components	Cost (AUD)
Agronomic inputs (machinery, seedling, fertiliser, herbicide, insecticide, fungicide, casual labour for chipping/thinning)	$5719 / ha / crop
Irrigation water and energy	$50.00 / ML
Harvesting labour	$1.10 / carton
Packaging	$2.50 / carton
Cooling	$0.50 / carton
Freight (to Brisbane market)	$0.84 / carton
National research & marketing levy	0.5% of sale price
Agent's commission	15% of sale price
Amortised capital cost of irrigation infrastructure (dependent on system CU)	$267- $533 / crop

9.3 Results and discussion

9.3.1 Effect of irrigation depth and uniformity on yield

As expected, the yield curves presented in Figure 9.1 reflect the form of the individual production functions. They show that increasing the irrigation uniformity generally increases the yield for all but very low depths of application. However, the benefits obtained by improvements in irrigation system uniformity are also influenced by whether a yield penalty is incurred (i.e. quadratic function) or not incurred (i.e. exponential function) when excessive water is applied. The total and marketable yield calculations are presented in Appendix 9.1 for both trials.

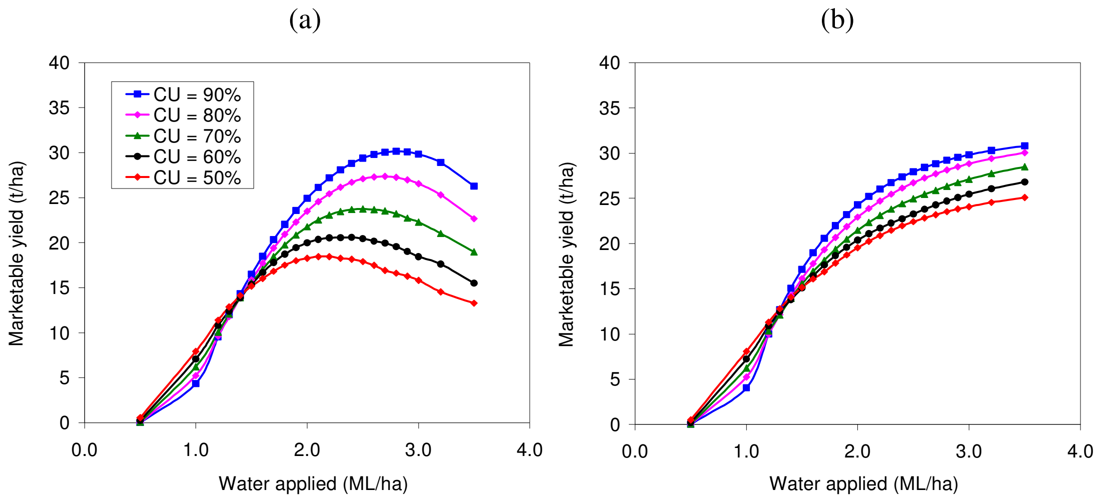


Figure 9.1 Effect of irrigation uniformity on the marketable yield of lettuce calculated using (a) quadratic and (b) exponential production functions from the autumn trial

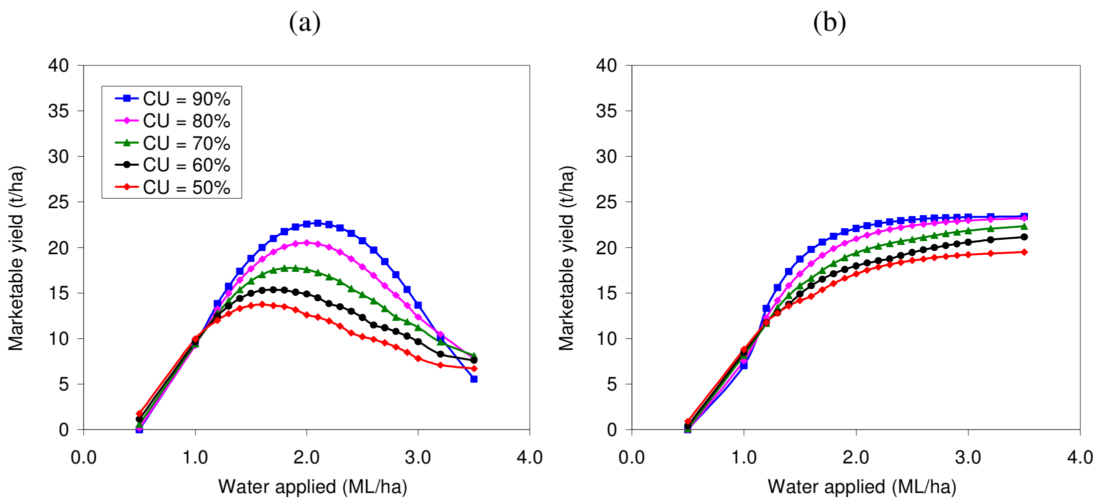


Figure 9.2 Effect of irrigation uniformity on the marketable yield of lettuce calculated using (a) quadratic and (b) exponential production functions from the winter trial

Where a quadratic production function is used (Figures 9.1a & 9.2a), the application depth at which maximum yield occurs increases as uniformity increases, that is, between 1.6 and 2.0 ML/ha for CU of 50% depending on the season, increasing to between 2.0 and 2.6 ML/ha for CU of 90%. The yield benefit associated with higher uniformity is greatest (up to 10 t/ha) when the depth applied is close to the crop water requirement (in this case ~ 2 to 3 ML/ha depending on the season). However, the benefits associated with increasing uniformity are substantially smaller when either higher or lower volumes are applied.

There is little or no yield difference between the different uniformities when the depth applied is less than 1.2 ML/ha. At these low application depths, a low uniformity may even result in higher yields than a high uniformity. In these cases, the high spatial variability in the water applied using the low uniformity irrigation system results in at least some (small) areas of the field receiving a water application which produces marketable product while the high uniformity has all areas of the field failing to produce any marketable product.

Where an exponential (i.e. yield plateau) production function is used (Figures 9.1b & 9.2b), there is no yield benefit associated with increasing the uniformity when the depth applied is less than 1.2 ML/ha and the benefit is relatively small (< 5 t/ha) at higher application depths. In general, the same yield can be achieved by either increasing the application system uniformity from 50% to 90% or by applying an additional irrigation depth of 1.0 to 1.4 ML/ha.

9.3.2 Effect of irrigation depth and uniformity on net economic return

Net economic returns (Figures 9.3 & 9.4, Appendix 9.2) were primarily influenced by the marketable yield (Figures 9.1 & 9.2). Hence, returns generally increased with improvements in irrigation system uniformity. However, the magnitude of benefit was a function of both the season and the total water applied.

Where a quadratic crop production response was assumed (Figures 9.3a & 9.4a), the economic benefits are maximised when the volume of water applied is close to the maximum yield potential (e.g. ~2.25 ML/ha). In this case, the net return can be increased by up to $11000/ha by improving the CU from 50% to 90%. However, the economic benefits are smaller when an exponential crop production response is assumed. There were also differences between the two seasons in the optimal water application range required to maximise benefits when the exponential production function was used. For the first season (Figure 9.3b), returns increased with increasing water application and were approximately \$4000/ha when 2 to 3 ML/ha was applied. For the winter season (Figure 9.4b), the maximum difference between the returns for CU of 50% and CU of 90% (approximately \$5000/ha) occurred when ~1.8 ML/ha of irrigation water was applied.

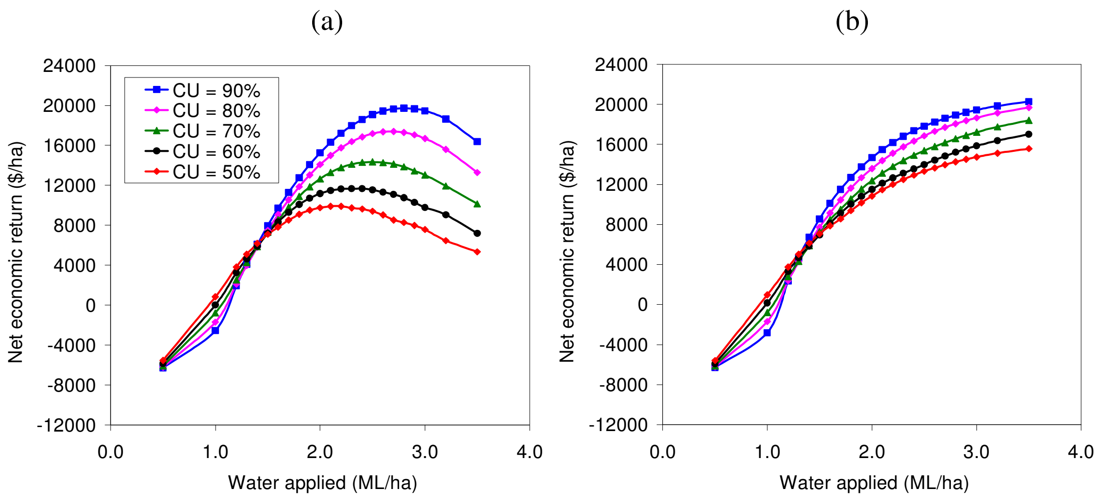


Figure 9.3 Effect of irrigation uniformity on the net economic return calculated using (a) quadratic and (b) exponential yield production functions from the autumn trial

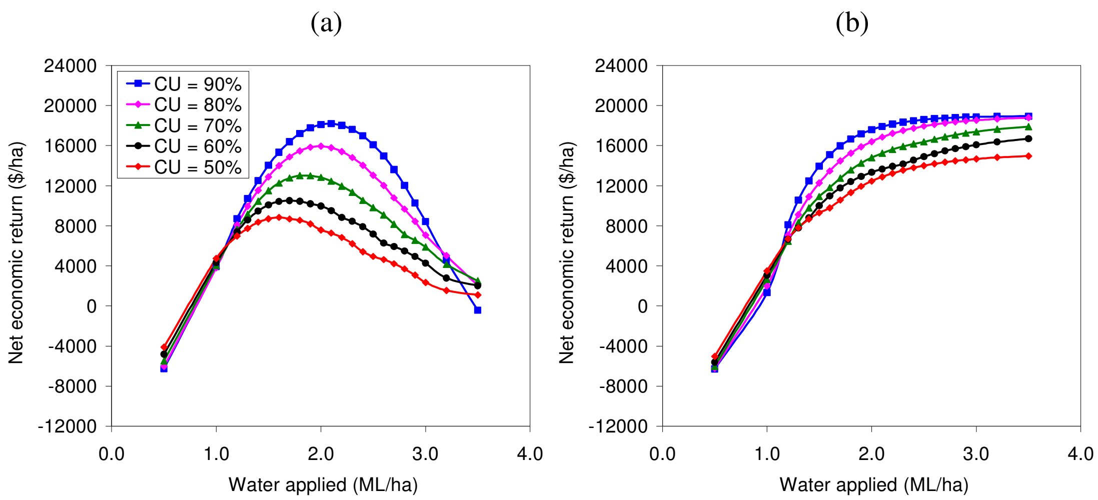


Figure 9.4 Effect of irrigation uniformity on the net economic return calculated using (a) quadratic and (b) exponential yield production functions from the winter trial

For both seasons and irrespective of which crop production function was used, there was little difference in economic returns as a result of uniformity when less than 1.5 ML/ha was applied. Indeed, applications of ~1 ML/ha during the first season demonstrate slightly higher returns from the low uniformity systems compared to the higher uniformities (Figures 9.3 a & b). The range of seasonal application depths over which substantial differences in economic returns are obtained due to application uniformity differences is narrow (generally between 1.5 and 2.5 ML/ha). This means that the benefits of application system improvement may be small if the total seasonal water application is outside of this range (e.g. due to inappropriate irrigation scheduling). It is also likely that even when the total seasonal water application is within the range for maximising returns the use of inappropriate irrigation timing or application depths for individual events would also reduce the magnitude of the benefit. In that case, fields with higher uniformity of applications would suffer proportionally greater production losses than those with low uniformity thus reducing the net return observed due to improvements in the application uniformity.

9.3.3 Investing in system improvement or increased application depths

Brennan (2008) suggested that depending on the depth of water applied and the crop production function used, it is possible to obtain the same economic return (per unit area) by either increasing the irrigation uniformity (i.e. incurring a higher capital cost) or by increasing the depth of water applied (i.e. incurring a higher operating cost). Where the crop has an exponential growth response to water (e.g. Figures 9.3b & 9.4b) or sub-optimal irrigation application volumes have been applied (Figures 9.3a & 9.4a), the increase in the operating cost associated with higher water application (generally ≤ 1.5 ML/ha) is relatively small compared to the cost of the application system upgrade. In this case, there is little incentive for growers to invest in improved application system uniformity. Hence, the incentive for growers to invest in improving irrigation performance is greatest where the crop has a quadratic production response to water and appropriate irrigation scheduling techniques have been used to maximise production.

Where there is sufficient irrigation water available, it is the uniformity of applications which limits the maximum yield and net returns achieved (Figure 9.3a).

However, under these conditions, the net return from both the existing and improved applications systems is positive and the difference in net return simply represents a foregone "opportunity cost".

When the volume of water available on-farm is limited but additional water is available for purchase off-farm, the difference in the gross margin between the current irrigation system uniformity and the target irrigation system uniformity provides a measure of the price which growers could pay to obtain additional water rather than invest in application system improvements. On-farm irrigation infrastructure is generally regarded as a depreciating asset while purchased water is generally considered an appreciating asset. It is this difference in long term investment perspective which many growers use to justify investment in the purchase of additional water rather than irrigation system upgrades.

Under water limited conditions where additional off-farm water is unable to be purchased, failure to improve the application system uniformity results in a "real" decrease in total farm scale net return either by reducing the yield per unit area (i.e. reducing water application per unit area) or by reducing the area available for production (i.e. maintain water application rate per unit area). Hence, improvements in irrigation uniformity provide an opportunity to potentially increase or maintain field production and net return with the available water. This confirms anecdotal observations of grower behaviour in the Lockyer Valley which suggest that lettuce growers are much more likely to invest in irrigation system upgrades when they are experiencing limitations in water availability and are unable to purchase additional water.

Growers who improve irrigation uniformity under conditions of limited water availability often seek guidance on whether to (a) maintain their production per unit area and use any water savings to increase the area planted or (b) maintain their application rates to maximise the production per unit area. The nature of the net economic return functions (e.g. Figures 9.3 & 9.4) suggest that the optimal strategy for a particular grower will be dependent on the shape of the production function and the seasonal depth of water applied (i.e. where the grower is operating on the curve). An example of a comparative analysis conducted using the quadratic production function (Figure 9.3) and assuming that the grower has been applying 2 ML/ha is shown in Table 9.2. In this case, the grower would be significantly better off by maintaining the current rate of water application on the same area after improving the irrigation system uniformity.

Table 9.2 Comparison of economic returns with improved irrigation system uniformity where the same total water volume (2 ML) is applied either to (a) a larger area maintaining crop yield per unit area or (b) the same area producing an increased yield per unit area

Option A		**Option B**	
Increase production by applying water volume to larger area		**Increase production by applying water volume to same area**	
Water used at CU of 50% (ML/ha)	2.0	Water used at CU of 50% (ML/ha)	2.0
Water used at CU of 90% (ML/ha)	1.6	Water used at CU of 90% (ML/ha)	2.0
Reduction in water at CU of 90% (ML/ha)	0.4	Net return for CU of 50% ($/ha)	$9,750
Extra area irrigated at CU of 90%	25%	Net return for CU of 90% ($/ha)	$15,259
Increase in net economic returns	**25%**	**Increase in net economic returns**	**56.5%**

9.3.4 Effect of product price on net economic returns

The price for the product has a substantial effect on the net economic return and the incentive for improving irrigation application system uniformity (Figure 9.5). The difference in maximum net return between systems with a CU of 50% and CU of 90% increased from ~$4000/ha (Figure 9.5a) to ~$16,000/ha (Figure 9.5b) as the lettuce price increased from $8 to $16/carton. This confirms that the economic benefits of irrigation system upgrades are larger with higher prices. However, at higher prices it is also possible to achieve positive net returns with low uniformity and across a wide range of irrigation application depths (i.e. with poor irrigation scheduling). Hence, while the potential gains are larger with higher prices, this is only a forgone opportunity cost for growers with lower performing irrigation systems and may not be a key driver of system upgrades.

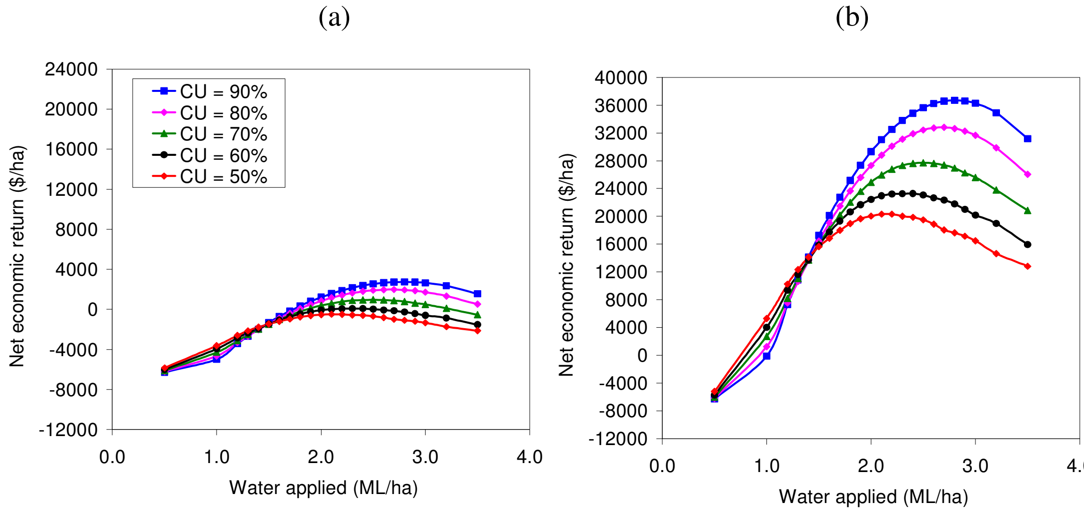


Figure 9.5 Net economic returns for lettuce price of (a) $8, and (b) $16 per carton (using the quadratic production function from the autumn trial)

At low product prices (e.g. $8/carton, Figure 9.5a), it is difficult to achieve a positive net economic return if CU ≤ 60%. However, application systems with CU of 70% are able to achieve small positive net returns and the range of water application depths over which a positive return can be achieved increases with irrigation uniformity (i.e. 1.9–3.2 ML/ha for CU of 70%; >1.8 ML/ha for CU of 90%). Hence, assuming access to capital is not constraining, low product prices may be expected to encourage upgrades of irrigation systems which have low uniformities.

The product price and uniformity of the irrigation applications also affect the depth of irrigation required to be applied to break-even (Figure 9.6). For application depths in the optimal production range (i.e. 2 to 3 ML/ha), application systems with a low uniformity have a higher break-even price (~ $8.4/carton) than those with high uniformity (~ $7.4/carton).

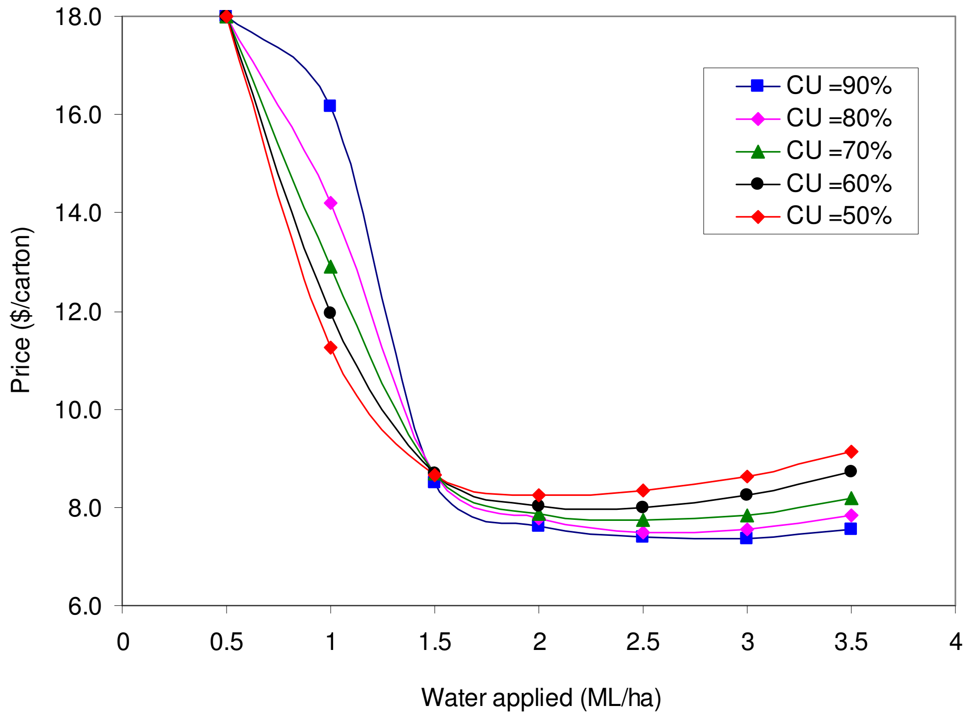


Figure 9.6 Effect of irrigation system uniformity and water application on the break-even lettuce price (using the quadratic production function from the autumn trial)

9.3.5 Effect of in-season rainfall on net economic returns

The presence of in-season rainfall serves to increase the effective uniformity of seasonal water applications. Hence, it substantially reduces the effect that poor irrigation uniformity has on both yield and net return (Figure 9.7, Appendix 9.3). Increasing the amount of rainfall increases the net returns for all levels of uniformity but the increase is larger for low CU compared to high CU systems. For example, where 2.5 ML/ha was applied, the net return during a season where half of the water application was rainfall (Figure 9.7d) was 74% higher for an irrigation CU of 50% but only 2.6% for a CU of 90% when compared to the net return for a season with no rainfall (Figure 9.3a). Where 75% of the mean seasonal water application is rainfall, there was no discernable difference between the net economic returns for different uniformities irrespective of the depth of water applied (Figure 9.7f).

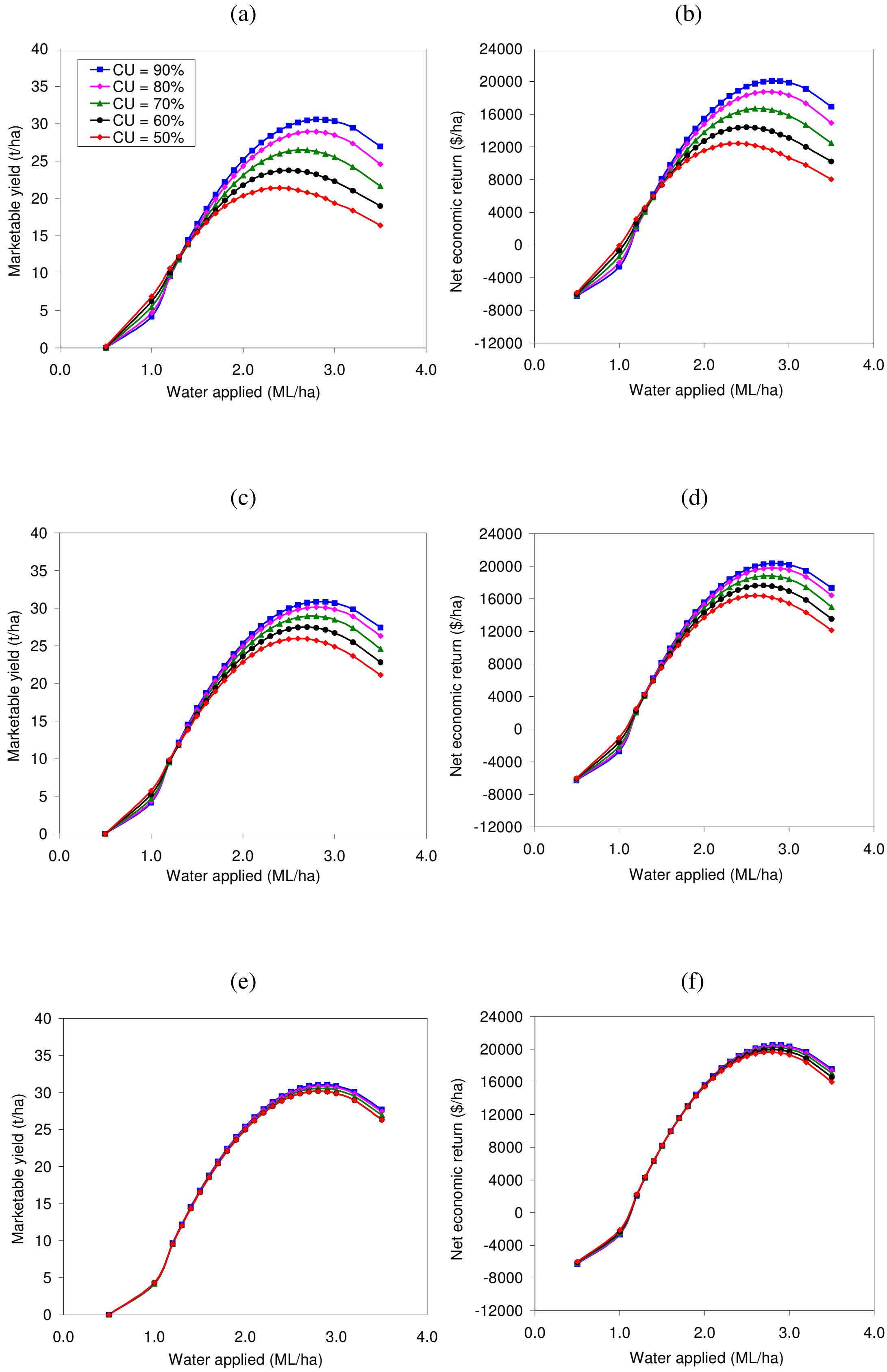


Figure 9.7 Marketable yield and net economic return for (a & b) 25%, (c & d) 50% and (e & f) 75% in-season rainfall, respectively (using quadratic production function from the autumn trial)

9.4 Conclusions

Net economic returns are primarily influenced by marketable yields for lettuce producers in the Lockyer Valley. Where the application uniformity is low, returns can generally be increased with improvements in irrigation uniformity but the magnitude of the benefit is dependent on the season rainfall in particular, nature of the crop production response and the total water applied. The benefits of system improvement are maximised when the crop has a quadratic production function and appropriate irrigation scheduling is used. However, where the crop has an exponential production function or inappropriate scheduling is used then the gains may be small or negative. Similarly, the presence of in-season rainfall reduces the marginal benefit of irrigation system improvement. The benefits of system improvement are negligible where effective rainfall meets 50% or more of the crop water requirements. The incentive for irrigation system improvement is greatest when water is limited and unable to be purchased. Periods of low product price also encourage irrigation system improvements as non-uniform systems have a higher break-even price and require increased management (e.g. scheduling) to remain viable. However, it is unlikely that capital will be available when commodity prices are low and not necessarily the time when growers are looking to upgrade the system.

Chapter 10. Conclusions and recommendations for further research

This study investigated the effect of irrigation uniformity on lettuce production and profitability in the Lockyer Valley, Queensland. A preliminary trial was conducted on a commercial farm to identify the impact of irrigation uniformity on crop growth (Chapter 3). This was followed by two trials (Chapter 4) conducted on a research station. These trials were used to evaluate the potential to use proximal and remote sensing tools for measuring spatial variations in crop growth (Chapter 5) and soil-water (Chapter 6). The variations in irrigation uniformity both across the field and during the season were also measured and the relationships between irrigation water application, soil-water (Chapter 7) and crop yields (Chapter 8) were determined. This data was then used to evaluate the economic benefits of improving irrigation uniformity for lettuce production (Chapter 9). While the data sets and outcomes are of particular interest to the local industry, the findings are also more broadly applicable to understanding the role of irrigation performance and management on the production and profitability of other crops growing in other regions.

10.1 Crop and soil-water sensors for yield mapping and evaluating irrigation performance

Image analysis of photographs taken by digital cameras mounted perpendicularly above the crop were found to produce measures of lettuce canopy area and head size which were well correlated with physical measurements (Chapter 5). This suggests that camera based systems could be used to map spatial variability in both lettuce canopy growth during the season and head yields prior to harvest. However, further development work is required to improve the camera platforms and image analysis software before this system could be used for routine measurement and analysis. Thermal infrared (i.e. crop water stress index) and multispectral reflectance (i.e. normalised difference vegetation index) measurements were not well correlated to either irrigation water applications or physical canopy area measurements (Chapter 5).

The apparent soil electrical conductivity (ECa) was found to be poorly correlated with the applied irrigation depths prior to sprinkler modification when the uniformity of the irrigations were relatively high (Chapter 6). However, the correlation improved after sprinkler modification due to the increasing differences in soil moisture. There was generally a poor relationship between the applied irrigation volumes and the difference in ECa measured before and after irrigation. However, this relationship was marginally better for the irrigations immediately after sprinkler modification presumably because the differences in water application across the field were greater and the differences in soil moisture were becoming more apparent. This data suggests that electromagnetic sensing may be used to identify the spatial variations in irrigation application where the irrigation uniformity is poor (CU < 70%) and the application patterns are consistent throughout the season but that the technique is not suitable for evaluating the performance of individual application events or where the irrigation uniformity is comparatively high.

10.2 Variations in the patterns of irrigation application

Substantial variations were found in the uniformity of individual irrigation applications throughout the season (Chapter 7). Similarly, the uniformity measured by catch cans at different grid locations in the same field during the same event was also found to vary widely. This suggests that uniformity measurements taken using a limited number of grids during a single irrigation event may not adequately reflect the performance of the irrigation system over the whole season.

Substantial variations were also found in the spatial patterns of irrigation water application with the patterns only being relatively consistent during the season when the Christensen's coefficient of uniformity (CU) was low (e.g. CU < 60%). This suggests that for relatively high uniformity systems (i.e. CU > 75%), the pattern is dominated by environmental (e.g. wind speed or direction) or operating conditions rather than the discharge from the individual sprinklers. The inconsistency in the pattern of application for these higher uniformity systems during the season may also be a contributory reason as to why growers do not report seeing spatial differences in yield which they can readily relate to irrigation non-uniformity.

10.3 Agronomic and economic benefits of improving irrigation uniformity

Lettuce canopy area was not significantly correlated with cumulative water application (Chapter 8) suggesting that this physiological characteristic is influenced more by environmental factors (e.g. radiation) than by water application. Correlations between head size and the water applied during the last three weeks of the season were higher than for the water applied during the whole season suggesting that the last three weeks of the season is a critical period for water stress. Large differences in lettuce head marketability were found between the low and high water application areas of low uniformity irrigation grids confirming that water plays a major role in head production.

Increasing water application generally resulted in increased yield and marketability. However, the yield and total water (irrigation and effective rainfall) applied data shows a high degree of scatter with increasing water application, confirming that other factors have a greater influence on yield when water is non-limiting. This raises an uncertainty over whether the crop water production function plateaus or decreases with excessive water application. Both quadratic (i.e. declining yield) and exponential (i.e. yield plateau) crop water production functions were found to fit the data equally well. This suggests that the application of excessive water to areas of the field via poor irrigation scheduling or non-uniform irrigation applications under commercial conditions may not result in significant yield penalties that are visually observable by the growers.

As expected, net economic returns for lettuce production are primarily influenced by the marketable yield (Chapter 9). In general, increasing water application also increases returns. Where the existing irrigation uniformity is low, returns can generally be increased with improvements in irrigation uniformity. However, the magnitude of the benefit is dependent on the season, nature of the crop production response and the total water applied. The benefits of system improvements are maximised when the crop has a quadratic production function and appropriate irrigation scheduling is used. However, where the crop has an exponential production function or inappropriate scheduling is used then the gains may be small or negative. Similarly, in-season rainfall reduces the marginal benefit of irrigation system improvement with negligible increases in returns when effective rainfall meets 50% or more of the crop water requirements.

Where the crop response to differences in water application is small, highly variable, and unable to be accurately measured or in cases where the growth response functions are not significant the growers will not adopt higher uniformity systems. Given (a) the large uncertainty in the exact shape of the crop water production function for lettuce grown in the Lockyer Valley (Chapter 8), (b) that the region has a long term average rainfall between 58 and 114 mm (~25 to 50% of crop water requirements) during any two month growing window between April and September (Table 4.1), and (c) many local growers do not schedule irrigations using objective monitoring tools and consequently often over irrigate, it seems reasonable to conclude that the economic benefits of irrigation uniformity improvements in this area are likely to be small. This is consistent with the findings of Brennan (2008). Hence, it is not surprising that many growers have not embraced irrigation system improvements except during periods of water shortage when they have been unable to purchase additional water supplies. The incentive for irrigation system improvement is greatest when water is limited and unable to be purchased (Chapter 9.3). Under these conditions, failure to improve the irrigation uniformity results in a decrease in net return either by reducing the yield per unit area (by reducing the irrigation volume applied per unit area) or by reducing the area irrigated. Periods of low product price would also be expected to encourage irrigation uniformity improvements as non-uniform systems have a higher-break even price and require increased management (e.g. scheduling) to remain viable.

10.4 Recommendations for further research

This work has been conducted using small grids within a single irrigated field on a single crop type. It should be noted that the specific results and conclusions would be expected to be impacted by the agronomic, soil and climatic factors as well as the irrigation management practices adopted within the trial. However, this work has identified several areas of research which could be addressed in future studies including:

- Further development of the proximal and aerial camera systems to enable real-time measurement and spatial analysis of crop growth and yield characteristics. This would require development of the camera mounting and platform to enable continuous measurement and most likely would involve the use of a video rather than still camera. A GPS unit should be included to provide positional information. The image analysis software also requires further development to automate both the image processing and enable the extraction of the required measurements. The system would require a ruggedised on-board computer to conduct the image processing and provide the data interface and storage capability. Once the revised system is developed, it would be sensible to evaluate the performance under a wider range of crop and operating conditions.
- The potential to use apparent soil electrical conductivity measurements for assessing irrigation performance requires further investigation. While these measurements were generally not well correlated with the small sprinkler irrigation applications applied in this study, it seems reasonable to expect that they may be better related to larger infiltrated depths more commonly associated with surface (i.e. furrow or bay) irrigation systems.
- Further research to identify the optimal irrigation uniformity as function of climatic factors (e.g. in-season rainfall) are required to improve the volume and timing of irrigation applications (scheduling) for a wider range of crops (broadacre, horticulture, viticulture), soil types and market conditions to obtain better profitability.
- The environmental benefit of decreased chemical inputs and reduced deep drain loss of nutrients associated with increased uniformity of irrigation application.
- Improved knowledge of yield depression in areas of excessive water application due to non uniform irrigation application.
- Better dissemination of information in relation to irrigation uniformity impacts on production and economic responses to growers. Farmer willingness to change management strategies should be based on evidence that they can decrease input costs and improve profitability without adverse environmental impacts.
- Evaluation of the interaction between management unit size and the spatial variability in environmental (e.g. soil) conditions. It seems likely that management units which consist of uniform soils will likely have higher optimum irrigation

uniformities than management units which have high spatial variations in soil properties.

- Investigations into the benefits of site specific irrigation management and the identification of the monitoring tools, decision framework and application systems to enable the optimisation of irrigation applications and scheduling.

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