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Effects of irrigation rate on the growth, yield, nutritive value, and water use efficiency of Carrot (*Daucus carota*) and Broccoli (*Brasiola oleracea*)

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has accepted for the award of any other degree or diploma in any university.

Daniel Peter Mantilen Ludong

Signed: _____

Date: _____

Acknowledgements

July 2008

Daniel Peter M. Ludong

Dedication

To my wife "Ai" and daughter "Chrystie", and the
whole "Ludong – Tumewu" family

"For all things give thanks to GOD, because this is what he expects of
you in CHRIST JESUS". (1 Thess 5:18)

Abstract

The effects of differential irrigation treatments on the water use of broccoli (c.v. Indurance) and carrots (c.v. Stefano) were studied in the rainy, winter season from July to September 2006 and in the dry, summer period from November 2006 to March 2007, respectively. Broccoli and carrots are produced on the Swan Coastal Plain region on Grey Phase Karrakatta Sand. Such soils generally have water holding capacities as low as 10 to 13%. This soil is typical to the Swan Coastal Plain and requires irrigation to be applied at rates of up to 150% of class A pan evaporation (Epan) to optimise growth and quality.

High spatial uniformity (an average of 90%) of water distribution (DU) was achieved with the sprinkler irrigation system. The average irrigation water use efficiencies (Eu) in both the experiments were relatively high, at 78% and 95% in broccoli and carrot trials, respectively. The numerous rainy days during the winter season affected the results of water application efficiencies (Ea) of the broccoli experiment, which ranged from 35% to 43%. This contrasted with the carrot experiment where the water application efficiencies (Ea) of the 100% Epan and Crop Factor (CF) treatments were 81% and 78%, respectively. For the carrot experiment the water application efficiencies for the 100% Epan and crop factor treatments were 14% higher than the 150% Epan treatment. These results indicate that the sprinkler irrigation systems in both experiments showed good performance makes the system suitable for experimental purposes and also for vegetable production on soils of this nature.

Despite the differences in irrigation volume, soil water contents remained very high and did not differ among treatments in both the experiments. The differential soil water stress index (DSWSI) for the 100% Epan (T_1) and variable water replacement (VR) (T_{VR}) treatments ranged from 0.74 to 1.71 for both broccoli and carrot trials. There were only small soil water tension differences among all the irrigation treatments and ranged from -2.4 kPa to -7.6 kPa, which was within the range between saturation and field capacity for sandy soil (0 to -10 kPa).

In the broccoli experiment, even though the 150% Epan (T_2) irrigation treatment received 46% and 61% more irrigation than the 100% Epan (T_1) and variable water replacement (T_{VR}) irrigation treatments respectively, the treatments appeared to be largely negated by the high incidence of rainfall during the growing season. For example, the total depth of water application at 150% Epan was 13.9% and 17.2% greater than 100% Epan and T_{VR} treatments respectively. As such the yield, biomass components and nutritional value (ascorbic acid and carotenoid content) did not vary among the treatments. However, irrigation was still required based on the set scheduling parameters and when considered in isolation of rainfall the irrigation crop water use efficiency (WUE_i) on T_1 and T_{VR} treatments increased by 1.6-fold compared to T_2 treatment.

For the carrot experiment the total depth of water application (rainfall and irrigation) for the 150% Epan treatment was 33% and 23% greater than at 100% Epan and Crop factor (CF) treatments, respectively. The yield (carrot roots) on a fresh weight basis (FW) for plants irrigated with the 150% of Epan and Crop factor (CF) treatments were 16% and 20% higher than the yield for plants irrigated with the 100% Epan treatment. Total (root and shoot) fresh weight of carrot plants irrigated

with the CF treatment was 17% higher than the total fresh weight of plants irrigated with the 100% Epan treatment. However, there were no significant differences between irrigation treatments for root and total (root and shoot) mass on a dry weight basis and the ratio of carrot root to shoot, on a fresh and dry weight basis. The root lengths for plants grown with the CF and 150% Epan irrigation treatments averaged 30 cm, and were 14% larger than the root lengths for the 100% Epan treatment. The plant height for plants grown with the CF irrigation treatment was 6% higher than at the 100% Epan irrigation treatment and leaf length at the CF irrigation treatment was 12% greater than at the 150% Epan irrigation treatment. The root diameter and leaf width of carrots were not significantly different for all treatments. There were no significant differences in ascorbic acid and total carotenoid content of carrot roots among the three irrigation treatments. The average values of antioxidant content from diphenylpicrylhydrazyl (DPPH) scavenging, ARP (anti radical power) and total trolox equivalent antioxidant capacity were 44.83%, 0.8789 and 1.056μmol TE/g, respectively. The reduction of the irrigation level treatment from the 150% Epan water replacement to the 100% Epan water replacement increased the percentage of the DPPH scavenging by 1.55%, and total antioxidant capacity (AOC) and ARP activities by 4.19%.

On a dry weight basis, the crop water use efficiencies (WUE) (irrigation plus rain water) of carrot plants irrigated with the 100% Epan and CF treatments, were the same (0.013 g/mm). However, these were 30% greater than the WUE values of carrots irrigated with the 150% Epan treatment. On a fresh weight basis, the WUE of carrot plants irrigated with the 100% Epan and CF (0.120 and 0.132 g/mm) treatments were 14% and 26% greater than the WUE of carrot plants irrigated with the 150% Epan treatment, respectively.

An example of the diurnal trends of the carrot's physiological responses to the irrigation treatments showed that on average, the rate of photosynthesis, stomatal conductance and intercellular CO_2 for carrot plants grown with the 150% Epan treatment was higher than the rate of photosynthesis, stomatal conductance and intercellular CO_2 at both the 100% Epan and CF treatments. However, not all the physiology measurements showed a significant difference among all the treatments. The variation in the physiological measurements was predominantly influenced by the change of temperature during the diurnal hours.

This study has proven the hypothesis that, on a free draining sandy soil, the irrigation treatments did not affect the growth and yield. However, there was a potential to reduce irrigation volumes from standard industry levels to maximise the WUE without decreasing the yield and crop quality, especially for broccoli and carrot, in Western Australia.

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Abbreviation

AA: ascorbic acid.

A_o: the initial absorbance or as referred to as control, is in absence of any sample

A_c: the value of absorbance for added sample concentration c

ABS: Australian Bureau of Statistics.

AH: an antioxidant species.

AO: the concentration of the antioxidant sample.

AOAC: Association of Official Analytical Chemists.

ARP or

$1/EC_{50}$:   antiradical power.

CR: a. capillary rise.

               b. crop factor

d: average depth of water stored or caught during the irrigation.

D_f or DP: deep percolation below the farm root-zone soil.

DPPH: diphenylpicrylhydrazil.

DU: distribution uniformity.

Dw/DM: dry weight.

Ea: water-application efficiency

Ec: water conveyance efficiency

Ed: water distribution efficiency

Eu: irrigation water use efficiency

EC_{50}:   efficient concentration 50%.

Epan/ E_{pan}: class A pan evaporation

ET: evapotranspiration

ET_o: the reference crop evapotranspiration.

ET_p: evapotranspiration potential.

FAO: Food and Agriculture Organization of the United Nations.

FOB: free on board.

Fw/FM: fresh weight.

HAT: hydrogen atom donation or transfer.

I: irrigation.

K_c: crop coefficient.

K_p: pan coefficient.

MAD: management-allowed depletion.

P: rainfall.

Q: the percentage reduction or "inhibition" or "quenching" or "scavenging" of the DPPH.

R: a radical species.

RO: surface runoff.

RWC: leaf relative water content

SF_{in}:   subsurface flow in.

SF_{out}:   subsurface flow out.

T_1:   treatment 1 (the 100% Epan water replacement treatment)

T_2:   treatment 2 (the 150% Epan water replacement treatment)

T_{VR}:   the variable water replacement (VR) treatment on the broccoli trial

T_{CF}:   the crop factor water replacement (CF) treatment on the carrot trial

Tw/TM: turgid mass/weight

Wa: volume of irrigation water applied / water delivered to the plant field.

Wd: water delivered from irrigation system / by a distribution system

Wi: water introduction into the distribution system.

Wu: water beneficially used.

Ws: water stored in the root zone soil during the irrigation.

WUE :   crop water use efficiency.

WUE_i :   crop water use efficiency, at actual irrigation (total volume of irrigation without volume of rain).

y:	the average of the absolute values of the deviation in depth of water stored or caught from average depth stored or caught during the irrigation.
Y:	crop yield (fresh weight (Fw) or dry weight (Dw)).
Δ SW:	soil water content.
ψ_m:	soil water matric potential.
ψ_p:	soil water pressure potential.
ψ_S:	soil water solute potential.
ψ_T:	soil water total potential.
ψ_z:	soil water gravitational potential.
ψ_t:	tissue water potential.
ψ_p:	pressure (turgor) potential.
ψ_s:	osmotic potential.

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Chapter 1: General introduction

Climate change and global warming are serious environmental issues for agricultural production. In spite of water resource shortages, water demand and consumption by global users including urban, industrial, agricultural and environmental users is increasing (Cooley *et al*., 2007).

Agriculture is a major consumer of water resources (for irrigation and food processing) on a regional and global scale (Fairweather *et al*., n.d; Khan and Abbas, 2007). Regardless of pressures on water supply and infrastructure costs, irrigation is an essential factor of crop production. Given the current limiting conditions of water use for irrigation, it is important to develop new management strategies to improve irrigation systems. The goal of efficient irrigation strategies is to maximise the return (in terms of yield and value) on the use of water whilst ensuring good nutrient utilization.

Efficient irrigation strategies can be achieved by developing an understanding of the relationships among plant, soil, water supply, and weather and implementing management strategies to reflect the different relationships identified (Alvino *et al*., 1990; Cooley *et al*., 2007; Gonzalez *et al*., 2005; Schwab *et al*., 1993). Sprinkler irrigation systems are one of the main irrigation techniques that are currently implemented in agricultural production (Dechmi *et al*., 2003).

Irrigation efficiency measurements reflect the effectiveness of an irrigation system in delivering water to plants or the effectiveness of irrigation in increasing plant production (Haman *et al*., 2005). "Irrigation water use efficiency" (Eu), Water application efficiency (Ea) and the distribution uniformity (DU) are commonly used parameters to evaluate the field performance of sprinkler irrigation systems (Hansen *et al.* 1980; Ley, 2003; Schwab *et al*., 1993). "Crop water use efficiency (WUE)" refers to the ratio of crop yield (dry or fresh weight) to the volume of water used to produce the crop (Haman *et al*., 2005; Schwab *et al*., 1993).

Fertiliser, especially nitrogen, should not be ignored when considering irrigation of crops (James *et al*., 1982). If water application is sufficient, the rate of growth of the crops will be dependent on nutrient supply (Schmidhalter *et al*., 1990). However, improper nitrogen fertilisation and irrigation management are major

factors contributing to water quality and shortage problems in agricultural production (Al-Kaisi and Yin, 2003). High levels of nitrogen leaching can occur because of excess irrigation water application (Neeteson and Carton 2000 cited in Rahn, 2002). Effective irrigation and fertiliser management can ensure optimal uptake of nitrogen and minimise offsite impacts and 'irrigation return flow' (IRF), which may be contaminated by salts and nitrates (Causape et al., 2006; Rahn, 2002).

Water requirements associated with evapotranspiration and the timing of maximum demand varies with different crops. The rate of evapotranspiration depends on crop factors which in turn are influenced by the crop genotype and stage of growth, atmospheric conditions (such as radiation, temperature, wind and humidity), management (including ground covers, plant density and soil water content (Allen et al., 1998; Schwab et al., 1993; Stern, 1979)) and other environmental factors (such as soil salinity, level of land fertility, hardness of the soil surface, disease and pests).

Carrots and broccoli are favoured vegetable crops produced in Western Australia, specifically around Perth on the Swan Coastal Plain area. These areas are characterised by sandy, free-draining soils. This type of soil makes it easy for cultivation and harvest, but the deep, sandy soil has a low water holding capacity (10% to 13%), and requires irrigation to supply water of up to 1.5-fold of class A pan evaporation (Epan) for maximum growth of crops during summer and winter seasons (Cirillo 2001 cited in Gibberd et al., 2003; Heisswolf and Deuter, 1992; McKay, n.d).

During the last two decades, most Australians have become increasingly concerned about food consumption patterns and diets. Fruits and vegetables are excellent sources of natural antioxidants, including carotenoids, ascorbates, tocopherols and phenolics for human dietary consumption. Antioxidants are believed to play an important role in the body's defense system against free radicals and have been associated with reduced risk of chronic diseases and functional disorders in the elderly, in addition to other health benefits (Alasalvar et al., 2005; Cao et al., 1996; Ou et al., 2002; Pellegrini et al., 2003; Zhang and Hamauzu, 2004). The most common antioxidants present in vegetables are vitamin C (ascorbic acid), vitamin E (tocopherols), carotenoids and phenolic compounds such as flavonoids (Ou et al., 2002).

Carrot and broccoli are generally referred to as excellent sources of natural antioxidants, and dietary fibre (Alasalvar *et al*., 2005; 'Fruit and vegetable manual*',* 1995; Zhang and Hamauzu, 2004). Application of nutrients (fertilisers) and irrigation may not only influence the yield and quality of field vegetable crops, but may also influence the nutritional quality of products used for human consumption. For example, the effects of fertilizer application on the chemical composition of vegetable products have previously been investigated (Sorensen, 1999). However, studies on the effects of an excess or shortage of irrigation on the nutritional quality of vegetables are limited.

These experiments have been conducted in winter and summer at the Medina Research Station of Western Australian Department of Agriculture and Food. The objective of this study is to investigate the influence of varying sprinkler irrigation rates on the growth and yield of broccoli in the winter; and carrots in the summer time.

This research tests the hypothesis that on free sandy soil irrigation rates do not affect growth and yield, but will determine crop water use efficiency (WUE).

Chapter 2: Literature review

2.1 Irrigation management

2.1.1 Sprinkler system

Well designed operations and a good understanding of the water delivery requirements and irrigation scheduling can create an efficient sprinkler irrigation system (Hansen *et al*., 1980). Sprinkler irrigation systems distribute water under pressure through pipes, emitted into the air over the land to simulate natural rainfall (Hansen *et al*., 1980; Stern, 1979).

Compared with flood or furrow irrigation systems, the advantages of sprinkler irrigation include:

- Applying sufficient water to any crop, soil type and topographic conditions;

- Greater water savings by accurately controlling irrigation time, volume of water applied and greater uniformity of water distribution;

- High water application efficiency;

- Reduced potential for environmental damage with low water erosion and runoff and;

- Potentail to be used to apply fertiliser (fertigation), control air temperature and humidity and reduce the hazard of frost damage (Dechmi *et al*., 2003; Hansen *et al*., 1980; Li and Rao, 2003).

However, disadvantages associated with the use of overhead sprinkler irrigation systems have been reported in a hilled system with sandy soil. For example, non-uniform wetting of the field and, with some weather patterns, excess water flow through the root zone causing leaching of nitrates and other soluble nutrients (Saffigna *et al*., (1976) and Starr *et al*., (2005) cited in Cooley *et al*., 2007)**.**

Another disadvantage associated with the performance of sprinkler irrigation is the impact of wind on irrigation distribution. For example, Dechmi *et al*. (2003) revealed that the irrigation water, when the wind speed was higher than 2.1 ms^{-1} (7.56 kph) significantly affected the grain yields. The variability of grain yield was also a result of non-uniform water distribution during the crop season.

2.1.2 Irrigation efficiency and uniformity

Efficiency is the percentage of an output divided by an input. This needs to be defined for a precise understanding of the term (Schwab *et al*., 1993). There are many definitions of "efficiency" to express the relationship between irrigation and plant performance.

Hansen *et al*. (1980) and Schwab *et al*. (1993) outline the basic irrigation efficiency concepts as follows:

Water use efficiency

There is no general agreement on a single definition to explain irrigation water use efficiency. Water use efficiency can be defined in two different ways (Haman *et al*., 2005):

The term "crop water use efficiency (WUE)" refers to the ratio of crop yield to the volume of water used to produce the crop.

$$WUE = Y/Wa \qquad\qquad (2.1.1)$$

Where, Y = crop yield (fresh weight (Fw) or dry weight (Dw)), and;
Wa = volume of irrigation water applied.

The second method is referred to as "irrigation water use efficiency" which is the ratio of the volume of water beneficially used to the volume of water delivered from an irrigation system:

Irrigation water use efficiency (Eu):

$$Eu = 100Wu/Wd \qquad\qquad (2.1.2)$$

Where, Wu = water beneficially used, and;
Wd = water delivered from irrigation system.

The irrigation water use efficiency (Eu) is therefore dependent on irrigation water for maintaining adequate soil moisture in the root zone for plant evapotranspiration (ET) and other beneficial uses that include leaching of salt, freezes protection, establishment of young plants and plant cooling. These water uses are reasonable and necessary for plant production (Haman *et al*., 2005).

Water conveyance efficiency (Ec):

$$Ec = 100Wd/Wi \qquad (2.1.3)$$

Where, Wd = water delivered by a distribution system, and;
Wi = water introduction into the distribution system.

The water-conveyance efficiency concept evaluates the water coming from a diversion, stream or reservoir along any point of a distribution system. This ratio for sprinklers in a pipeline conveyance system may be approximately 1.0 (Haman *et al*., 2005).

Water application efficiency (Ea):

$$Ea = 100Ws/Wa \qquad (2.1.4)$$

Where, Ws = water stored in the soil root zone during the irrigation, and;
Wa = water delivered to the plant field.

This efficiency focuses on the measurement of the water delivered and water stored within the root zone of the soil, where plants use it for evapotranspiration (Haman *et al*., 2005). Well designed sprinkler irrigation systems generally have approximately 75% water application efficiency. Sprinkler irrigation system Ea can be applied to a small individual furrow or border, a field or an entire farm project. However, the application of sprinkler irrigation Ea, when applied to large field areas overlaps the definition of conveyance efficiency (Hansen *et al*., 1980).

Neglecting evaporation losses, wind drift and assuming no surface runoff and lateral seepage on the soil, for sprinkler irrigation water systems the relationship between water delivered (Wa), water stored in the soil root zone (Ws) and deep percolation below the farm root-zone soil (Df) can be defined as follows:

$$Wa = Ws + Df \qquad (2.1.5)$$

Hence

$$Ea = 100(Wd - Df)/Wa \quad \text{(Hansen et al., 1980)} \qquad (2.1.6)$$

Efficiency of application of irrigation systems is predominantly influenced by the depth of water applied. Land and water spread uniformity, irrigation method, size of irrigation stream, length of run, soil texture, and permeability are the variable factors that influence the time the irrigator keeps water running until the sufficient depth of water is achieved (Hansen *et al*., 1980).

Water distribution efficiency (Ed)

Water distribution efficiency (Ed) can be expressed as the effectiveness of irrigation uniformity and is measured by the Christiansen coefficient of uniformity (UC) (Dechmi *et al*., 2003; Hansen *et al*., 1980; Schwab *et al*., 1993).

$$Ed = 100 \ (1\text{-y/d}) \tag{2.1.7}$$

Where, y = average of the absolute values of the deviation in depth of
water stored or caught from average depth stored or caught
during the irrigation,
d = average depth of water stored or caught during the irrigation.

This coefficient indicates the degree to which water has been applied and penetrated to a uniform depth throughout the field. The acceptable value of this efficiency is above 0.8. The more uniform water is distributed, the more even the crop response will be (Schwab *et al*., 1993). Variation in distribution is considered in terms of water distribution efficiency. The depth of water application is the calculated depth of water application divided by the water-distribution efficiency (Ed) (Hansen *et al*., 1980):

$$Depth \ of \ water \ applied = \frac{the \ depth \ of \ calculated \ water}{the \ water \ distribution \ efficiency} \tag{2.1.8}$$

A different measurement, which is also commonly used, is the distribution uniformity (DU):

$$DU = \frac{average \ low-quarter \ depth \ of \ water \ stored \ or \ caught}{average \ depth \ of \ water \ stored \ or \ caught} \tag{2.1.9}$$

The average low-quarter depth is the average of the lowest one fourth of all values where each value represents an equal area. DU values above 0.7 are considered acceptable (Schwab *et al*., 1993).

Irrigation efficiency values will vary depending on the type of irrigation system and on many other factors, such as maintenance, soil, plant, and climate characteristics (Haman *et al*., 2005). Due to the numerous efficiency definitions used, it is necessary that the term efficiency be clearly defined for each specific application (Haman *et al*., 2005). In the experiments used in this study, real water-use efficiency is the ratio of the volume of water beneficially used to the volume delivered from irrigation water system and is called "irrigation water use efficiency (Eu)". And the ratio of dry or fresh weight of plant produced to the volume delivered from the irrigation water system is identified as "Crop water use efficiency (WUE)".

2.1.3 Irrigation water requirements and scheduling

Irrigation scheduling is the use of water management strategies to optimise yield by prevention of the over application of water, water shortage and drought stress. Proper scheduling to achieve the most efficient irrigation water use will reduce cost and the use of fertilisers and pesticides. Conversely, over irrigation can decrease yields due to loss of soil aeration and fertiliser leaching, and increase water and energy cost. In addition, there is also a potential risk of raised water tables and water pollution associated with over irrigation (Alvino, 1990; Evans *et al*., 1996; Schwab *et al*., 1993).

Scheduling is do not only based on the soil-water estimation using an accounting approach, but also more recently, scheduling techniques have been developed that are based on the moisture status or stress conditions of the crop or soil. Plant-based indicators include: plant wilting, leaf or canopy temperatures, leaf water potentials. Whilst soil-based indicators include: feel and appearance, tensiometers, porous blocks, gravitimetric sampling, and neutron probes. Remote sensing of crop stress using infrared satellite imagery is another method being evaluated for future irrigation water scheduling (Evans *et al*., 1996; Schwab *et al*., 1993).

Water balance techniques can also be used to obtain a record of the estimated water in the root zone. When water depletion reaches a level known as the management-allowed depletion (MAD), irrigation is scheduled. MAD is used as a guide to determine how much water will be added or removed from the soil root zone (Evans *et al*., 1996).

Irrigation water requirements define the total amount of water that must be supplied during the growing period to a crop that is not limited by water, fertiliser, salinity, or diseases. To obtain maximum yield, the most important factor is to determine the frequency of irrigation to keep sufficient water in the soil field reflective of the water availability and crop needs (Schwab *et al*., 1993).

A plant does not efficiently use all available water. As such, it is necessary to apply more than what will be actually transpired by the plant in the field. To calculate the water requirements for a crop, it is necessary to consider the performance of all the irrigation system efficiencies, such as water application efficiency (Ea), water conveyance efficiency (Ec) and water distribution efficiency

(Ed). The growing period is also an important factor to consider because water consumptive use of plants varies from stage-to-stage (Fig. 2.1.1) (Hansen *et al*., 1980).
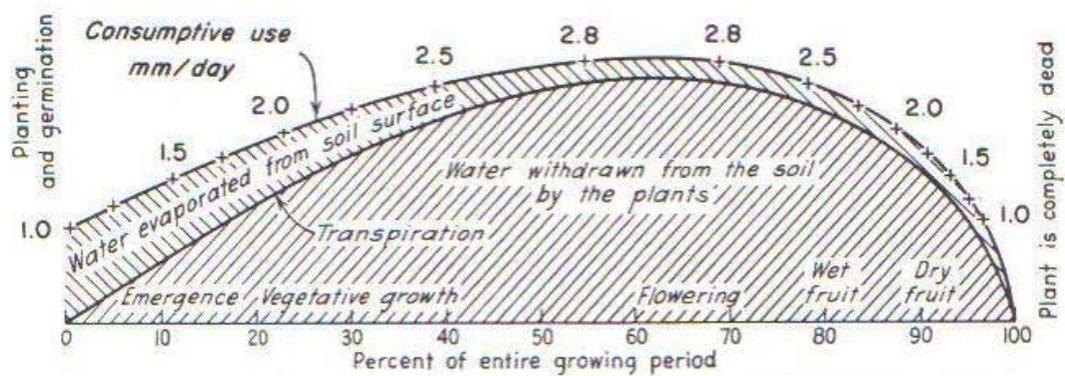
Figure. 2.1.1 Consumptive use of water for various periods of growth (Hansen *et al*., 1980).

During a crop's growing period, the frequency of irrigation can be determined by dividing the amount of water depletion from the soil by the consumptive use per day. The growing period, rate of consumptive use, depth of rooting, efficiency of irrigation and water holding capacity of the soil all need to be considered to determine the duration of water applied (Hansen *et al*., 1980). An optimum irrigation schedule results in maximum profit and provides optimum use of the water and energy (Evans *et al*., 1996).

2.2 Plants, soil, and irrigation relationship

2.2.1 Crop productions and irrigation

There are many factors that influence the crop production/irrigation relationship, such as soil water holding capacity, climate characteristics, irrigation amount and timing, and the type of crop. As such yield increases from irrigation are not constant from location to location with time, or from one level of irrigation to another (James *et al*., 1982).

The total amount of water required for a crop's growth might not all come from the irrigation system. Precipitation or upward flow from a water table may contribute substantially towards fulfilling crop water requirements. The irrigation water requirement is therefore generally calculated from the difference between the crop water requirements and effective precipitation as determined by water balance

analyses. Besides additional water for leaching of salts and compensation for non-uniform water applications, the main irrigation water requirement of the crop is evapotranspiration (ET) (Allen, *et al*., (FAO 56), 1998; Walker, (FAO 45), 1989). ET can be determined by measuring the various components of the soil water balance (Allen, *et al*., (FAO 56), 1998).

2.2.2 Evapotranspiration

The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement.. Crop evapotranspiration refers to the amount of water that is lost through evapotranspiration, whilst crop water requirement refers to the amount of water that needs to be supplied to the crop (Allen, *et al*., (FAO 56), 1998).

Estimations of evapotranspiration must be known when planning an irrigation system. A crop's water consumption to crop evapotranspiration (ET), is the sum of two terms: transpiration and evaporation (Hansen *et al*., 1980; Nakayama and Bucks, 1986; Schwab *et al*., 1993; Stern, 1979). The simultaneous processes of evaporation and transpiration are difficult to separate from each other. Most water loss is by soil evaporation in the early stages when the crop is small, whilst when the crop is well developed and the entire canopy covers the soil, transpiration is responsible for the bulk of water loss (Fig.2.2.1.) (Allen, *et al*., (FAO 56), 1998).

Soil water balance

The relationship between irrigation and evapotranspiration (ET) can be expressed as a water balance. The method consists of assessing the incoming and outgoing water fluxes within the crop's root zone over a period of time (Figure 2.2.1). This soil water balance method can usually only give ET estimates over long time periods of the order of weeklong or ten-day periods.
It refers to the following equation:

$$ET = I + P - RO - DP + CR \pm \Delta\,SF \pm \Delta\,SW \qquad (2.2.1)$$

Where, I: irrigation, P: rainfall, RO: surface runoff, DP: deep percolation, CR: capillary rise, Δ SF /: subsurface flow in (SF_{in}) or out (SF_{out}), and Δ SW: soil water content (Allen, *et al*. (FAO 56), 1998; James *et al*., 1982; Nakayama and Bucks, 1986).

Crop evapotranspiration (ET) under standard conditions (ET_o) is a reference evapotranspiration, sometimes called evapotranspiration potential (ET_p), which can be calculated from climate data. The reference crop evapotranspiration (ET_o) represents the evapotranspiration from standardised vegetated surfaces closely resembling an extensive surface of green grass of uniform height, actively growing, completely shading the ground with adequate water (Allen, *et al*., (FAO 56), 1998; Smajstria *et al*., 2000).

Furthermore, to estimate ET for a specific crop, the evapotranspiration reference ET_o (or ET potential) must be multiplied by a crop water use coefficient (K_c). K_c values are assumed to be constants for a specific crop, stage of growth, and cultural conditions. K_c values are typically given as average monthly values for perennial crops and as a function for the stage of growth for annual crops (Smajstria *et al*., 2000). Allen, *et al*., (FAO 56), (1998) showed the relation between the ET_c and ET_o by the following equation:

$$ET_c = K_c\, ET_o \qquad\qquad (2.2.2)$$

where K_c is the crop coefficient.

The Penman-Monteith method is strongly recommended by FAO (Allen, *et al*., (FAO 56), (1998) as the standard method to determine the reference evapotraspiration (ET_o) from meteorological data. The method provides consistent ET_o values in all regions and climates. It also closely approximates standard conditions of grass ET_o. This method requires radiation, air temperature and humidity and wind speed data. FAO simplified the Penman-Monteith method by the following equation:

$$ET_0 = \frac{0.408\Delta\left(Rn - G\right) + \gamma\dfrac{900}{T + 273}U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \qquad\qquad (2.2.3)$$

where

ET_0: reference evapotranspiration [mm day^{-1}]
Rn: net radiation at the crop surface [MJ m^{-2} day^{-1}]
G: soil heat flux density [MJ m^{-2} day^{-1}]
T: mean daily air temperature at 2 m height [^{0}C]
U_2: wind speed at 2 m height [m s^{-1}}
e_s: saturation vapour pressure [kPa]
e_a: actual vapour pressure [kPa]
$e_s - e_a$: saturation vapour pressure deficit [kPa]

Δ: slope vapour pressure curve [kPa $^0C^{-1}$]
γ: psychrometric constant [kPa $^0C^{-1}$]

To determine the reference evapotraspiration (ET$_o$) value of more than one month and for areas where climatic data only cover air temperature, the Blaney-Criddle equation is still recommended for use (Allen, *et al*., (FAO 56), 1998).

$$ET_0 = p(0.46\,T_{mean} + 8) \qquad\qquad (2.2.4)$$

where

ET_0: reference evapotranspiration [mm day^{-1}] as an average for a period of 1 month
p: mean daily percentage of annual daytime hours
Tmean: mean daily air temperature [^0C]
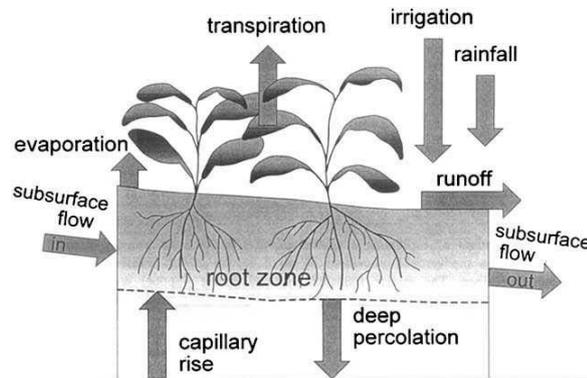
Figure. 2.2.1 Plant and **s**oil water balance (Allen *et al*., (FAO 56), 1998).

ET estimated from pan evaporation

An evaporation pan in which water is evaporated from an open water surface provides a value of the integrated effect of radiation, air temperature, air humidity and wind on evaporation. By observing the evaporation loss from a water surface and applying empirical co-efficients to relate pan evaporation to computed ET$_o$ from the Penman-Monteith method, pan evaporation has proved its practical value and is close to estimated reference evapotranspiration (ET$_o$) value. When using the pan evaporation method, calculations should be determined for periods of ten days or longer (Allen, *et al*., (FAO 56), 1998; Smajstria *et al*., 2000). The pan evaporation method is related to the reference evapotraspiration (ET$_o$) by an empirically derived pan coefficient:

$$ET_o = K_p \cdot E_{pan} \qquad\qquad\qquad (2.2.5.)$$

Where, ET_o is reference evapotranspiration;
      K_p is pan coefficient and;
      E_{pan} is pan evaporation.

An accurate reference for crop water use from pan evaporation, besides depending upon climatic factors and the amount of water in the pan, must be constructed, maintained and located according to standard specifications or coefficient of pan evaporation (Smajstria *et al*., 2000). Different types of pans exist such as the colour, size, and position of the pan have a significant influence the pan coefficient. The sitting area of pan evaporation where are surrounded by bare soil, pavement, or a well watered crop also influence the coefficient values (Allen, *et al*., (FAO 56), 1998; Smajstria *et al*., 2000).

The rate of evapotranspiration depends on the crop variety, its stage of growth and the atmospheric conditions (such as radiation, temperature, wind and humidity). Ground cover, plant density and soil water content will also have an influence (Allen, *et al*., (FAO 56), 1998; Schwab *et al*., 1993; Smajstrla *et al*., 2000; Stern, 1979). Other factors, such as soil salinity, poor land fertility, limited application of fertilisers, structure of soil horizons, the absence of diseases, pest control and poor soil management may possibly inhibit the crop development and reduce evapotranspiration (Allen, *et al*., (FAO 56), 1998).

2.2.3 Soil water relation

Soil water relations play an important role in the determination of how effective irrigation will be in supporting crop production. After supplying water by either irrigation or precipitation, soil moisture can be stored in quantities over a period of time dependent on soil type, climatic conditions and the type of crop. Soil water is slowly depleted as the crop uses water through evapotranspiration. An understanding of soil characteristics is very important for crop production and irrigation (James *et al*., 1982; Schwab *et al*., 1993; Stern, 1979).

When gravitational water has been removed, the moisture content of soil is defined as field capacity (Hansen *et al*., 1980). The water holding capacity or field capacity of the soil is the basis of knowing when irrigation water should be applied (James *et al*., 1982; Schwab *et al*., 1993; Stern, 1979). Irrigation can raise the soil water content to the field capacity. In either sprinkler or surface irrigation, the

infiltration capacity and the permeability of the soil will determine how fast water can be applied (Schwab *et al*., 1993).

For irrigation management, it is helpful to know the soil water potential rather than knowing just the soil water content. The plant root's ability to extract the soil water is directly related to the total soil water potential. The components of soil water potential are gravitational ψ_z, matric ψ_m, pressure ψ_p, and solute ψ_s. The relationship of these component potentials is defined as the total potential by the equation:

$$\psi_T = \psi_z + \psi_m + \psi_p + \psi_s \tag{2.2.6}$$

The basic unit for soil water potential is pressure in kPa or bars (James *et al*., 1982).

The soil matric water potential is the most important amongst soil water potential components. One of the basic soil properties required to manage irrigation effectively is the relationship between soil water content and soil matric water potential. The soil matric water potential is related to the attraction that the solid soil matrix has for water; it is defined as the vertical distance from reference position in the soil to the top of a water column in equilibrium with the reference point (James *et al*., 1982).

A tensiometer device is used to measure the soil matric water potential. The values of soil matric water potential are zero or negative. This value represents the transfer of energy as water flows from high to low energy, from the soil to the plant root. Determination of the critical soil matric water potential value at which irrigation should be applied is different for different crops, growth stages, and ranges depending on local conditions (James *et al*., 1982). For example, the soil matric water potential at which water should be applied for maximum yields for carrot and broccoli crops ranges from -53.9 to -63.7 kPa and -44.1 to -68.8 kPa, respectively (James *et al*., 1982). Sandy soils will drain readily, with the soil matric water potential tending to be near -10 kPa at field capacity, while clay soils drain very slowly, so clays tend to a tension toward -33 kPa (Hansen *et al*., 1980).

Water flows from high to low energy potential. Plants must rapidly adjust their internal water potential as soil water content changes both with time and space across a field to enable the movement of water from the soil to the roots. In addition to atmospheric demand the total water potential within a plant may be affected by change in solute concentrations and turgor pressure. Increased solute concentration in plant "sap" lowers the total root water potential, generating tension to pull in

water. Conversely, when soil water content outside the root cells decreases it can also cause the solute concentration in the soil to increase, making it more difficult for a plant to absorb water (Allison and Jones, 2005).

2.2.4 Water relation and photosynthesis

Photosynthesis is a series of integrated systems independently controlled by various environmental and genetic factors. This oxidation-reduction reaction can be summarised by the following equation:

$$6CO_2 + 12H_2O \longrightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O \text{ (Hopkins and Huner, 2004)} \qquad (2.2.5)$$

The movement of CO_2 and H_2O vapour between the leaf mesophyll and the atmosphere occurs through a series of variable resistances. Photosynthesis is linearly related to the partial pressure of CO_2 in the intercellular space, p $(CO_2)_i$ (Krieg, 1983). The net photosynthetic rate can be measured in the laboratory as either the uptake of CO_2 or the evolution of O_2 (Hopkins and Huner, 2004).

Photosynthesis primarily determines the growth rate and productivity of green plants. Leaf area per plant and the photosynthetic rate per unit leaf area are two important components of photosynthetic activity. The development of leaf area is very sensitive to stress in most plants and largely limits plant productivity. The photosynthetic rate is also quite sensitive to stress related to stomata conductance limitations to gas exchange. The stomata then respond to the reduced photosynthetic activity to maintain an optimum exchange of H_2O vapour and CO_2. The genetic differences in stomatal conductance that influence photosynthetic rate may increase water use efficiency if this trait is heritable and can be translated to the whole canopy (Krieg, 1983).

Photosynthesis can be affected by water stress in two main ways. Firstly the epidermis of leaves contains pores (stomata) that provide the exchange of gases between the internal air spaces and the ambient environment. Stomata are involved in controlling the uptake of CO_2 for photosynthesis and transpirational water loss. Closure of stomata under water stress normally cuts off access of the chloroplasts to the atmospheric supply of carbon dioxide and increases photosynthesis. Secondly, there are direct effects of low cellular water potential on the structural integrity of the photosynthetic machinery (Hopkins and Huner, 2004).

The water status of plant cells is constantly changing as the cells adjust to fluctuations in the water content of the environment or changes in the metabolic state (Hopkins and Huner, 2004). Leaf water potential is the common immediate measure of plant water deficit (Blum, 1988). The relationship between tissue water potential (ψ_t), pressure (turgor) potential (ψ_p), osmotic potential (ψ_s) is expressed as:

$$\psi_t = \psi_p + \psi_s \qquad\qquad (2.2.6)$$

As a water deficit develops, both water potential and osmotic potential decline (becoming negative) at different rates. Water potential decreases at a greater rate than osmotic potential. The difference between them is the turgor potential (Blum, 1988).

2.2.5 Leaf relative water content (RWC)

Relative water content (RWC) measurements in leaf tissues are commonly used to assess the water status of plants (Shepherd, 1977; Yamasaki and Dillenburg, 1999). Leaf water status is closely related to several leaf physiological variables, such as leaf turgor, growth, stomatal conductance, transpiration, photosynthesis and respiration. Leaf relative water content has been widely used to quantify the water deficits in leaf tissues as an indicator of plant water balance. Plant water balance expresses the relative amount of water present in the plant tissues (Yamasaki and Dillenburg, 1999).

Measurement of the current water content of the sample leaf tissue relative to the maximal water content the sample can hold at full turgidity is a measure of water deficit in the leaf (*Relative water content*, n.d; Yamasaki and Dillenburg, 1999). The relative water content (RWC) of plant leaf tissue is expressed as:

$$\text{RWC (\%)} = [(\text{FM-DM})/(\text{TM-DM})] \times 100 \qquad\qquad (2.2.7)$$

where , FM, DM, and TM are the sample tissue fresh, dry and turgid masses (or weight) respectively (Shepherd, 1977; Yamasaki and Dillenburg, 1999).

According to Barrs and Weatherley (1962) (cited in Yamasaki and Dillenburg, 1999), there are two phases of tissue imbibitions or water absorption. Phase I indicates a high initial rate of water absorption, followed by a prolonged period of slow absorption as phase II. The amount of water absorbed during phase I

is commonly interpreted as being the amount of water needed to compensate for the water deficit of the tissue. Further water absorption (Phase II) is affected by cell expansion, thus the changes of masses occurring through this phase should be ignored for estimating RWC.

Imbibition by leaves from water–stressed plants is slower than that of unstressed leaves and a sufficient time period for tissues to rehydrate is about 24 hours (Shepherd, 1977). The normal value of RWC ranges between 98% in turgid and transpiring leaves to about 40% in severely stressed leaves. In most crop species, the wilting range is between RWC 60% to 70% (Barrs and Whetherley, 1962 cited in *Relative water content*, n.d.). RWC can range from 85% to 100% and be categorised as moderate stress to full turgidity (Shepherd, 1977). The method should result in between 2% to 3% of RWC of statistically significant difference between treatments (Barrs and Whetherley, 1962 cited in *Relative water content*, n.d.).

2.2.6 Nitrogen in irrigated soils

Plant demand for nitrogen (N) can be satisfied from a combination of soil and fertiliser N to ensure optimum growth. The soil nitrogen transformations are intimately related to the status of soil moisture. When soil moisture is optimum, all of the biological processes – plant nitrogen uptake and growth, residue decomposition, ammonification and nitrification proceed at a maximum rate dependent on soil temperature. When moisture is limited, these biological processes operate very slowly (James *et al*., 1982). However, if the moisture is excessive, nitrogen (NO_3-N) leaching may occur and oxygen in the soil may be reduced, resulting in denitrification and a reduction in root respiration. This condition may affect plant growth (James *et al*., 1982; Rahn, 2002).

Because of the interaction between soil nitrogen and moisture availability, there is an optimum combination of nitrogen and water for maximum crop production. If either nitrogen or water varies markedly above or below this optimum level, crop yields will reduce. To obtain high yield production, irrigation and fertiliser application at the correct rate and time are required (James *et al*., 1982). El-Shikha *et al*'s, (2007) experiments on broccoli revealed that nitrogen had a significantly higher impact than water on growth and yield.

The efficacy and utilisation of N by crops is affected by the availability of water, particularly on lighter soils in drier regions. Rahn (2000) demonstrated that

the early growth benefit of starter fertiliser in broccoli crops on sandy soils was restricted when water supply was not adequate. In drier regions, the introduction of trickle irrigation with fertiliser (fertigation) opens up the possibility for more effective utilisation of N and water (Scaife and Yosef, 1995 cited in Rhan, 2002).

2.3 Carrot

Carrot (*Daucus carota*, family Daucaceae) is one of the important root crops with variations in color and shape. For example, carrot colour can range form white to yellow, orange, red and purple, whilst shape can vary between short stumps to tapering cones. Root diameter and length can also vary accordingly between 2 cm to 6 cm, and 6 cm to 30 cm, respectively. It generally has a bright orange tapering root and is closely related to celery, parsnip and dill ('Fruit and Vegetable Manual', 1995; Kotecha *et al*., 1998; Rubatzky *et al*., 1999).

2.3.1 Climate and soil

Carrot is a temperate climate crop. It is available all year round, develops normally within a wide range of temperatures, and is grown throughout the world, with the exception of the very warmest areas. The best temperature for getting excellent root growth, good color and quality is between 15°C and 20°C. Seeds of carrot may germinate at low temperatures but the germination period is shorter at higher temperatures and a soil temperature of at least 10°C is recommended. Carrots are tolerant of long days, but need low temperatures to induce flowering ('Fruit and Vegetable Manual', 1995; 'In Depth Guide to Cultivation', n.d.; Kotecha *et al*., 1998; Nonnecke, 1989).

Carrots prefer sandy and light sandy loams, stone free, well drained and aerated, fertile soils with plenty of humus. Rich sandy peaty soils are perfect for providing the best conditions for the carrot roots to penetrate deeply and swell. However, light-textured soils usually have low moisture retention, often a low plant nutrient content, and are more easily leached. Therefore, the soil requires additional fertiliser and frequent irrigation throughout the growth stages to achieve high yields. Light-textured soils are preferred for fresh market carrots in order to facilitate harvesting, and to produce smooth root surfaces ('Fruit and vegetable manual', 1995; Kotecha *et al*., 1998; McKay, n.d.; Rubatzky *et al*., 1999).

2.3.2   Soil moisture and fertilisation

The availability of appropriate moisture throughout the growing season is one of the most important production requirements. Soil should be near field capacity throughout growth (Nonnecke, 1989; Rubatzky *et al*., 1999). To achieve desired root quality and surface smoothness of root crops, a uniform and adequate moisture supply during growth is important (Nonnecke, 1989). While carrots generally require 20 mm of water from rainfall or irrigation each week during the growing period ('In depth guide to cultivation', n.d.), the frequency and volume of irrigation is dependant on soil type, season, and variety (Kotecha *et al*., 1998).

Stress associated with low levels of soil moisture will delay growth and reduce yields early in the season. As a result, quality may decrease soon after further into the season (Rubatzky *et al*., 1999). Water stress may result in root cracking and hardening during root development (Kotecha *et al*., 1998).

Carrots are intolerant to waterlogging. Excessive soil moisture results in limited soil aeration. This condition will limit nutrient and water uptake, and will increase the process of nitrification in the soil. Excessive soil moisture during growth will also decrease carrot root color, length and shape, and increase the number and size of fine fibrous roots (Rubatzky *et al*., 1999).

According to McKay (n.d.), carrots require relatively low fertiliser compared to many other vegetable crops. However, in sandy soils, they require moderate levels of fertilisers for higher yields. For example, a 60 t/ha carrot crop removes about 100 kg of nitrogen per hectare. Fertiliser recommendation for a carrot crop is based on the soil type, variety, and seasonal conditions (Nonnecke, 1989; Kotecha *et al*., 1998). However, for the majority of field conditions, fertiliser levels commonly used include a base application per hectare of between 75 to 150 kg of nitrogen; 25 to 125 kg of phosphorus; and 0 to 175 kg of potassium (Kotecha *et al*., 1998).

Many nitrogen sources are quite easily leached by water, therefore only a portion of the total amount is applied initially. The remainder is applied at one or more times throughout crop growth (Rubatzky *et al*., 1999). Especially under high moisture conditions, side dressing with N after or through the irrigation system, will benefit carrot production. Carrots respond best to the ammonia form of N. Other forms may cause leaf burning (Nonnecke, 1989). Excessive N causes branching and hairy, fibrous roots ('In depth guide to cultivation', n.d.).

Carrots consume high levels of potassium. The phosphorus and potassium components of fertiliser are supplied before planting since these minerals are less mobile and difficult to leach. Potassium deficiency results in less root sweetness and pale flesh (Rubatzky *et al*., 1999). Carrots are also susceptible to magnesium deficiency in acid soils and boron deficiency in sandy soils. Therefore, pH for soils should range within 6.5 to 7.5 for best results ('In depth guide to cultivation', n.d.).

2.3.3 Carrot production in Australia

Carrots are the third most important vegetable crop produced in Australia, with only potatoes and tomatoes produced in greater volumes. During one year, in 2005, the production increased by 4% to 316,699 tonnes from about 6,530 hectares with value up by 11% to about $166 million (ABS 7121.0, 2005; ABS 7503.0, 2005). The Australian carrot industry has been expanding steadily with increasing domestic and export markets. In 2006, South Australia was the leading state with 28.2% of the nation's carrot production followed by Western Australia, which produce 23.7% of the total Australian carrot production. The Australian carrot market has a total market value of AUS $38.4 m (ABS 7502.0, 2006). In Western Australia, carrots are the fourth biggest crop produced after barley, wheat and apples. Total production in 2005 was 66.2 tonnes from about 1,200 hectares (ABS 7123.5.55.001, 2005).

Most of the carrot varieties grown in Australia belong to one of the following varieties: Imperator, Autumn King, Nantes, and Chantenay. More recently, the Japanese Kuroda type carrots are grown, principally in Tasmania for exporting to Japan. During the 1990's, Nantes varieties became the most important type of carrot grown in Australia (McKay, n.d.).

2.4 Broccoli

Broccoli, *Brassica oleracea* L. var. *italica*, a member of *the Brassicaea* (mustard) family, is a horticultural hybrid closely related to cauliflowers and cabbages, with a similar the cultural requirements. The plant forms a tight head of flowers, blue/green buds, with thick fleshy green stalks. It is available all years round, growing in temperate and subtropical climate. Broccoli is a floral vegetable, developing rapidly, and is usually harvested when the flowering heads are immature (Burt and McKay, 1999; 'Fruit and vegetable manual', 1995; Nonnecke, 1989; Rangavajhyala *et al*., 1998).

2.4.1 Climate and soil

Broccoli grows best in the cool-season. Broccoli seed will germinate and grow from 4 to 35 ^{o}C, but optimum growth is obtained when monthly air temperatures average from 15 to 21 ^{o}C. Very heavy winter frosts (below –3 ^{o}C) can damage heads and will kill young seedlings (Burt and McKay, 1999; LeStrange *et al*., n.d; Nonnecke, 1989). Some broccoli cultivars will tolerate hot conditions, however both quality and yields are reduced when the nighttime average temperatures rise above 15 ^{o}C. Commercial planting, under optimum conditions will result in large, leafy plants producing a compact flower head on a tall, green, branching stalk with a center flower head diameter from 7.5 to 20 cm (LeStrange *et al*., n.d; Nonnecke, 1989). During rainy weather, plants have the potential to become infected with diseases such as black rot and bacterial soft rot. In the warmer months broccoli can be attacked by vectors, such as butterflies and moth larvae that can be difficult to control (Burt and McKay, 1999; Heisswolf and Deuter, 1992).

Although broccoli grows best on a well-drained soil, it may be grown on a wide range of soil textures, such as light, heavy, or muck soils, with suitable cultivars. (Burt and McKay, 1999; Nonnecke, 1989). Fields with light soil are often designated for winter/spring crops to minimise potential harvest delays caused by rain (LeStrange *et al*., n.d.). Broccoli grows best in soils that are slightly acidic to neutral (pH 5.7-6.2 by the calcium chloride system of measurement, or pH 6.5-7.0 by water system of measurement) (Burt and McKay, 1999)

2.4.2 Water and fertilisation

Like others in the *Brassicas* family, broccoli requires plenty of water to maintain high water uptake for good performance (Nonnecke, 1989). The amount and frequency of water for a broccoli crop depends upon the soil type, environmental conditions, location and maturity. Broccoli is irrigated either by sprinkler or furrow irrigation from stand establishment through to harvest in all growing region. A broccoli crop requires about 3 to 4 megalitres of water (equivalent to 300 to 400 mm of water over 1 ha of land) per hectare. In the first week after transplanting or seeding, several light irrigations need to be applied (10 to 15 mm) until the crop is well established (Heisswolf and Deuter, 1992; LeStrange *et al*., n.d.).

Broccoli should be grown quickly without stress immediately after transplanting, when the crop is buttoning and filling heads. A sufficient water supply is essential to gain economic yields of high quality broccoli (Burt and McKay, 1999; Heisswolf and Deuter 1992).

In heavy soils, water can be applied in a single irrigation per week. But, for light soils or during warm weather, two irrigation applications per week are recommended. Overhead irrigation is used almost exclusively for broccoli. Plants are to be watered in the morning so that the foliage is dry by evening. This will reduce the risk of disease (Heisswolf and Deuter, 1992).

Broccoli has greater salt tolerance than most other common vegetables (Burt and McKay, 1999; LeStrange *et al*., n.d). If water of 1500 mg/L of total salts is used for irrigation, the crop may lose 20% of yield. Iron levels from water should have less than 0.5 mg/L otherwise heads may be too stained for marketing (Burt and McKay, 1999)

The application of fertilisers to broccoli crops is dependent upon many factors including variety, soil type and region. Soil should be analysed for nutrients to help indicate the phosphorus (P) and potassium (K) requirements. Total nitrogen (N) applied to the crop ranges from 112 kg to 224 kg per hectare (LeStrange *et al*., n.d.; Nonnecke, 1989).

Regular supplies of nutrients are essential to obtain high yield and quality. Plants become stunted with discolored leaves if fertiliser is inadequate (Burt and McKay, 1999). The most effective method of fertiliser application is to apply P and K at about 56 kg/ha, whilst N is applied pre-plant with additional 56 kg/ha to 168 kg/ha side-dressed or water-run in one to three applications throughout the growing period (Heisswolf and Deuter, 1992; LeStange *et al*., n.d.; Nonnecke, 1989). After planting, top-dressings of fertilisers to the soil may be applied by machine or hand. With sprinklers, apply water uniformly with fertiliser through the irrigation water (fertigation) (Burt and McKay, 1999).

2.4.3 Broccoli production in Western Australia

According to Australian Bureau of Statistics the Western Australian *Brassica* crop production in 2005 was valued at about $41 million. The domestic market dominates the Australian broccoli market, with a reported a value of $38 million in comparison to the export market, which was valued at $3 million FOB. This *Brassica* vegetable industry, supported by the Western Australian government, is pursuing productivity improvement, quality assurance and marketing. South East Asia accounts for majority of the Austrlaian broccoli export markets. Close to 78% of *Brassica* vegetable consumption in Singapore, Malaysia and Brunei is imported from Western Australia (Lancasterand Gartrell, 2006).

Broccoli is one of the three main *Brassica* crops with the highest production and rapid expansion. For example, broccoli production in 2005 was 7,672 tonnes with gross value of $16.3 million, compared to5,518 tonnes in 2003 (ABS. 7121.0, 2003; and Lancaster and Gartrell, 2006).

Variety selection has enabled good crops to be produced throughout the year in Perth area. The major varieties grown in Western Australia are hybrids originating from the Sakata Seed Company in Japan. Good varieties produce uniform dark green domed head with uniform small bead (bud size), no leaf bracts within the head and broad angle of branching within the head. The main varieties grown in the Perth area are Marathon, Bushido, Raider/Atlantic, Green Belt, Generation and Pacific (Burt and McKay, 1999).

2.5 Food nutritional quality

Growing evidence implies that increased consumption of vegetables provides health benefits to consumers (Zhou and Yu, 2006). Fruits and vegetables are excellent dietary sources of natural antioxidants, including caretenoid, ascorbate, tocopherols and phenolics for human dietary consumption (Zhou and Yu, 2006). Antioxidants are believed to play an important role in the body's defense system against harmful free radicals with reduced risk of chronic diseases and elderly functional disorder in addition to other health benefits (Alasalvar *et al*., 2005; Cao *et al*., 1996; Ou *et al*., 2002; Pellegrini *et al*., 2003; Zhang and Hamauzu, 2004). The most common antioxidants present in vegetables are vitamins C and E, carotenoids, flavonoids and more (Ou *et al*., 2002).

Carrot and broccoli can be used as excellent sources of natural antioxidants including vitamins A, C and others. In addition, they are good sources of dietary fibre (Alasalvar *et al*., 2005; 'Fruit and vegetable manual'*,* 1995; Zhang and Hamauzu, 2004). Application of nutrients (fertilisers) may not only influence the yield and quality of field vegetable crops, but also the chemical composition of the marketable product that may be used to control and improve the nutritional quality of product, used for human consumption. The effects of fertiliser application on the chemical composition of vegetable products has previously been investigated (Sorensen, 1999)

2.5.1   Nutrient composition

Carrot root is a rich source of β-carotene, the precursor of vitamin A. Indeed with little vitamin C, carrots are also a good source of carbohydrates and minerals, such as calcium, phosphorus, iron and magnesium (see Appendix 2.) (Lorenz and Maynard, 1997; Kotecha *et al*., 1998; Nonnecke, 1989; Rangavajhyala *et al*, 1998). The carotenoid content present in carrot is associated with the color of the root: the more carotenoid results in more yellow and orange in carrots (Kotecha *et al*., 1998).

In contrast, Broccoli is known to be rich in vitamin C (ascorbic acid), but have less carotenoid (Lorenz and Maynard, 1997; Ou *et al*., 2002; Rangavajhyala *et al*., 1998). Thiamine, riboflavin, niacin and folic acid are also present in appreciable amount in carrot roots (Kotecha *et al*., 1998; Rubatzky, 1999) and broccoli heads (Rangavajhyala *et al.,* 1998).

It is important to optimise the diet from nutrient compounds, especially vitamin C, carotene, dietary fiber, potassium and boron in vegetable food products, because a relatively high proportion of the total human intakes of these components originate from vegetables (Southgate and Bingham, 1979 cited in Sorensen, 1999). Sorensen (1999) investigated how nitrogen application influenced the concentration of mineral elements and organic constituents of vegetable products and plant production. The increased nitrogen supply decreased the concentration of dry matter, potassium, sucrose, vitamin C and dietary fiber in broccoli heads and leaf vegetable crops, but increased the concentration of nitrate, nitrogen and carotene.

In the carrot root, an increased nitrogen supply slightly increased the dry matter percentage; the concentration of nitrogen and nitrate. The concentration of carotene of carrot roots was positively correlated with the concentration of nitrogen.

The concentration of phosphorus, potassium, calcium, magnesium, iron, sulphur, and boron in broccoli decreased with increased nitrogen supply. With the exception of calcium and magnesium, this was also the case in carrot roots (Rahn, 2002).

Irrigation or water applied to vegetable crops may indirectly affect the vegetables' nutrient compositions, because the efficacy and utilisation of nitrogen by crops is limited by the availability of water, particularly in lighter soils in drier regions (Rahn, 2002). Soil nitrogen transformations are intimately related to the status of soil moisture. When soil moisture is optimum, all of the biological processes – plant nitrogen uptake and growth, residue decomposition, ammonification and nitrification – proceed are at a maximum rate dependent on soil temperature. When moisture is limited, these biological processes operate very slowly. However, if the moisture is excessive, nitrogen leaching may occur (James *et al*., 1982; Rahn, 2002).

2.5.2   Carotenoids and ascorbic acid

Carotenoids are widespread and important natural pigments found in vegetables and fruits acting as pro-vitamin A which can be converted to vitamin A (Choong, 2005). Carrots in particular are an important source of pro-vitamin A carotenoids. About 40 carotenoids are known, of which β-carotene generally represents approximately half of the total amount of carotenoid content (Rubatzky, 1999; Sorensen, 1999).

High carotene carrots are used as raw products for carotene extraction. This natural source of carotene serves as a nutritional alteration and as food coloring (Rubatzky, 1999).

Carotenoids are not developed in the carrots roots uniformly. Carotene synthesis is higher in more matured tissues than in new tissues. The concentration decreases longitudinally from the upper roots to the root tip. It is also typical that phloem tissues have a higher concentration than xylem tissues. The carotene rate increases parallel with carrot growth whilst, near the time of harvest (about the maximum growth), the concentration generally tends to slightly decrease (Rubatzky, 1999).

The content of carotene in the crops varies with cultivars, stage of maturity, and environmental factors such as location, season including soil moisture and temperature (Melédez-Martinez *et al*., 2007; Rubatzky, 1999). Soil fertility

generally has an effect on carotene content (Rubatzky, 1999; Sorensen, 1999). High soil moisture content tends to reduce root carotene content. Sandy soil commonly produce carrots, with small increases in carotene levels than other soil types. Carrots' grown at temperatures ranging between 15 and 21 ^{o}C, can result in optimum carotene synthesis levels. However, temperatures greater than 30 ^{o}C and less than 5 ^{o}C, greatly reduce carotene synthesis (Rubatzky, 1999). Carotene of carrot roots is positively correlated with its nitrogen concentration. Increased nitrogen supply can slightly increase the concentration of carotene in carrot roots (Sorensen, 1999).

Vitamin C is defined as the generic name for all compounds revealing the biological activity of ascorbic acid (AA) (Lee and Kader, 2000). Ascorbic acid is a one of the most significant organic acids in fruits and vegetables (Melédez-Martinez *et al*., 2007). Fruits and vegetables supply more than 90% of the vitamin C in humans (Lee and Kader, 2000). Vitamin C is a phytonutrient that is well known as having antioxidant properties (Alsalvar *et al*., 2005; Lee and Kader, 2000), which is essential in the prevention of several diseases, such as common colds and cancer (Sorensen, 1999).

Broccoli, cauliflower, onions and Chinese cabbage contain high vitamin C (Bahorun *et al*., 2004). Many pre-harvest and harvest factors influence the vitamin C content of horticultural crops. Pre-harvest factors include: genotypic variation, climate conditions and culture practices, whilst harvest factors include; maturity at harvest and harvesting method (Lee and Kader, 2000; Melédez-Martinez *et al*., 2007). Sorensen *et al*., (1995) and Toivonen *et al*., (1994) cited in Lee and Kader, (2000) demonstrated increased the content of dietary fiber, vitamin C, protein, calcium, magnesium and manganese for Leek and broccoli grown with reduced irrigation.

2.5.3 Antioxidants

Oxidation is the process of transferring electrons from one atom to another, with molecules losing an electron on being oxidised. By aerobic respiration, the free radicals are generated in the human body when oxidation occurs. Free radicals are not only from oxidative damage inside the human body, but also are caused by unhealthy environments, such as cigarette smoke, air pollution, ultra-violet light and ionizing radiation (Pietta, 2000 cited in Choong, 2005). Antioxidants function as the

main defense mechanism in the body preventing damage done by free radicals (Choong, 2005).

Dietary antioxidants are found in various fruits and vegetables, including broccoli heads and carrot roots. Antioxidants from fruits and vegetables are recognized as important phytonutrients, including phenolic compounds, anthocyanins, carotenoids, vitamin C and vitamin E (Zhang and Hamauzu, 2004). Plant-based diets as an antioxidant source are widely suggested to contribute to reduce the risk of development of chronic diseases, such as cancer, atherosclerosis, cardiac dysfunctions, diabetes, hypertension and neurodegenerative disorders because of free radicals (Bahorun et al., 2004). Antioxidants are also used as food additives by the food industry to delay the oxidation process (Brand-Williams et al., 1995; Yu et al., 2002).

DPPH method

The stable free radical diphenylpicrylhydrazyl (DPPH), with a deep purple or violet color, is one simple and rapid method currently used for estimating the antioxidant activity (Gil et al., 2002; Molyneux, 2004; Prior et al., 2005). Using DPPH, the antioxidant activity is determined by reacting the antioxidative of specific samples or extracts to a stable free radical, 2,2-Diphenyl-1-picrylhydrazyl (DPPH) in a methanol solution (Brand-Williams et al., 1995).

This essay is based on the measurement of the ability of antioxidants to quench the DPPH. The reaction of DPPH is indicated by monitoring the decrease in its absorbance, at a characteristic wavelength during the reaction using a spectrophotometer (Pior et al., 2005). The absorbance measurements by researchers vary from 515 nm to 520 nm (Molyneux, 2004). In its radical form, DPPH absorbs at a specific wavelength, but upon reduction by an antioxidant (AH) or a radical species (R), the absorption disappears when the reactions reach a "plateau" (Brand-Williams et al., 1995). The recommended time of reaction originally was 30 minutes. However, recently research identified that the rate of reaction varies depending on the substrates (Brand-Williams et al., 1995; Molyneux, 2004).

Furthermore, Brand-Williams et al. (1995), Molyneux (2004) and Prior et al. (2005) explained the ability of the antioxidant to quench free radicals by hydrogen atom donation or transfer (HAT) as:

$$X + AH \rightarrow X\text{-}H + A \tag{2.5.1}$$

or on DPPH :

$$DPPH + AH \rightarrow DPPH\text{-}H + A \qquad\qquad (2.5.2)$$

One parameter that is commonly used to work in terms of the percentage reduction of the DPPH (Q) is concentration of reducing agents. The reducing agent and HAT, also decolourises DPPH (Molyneux, 2004; Pior *et al*., 2005).

The reduction formula is defined as:

$$Q = 100 \, ((A_o - A_c)/A_o \qquad\qquad (2.5.3)$$

Where A_o is the initial absorbance, referred to as the control, is in absence of any sample and A_c is the value for added sample concentration (Molyneux, 2004). In other cases, the results are presented in the form of residual concentration of DPPH (Brand-Williams *et al*., 1995).

Another parameter that has been used recently for the interpretation of the results from the DPPH method is anti-radical activity. Anti-radical activity is defined as the amount of antioxidant causing the initial DPPH activity to be reduced by 50%, called efficient concentration 50 (EC_{50}).

$$EC_{50} = mol/L \ AO/ \ mol/L \ DPPH \qquad\qquad (2.5.4)$$

Where, mol/L AO is the concentration of the antioxidant sample and mol/L DPPH is the concentration of DPPH decreased by 50%.

This parameter is seen as a disadvantage when the results are represented graphically as a bar chart or in numerical form. For that reason, the EC_{50} was transformed in term $1/EC_{50}$, known as antiradical power (ARP). Therefore, the larger the ARP, the more efficient the antioxidant (Brand-Williams *et al*., 1995; Molyneux, 2004).

$$ARP = 1/EC_{50}, \qquad\qquad (2.5.5)$$

The antioxidant value by DPPH method can also be determined as Trolox equivalents. A standard curve is generated by using known concentrations of Trolox. The Trolox equivalents of the sample are calculated using linear or quadratic relationships between Trolox concentration (Y) (μM) and X, which represents the net

absorbance reading (absorbance sample – absorbance blank). Data is expressed as micromoles of Trolox equivalents (TE) per liter or per gram of sample (μmol of TE/g or μmol of TE/L) (Prior *el al*., 2005; Yu *et al*., 2002).

Because the different methods with different antioxidant compounds are based on different reaction mechanisms, this method like the other methods does not actually reflect the full antioxidant capacities (Ou *et al*., 2002; Pellegrini *et al*., 2003). Total antioxidant capacities need to reveal both aqueous ("hydrophilic") and lipid ("lipophilic") capacity and physiological activity, required for both hydrogen atom transfer ("radical quenching") and electron transfer ("radical reducing") (Pellegrini *et al*., 2003; Prior *et al*., 2005).

Although fruits and vegetables are rich sources of different phytonutrients, such as vitamin C, E and β-carotene, including antioxidant properties, (Prior *et al*., 1998 cited in Alasalvar *et al*., 2005), according to Gil *et al*., (2002), the significant contribution of the antioxidant activity from the fruits and vegetables are from total phenolics. In their experiment on stone fruit cultivars, they found out a strong correlation between total phenolics and antioxidant activity. The contributions of phenolic compounds to antioxidant activity was much greater than those of vitamin C and carotenoids.

The variation of antioxidant activity values among the same vegetables is obviously influenced by geographical differences or location, weather conditions, and harvest periods, cultivars (Ou *et al*., 2002; Pellegrini *et al*., 2003; Singh *et al*., 2007). Zhou and Yu (2006) observed in hard winter wheat varieties, that the antioxidant properties were altered by solar radiation. Compared with wheat from low elevation, stronger solar radiation at high elevations resulted in high antioxidative components in vegetable products (Yu *et al*., 2003 cited in Zhou and Yu, 2006).

2.6 Conclusions

Sprinkler irrigation is one of the several main irrigation technologies. During the last few decades, the acreage of production has increased resulting in an increased adoption of irrigation systems. Irrigation is provided to obtain optimum yields. However, over irrigation should be avoided as this can decrease yields by reducing soil aeration and leaching fertilisers, whilst also increasing water and

energy costs. In addition, irrigation can contribute to higher water tables and water pollution. Irrigation efficiency measurements reflect the efficiency of an irrigation system in delivering water to plants or the effectiveness of irrigation in increasing plant production. Soil water relations play an important part in determining how effective irrigation will be in supporting the water needs for crop production. Soil may have the ability to store large quantities of water for long periods of time. However, water slowly depletes by crop use due to evapotranspiration. To obtain high yield production, irrigation and nitrogen fertiliser requirements must be applied at the correct time and rate.

Chapter 3: Irrigation system critical assessment

3.1 Introduction

Irrigated agriculture is a major water consumer at both regional and global scales (Fairweather *et al*., n.d; Khan and Abbas, 2007). On a Western Australian basis agricultural irrigation utilises a total of 520 gigalitres (GL) of water every year with about 55% allocated for the production of horticultural crops (Brennan, 2006). In Western Australia, horticulture products are grown for domestic and export consumer markets. Over the past 8 years, WA vegetable and fruit exports have grown on an average of 5 and 10% per year, respectively.

Climate change and global warming are very serious issues facing agricultural production. In spite of water resource shortages, water demands are increasing (Cooley *et al*., 2007), water supplies for agriculture are diminishing and becoming increasingly expensive. However irrigation is still needed because it is essential for crop production. As such, it is important to develop new management strategies for irrigation based on an understanding of the relationships among plant, soil, water supply and weather to ensure minimal water is lost to non-productive sinks such as drainage and yield is maximised (Alvino *et al*., 1990; Cooley *et al*., 2007; Gonzalez et *al*., 2005; Schwab *et al*., 1993).

Sprinkler irrigation is the one of the main techniques currently used for irrigation (Dechmi *et al*., 2003). Good design, management practice, understanding of crop water requirements and associated irrigation scheduling, can be utilised to improve efficiency of sprinkler irrigation systems (Hansen *et al*. 1980). Water is distributed by the sprinkler irrigation method under pressure through pipes and emitted into the air over the land to simulate natural rainfall (Hansen *et al*., 1980; Stern, 1979). Irrigation applications can also be used to control air temperature and humidity on hot days and reduce the risk of frost damage (Hansen *et al*., 1980). Sprinkler irrigation systems are an appropriate means of applying water to a wide range of crops, soil, and topographies. Sprinkler irrigation systems are particularly suited to porous (sandy) soil with high infiltration rates (Dechmi *et al*., 2003; Hansen *et al*., 1980; Li and Rao, 2003).

While it is possible to achieve comparatively high water application efficiencies with sprinkler irrigation, the performance of the sprinkler irrigation systems can be very sensitive to wind, pressure variations and design limitations, all of which will result in poor uniformity of water distribution (Dechmi *et al*., 2003;

Hansen *et al*., 1980). Poor uniformity of water distribution can result in localised water deficits in some parts of the field and elevated rates of loss to drainage in other parts (Hansen *et al.*, 1980).

After installing a sprinkler irrigation system, it is necessary to assess and evaluate in-field performance (Ley, 2003). The assessment should include determination of water distribution uniformity (DU), water application efficiency (Ea) and "irrigation water use efficiency" (Eu) (Hansen *et al.*, 1980). Water application efficiency focuses on the ratio of water delivered that is retained within the root zone of the soil, for evapotranspiration (ET) (Haman *et al.*, 2005). Irrigation water use efficiency (Eu) differs from crop water use efficiency (WUE), as irrigation water use efficiency (Eu) is the effectiveness of water delivered from an irrigation system to the plant area for all beneficial uses, including plant evapotranspiration (ET), leaching, frost protection, the establishment of young plants and plant cooling (Haman *et al*., 2005). The results of this evaluation should be used for the ongoing improvement of irrigation systems and water resource management (Hamman, 2005; 'Irrigation water management', 1997). Continuous assessment and evaluation of operations and management is vital to irrigation systems as it can lead to improved water and energy conservation and minimise potential for nutrient leaching. Increased water and energy conservation and reduced nutrient leeching may increase efficiency of production yields, biomass and product quality, whilst also reduce the risk of water pollution ('Irrigation water management', 1997).

Both broccoli and carrot crops that were used in these experiments were grown on a Grey-Phase Karrakatta sandy soil (Bolland, 1998) with a water holding capacity of 10% to 13%. On these soils irrigation applications up to 1.40 to 1.50-fold of class A pan evaporation (Epan) are required to optimise growth and quality (Burt and McKay, 1999; Gibberd *et al.*, 2003; McKay, n.d).

These experiments have been conducted in winter and summer at the Western Australian Department of Agriculture Medina Research Station. The objective of this study was to evaluate the performance of the sprinkler irrigation system used on site. The irrigation system was evaluated on distribution uniformity (DU), water application efficiency (Ea), and the irrigation water use efficiency (Eu) of each treatment on broccoli and carrot experimental crops in winter and summer respectively.

3.2 Methodology

3.2.1 Location and layout detail

Two experiments were conducted at the Medina Research Station, Western Australian Department of Agriculture and Food (DAFWA) (32.13^0S and 115.38^0E) (Gibberd *et al*., 2003). The first experiment was on broccoli conducted in the cool season, July 2006, and the second experiment was on carrot in the warm season, November 2006. The soil type at this location is Grey-Phase Karrakatta Sand (Bolland, 1998). Prior to the establishment of the experiments, the soil was cultivated to 400 mm depth with a rotary hoe and a basal fertiliser (at 12 plots of 6.0 x 6.5 m), and Medina trace element mix were applied. Beds 1.5 m wide and 0.15 m high were formed. Four Beds in each plot were irrigated using 4 unit of Nelson S10 spinner sprinklers. Each sprinkler was set with a black high angle spinner, has 5.8 to 6.7m radius of water distribution pattern and brown nozzle, emitted 752 L/hour volume of water (operated at 150 kPa), on 1.5 m risers at 6.0 x 6.5 m spacing.

3.2.2 Irrigation treatments and experimental design

Both experiments had similar designs. Irrigation was similar for all treatments during emergence and establishment. Irrigation treatments commenced immediately after transplanting for broccoli and 21 days after sowing (DAS) for carrot crops. Treatments consisted of three rates of sprinkler irrigation, each with four replicates, arranged in a randomised block design. The broccoli and carrot had 5 and 8 sampling times with 4 crops and 1.0 x 0.5m spot sample each plot, respectively.

The three irrigation treatments for the broccoli trial were:

- Treatment 1 (T_1) = 100% Epan replacement;

- Treatment 2 (T_2) = 150% Epan replacement; and

- Treatment 3 (T_{VR}) = Variable water replacement (VR), which maintained the volumetric soil water content at field capacity not less than 11% (v/v).

For the carrot trial, the irrigation treatments were:

- Treatment 1 (T_1) = 100% Epan replacement;

- Treatment 2 (T_2) = 150% Epan replacement; and

- Treatment 3 (T_{CF}) = Variable evaporation coefficient replacement basic on carrot crop factor (CF)* multiplied by 100% Epan replacement.

.*The crop factor (CF) values were established by the Department of Agriculture and Food, Western Australia (DAFWA), based on previous experiments conducted by McKay et al., (nd) (unpublished report)

The irrigation schedule was based on the equivalent previous day's pan evaporation (Epan). The equivalent pan evaporation value was calculated every 15 min from weather station data (Medina weather station, Bureau of Meteorology, WA) using the modified Penman-Montieth equation (FAO 56).

3.2.3 Measurements

a. Weather data

An automatic weather station located nearby on the research station recorded evaporation and relative humidity. Actual rainfall, together with water irrigation, was recorded using rain gauges at the experimental site.

b. Irrigation assessments

Distribution uniformity:

The irrigation water depths for determination of distribution uniformity (DU) were determined using water catchers (cans). Each plot had 16 water catchers, distributed at equal distances. All plots on the field were assumed to have similar sprinkler irrigation systems.

$$DU = C_{1/4}/C$$

where, $C_{1/4}$ = average low-quarter depth of water caught, and
C = average depth of water caught (Haman *et al*., 2005; Schwab *et al*., 1993).

Water application efficiency: Ea = 100 Ws/Wa

where, Ws = water stored in soil root zone during the irrigation,
Wa = irrigation water delivered from sprinklers and rainfall on the plot (Haman *et al.*, 2005; Hansen *et al.*, 1980; Schwab *et al*., 1993).

Measurements were conducted over a lengthy period of time (weekly) where the soil water volume is constant at the start and end of the measurement period. Ws can be substituted for estimated evapotranspiration (ET) based on the soil water balance method. Three assumptions were made reflective of the soil type. It was assumed that there was no contribution from subsurface flows and runoff; water applications moved directly downward to the soil root zone and that all excess water drained below the root zone (Allen *et al.*, (FAO 56) 1998; James *et al.*, 1982; Nakayama and Bucks, 1986).

The given assumptions are incorporated into the following equation:

$$Ws = ET = I + P - DP$$

Where; I: Irrigation, P: rainfall, DP: deep percolation (Allen *et al.*, (FAO 56) 1998; James *et al.*, 1982; Nakayama and Bucks, 1986).

Lysimeters were used to estimate drainage beneath the experimental crops and deep percolation (DP). Hence:

$$Ea = 100 \, ET/Wa$$

Irrigation water use efficiency (Eu):

$$Eu = 100 \, Wu/Wd$$

Where: Wu = uniform actual irrigation water depth of water beneficially used by ET and other uses. (It was taken from water catcher, subtracted from rainfall and multiplied by the average DU).

Wd = water delivered to the plot from calculated sprinklers discharge is given from the sprinkler catalogue specification (Haman *et al.*, 2005; Hansen *et al.*, 1980; Schwab *et al.*, 1993).

Water beneficially used is irrigation water applied for maintaining adequate soil moisture in the root zone for plant evapotranspiration (ET), and other beneficial uses, such as leaching of salt, freezes protection, establishment of young plants, and plant cooling. Calculated water use is necessary for plant production; however it is not of particular use for production systems (Haman *et al.* 2005).

3.2.4 Statistical analysis

The impact of treatments on the stated variable parameters were analysed by one-way analysis of variance (ANOVA) GenStat Release 8.2 statistical software. Mean treatment comparisons were calculated using LSD's calculated at P=0.05 (Christensen, 1996; Gomez and Gomez, 1984; McConway, 1999; Payne, 2005; Steel and Torie, 1960).

3.3 Results

3.3.1 Weather conditions

The first experiment (winter season) started on 13th July 2006 and ended on 19th September 2006. During the 68-day experimental period, 35 days of rain were recorded. Average 14 day rainfall ranged from 1.2 mm/day to 7.9 mm/day, and the number of rain days ranged from 4 to 13. The second experiment commenced in the summer season from 29th November 2006 to 20th March 2007. During the 102 day summer season experimental period, only 12 days of rain were recorded. No rainfall was experienced in weeks 10 and 16. Average 14 day rainfall ranged from 0.0 mm/day to 1.0 mm/day and the number of rain days ranged from 0 to 3 days. The average evaporation ranged from 6.4 mm/day to 7.9 mm/day respectively (Table 3.3.1).

Table 3.3.1. Average (14 day) rainfall (mm), evaporation (mm), cumulative evaporation (mm) and number of rain-days. From 13 July to 19 September 2006 (broccoli trial) and from 29 November 2006 to 20 March 2007(carrot trial).

Week	Average		cumulative evaporation (mm)	number of rain-days
	rain (mm)/day	Epan (mm)/day		
Winter experiment - Broccoli				
2	5.1	2.4	31.7	4
4	4.2	2.2	62.4	13
6	7.9	2.4	95.9	9
8	1.6	3.5	145	6
10	1.2	3.9	199.7	7
Summer experiment - Carrot				
2	0.2	7.9	110.4	2
4	0.1	7.9	220.9	1
6	1.0	7.2	321.4	1
8	0.4	7.7	429.6	2
10	0.0	7.8	538.8	0
12	0.4	6.4	628.7	3
14	0.5	6.6	720.7	3
16	0.0	7.1	819.4	0

Resource data taken from weather observation at Medina Research Centre. Government of WA, Bureau of Meteorology and Department of Agriculture.

3.3.2 Water distribution uniformity

Water distribution uniformity (DU) was assessed to evaluate the sprinkler irrigation system after 10 min, 15 min and 20 min irrigation run times, with 3 to 4 replications respectively.

The average DU at 15 min sprinkler operation times was 1.3% and 4.3% higher than the average DU at 10 min and 20 min operation times. For example, the range of DU after 10 min of sprinkler operations was between 84.0% and 89.4% and 20 min sprinkler operations was between 89.3% and 91.6%. Whilst, at 15 min of sprinkler operations, DU was between 90.8% and 93.8%. Except the fourth replicate, all replications at 15 and 20 min operation times had a DU above 90%. However, all replications on 10 min operation time did not exceed the DU 90%. The average DU of all measurement was 90.2% (Table 3.3.2.).

Table 3.3.2 Average water distribution uniformity, DU (%) for 3 selected duration times (20, 15, and 10 min) on sprinkler irrigation experiment site.

Rep	Duration (min)			Mean
	20	**15**	**10**	
1	92	91	89	
2	91	92	85	
3	91	94	89	
4	89	-	-	
Mean	90.71 $\pm$ 0.49	92.04 $\pm$ 0.93	87.7 $\pm$ 1.50	**90.15 $\pm$ 1.28**

Each replication has 16 water caught and were distributed with same distance. Data are means $\pm$ s.e.m

3.3.3 Water application efficiency

Water application efficiencies (Ea) were calculated as the ratio of the estimated evapotranspiration (ET) to the total depth of water applied as irrigation and rainfall. In sandy soil, it was assumed there were no runoff and a zero contribution from subsurface flows. It was also assumed that water applications moved directly downward to the soil root zone and that all excess water drained to below the root zone (Allen *et al*., (FAO 56) 1998; James *et al*., 1982; Nakayama and Bucks, 1986).

In the broccoli experiment, the total depth of water application at 150% Epan was 13.9% and 17.2% greater than at 100% Epan and VR treatments. Total drainage (depth of water intercepted by the drainage lysimeters) ranged from 225.8 mm to 259 mm and was not significantly different among the treatments. The amount of estimated evapotranspiration (ET) or water stored at 150% Epan was 12.8% and

40.5%, greater than at 100% Epan and VR treatment. A significant difference was only observed between the water depth at 150% Ep and VR treatments. In this experiment, differences among the treatments for irrigation application efficiencies (Ea) were minimal. Ea ranged from 35% to 43% among the treatments and there were no significant difference between the mean values.

Table 3.3.3 Total water application from irrigation and rainfall (Wa) (mm), lysimeter depth (mm), estimated evapotranspiration (ET) or water stored (Ws) in the soil root zone and water application efficiency, Ea (%) on broccoli treatment (T_1, T_2 and T_{VR}) and on carrot (T_1, T_2 and T_{CF}) in the field experiments

Treatment	Wa (mm)	Lysimeter (mm)	Ws (mm)	Ea (%)
Broccoli trial				
T_1	394 b	226 ns	169 ab	42.8 ns
T_2	449 a	259 ns	190 a	42.3 ns
T_{VR}	383 b	248 ns	135 b	35.3 ns
lsd (P = 0.05)	23.2	44.8	44.9	10.0
s.e.m	6.71	12.95	12.98	2.89
Carrot trial				
T_1	856 b	163 b	693 ns	80.9 a
T_2	1137 a	395 a	741 ns	65.4 b
T_{CF}	926 b	205 b	721 ns	78.0 a
lsd (P = 0.05)	79.9	90.3	87.01	8.5
s.e.m	23.08	26.10	25.14	2.46

The three irrigation treatments, for the broccoli trial were T_1: 100% Epan; T_2: 150% Epan; and T_{VR}: Variable water replacement to maintain ($>=$) 11% volumetric soil water content and for the carrot trial were T_1: 100% Epan; T_2: 150% Epan; and T_{CF}: Crop factor multiplied by 100% Epan. Water application efficiency was water stored depth divided by total water application, and data are mean (n=4), different letters following data within a column indicate a significant difference between means (ns = no significant treatment effect).

In the carrot experiment, the total depth of water application for the 150% Epan treatment was 33% and 23% greater than at 100% Epan and CF treatments respectively. Water application at 150% Epan was significantly different from the others.

Total drainage water or lysimeter depths among all treatments followed a similar pattern. The depth of drainage for the 150% Epan treatment was 143% and 92% greater than the depth of drainage 100% Ep and CF treatments respectively. However, the amount of water stored had no significant difference among the treatments. In contrast to the broccoli experiment, the irrigation application

efficiencies (Ea) for the 100% Epan and CF treatments in carrot experiment were significantly different than the Ea for the 150% Epan treatment. The Ea at 100% Epan and CF treatments were 16% and 13% greater than the Ea at 150% Epan treatment respectively (Table 3.3.3.)

3.3.4 Irrigation water use efficiency

Irrigation water use efficiencies (Eu) were determined from the uniformed actual irrigation water depths taken from water catchers (minus rainfall) and divided by the calculated delivered irrigation water from sprinkler systems (sprinklers discharged). The depth of actual irrigation water was determined from the total water (irrigation water and rainfall) collected from the middle rain gauge of each plot, minus the total rainfall depth. The uniformed actual irrigation water depth on the entire plot was determined by the amount of actual irrigation water, multiplied by the average of distribution uniformity value (90.2%).

Average operation times of sprinklers for broccoli growth in the winter season experiment were 38 min, 59 min and 37 min per week; resulting in water discharged about 101 mm, 158 mm and 98 mm for the 100% Epan, 150% Epan and VR treatments respectively. The amount of uniformed actual irrigation water depth on treatment 2 (T_2) with 150% water replacements of evaporation (Epan) was the highest, with 130 mm followed by treatment 1 (T_1) with 100% Epan water replacement, and treatment 3 (T_{VR}) with variable water replacement. The total irrigation water depth on treatment 2 (T_2) was 61% and 84% higher than treatment 1 (T_1) and treatment 3 (T_{VR}) respectively.

The amount of irrigation water in each treatment during the carrot growth period in the warm season experiment was different from the amount of irrigation water from the broccoli experiment. The average sprinkler application operation time for each treatment during the experiment was 176 min, 246 min and 203 min per week. Uniformed actual irrigation of water depths for the 100% Epan (T_1), 150% Epan (T_2) and Crop Factor (CF) (T_{CF}) treatments were 736 mm, 988 mm and 798 mm reflective of sprinkler application operations times. The irrigation water depth for the 150% Epan treatment was 34% and 24% higher than the water depth for the 100% Epan and CF treatments, respectively. In this experiment, similar to the broccoli experiment, the water depth at 150% Epan treatment was significantly greater than the others treatments.

The irrigation water use efficiencies (Eu) of this sprinkler irrigation system of all treatments from the broccoli experiment ranged from 72% to 83%, whilst the carrot experiment ranged from 92% to 98%. There were no significant differences between Eu in all treatments in both experiments (Table 3.3.4.).

Table 3.3.4 The duration of sprinkler operation (min), rainfall (mm), calculated delivered water depth (Wd) (mm), uniformed irrigation beneficially water used depth (Wu) (mm), and water use efficiency, Eu (%) on broccoli treatment (T_1, T_2 and T_{VR}) and on carrot (T_1, T_2 and T_{CF}) in the field experiments

Treatment	Duration (min)	Rain (mm)	Wd (mm)	Wu (mm)	Eu (%)
Broccoli trial					
T_1	379	274	101	81 b	80 ns
T_2	591	274	158	130 a	83 ns
T_{VR}	368	274	98	71 b	72 ns
lsd (P = 0.05)				20.9	18.5
s.e.m				6.05	5.33
Carrot trial					
T_1	2816	36	751	736 b	98 ns
T_2	3935	36	1049	988 a	94 ns
T_{CF}	3247	36	866	798b	92 ns
lsd (P = 0.05)				72.0	7.1
s.e.m				20.81	2.04

All of irrigation water not including rainfall and the uniformed beneficially irrigation water depth was determined from the irrigation water depth multiplied by 90.2%, the efficiency Eu was the uniformed beneficially water used depth divided by calculated delivered water depth from the sprinklers discharged, and uniformed actual water depth data are mean (n=4), different letters following data within a column indicate a significant difference between means (ns = no significant treatment effect).

3.4 Discussion

These experiments show that the sprinkler irrigation system was suitable for both the crops. The distribution uniformity (DU) assessment of the sprinkler irrigation system ranged from 85% to 93%, with an average of 90.2%. As high spatial uniformity of water distribution was achieved, there was minimal variation from the average in the depth of water applied at different points in the plot (Haman and Yeager, 2005; Ley, 2003). This can be defined as every spot in each irrigated plot area that received an excess or lesser amount of water equal or close to 10% of the rated (target) amount of water application. This distribution uniformity value is high compared to the acceptable value of above 80% (Haman *et al.*, 2003).

According to Hartz (1999) and Haman *et al.* (2005), there is no system that can apply the exact amount of irrigation water required with perfect uniformity. Therefore the amount of irrigation water should be applied to suit the crop needs in the driest part of the field. Generally, the water application should be adjusted by 10% to 20% to compensate for non-uniformity of the system (Hartz , 1999).

The water application efficiencies (Ea) in the broccoli experiment were low. Differences among the treatments were minimal, ranging from 35% to 43% mainly due to the numerous rainy days during the season. It was not possible to separate the rainwater and irrigation water when calculating the weekly amount of water stored in the root zone and lysimeter. Therefore, to calculate these efficiencies, the amount of water applied from the irrigation system was not only the water delivered from sprinklers but also from rainfall. The water excesses from 100% Epan (T_1), 150% Epan (T_2) and VR (T_{VR}) treatments were close to 57%, 58% and 65% from the total water applied to each treatment respectively. The 274 mm of total rainfall collected during the time of this experiment distorted the treatments. Therefore, this experiment is not representative of the treatments as planned.

Excess water application can be reduced by calculating the crop water requirements, based on the previous day's evaporation and predicted rainfall events and amounts. Rainfall events should always be considered as a supplement when water is applied through the irrigation system. Therefore, in moderate to high rainfall seasons, before irrigation water is applied to the site, a decision must be made on the volume of irrigation water applied to the site dependant on water depletion and rainwater ('Irrigation Water Management', 1997). Rainfall between

2.5 to 18.7 mm can be considered as effective for crop requirements to be retained in the root zone. However, a light rain can increase and distribute the concentration of salts present on the topsoil into the soil root zone. In such circumstances, irrigating immediately after rain will leach the salt away from the roots. Precipitation over 18.7 mm will generally be sufficient to minimise this problem (Hartz , 1999; 'Irrigation Water Management', 1997).

Contrary to the broccoli experiment, the water application efficiencies (Ea) of the carrot experiment were high. The 100% Epan (T_1) and Crop Factor (CF) (T_{CF}) treatments had an Ea of 81% and 78% respectively. They were above the acceptable value of 75% for sprinkler irrigation, and about 14% higher than the 150% Epan treatment (Hansen, 1980). The low water application efficiency of the 150% Epan treatment (T_2) was reflective of the excessive water applications required to sustain this level of irrigation. It was indicated in this experiment that even with a high distribution uniformity, the 150% Epan water applied had a low irrigation efficiency because about 35% of the water applied was lost to deep percolation (Hill, 2000). Rare, light rainfall experienced in the duration of this experiment (with average 0.2 mm per week (Table 3.3.1.)) has been ignored as it was assumed to have evaporated from the soil surface rather than to be used by the crops (Hartz, 1999).

For this trial it was assumed that among all the treatments, the amount of water "stored" (the difference between water delivered and percolation or water balance) in the sandy soil root zone, which is used to substitute crops use for evapotranspiration (Haman *et al.*, 2005), was not significantly different among the treatments. On this basis the crops for the three treatments consumed almost the same amount of water applied with an average 718 mm throughout the season. As the uniformity of distribution (DU) average was 90%, the water applied to the 100% Epan and CF treatments exceeded water store by 21%. This is ideal for this experiment as 21% excessive water application would compensate for the 10% non-uniformity and assured there was no localised shortage of water in the plots (Haman *et al.*, 2005; Hartz , 1999). The 150% Epan treatment lost 15% of water applied to drainage below the root zone by deep percolation. Water replacement for the 150% Epan water treatment should be considered when the sprinklers operate on a hot, dry and windy day. In such conditions, the effectiveness of the sprinkler irrigation system will be reduced from 50% to 100% (Calder, 2005; Haman *et al*., 2005).

The irrigation water use efficiency (Eu) of the sprinkler system in both experiments (broccoli and carrot) was not affected by all treatments (Table 3.3.4.). However, the average irrigation water use efficiency was relatively high at 78% and 95% in the broccoli and carrot trials, respectively. These irrigation water use efficiency values exceeded the acceptable level of 75% for sprinkler systems. Therefore, results indicate that the sprinkler irrigation system in both the experiments was efficient and reliable.

Conclusion

The evaluation of the results from this sprinkler irrigation system reveals a high level of water distribution uniformity (90.2%) and irrigation water use efficiency (for broccoli and carrot trial the average was 78% and 95% respectively). This makes the system feasible for irrigating crops and experiments of this nature. Low water application efficiencies in the broccoli experiment and at the 150% Epan treatment in the carrot experiment were significantly affected by over-irrigation because of heavy rainy days during the growing period, or according to the proposed treatment. Beside the irrigation efficiencies (Ea and Eu) of the sprinkler irrigation system were dependent on water distribution uniformity. The variation of these efficiencies can also be influenced by the season. In the rainy winter season rainfall must be considered to calculate the overall irrigation applications required for the crop, which in turn will influence the overall irrigation system efficiency.

Chapter 4: Impact of irrigation on winter broccoli growth, productivity and water use efficiency

4.1 Introduction

Western Australia is a region known for producing high quality *Brassica* vegetable crops. The Swan Coastal Plan is located in a close proximity to Perth, and produces a large proportion of Western Australia's *Brassica* vegetable crops. The Swan Coastal Plain soil profile consists of free-draining, sandy soils suitable for the cultivation and harvest of *Brassica* vegetable crops (Burt and McKay, 1999; Heisswolf and Deuter, 1992; Lancaster and Gartrell, 2006).

The Australian Bureau of Statistics (ABS) reported *Brassica* production in Western Australia in 2005 to be valued at $41 million (AUD). The *Brassica* market in Western Australia is heavily dependent on the domestic market ($38 million) in comparison to the export market ($3 million (AUD) FOB). Broccoli is one of three main *Brassica* vegetable crops in Western Australia and its production is expanding. Broccoli production in 2005 totaled 7,672 tonnes in comparison to 3,321 tonnes in 1996 (Burt and McKay, 1999; Lancaster and Gartrell, 2006).

Today, producers have the capacity and ability to select from a range of broccoli genotypes that vary in tolerance to temperature. This is beneficial to broccoli production as crops can be produced in both hot and cool seasons (Burt and McKay, 1999; Heisswolf and Deuter, 1992; Subbarao *et al*., 2007). Broccoli production requires large irrigation volumes to maintain productivity and quality. An adequate supply of water and nutrients is essential to ensure economical yields of high quality broccoli. To avoid waterlogging problems associated with poorly drained soils or heavy clay soil, free-draining soils are utilised (Burt and McKay, 1999; Heisswolf and Deuter, 1992; Nonnecke, 1989). However, free-draining soils such as those used in this study (Grey Phase Karrakatta Sand) (Bolland, 1998), have a low water holding capacity of between 10% and 13%. Thus, irrigation is often applied at levels of up to 1.40- to 1.50-fold of class A pan evaporation (Epan) in order to optimise growth and quality (Burt and McKay, 1999; Gibberd *et al*., 2003; McKay, n.d.). This level of irrigation will result in large losses to drainage and may subsequently be associated with leaching nutrients from the rooting zone. Drainage and leaching may potentially contribute to the eutrophication of nearly drainage basins or subsurface water resources (Zotarelli *et al.*, 2007).

In a previous study, El-Shikha *et al.* (2007) utilised the Agricultural Irrigation Imaging System (AgIIS) to facilitate the management and application of four irrigation and nitrogen (N) treatments to determine the effects on broccoli yields. The research identified that the application of N had a greater effect on broccoli quality and yields than irrigation. For example, when grown with optimal levels of N broccoli yields were reduced by 20% when irrigation was reduced by 14% in comparison to optimal irrigation yields. Conversely, broccoli yield was reduced by 42% when nitrogen availability was reduced for plants grown with optimal irrigation. Overall, this study clearly demonstrates a relationship between N and irrigation - an effect which is likely to be exacerbated on sandy soils due to leaching of N (McPharlin *et al*., 1992 cited in Gibberd *et al*., 2003).

Another study analysed the effect of irrigation treatments from 47% to 151% of Epan water replacement on carrot yield and biomass. Carrots monitored in the experiment were grown on coarse-textured, sandy soils. Results demonstrated that carrot yield and shoot biomass was not influenced by a reduction in irrigation from 151% to 124% of Epan water replacement levels. However, yield and shoot biomass was reduced up to 91% and 87% by a reduction in the volume of irrigation below 97% Epan. Results recorded in this study identified that reducing the irrigation level from 151% to 97% Epan resulted in a 17% increase of WUE. However, a reduction in irrigation levels below 97% Epan resulted in a large reduction in WUE (Gibberd *et al*., 2002).

Each of the above experiments was conducted at different irrigation times and volumes. In the study of El-Shikha *et al.* (2007), irrigation was applied when predicated soil water depletion reached 35% of the total available soil water within the root zone. Whilst in the study by Gibberd *et al.* (2002), the irrigation schedule and volume was determined on the basis of the previous day's evapotranspiration. For the current study the two approaches of El-Shikha *et al.* (2007) and Gibberd *et al*., (2002), were combined with a control treatment set at the upper industry standard of 150% Epan. The first treatment was set at 100% of Epan i.e., a level similar to that identified by Gibberd *et al*., (2003) to optimize WUE. The second treatment was a VR which applied irrigation based on the water drawn into the root zone similar to El-Shikha *et al*. (2007) with a minimum soil water volume of 11 % (v/v).

This study seeks to investigate the impacts that reduced irrigation volumes, may have on crop water use efficiency. This will be measured by the ratio of crop

yields to the volume of water used to produce the crop (Haman *et al*., 2005). Based on the results of Gibberd *et al.* (2003), this research tested the hypothesis that, on a free draining sandy soil, all three irrigation treatments would not affect the growth and yield of broccoli crops. However, they would affect the WUE.

4.2 Methodology

4.2.1 Location and agronomy

This experiment was conducted at the Medina Research Station, Western Australia Department of Agriculture and Food (DAFWA) (32.13^{o}S and 115.38^{o}E) (Gibberd *et al*., 2003). The soil type at this location was Grey Phase Karrakatta sand (Bolland, 1998). Prior to the establishment of the experiments, the soil was cultivated to 400 mm depth with a rotary hoe. Basal fertiliser of double superphosphate of 175 kg/ha (680 g/plot of 6.0 m x 6.5 m), and the Medina Trace Element mix without Molybdenum at 150 kg/ha (600 g/plot) was applied. Beds 1.5 m wide and 0.15 m high were formed. The area was irrigated using Nelson S10 spinner sprinklers operated at 150 kPa on 1.5 m risers at 6.0 m x 6.5 m spacing. Two- week-old broccoli (cv. Endurance) seedlings were transplanted by hand at 60 cm x 40 cm spacing. Standard cultural practices were applied during the growth of the crops. Nitrogen (N) and other nutrients were applied weekly from the first to the ninth week, with watering cans prior to irrigation. Total fertiliser applications equated 364.6 kg N/ha, 325 kg K/ha, 22.9 kg Mg/ha and 15 kg Borax/ha.

4.2.2 Irrigation treatments and experimental design

The irrigation treatments and experimental designs have been explained in chapter 3 sub heading 3.2.2. (specifically for broccoli trial).

4.2.3 Measurements
a. Weather data

An automatic weather station located nearby on the research station recorded relative humidity, air temperature, wind speed, wind direction, rainfall and evaporation every 15 min. Daily values were calculated between 0900 h.s of the current and previous day.

b. Irrigation water application

Irrigation, rainfall and drainage volumes were measured once per week. Irrigation and rainfall were measured using rain gauges placed in the middle of each plot. Plots were laid over drainage lysimeters and installed at 1m in depth. Water from lysimeters was pumped out to estimate the loss of water to drainage.

c. Soil moisture content and soil water potential

Soil water potential was measured at 15 cm, 30 cm and 45 cm depths using low-range tensiometers (Irrometer[®] Company, USA) equipped with pressure sensing transducers. Volumetric soil moisture content was measured using calibrated water content reflectrometers (Campbell CS625[®]). A computer logged output from both probes every 15 min.

d. Biomass and other plant measurements

Plant samples were taken every 2 weeks, 28 d after transplanting. Plant height, leaf number, width and length were measured. Shoots and the broccoli head (compound floral primordia, flowers and stems) were separated from the roots. Shoot and head fresh weight was recorded similarly with shoot and head dry weight after drying at 75°C for 48 hours.

e. Leaf relative water content

Leaf relative water content (RWC) was determined for 6 cm^2 samples taken from the lamina of 8 plants in each plot before noon. Samples were collected into pre-weighed test tubes, sealed and chilled prior to returning to the laboratory. Fresh weights (Fw) were then measured and leaf disks were floated on deionised water in the dark for 24 hours, dried gently with filter paper and turgid weights (Tw) recorded. Leaf samples were then oven dried at 70°C for 24 hours and cooled in a dessicator prior to the determination of dry weight (Dw). RWC was calculated as:

(Fw-Dw)/(Tw-Dw) x 100%

(*Relative Water Content* n.d.; Coombs et al., 1985; Yamasaki and Dillenburg, 1999).

4.2.4 Statistical analysis

The effect of irrigation treatments on the variable parameters was analysed by one way analysis of variance (ANOVA) using GenStat Release 8.2 statistical software, except soil water potential data as it had only one replicate.

The mean for all treatments were compared using LSD's calculated at P=0.05 (Christensen, 1996; Gomez and Gomez, 1984; McConway, 1999; Payne, 2005; Steel and Torrie, 1960).

4.3 Results

4.3.1 Irrigation, evaporation and rain condition

The broccoli growing period extended for 70 days (d), from 13th July 2006 to 19th September 2006. During the growing period, rainfall was recorded on 38 d ranging from 0.2 mm to 26.8 mm/d, with a total of 274 mm. A total of 200 mm of evaporation was measured as Epan. Daily evaporation varied from 0.5 mm to 4.8 mm over the course of the growing period.

The total volume of irrigation and rain water measured for the 100% Epan (T_1), 150% Epan (T_2) and VR (T_{VR}) treatments were 394 mm, 499 mm and 383 mm respectively (Fig. 4.3.1.). Although this experiment aimed to establish irrigation volumes of 100% and 150% Epan replacement, the high level of rainfall experienced during the experimental period impeded the application of the irrigation treatments and irrigation plus rainfall exceeded the proposed total treatments by 197%, 250% and 191% Epan on T_1, T_2 and T_{VR}, respectively. Total irrigation volumes were 120 mm (T_1), 175 mm (T_2) and 109 mm (T_{VR}). The total volume of water accumulated for the T_2 treatment was 46% and 61% higher than T_1 and T_{VR} treatments, respectively (Table 4.3.4.).

The average accumulation of irrigation plus rainfall throughout the experiment for the T_2 treatment was 449 mm. The T_2 total water volume was 13.9% and 17.2% higher than the T_1 and T_{VR} treatments. As such the total irrigation plus rainfall for T_2 was significantly higher than for the T_1 and T_{VR} treatments. However; the difference between T_1 and T_3 treatments was not significant.

4.3.2 Yield and growth

Rainfall received throughout the duration of the experiment minimised the difference among irrigation treatments. Thus, there was no significant effect associated with the different irrigation treatments on broccoli yield (Table 4.3.1.). There was also no significant difference in head diameter, plant height, leaf number and leaf area among the treatments (Table 4.3.2.).
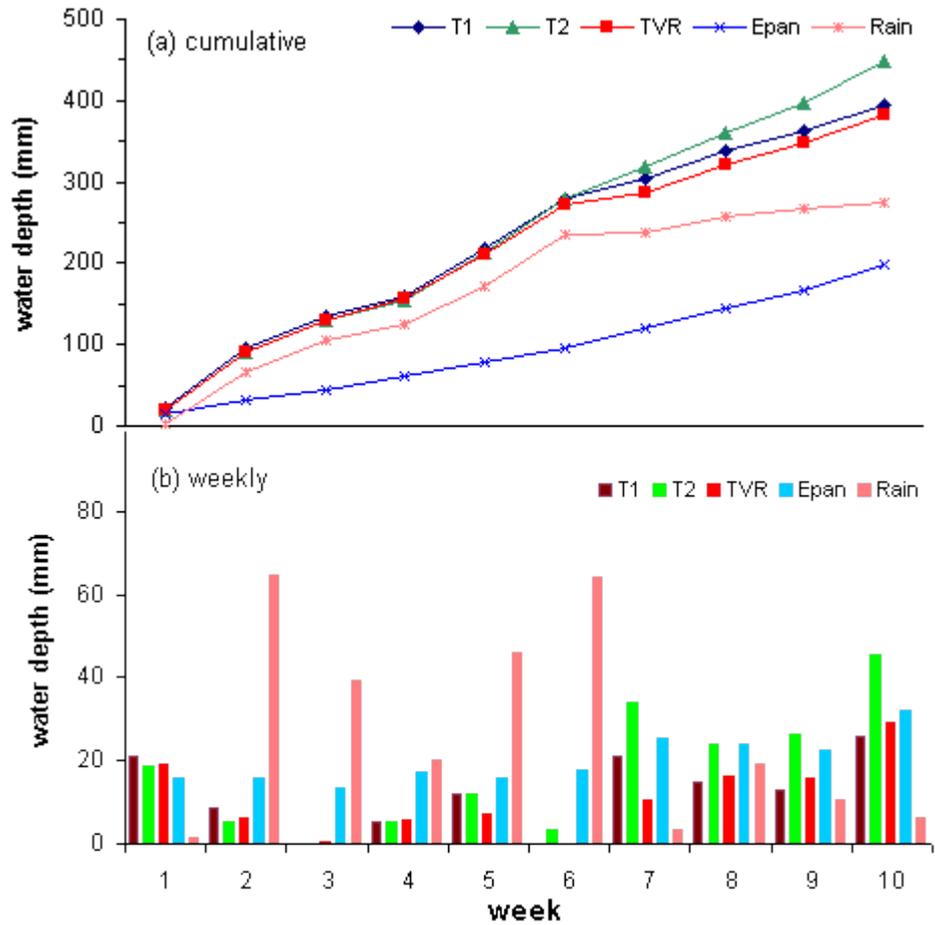
Fig. 4.3.1 (a) The cumulative and (b) weekly value of evaporation (Epan), rainfall and water applied plus rainfall for plants submitted to three irrigation treatments.
T_1= 100% Epan; T_2 = 150% Epan and T_{VR} = VR treatment. Irrigation water depth values are accumulated from the weekly data. Rainfall and evaporation values are accumulated from daily data.

Table 4.3.1   The average of the shoot and head fresh and dry weight per plant (g/plant) at harvest for broccoli plants grown with 100% Epan (T_1), 150% Epan (T_2) and variable water replacement (VR) (T_{VR}) irrigation treatments.

Treatment	Shoot		Head	
	Fresh weight (g/plant)	Dry weight (g/ plant)	Fresh weight (g/plant)	Dry weight (g/plant
T_1	1774.4	163.1	154.9	24.0
T_2	1706.2	152.0	147.9	22.6
T_{VR}	1630.2	152.8	146.9	21.6
lsd (.05)	323.5	35.3	30.3	8.4
s.e.m	93.5	10.2	8.7	2.4

The measurement was from 4th week after planting to harvest on 10th week. Data are means $\pm$ s.e.m (n=4) and all treatments did not differ significantly.

Table 4.3.2   The average of head diameter per plant (cm), leaf number per plant, plant height (cm) and leaf area (cm^2) for broccoli plants grown with T_1, T_2 and T_{VR} irrigation treatments.

Treatment	Head diameter (cm)	Plant height (cm)	Leaf	
			number (unit)	area (sq.cm)
T_1	11.5	61.8	59.1	6589.3
T_2	11.4	62.1	61.7	6195.7
T_{VR}	11.2	62.7	63.4	7200.6
lsd (.05)	1.4	6.2	14.5	2244.8
s.e.m	0.4	1.8	4.2	648. 7

The measurement was from 4th week after planting to harvest on 10th week. Data are means $\pm$ s.e.m (n=4) and no treatment differ significantly.

4.3.3   Crop water use efficiency

Crop water use efficiency (WUE) of broccoli was determined as the ratio of yield (head dry or fresh mass (g/plant)) divided by the total depth of the irrigation plus rainfall (mm). The irrigation volume for T_2 was higher than the irrigation volumes for T_1 and T_{VR} treatments. However, there was no significant difference in WUE among all treatments for both dry and fresh weight bases (Table 4.3.3).

However, when crop water use efficiency was calculated based on the volume of irrigation without rain water, the crop water use efficiencies (WUE_i) of plants grown with both T_1 and T_{VR} treatments was higher than for plants grown with the T_2 treatment by an average of 1.5-fold when measured on dry weight basis and 1.6-fold when measured on a fresh weight basis. There were no significant differences between total irrigation volumes (without rain) and water use efficiency (WUE_i) between the T_1 and T_{VR} treatments (Table 4.3.4).

Table 4.3.3 Total irrigation and rainfall (mm), head dry weight (g DW/plant), head fresh weight/plant (g FW/plant), and crop water use efficiency (WUE$_T$) for broccoli plants grown with T$_1$, T$_2$and T$_{VR}$ irrigation treatments.

Treatment	Irrigation +rain (mm)	Head DW (g/pant)	Head FW (g/plant)	WUE (g DW/mm)	WUE (g FW/mm)	WUE (kg.ha^{-1} .mm^{-1})*
T$_1$	394.3 b	24.0	154.9	0.06	0.39	15.6
T$_2$	449.0 a	22.6	147.9	0.05	0.33	13.2
T$_{VR}$	383.0 b	21.6	146.9	0.06	0.39	15.6
lsd (P = 0.05)	23.2	8.4	30.3	0.02	0.07	-
s.e.m	6.7	2.4	8.7	0.01	0.02	-

The total irrigation values were determined from weekly data. Data are means (n=4). *yield data were converted from g FW/head/plant to kg/ha (assuming that 1 ha has 40000 plants (Heisswolf and Deuter, 1992)).

Table 4.3.4 Actual irrigation (minus rainfall) (mm), broccoli head dry weight (g DW/plant), broccoli head fresh weight (g FW/plant), and crop water use efficiency (WUE$_I$) of broccoli on T$_1$, T$_2$ and T$_{VR}$ irrigation treatments.

Treatment	Actual irrigation (mm)	DW (g/head)	FW (g/head)	WUE$_i$ (g DW/mm)	WUE$_i$ (g FW/mm)	WUE$_i$ (kg.ha^{-1} .mm^{-1})*
T$_1$	119.9 b	24.0	154.9	0.20 a	1.29 a	51.6
T$_2$	174.6 a	22.6	147.9	0.13 b	0.84 b	33.6
T$_{VR}$	108.6 b	21.6	146.9	0.20 a	1.40 a	56.0
lsd (P = 0.05)	23.2	8.4	30.3	0.03	0.32	-
s.e.m	6.7	2.4	8.7	0.01	0.09	-

The actual irrigation values were determined from weekly data. Data are means (n=4).

4.3.4 Differential soil water stress index

The differential soil water stress index (DSWSI) was determined by the ratio of soil water potential of all treatments relative to T$_2$ at 0-45 cm depths. The soil water stress indices for the 100% Epan and variable water replacement (VR) treatments are indicated as T$_1$ and T$_{VR}$ respectively. These values are dimensionless.

$$DSWSI = \psi_s i / \psi_s ww \tag{4.3.1}$$

where, ψ_si: soil water potential of all treatments relative

$\psi_s$ww: soil water potential on well watered treatment (T$_2$)

From weeks 4 to 8 the differential soil water stress index for the T$_1$ and T$_{VR}$ treatments ranged from 0.94 to 1.24. A differential soil water stress index below 1 (one) indicates that the soil water potential is less negative than T$_2$. For example, the average soil water potential for the 100% Epan (T$_1$) irrigation treatment was less negative than the average soil water potential at 150% Epan (T$_2$) on 4th and 6th weeks (Table 4.3.5).

Table 4.3.5 Average soil water potential (kPa) and differential soil water stress index (DSWSI) at 0-45 cm depths for broccoli irrigated with T_1, T_2 and T_{VR} treatments.

Week	Soil water potential (kPa)			DSWSI	
	T_1	T_2	T_{VR}	T_1	T_{VR}
4th	-3.14	-3.31	-3.70	0.95	1.12
6th	-3.01	-3.20	-3.39	0.94	1.06
8th	-3.80	-3.58	-4.43	1.06	1.24
10th	-5.20	-3.68	-9.34	1.41	2.54

soil water potential data were calculated on a 2 week basis from data recorded every 15 minutes.

Results from the 10th week identified that the differential soil water stress index for T_1 and T_{VR} treatments were 1.4- and 2.2- fold higher than the averages on the 4th to 8th week respectively. The soil water potential for the T_1 treatment was less negative than the T_{VR} treatment, the DSWSI for the VR (T_{VR}) treatment was 1.8- fold than the 100% Epan (T_1) treatment . (Table 4.3.5 and Fig 4.3.2).
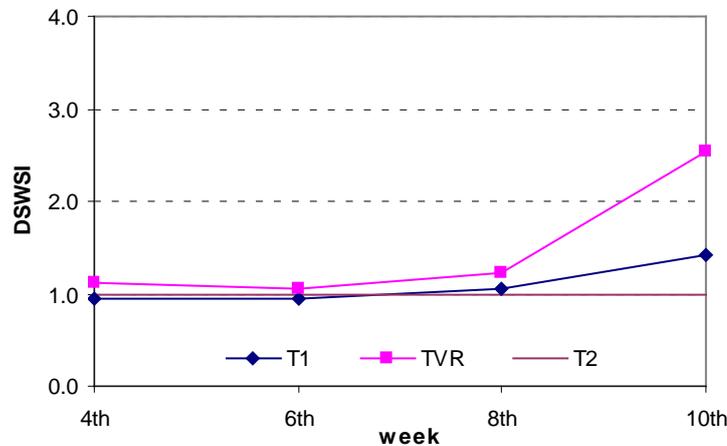
Figure. 4.3.2 The average of DSWSI as determined by the ratio of soil water potential of the 100% Epan (T_1) and VR (T_{VR}) treatments relative to the 150% Epan (T_2) treatment.

4.3.5 Leaf relative water content

Leaf relative water content (RWC) observations ranged from between 84.4% and 92.2% for all irrigation water treatments from the 4th to the 10th week and there was no significant difference among all irrigation treatments during this period. However, the average RWC for the 100% Epan treatment consistently had the lowest measurement and smallest variation. The 100% Epan treatment had an average value

of 86.7% during the 6 week trial period, whilst the average RWC on the 150% Epan and VR treatment were relatively high at 88.4% and 88.2% respectively (Fig. 4.3.3).
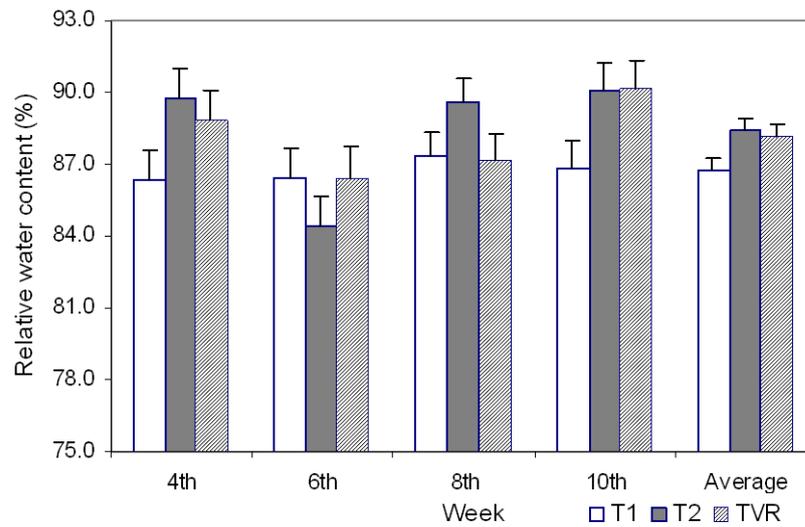
Figure. 4.3.3 Relative water content (RWC) of broccoli leaves. Data are 6 week average values (± s.e.m) derived from measurements every 14 d for broccoli irrigated with T_1: 100% Epan water replacement, T_2: 150% Epan water replacement and T_{VR}: variable water replacement (VR) treatments.

4.4 Discussion

Based on the outcomes of the experiment described in this chapter, it can be concluded that the irrigation treatments did not affect the yield of the winter broccoli crop. Similarly, the effect of the treatments on crop water use efficiency (WUE) was not significant. However, this result is influenced by the large contribution of rainfall and when calculated on the basis of irrigation volume alone, there was a significant difference between crop water use efficiency (WUE_i).

Rainfall alone exceeded evaporation (Epan) by 1.37-fold. However, although rain was frequent the low water holding capacity of the soil irrigation was required to supplement soil water content. This was evident by T_{VR}, which by definition requires both irrigation and rainfall to maintain soil water content above 11% v/v. For this treatment an additional 109 mm of irrigation water was applied above the rainfall requirements. T_1 and T_2 treatments were scheduled on the basis of industry standard practice of daily replenishment of evaporation (Epan) when evaporation (Epan) volume exceeded rainfall.

The effectiveness of irrigation treatments was reduced due to the 274 mm of rainfall experienced throughout the duration of this experiment. The treatments had

no effect on yield (in g/plant on dry and fresh basis weight) and growth (head diameter, plant height, leaf number and leaf area) parameters (Table 4.3.1 and Table 4.3.2). The small difference of total water applied (volume of irrigation included rain) between treatments resulted in no significant difference among crop water use efficiencies (WUE). However, when the amount of actual irrigation for each treatment was calculated without the volume of rain water, the 150% Epan (T_2) irrigation treatment was 46% and 61% higher than the 100% Epan (T_1) and VR (T_{VR}) irrigation treatments respectively. Compared to T_2, the crop water use efficiency (WUE_i) for plants grown with the T_1 and T_{VR} treatments was 1.5-fold higher on a dry weight basis and 1.6-fold higher on a fresh weight basis (Table 4.3.4).

The reduction in the volume of water applied from T_2 to T1 and T_{VR}, did not affect the size of the broccoli heads. For all treatments the head diameter ranged from 11.2 cm to 11.5 cm. The diameter of broccoli heads still compiled with commercial standards (10 cm to 12 cm) (Heisswolf and Deuter, 1992; and Burt and McKay, 1999). Overall, a high WUE_i can reduce the volume of water and costs associated with quality broccoli production. However, this experiment did not examine other factors that constitute market standards for quality such as the shape, colour, maturity of the head and stem condition.

Although rain occurred every week during the growing period and total water applied exceeded the original total irrigation water required there was an abundance of rain water particularly between the second and sixth weeks. On free-draining sandy soil with low water holding capacity (or field capacity between 10%-13% v/v) the bulk of the water would have drained rapidly from the root zone soil. Therefore, the excess of rainwater was a waste (Hansen *et al*., 1980; Schwab *et al*. 1993).

Excess water collected during the rainy season was due to the application of both rain and irrigation water. For example, as the amount of irrigation water applied was determined based on the previous day's evaporation it was not uncommon for rainwater to be experienced at the site on the same day as irrigation. This led to a large volume of water lost to drainage. Regardless of this, irrigation was still required to fill the gap between the crops daily water requirements and the volume of rain according to each treatment for a larger proportion of the growing period. Irrigation was also required on a weekly basis to wash the leaves after aqueous fertiliser sprays had been applied.

Soil water potential determines the movement of water between the soil and the plant. As the volume of soil water increases the soil water potential generally increases (Allison and Jones, 2005; James *et al*., 1982).   A tensiometer is the primary method utilised to measure the soil water potential in the field. Tensiometers can be used to monitor the soil water status in field crops (James *et al*., 1982) or to regulate irrigation scheduling and volume (El-Shikha *et al*., 2007).   In this experiment, the differential soil water stress index (DSWSI) was determined by the ratio of soil water potentials of all treatments relative to T_2.   The DSWSI remained closer to one for most of the experiment (up to the 10th week).   These results imply that there was no significant difference in soil water potential among the irrigation treatments and different soil depths.   Furthermore, the soil water potential ranged from –3.0 kPa to –9.3 kPa among the treatments – well within the range between saturation and field capacity for sandy soils (0 to -10 kPa) (Hansen *et al*., 1980).

On the 10th week the DSWSI increased and soil water tension became increasingly negative and exceeded the soil field capacity potentially resulting in stressed soil conditions. Quality improvement for some vegetables can be influenced by soil moisture stress and soluble solids content (Hartz, 1999). In broccoli, soil moisture stress imposed near head maturity appeared to have a positive benefit on head color and stem turgor (Wurr *et al*., 2002). However, in this experiment there did not appear to be any influence of the small differences in soil water potential among the irrigation treatments.

Leaf relative water content (RWC) is widely used as an indicator of plant water balance as it estimates the current water content of the leaf tissue based on the maximum water content it can hold at full turgidity (Barrs and Whetherley, 1962; Yamasaki and Dillenburg, 1999). The amount of water absorbed during imbibitions to achieve turgid weight is interpreted as the amount of water required to compensate the water deficit of the leaf tissue due to water stress (Shepherd, 1977). Leaf water status is therefore related to several leaf physiological variables, such as leaf turgor, growth, stomatal conductance, transpiration, photosynthesis and respiration (Kramer and Boyer, 1995 cited in Yamasaki and Dillenburg, 1999).

Experiment results show that all treatments from weeks 4 to 10 have a RWC range from moderate stress (85%) to full turgidity (98%) (Shepherd, 1977). This indicates that the leaf tissue of plants at all plots was not influenced by irrigation

treatments. However, the average leaf water status on T_2 had significantly less stress in comparison to T_1 for 6 weeks of the trial period.

Irrigation scheduling is the use of water management strategies to prevent the over application of water, water shortages and/or relieve drought stress to minimise yield loss. Efficient irrigation scheduling will reduce operation costs and the use of fertilisers and pesticides (Alvino, 1990; Evans *et al*., 1996; Schwab *et al*., 1993). Irrigation scheduling is based on pan evaporation data collected within the field. Pan evaporation is used frequently as it is simple to use and easy to apply in the field (Elliades, 1988). However, it is difficult to predict the volume of rainfall and plant water requirements using pan evaporation as rainfall may be experienced after irrigation has been applied to the site. In this situation, data collected by pan evaporation will not give a sound representation of plant water requirements. The application of pan evaporation in this experiment resulted in wastewater due to the excess water volume capacity of the given irrigation treatments. To avoid potential wastewater risks, irrigation scheduling can be determined using soil moisture monitoring devices to identify the soil water depletion. The soil water depletion can be determined when the percentage reaches total available soil water within the root zone, based on soil and plant characteristics (El-Shikha *et al*., 2007).

Conclusion

Irrigation and rainfall had an impact on the depth of water applied to all irrigation treatments, however there was no significant effect on broccoli yield and quality. Likewise, there was no significant difference in WUE among the irrigation treatments when rainfall was included. However, a difference exists among treatments in WUE_i between irrigation treatments when rainfall is not included. This is an important finding while there were no signs of soil and leaf water stress among the irrigation treatments. Throughout the experiment, irrigation was frequently required to supplement water requirements and maintain growth conditions in the absence of soil and water stress. Collectively these results indicate that there is a need to isolate the irrigation component of the water balance during winter crop production and that irrigation requirements need to be critically assessed against current environmental conditions rather than recent evaporation values (as utilised in this experiment and widely used by industry).

Chapter 5: Impact of irrigation on summer carrot growth, productivity and water use efficiency

5.1 Introduction

Carrots are the third most important vegetable crop produced in Australia with only potatoes and tomatoes produced in larger volumes. In 2006, Western Australia was the second largest producer of carrots after South Australia with 24% of the total value of Australia's AUS $38.4 m carrot production (ABS 7502.0, 2006). In Western Australia carrots are the 4th most valuable crop after barley, wheat and apples. The total production in 2005 was 66.2 tonnes from an area of about 1,200 hectares (ABS 7123.5.55.001, 2005).

Western Australia, in particular the Swan Coastal Plain which has free-draining sandy soils highly suitable for cultivating and harvesting, is known as a favorable place for producing quality carrots and also other vegetables (Burt and McKay, 1999; Heisswolf and Deuter, 1992; Landcaster and Gartrell, 2006). However, the free-draining soil, such as that used in this study, Grey Phase Karrakatta sand (Bolland, 1998), has a water holding capacity of only 10% to 13% and needs irrigation applied at up to 1.40 to 1.50-fold of class A pan evaporation (Epan) to optimise growth and quality (Burt and McKay, 1999; Gibberd *et al*., 2003; McKay, n.d.). Such levels of irrigation application, by definition, make a large contribution to drainage and subsequently may also be associated with leaching of nutrients from the root zone, and potentially also contribute to eutrophication of nearby drainage basins or subsurface water resources (Zotarelli, 2007).

In a previous study conducted by Gibberd *et al*., (2003) to determine the effect of irrigation treatments (from 47 to 151% of class-A pan evaporation (Epan) water replacement) for carrots grown on coarse-textured sandy soil it was shown that the root yield and shoot biomass were not affected by a reduction in irrigation from 151 to 124% of class-A pan evaporation (Epan) water replacement levels. However, yield and shoot biomass were reduced by up to 91% and 87%, respectively by reductions in irrigation volume below 97% of Epan. In this study, reducing the irrigation level from 151% to 97% of Epan water replacement resulted in a 17% increase in crop water use efficiency (WUE); while, a reduction in the irrigation levels below 97% of Epan had resulted in a large reduction in WUE (Gibberd *et al*., 2003).

In the current study, an irrigation level of 150% of Epan was used as a control treatment selected to represent the upper industry standard (Gibberd *et al*., 2003 ; Heisswolf and Deuter, 1992; McKay, n.d.). This was combined with first treatment, of 100% of Epan (based on the previous day's evaporation) and second treatment based on a carrot crop factor (CF) derived by McKay *et al*. (n.d) (unpublished report) from a previous experiment at the same site.

The objective of this study was to investigate the potential to reduce irrigation volumes and maximise crop water use efficiency, referred to as the ratio of crop yield to the volume of water used to produce the crop (Haman *et al*., 2005). An example of the diurnal trends of the physiological response to water treatments was also observed for plants grown at 73 and 75 DAS. Based on the results of Gibberd *et al*. (2003), this research tested the hypothesis that, on a free draining sandy soil, the three irrigation treatments would not affect the growth and yield, but would affect crop water use efficiency (WUE).

5.2 Methodology

5.2.1 Location and agronomy

This field experiment was conducted at Medina Research Station, (DAFWA) (32.13^oS and 115.38^oE). The experiment was established in the warm season, November 2006. The soil type at this location is Grey Phase Karrakatta sand (Bolland, 1998). Prior to the establishment of the experiments, the soil was hoed to 400 mm depth with a rotary hoe and basal fertiliser of double superphosphate at 175 kg/ha (680 g/plot of 6.0 x 6.5 m), and Medina trace element mix without molybdenum at 150 kg/ha (600 g/plot) was applied. Beds 1.5 m wide and 0.15 m high were formed. The area was irrigated using Nelson S10 spinner sprinklers operated at 150 kPa on 1.5 m risers at 6.0 x 6.5 m spacing. Carrot (cv. Stefano) seeds were sown with a precision vacuum seeder at 7 cm spacing and 1.2 cm depth into moist soil with 4 double rows per bed. Standard cultural practices were applied during the growth of the crops. In brief, nitrogen and other nutrients were applied weekly, from the 1st week after sowing until the 16th week with watering cans prior to irrigation. The total fertiliser application equated to 315 kg N, 255 kg K, 15 kg Mg and 10 kg Borax per hectare.

5.2.2 Irrigation treatments and experimental design

Refer to chapter 3 sub heading 3.2.2. (specifically for carrot trial).

5.2.3 Measurements

a. Weather data

An automatic weather station located nearby on the research station recorded relative humidity, air temperature, wind speed, wind direction, rainfall and evaporation every 15 min. Daily values were calculated between 09.00 hrs of the current and previous day.

b. Irrigation water application

Irrigation, rainfall and drainage volumes were determined every week. Irrigation and rainfall were measured using rain gauges placed in the middle of each plot. Plots were laid over drainage lysimeters installed at 1 m depth. Water from lysimeters was pumped out to estimate the loss of water to drainage.

c. Soil moisture content and soil water potential

Soil water potential was measured at 15, 30 and 45 cm depths using low-range tensiometers (Irrometer$^®$ Company, USA). Equipped with pressure sensing transducers. Volumetric soil moisture content was measured using a calibrated water content reflectrometer (Campbell CS625$^®$). The outputs from both probe types were logged by a computer every 15 min.

d. Biomass and other plant measurements

Plant samples were taken every 14 d from 35 d after sowing (DAS). Plant height, leaf number, width and length were measured. Fresh weights of the shoots and roots were recorded. Shoots were separated from the roots. The fresh weight of the shoots and roots were recorded. Dry weight of roots and shoots were recorded after drying at 75 ^{o}C for 48 hours.

e. Physiological measurements

Diurnal measurements of leaf water potential and leaf photosynthesis were carried out 4 weeks before harvest. On 19th and 21st February 2007, approximately from 09.00 hrs to 14.00 hrs, leaf water potential (ψ_l) was determined using a pressure chamber (Soil moisture equipment corp. Santa Barbara, CA USA) and the photosynthesis rate and vapour pressure deficit were measured by portable infra-red gas analysis (Li-Cor 6400 Li-cor Inc, Lincoln, Nebraska, USA). Photosynthetic and stomatal conductance rates were corrected for the actual leaf area by using a Li-Cor area meter (model LI 3100 Li-cor Inc, Lincoln, Nebraska, USA). Canopy and air temperature were detected using an infrared thermometer (Fluke 574).

5.2.4 Statistical analysis

The effect of the treatments on the variable parameters, excepting soil water potential data, as it had only one replication, were analysed by one way analysis of variance (ANOVA) GenStat Release 8.2 statistical software, .

A comparison of the means of treatments each time was undertaken using LSD's calculated at P=0.05 (Christensen, 1996; Gomez and Gomez, 1984; McConway, 1999; Payne, 2005; Steel and Torie, 1960).

To determine the effects of irrigation treatment on the relationship among photosynthesis, vapour pressure deficit, leaf water potential and intercellular CO_2 simple linear regressions was used. The difference between the slopes and intercepts of regression lines were determined by Student's t-test (P = 0.05) (Gomez and Gomez, 1984; Zar, 1984).

5.3 Results

5.3.1 Irrigation, evaporation and rain condition

The carrot growth period extended for 102 d from 29th November 2006 to 20th March 2007, during which only 12 rainy days were recorded (0.2 to 12.4 mm/d), with a total of 36.2 mm. A total class A pan evaporation (Epan) of 819 mm was measured from daily values varying from 2.5 to 10.5 mm. For the 100% Epan (T_1), 150% Epan (T_2) and crop factor (CF) (T_{CF}) treatments, the total depths of irrigation plus rain were 856, 1137 and 926 mm, respectively which equated to 105, 139, and 113% of Epan (Fig. 5.3.1.). The accumulation of 1137 mm of irrigation water and rainfall at the 150% Epan treatment was 33 and 23% higher than at the 100% Epan and crop factor (CF) treatments, respectively. The 150% Epan treatment was significantly different from the 100% Epan and the CF treatments. However, the difference between the 100% Epan and the CF treatment was on average 8% and not significant (Table 5.3.3.).

The actual total irrigation water (without rain) levels were 820, 1100 and 890 mm of depth for the 100% Epan (T_1), 150% Epan (T_2) and crop factor (CF) (T_{CF}) treatments, respectively. The actual irrigation water amount at the 150% Epan treatment has 34% and 24% higher than at the 100% Epan (T_1) and crop factor (CF) (T_{CF}) treatments, respectively.

5.3.2 Yield and growth

When carrots were harvested 16 weeks after sowing, the yield of carrot roots on a fresh weight basis (carrot root g/plant) of plants irrigated with the 150% Epan and crop factor (CF) treatments were 16% and 20% higher than the yield of plants irrigated with the 100% Epan treatment. The total (root and shoot) fresh weight of carrot plants irrigated with the CF treatment was 17% higher than the total fresh weight of plants irrigated with the 100% Epan treatment. However, the total fresh weight was not significantly different between the 100% and 150% Epan treatments, and between the CF and the 150% Epan irrigation treatments.
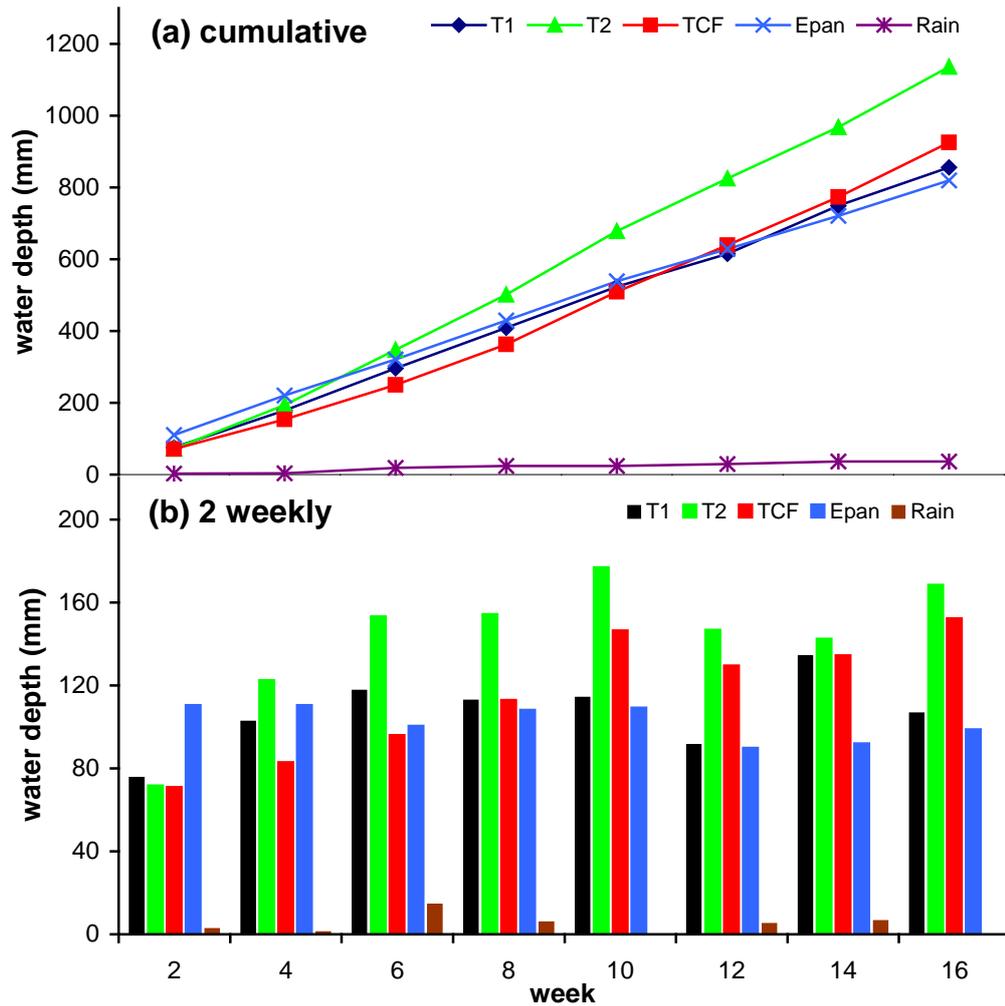
Fig. 5.3.1 (a) The cumulative and (b) 2 weekly totals of evaporation (Epan), rainfall, and water applied plus rainfall for the 3 irrigation treatments (mm) - T_1: the 100% Epan water replacement treatment, T_2: the 150% Epan water replacement treatment and T_{CF}: the crop factor (CF) replacement treatment.

Irrigation water depth values are weekly observations. Rainfall and evaporation values are daily observations.

There were no significant differences among the irrigation treatments on root mass and the total (root and shoot) plant mass when they were measured on a dry weight basis. Although the root to shoot ratio varied from 4.3 to 5.2 and 3.6 to 4.2 among treatments with an average 4.8 and 3.0 in a fresh and dry weight basis respectively, the errors were large and differences among the irrigation treatments were not significant (Table. 5.3.1).

Table 5.3.1 The average of the total (root and shoot), root fresh and dry weight and the root: shoot ratio (g/plant) at harvest for carrot plants grown with either 100% Epan (T_1), 150% Epan (T_2) and crop factor (CF) (T_{CF}) water replacement irrigation treatments.

Treatment	Root+shoot		Root		Root-shoot ratio	
	fresh weight (g/plant)	dry weight (g/plant)	fresh weight (g/plant)	dry weight (g/plant)	fresh weight basis	dry weight basis
T_1	126.1 b	15.5 ns	102.4 b	11.2 ns	4.3 ns	2.6 ns
T_2	141.9 ab	15.5 ns	119.0 a	11.8 ns	5.2 ns	3.2 ns
T_{CF}	148.0 a	16.5 ns	122.4 a	12.4 ns	4.9 ns	3.1 ns
lsd (P=0.05)	17.69	2.26	16.32	1.86	1.00	0.61
s.e.m	5.11	0.65	4.72	0.54	0.29	0.18

Data are means (n=4), different letters following data within a column indicate a significant difference between means (ns = no significant treatment effect).

Total (shoot and root) and root dry mass achieved maximal values for plants grown with all treatments at 14 weeks after sowing. However, when measured on a fresh weight basis, only the 100% Epan treatment achieved the maximum biomass at week 14. The total and root biomass (both on a dry and fresh weight basis) at the 14th week were also not significantly different among all treatments (Fig. 5.3.2).

Root length and diameter, plant height, and leaf length and width

When harvested on 102 DAS, the root lengths of carrots grown with the CF and 150% Epan irrigation treatments were 14% longer (mean length = 30 cm) than the root lengths at the 100% Epan treatment. The plant heights varied from 26 to 30 cm and the leaf length varied from 17 to 19 cm, and were only significantly different between the CF and 100% Epan treatments, and between the CF and 150% Epan treatments, respectively.

Table 5.3.2 Root length and diameter, plant height, maximum leaf length and leaf width (cm) at harvest for carrots grown with either T_1, T_2 and T_{CF} water replacement irrigation treatments.

Treatment	Root		Plant	Leaf	
	length (cm)	diameter (cm)	height (cm)	length (cm)	width (cm)
T_1	26.2 b	3.4 ns	44.5 b	18.1 ab	16.1 ns
T_2	29.5 a	3.5 ns	44.8 ab	17.0 b	16.8 ns
T_{CF}	29.9 a	3.6 ns	47.3 a	19.1 a	16.7 ns
lsd (P=0.05)	0.80	0.06	2.65	1.50	2.09
s.e.m	2.76	0.22	0.77	0.43	0.60

Data are means (n = 4), different letters following data within a column indicate a significant difference between means (ns = no significant treatment effect).

The plant height for carrot plants grown with the CF irrigation treatment was 6% larger than for those grown with the 100% Epan irrigation treatment and the leaf length at the CF irrigation treatment was 12% longer than at the 150% Epan irrigation treatment. Root diameter and leaf width did not differ among the treatments (Table 5.3.2)
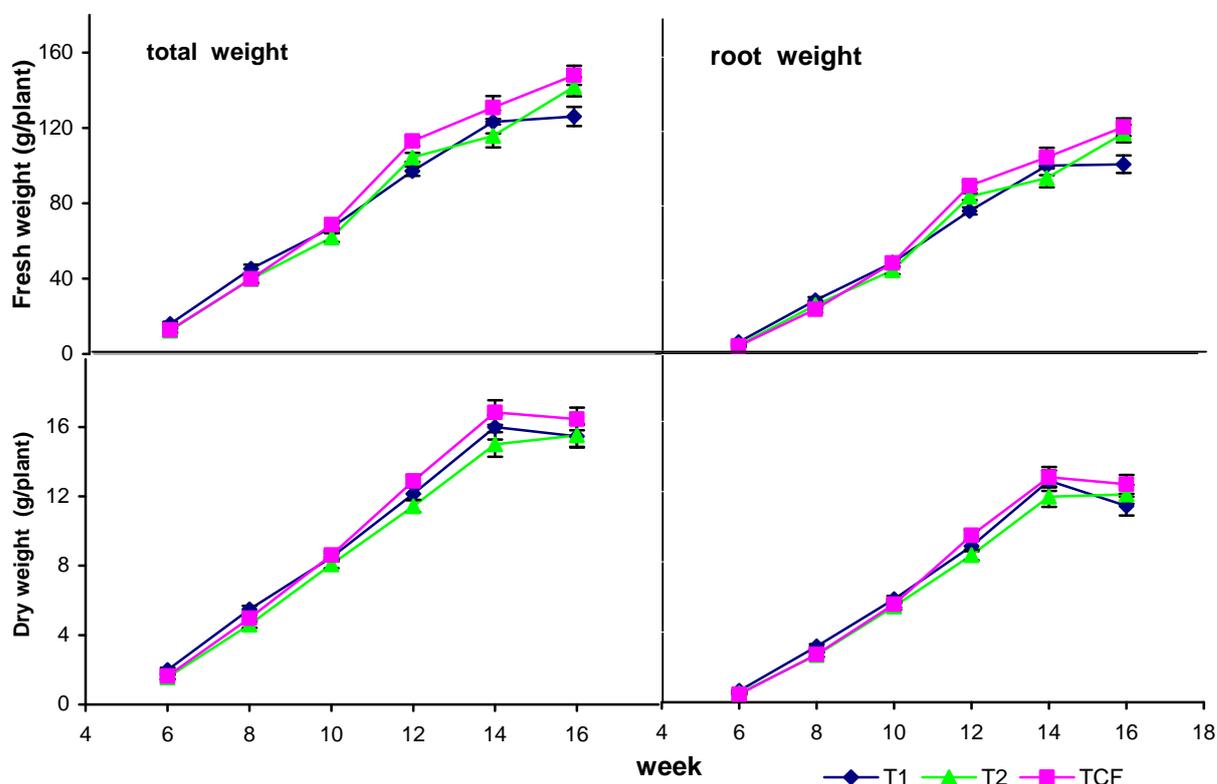
Figure. 5.3.2 Total weight (root and shoot) and root fresh and dry weights from 6 weeks to 16 weeks after sowing for carrots grown with irrigation level treatments; T_1: 100% Epan, T_2: 150% Epan and T_{CF}: crop factor (CF).
Data are means $\pm$ s.e.m. (n=4)

5.3.3 Crop water use efficiency

The crop water use efficiency (WUE) (g/mm) was calculated for each treatment as the ratio of the total biomass (dry weight or fresh weight basis) of carrot roots to the total depth of the irrigation plus rainfall (mm). When calculated on a dry weight basis, the WUE of carrots irrigated with the 100% Epan and CF treatments were similar and 30% greater than the WUE of carrots irrigated with the 150% Epan treatment. On a fresh weight basis, the WUE of carrot plants irrigated with the 100% Epan and CF treatments were 14 and 26% greater than the WUE of plants irrigated with the 150% Epan treatment, respectively (Table 5.3.3).

Table 5.3.3 Total depth of irrigation and rainfall (mm), root dry weight (g DW/plant), root fresh weight (g FW/plant) and crop water use efficiency (WUE) for carrot plants grown with T_1: 100% Epan, T_2: 150% Epan and T_{CF}: Crop factor (CF) irrigation treatments.

Treatment	Irrigation plus rainfall (mm)	DW (g/plant)	FW (g/plant)	WUE (g DW/mm)	WUE (g FW/mm)
T_1	856 b	11.2 ns	102.4 b	0.013 a	0.120 a
T_2	1136 a	11.8 ns	119.0 a	0.010 b	0.105 b
T_{CF}	926 b	12.4 ns	122.4 a	0.013 a	0.132 a
lsd (P=0.05)	79.9	1.86	16.32	0.002	0.015
s.e.m	23.1	0.54	4.72	0.001	0.004

Data are means (n = 4), different letters following data within a column indicate a significant difference between means (ns = no significant treatment effect).

5.3.4 Differential soil water stress index

Differential soil water stress index (DSWSI) was determined as the ratio of soil water potential on the average 0-45cm depth of all treatments relative to the soil water potential of the 150% Epan treatment. The soil water stress indices for the 100% Epan and crop factor (CF) treatments is indicated as T_1 and T_{CF} respectively. The DSWSI formula is the same as is used on chapter 4 (equation (4.3.1).

From week 6 to 14 week, the differential soil water stress indices for the 100% Epan and CF treatments were close to 1 in a range from 0.75 to 1.46 (Table 5.3.4). Specifically, the differential soil water stress indices of the T_1 and T_{CF} treatment fluctuated between the 6th to 10th week, on the 8th week both of the treatments had the lowest DSWSI, were 0.83 and 0.75, respectively. For the 100% Epan treatment the DSWSI on the 16th week, was 1.7- fold than the average values from the weeks before at the same treatments. However for CF treatment (T_{CF}) the DSWSI from week 10th to the 16th were relatively constant; Also the soil water potential values for T_2 and T_{CF} were almost the same. (Table 5.3.4 and Fig 5.3.3).

Table 5.3.4 Soil water potential (kPa) and differential soil water stress index (DSWSI) at 0-45 cm depths for carrot on the T_1, T_2 and crop factor (CF) (T_{CF}) irrigation treatments.

Week	Soil Water Potential (kPa)			DSWSI	
	T_1	T_2	T_{CF}	T_1	T_{CF}
6th	-3.59	-4.23	-3.24	0.85	0.77
8th	-3.54	-4.28	-3.22	0.83	0.75
10th	-3.98	-3.10	-3.10	1.29	1.00
12th	-4.36	-3.31	-3.32	1.32	1.00
14th	-4.84	-3.32	-3.47	1.46	1.04
16th	-5.98	-3.11	-2.95	1.93	0.95

Soil water potential data are 2 weekly means summarised from records taken at 15 minutes intervals.
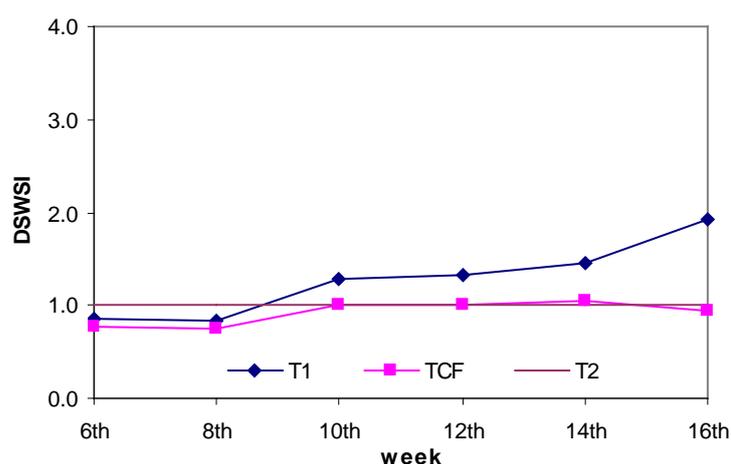
Fig. 5.3.3 The average DSWSI was determined as the ratio of soil water potential of the 100% Epan (T_1) and Crop factor (CF) (T_{CF}) treatments relative to the 150% Epan (T_2) treatment, at 0-45 cm depth.

5.3.5 Physiological assessment

Diurnal measurements of air and canopy temperatures, net leaf photosynthesis rate (Pn), vapour pressure deficit, leaf water potential (ψ_l), stomatal conductance and intercellular CO_2 were carried out on 19th and 21st of February 2007. Data were recorded approximately every hour from 09.00 to 14.00 and 08.00 to 14.00 on the 19th and 21st February 2007 respectively.

a. Canopy temperature

Generally, the average air temperatures over the 2 days of measurements were lower than the canopy temperatures of all treatments. Furthermore, on the second day temperatures were higher than on the first day. Air temperature ranged between 23.1 to 27.0 ^{o}C (first day) and 24.3 to 29.1 ^{o}C (second day), during the

measurement periods, respectively. On both days air and canopy temperatures (air and all the treatment canopies) reached maximum values between 11.00 to 12.59 h

Table 5.3.5 Air and canopy temperatures for the plants grown with 100% Epan, 150% Epan and crop factor (CF) treatments.

Time of day	Air temperature (^{o}C)	Canopy temperature (^{o}C) at treatment site		
		100% Epan	150% Epan	crop factor (CF)
Day 1				
09:00 - 09:59	24.4	-	21.3	21.7
10:00 - 10:59	24.6	24.0	23.9	23.3
11:00 - 11:59	27.0	27.4	26.3	28.3
12:00 - 12:59	26.4	28.4	26.4	28.2
13:00 - 13:59	23.1	24.8	26.2	24.5
Mean	**25.1**	**26.2**	**24.8**	**25.2**
Day 2				
08:00 - 08:59	24.3	25.2	23.8	-
09:00 - 09:59	27.1	30.0	26.9	25.2
10:00 - 10:59	28.5	27.8	28.9	29.3
11:00 - 11:59	29.1	31.8	30.9	30.8
12:00 - 12:59	29.0	31.4	30.4	31.6
13:00 - 13:59	29.1	30.1	30.7	32.4
Mean	**27.9**	**29.4**	**28.6**	**29.9**

Diurnal measurements of air and canopy temperature were performed on Monday, 19 and Wednesday, 21 February 2007.

The canopy temperatures for carrot plants grown with the 150% Epan treatment were generally lower than 100% Epan and CF treatments. On the first day, the average of the canopy temperatures at the 100% Epan, 150% Epan and CF treatments were 26.2, 24.8, and 25.2 ^{o}C and on the second day they averaged 29.4, 28.6, and 29.9 ^{o}C, respectively (Table 5.3.5.).

b. Leaf photosynthesis rate

There was no effect of the irrigation treatment on the leaf photosynthesis rate (Pn) during the measurements on the first day (19th February 2007). On the second day measurements (21st February 2007), when the average of Pn was at the maximum rate (until 09.59 h), the 150% Epan treatment was 77%, significantly higher than the 100% Epan treatment. Over the day the average rate of (Pn) at the 150% Epan treatment was 5.6 and 4.0 μmol CO_2/m^2.s higher than the Pn at the CF and 100% Epan treatments (Table 5.3.6. and Fig. 5.3.4).

c. Vapour pressure deficit

The leaf to air vapour pressure deficit (VPD) varied from 0.73 to 1.3 kPa at the first hour of measurement to maximum values at 1.5 and 2.3 kPa, at 12.00 - 12.59 h on the first and second days of measurement, respectively.

On the first day there was no significant difference in the values of VPD among all the treatments at 09.00 - 09.59 h. In the following hours, the VPD value at the CF treatment was 8.5% greater than the VPD value at the 100 and 150% Epan treatments. During the second day from 08.00 to 13.59 h, VPD of plants grown with the 100% Epan treatment, was 7.8% greater than the 150% Epan treatment. The vapour pressure deficit (VPD) values at the 100% Epan and CF treatments were 12.2% and 8.5% higher than at the 150% Epan treatment at 12.00 - 12.59 h, when the VPD values peaked (Table 5.3.6 and Fig. 5.3.4).

d. Leaf water potential

On the first day of measurements there were no significant differences among treatments in regard to leaf water potential. However, on the second day the leaf water potential of carrots grown with the CF treatment was 45% less negative than carrots grown with the 100% and 150% Epan treatments. However there were no significant differences among the treatments (Table 5.3.6 and Fig. 5.3.4).

Table 5.3.6 Influence of irrigation level and time of the day on the rate of photosynthesis (Pn), vapour pressure deficit (VPD) and leaf water potential (ψ_l) of carrot plants grown with 100% Epan, 150% Epan and CF irrigation treatments.

Irrigation treatment	Time of day (hours)						
	08.00-08.59	09.00-09.59	10.00-10.59	11.00-11.59	12.00-12.59	13.00-13.59	mean
Photosynthesis (μmol CO_2/m^2.s)							
19-Feb-07							
100% Epan		21.2ns	23.0ns	17.8ns	20.8ns	17.2ns	20.0
150% Epan		26.8ns	23.6ns	21.0ns	19.7ns	21.3ns	22.5
Crop factor		27.0ns	20.5ns	19.4ns	15.7ns	22.4ns	21.0
lsd (P= 0.05)		9.81	8.50	8.08	6.51	20.96	
21-Feb-07							
100% Epan	22.0b	13.7b	22.6ns	16.6ns	15.3a	11.0ns	16.9
150% Epan	30.8a	24.3a	20.9ns	17.3ns	16.7a	15.1ns	20.9
Crop factor	18.9c	16.7ab	15.8ns	16.6ns	10.8b	12.9ns	15.3
lsd (P= 0.05)	2.09	9.12	9.28	2.35	3.33	10.05	
Vapour pressure deficit (kPa)							
19-Feb-07							
100% Epan		0.82ns	0.95b	1.38ab	1.47b	0.99a	1.12
150% Epan		0.70ns	0.90b	1.44a	1.46b	1.05a	1.11
Crop factor		0.68ns	1.05a	1.32b	1.59a	0.88b	1.10
lsd (P= 0.05)		0.207	0.071	0.064	0.109	0.094	
21-Feb-07							
100% Epan	1.37a	1.79a	1.62a	2.16a	2.39a	2.24ns	1.93
150% Epan	1.29b	1.61b	1.64b	1.98b	2.13b	2.08ns	1.79
Crop factor	1.34ab	1.58b	1.83b	2.05ab	2.31a	2.19ns	1.88
lsd (P= 0.05)	0.076	0.086	0.181	0.145	0.085	0.327	
Leaf water potential (kPa)							
19-Feb-07							
100% Epan		-733ns	-1093ns	-1200ns	-1387ns	-1313ns	-1145
150% Epan		-713ns	-993ns	-1020ns	-1193ns	-1180ns	-1020
Crop factor		-753ns	-1033ns	-1037ns	-1307ns	-1117ns	-1049
lsd (P= 0.05)		99.4	34.0	387.0	428.8	348.0	
21-Feb-07							
100% Epan	-833ns	-887ns	-900a	-1400b	-1140ns	-1207ns	-1061
150% Epan	-800ns	-923ns	-1067b	-1393b	-1187ns	-1213ns	-1097
Crop factor	-652ns	-753ns	-900a	-967a	-1093ns	-1383ns	-958
lsd (P= 0.05)	235.1	387.7	123.7	279.2	273.3	110.5	

Diurnal measurements of leaf photosynthesis (Pn), vapour pressure deficit, and leaf water potential (ψ_l) were performed on 73 and 75 DAS from 08.00 – 14.00 hours and are means (n=3), different letters following data within a column indicate a significant difference between means (ns = no significant treatment effect).
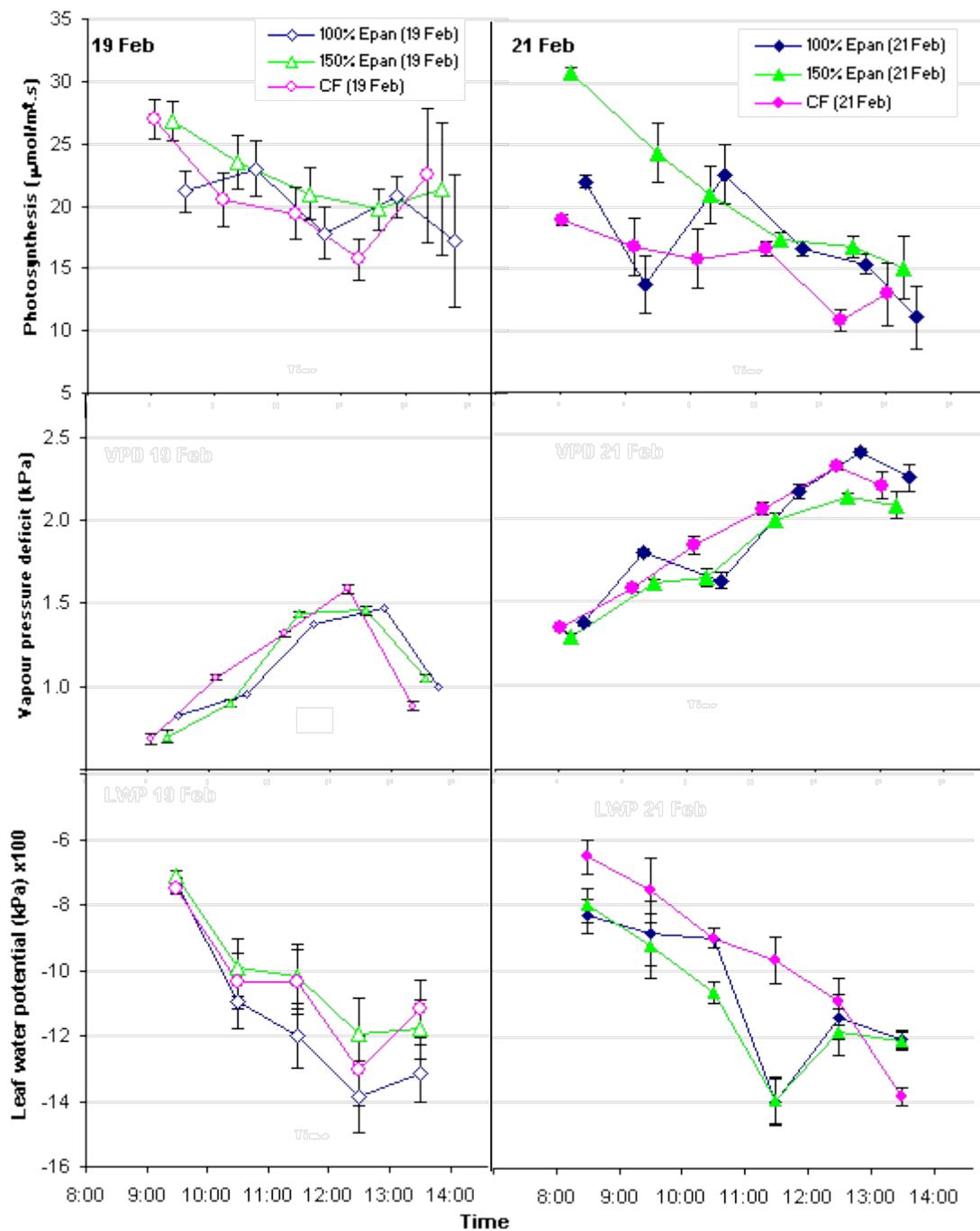
Figure 5.3.4 The influence of irrigation on the rates of net laminae photosynthesis, vapour pressure deficit and leaf water potential of carrot plants measured on (a) 19 February 2007 and (b) 21 February 2007.

Measurements were taken 74 days after sowing (28 days before harvesting) for plants grown with irrigation level treatments; T_1: 100% Epan, T_2: 150% Epan and T_{CF}: crop factor (CF). Data are means $\pm$ s.e.m. (n=3).

e. Stomata conductance and intercellular CO_2

Similar to the trends for the rate of photosynthesis, on the first day (19th February 2007) there was no significant effect of the treatments on the rates of stomatal conductance. However, during the second day (21st February 2007), the average stomatal conductance value for carrots grown with the 150% Epan treatment was 31.5% higher than the values for carrots grown with the 100% Epan and the CF treatments.

Table 5.3.7 Influence of irrigation level and time of the day on the stomatal conductance and intercellular CO_2.

Irrigation treatment	Time of day (hours)						
	08.00-08.59	09.00-09.59	10.00-10.59	11.00-11.59	12.00-12.59	13.00-13.59	mean
			Stomatal conductance (mol/m^2.s)				
19-Feb-07							
100% Epan		0.09b	0.22ns	0.19ns	0.27ns	0.10ns	0.17
150% Epan		0.30ab	0.22ns	0.23ns	0.25ns	0.25ns	0.25
Crop factor		0.32a	0.16ns	0.20ns	0.16ns	0.12ns	0.19
lsd (P= 0.05)		0.222	0.168	0.097	0.111	0.271	
21-Feb-07							
100% Epan	0.26b	0.14c	0.30ns	0.18b	0.15b	0.10ns	0.19
150% Epan	0.43a	0.35a	0.24ns	0.25a	0.20a	0.17ns	0.27
Crop factor	0.24b	0.24b	0.18ns	0.20b	0.10c	0.12ns	0.18
lsd (P= 0.05)	0.064	0.128	0.166	0.041	0.036	0.129	
			Intercellular CO_2 (μmol/mol)				
19-Feb-07							
100% Epan		80b	154ns	192ns	217a	102b	149
150% Epan		191a	166ns	199ns	214a	198a	194
Crop factor		194a	139ns	184ns	187b	77b	156
lsd (P= 0.05)		28.0	113.7	34.7	20.0	38.8	
21-Feb-07							
100% Epan	211ns	187b	219ns	199b	182b	178ns	193
150% Epan	226ns	231a	197ns	232a	213a	205ns	215
Crop factor	224ns	234a	207ns	212b	180b	159ns	198
lsd (P= 0.05)	23.3	32.2	43.3	14.2	23.5	71.5	

Diurnal measurements of stomatal conductance and intercellular CO_2 were performed on 73 and 75 DAS from 08 00 - 14 00 hours measurements and are means (n=3), different letters following data within a column indicate a significant difference between means (ns = no significant treatment effect).

A similar trend was also evident for the intercellular CO_2. During the first day, the average intercellular CO_2 values between the treatments ranged from 149 to 156 μmol/mol. The average intercellular CO_2 values for grown with the 150% Epan treatment were 23% and 20% higher than at the 100% Epan and the CF treatments, respectively. On the second day of measurements, the values were higher than the previous day and ranged from 193 to 215 μmol/mol. The average intercellular CO_2 value for plants grown with the 150% Epan treatment was 10% and 8% higher than those for the 100% Epan CF treatments (Table 5.3.7 and Fig. 5.3.5).
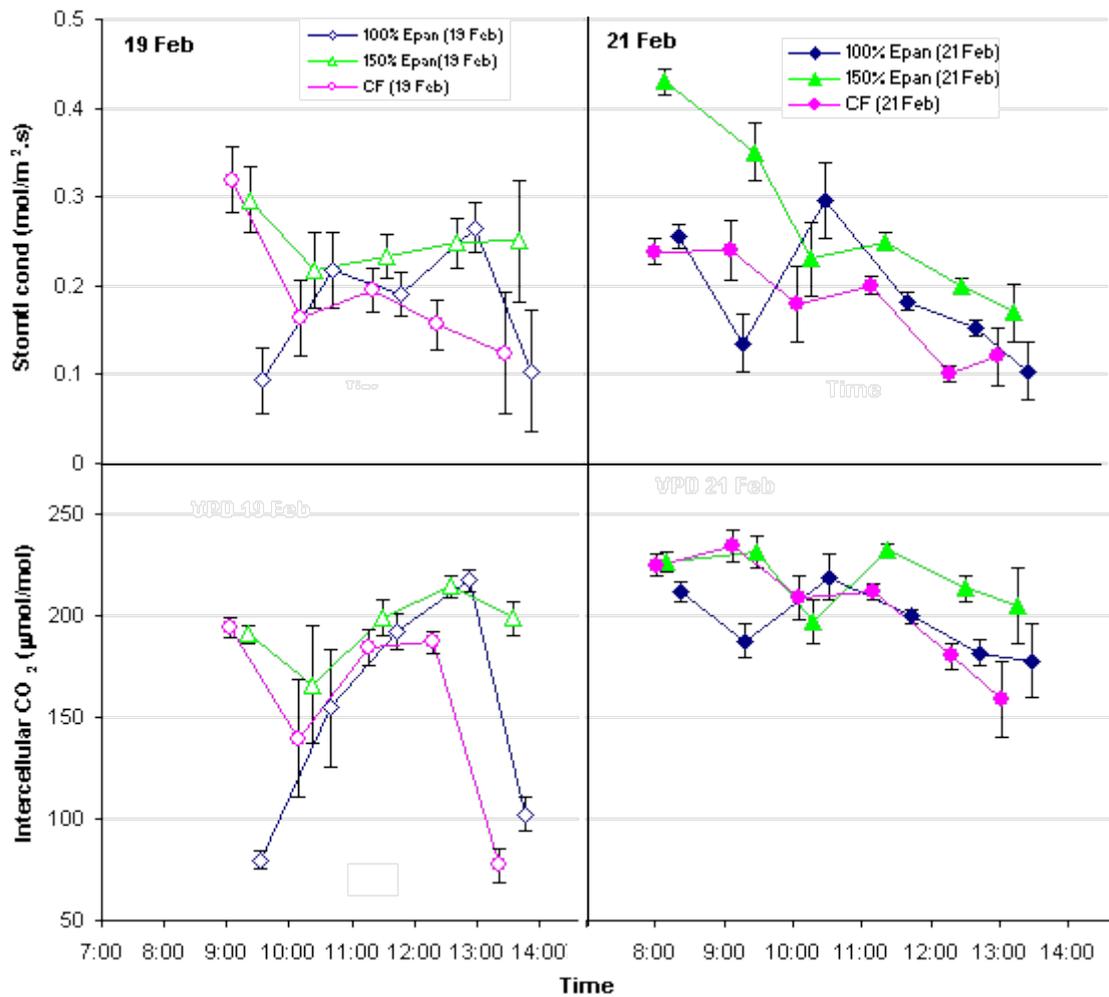
Figure 5.3.5 The influence of irrigation treatments on the diurnal changes in the rates of stomatal conductance and intercellular CO_2 of carrot plants measured on (a) 19 February 2007 and (b) 21 February 2007.
Measurements were taken 74 days after sowing (28 days before harvesting) on irrigation level treatments; T_1: 100% Epan, T_2: 150% Epan and T_{CF}: crop factor (CF). Data are means ± s.e.m. (n=3).

By combining the two days measurements it was possible to develop correlations between the parameters (Fig. 5.3.6.), of these only the slope and intercept of linear regressions between the leaf water potential (ψ_l) and photosynthesis (Pn) (graph c) were significantly different (P<0.05) between the 150% Epan and 100% Epan treatments, and between the 150% Epan and CF treatments.

The slope and intercept of linear regressions between the vapour pressure deficit (VPD) and photosynthesis rate (Pn), vapour pressure deficit (VPD) and leaf water potential (ψ_l), and intercellular CO_2 (Ci) and photosynthesis (Pn) did not differ significantly (P > 0.05) among all the treatments (Fig. 5.3.6).
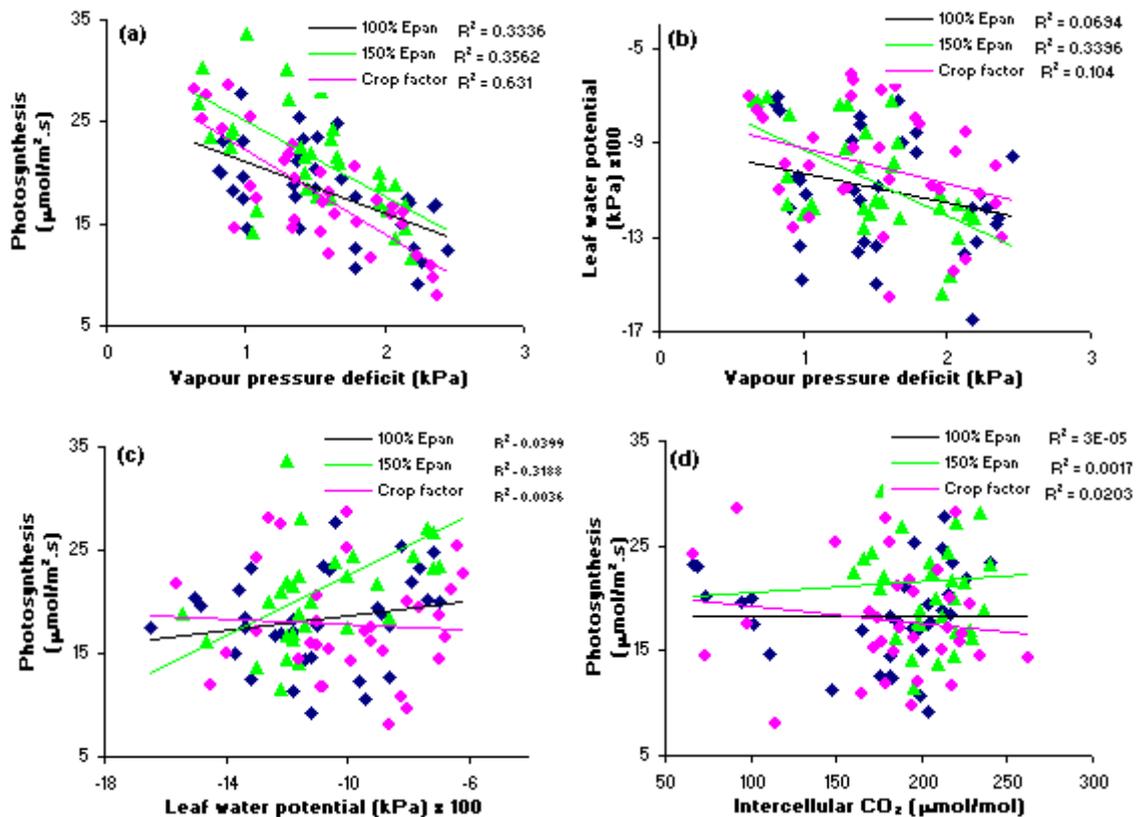
Figure 5.3.6 The relationship between: (**a**) vapour pressure deficit (VPD) and photosynthesis (Pn), (**b**) vapour pressure deficit (VPD) and leaf water potential (ψ_l), (**c**) leaf water potential (ψ_l) and photosynthesis (Pn), (**d**) intercellular CO_2 (Ci) and photosynthesis (Pn) of carrot plants irrigated with the 100% Epan, 150% Epan and crop factor (CF) irrigation treatments. Data points are measurements performed from 08.00 to 13.59. Only in the graph c (between the leaf water potential (ψ_l) and photosynthesis (Pn)) the regression slopes and intercepts at the 150% Epan treatment was significantly different from the 100% Epan and CF treatments (P<0.05), the slopes and intercepts at all regressions in other graphs a, b and d did not differ significantly (P >0.05).

5.4 Discussion

The results of this research have proved the hypothesis, i.e., on a free draining sandy soil, the three irrigation treatments did not affect the yield (root biomass) and total plant biomass (root and shoot). But did affect the crop water use efficiency (WUE). The crop water use efficiencies (WUE) of plants irrigated with the 100% Epan and the crop factor (CF) treatments were higher than the industry standard 150% Epan treatment irrigation water application (Gibberd *et al*., 2003). However, if the yield was measured on a fresh weight basis, the root yield at the 100% Epan treatment was significantly lower than the 150% Epan and CF treatments. The CF treatment received 1.13-fold of Epan class A pan evaporation (Epan), and was significantly greater than the 100% Epan treatment in plant height and root length; it was also greater than the 150% Epan treatment in leaf length. This result was similar to the previous experiment conducted by Gibberd *et al*. (2003) in that the yield (root fresh weight basis) at the 151% Epan treatment was not different to the 124% Epan treatment, but was higher than that on the 97% Epan treatment. Also, the reduction in irrigation to 124% Epan in the Gibberd *et al*. (2003) study resulted in an increase in WUE. In their study the root:shoot ratio of plants irrigated with greater than 100% Epan also did not differ and was relatively high (Gibberd *et al*., 2003) compared to the current study. Collectively, these results reveal that, with regulated water deficits (i.e. irrigation lower than the current industry standard) yields and WUE can be improved.

In this experiment the total irrigation plus rainwater applied did not equate to the anticipated levels for each treatment. For example, for the 100% Epan and 150% Epan treatments, the actual values were 105% and 139% Epan, respectively and for the CF it was 113% Epan (Fig. 5.3.1.). To minimise inaccurate irrigation water application, besides calculating the previous day's evaporation, the amount of irrigation water applied should also consider the prediction of the current evaporation, based on the weather forecasting (Elliades, 1988).

The soil matric water potential is related to the soil water content; it is one of the basic soil properties required to manage irrigation effectively (James *et al*., 1982). The soil matric water potential influences the water potential gradient associated with water flux into plant roots. As the soil water content increases, the water potential becomes less negative (James *et al*., 1982; Allison and Jones, 2005). From the week 6 to 14; the differential soil water stress index (DSWSI) value from

the 100% Epan and CF treatments was relatively stable and close to 1 except the 2 prior weeks measurements had some variation in the soil water potential (Fig. 5.3.3.). These findings imply that there were only small soil water tension differences among all the irrigation treatments in the 0-45 cm soil depths. The soil tension ranged from –3.0 to –6.0 kPa with an average of -4.4, -3.6 and -3.2 kPa at the 100%, 150% Epan and CF irrigation treatments, respectively, and was therefore within the range between the saturated and field capacity for a sandy soil (0 to -10 kPa) (Hansen *et al*., 1980). This indicates a small probability of soil water stresses for all the treatments.

There is a potential to enhance crop water efficiency by monitoring the soil matric water potential to regulate irrigation timing and volume (El-Shikha *et al*., 2007). Soil matric water potential can be measured with a tensiometer (James *et al*., 1982). Another alternative is to regulate the effectiveness of the irrigation scheduling by determining the differential soil water stress index (DSWSI); the DSWSI increases when the soil water tension (which is compared with standard or control soil water tension), is more negative, exceeding the soil field capacity. This indicates that the soils stressed and were needed irrigation. However, to avoid the incidence of root splitting and corrugation, the soil moisture has to be protected from large fluctuations (Rubatzky *et al*., 1999).

Photosynthesis (Pn) for carrot plants grown with the 150% Epan treatment was higher than the Pn of carrots grown with the CF and 100% Epan treatments. The results confirm Turner's (1990) statement that reductions in the amount of water applied will decrease the rate of the photosynthesis. In this experiment it is demonstrated that the rate of photosynthesis has a negative correlation with the air and canopy temperature. Environmental factors, such as air and canopy temperature, influence the photosynthesis rate directly or indirectly (Gibberd *et al*., 2003). The leaf photosynthesis rate was relatively high in the morning hours when the temperature was low, and also when the average day temperature was low. Similar to the leaf photosynthesis rate, the stomatal conductance rate is also influenced by environmental and internal factors, such as light, CO_2 level, temperature and the water status of the plant (Hopkins and Huner, 2004). For example, with this experiment, on the second day of measurements, the high level of irrigation (150% Epan treatment) showed a higher stomatal conductance rate than the two lower irrigation level treatments. As previously described by Gibberd *et al*. (2003) the

variation of the leaf photosynthesis rate in carrots is predominantly caused by a reduction in stomatal conductance as demonstrated by a concomitant reduction in the intercellular CO_2 concentration.

Conclusion

Compared to the standard industry irrigation level, regulated water deficit treatments of 100% Epan and CF irrigation level have the potential to increase the crop water use efficiency by 14 and 26% respectively. Also, the reduction of irrigation levels from the 150% Epan water replacement to the CF and 100% Epan water replacement did not affect the yields (carrot root on a dry weight basis) and the physiological aspects, such as the rate of photosynthesis, stomatal conductance and intercellular CO_2.

Chapter 6: Food nutritional quality

6.1 Introduction

Food nutritional quality for human dietary needs is a vital aspect and main objective for agricultural production. Food nutritional quality is paramount in fruit and vegetable production. Various researchers have identified that consuming high quality fruits and vegetables has anti-aging and disease risk reduction benefits (Alasalvar *et al*., 2004; Bahorun *et al*., 2004).

Ascorbic acid and carotenoids are two important nutrient components of vegetable products. For example, broccoli and carrot are two vegetables, which are a rich source of ascorbic acid and carotenoids, respectively (Lorenz and Maynard, 1997 and Ou *et al.* 2002). Research analysing natural sources, such as fruit and vegetables vitamins and antioxidants is becoming increasingly prominent in the literature (Alasalvar *et al*., 2005; Gil *et al*., 2002; Ou *et al*., 2002; Singh, 2007; Zhang and Hamauzu, 2004; Zhou and Yu, 2006). Antioxidants include vitamins that protect human body from the effect of free radicals (Ou *et al*., 2002 and Molyneux, 2004).

Previous research has reported the influence of irrigation and fertiliser on carrot yield; quality (shape, size and disease), water use efficiency; physiological responses and nutrient up-take (Gibberd *et al*., 2000). Other researches have observed the effects of pre-harvest factors (temperature, light intensity and water) on post-harvest quality of various vegetables (Wurr *et al*., 2002).

Overall, it was difficult to find quality published research that has observed the effect of irrigation on the nutrient quality and vitamin composition of fruit and vegetables. Therefore, the objective of this experiment was to observe the effect of three different irrigation levels on ascorbic acid and total carotenoid content of broccoli and carrot.

6.2 Methodology

6.2.1 Location and layout detail

For the detail of this sub heading please refer to sub heading location and layout detail in chapter 4 and 5.

6.2.2. Irrigation treatments and experimental design

The irrigation treatments and experimental design can be refered in to chapter 3 sub heading 3.2.2. For laboratory analyses (ascorbic acid and total carotenoid) each replicated had 4 samples.

6.2.3 Laboratory analysis

Food nutritional quality, specifically ascorbic acid and total carotenoid content of carrot root and broccoli head products was determined at the post-harvest laboratory, Muresk Institute, Curtin University of Technology.

a. Ascorbic acid assay

This protocol is based on the combination of Jagota and Dani (1982) and AOAC (1996) methods. Five g of fresh tissues were homogenized with 25 ml of 6% metaphosphoric acid. The homogenate was centrifuged at 3000 rpm for 10 min and filtered with filter paper. The supernatant was collected and an addition of 200 μl of 3% meta-phosphoric acid and 200 μl of folin reagent (1:5) in 400 μl filtered supernatant was applied. 1400 μl distilled water was added to the solution to make the total volume to 2200 μl. The content was mixed for 10 min. After 10 min, the sample was read with the absorbance adjusted to λ =760 nm using a 2 ml plastic disposable cuvette. The ascorbic acid sample was calculated by using the standard curve with known concentration of ascorbic acid: $Y = 0.0114 X – 0.0063$ ($R^2 = 0.999$) (AOAC, 1996; Jagota and Dani, 1982).

b. Total carotenoid assay

The basis of this protocol was taken from Hendry and Grime (1993). In brief, 1 g of fresh mass was ground to make a tissue sample in a 20 ml volume of absolute ethanol. The ground material was placed in a centrifuge tube and spun at 10000 g for 10 min. The absorbance measurement of the whole ethanol extract was taken at λ:

663, 645 and 480 nm. Absolute ethanol was used as the blank for zeroing the machine. Total carotenoid concentration in mM = (A480 + (0.114 x A663) – (0.638 x A645)): 112.5, where A480, A663 and A645 were the values for absorbance at wavelengths λ: 480, 663 and 645 nm respectively.

6.2.4 Statistical analysis

All data collected were subjected to analysis of variance (ANOVA) one-way design in randomised block using GenStat Release 8.2 statistical software.

A comparison of the means of treatments each time was done using lsd's calculated at $P=0.05$ (Christensen, 1996; Gomez and Gomez, 1984; McConway, 1999; Payne *et al*., 2005; Steel and Torrie, 1960).

6.3 Results

The averages of ascorbic acid and total carotenoid content in broccoli heads from all treatments were 13.9 mg and 3.0 mg, in 100 g fresh weight (FW), in contrast to carrot roots and which were 4.6 mg and 12.2 mg, in 100 g FW respectively.

6.3.1 Broccoli head

In the broccoli trial, the actual irrigation volume applied to the 150% Epan treatment was 13.9% and 17.2% higher than the 100% Epan and VR treatments (for detail please refer to chapter 4 sub heading 4.3.1). However, there was no significant difference between 100% Epan and VR treatments.

The ascorbic acid and total carotenoid content in broccoli heads ranged from 13.5 to 14.5 and 3.0 to 3.1 mg/100g FW. Although the volume of the irrigation between the 150% and 100% Epan treatments was significantly different, the ascorbic acid and total carotenoid contents were not significantly affected by all treatments (Table 6.3).

Table 6.3 Ascorbic acid (mg/100g fresh weight) and Carteniods (mg/100g fresh weight) content in broccoli heads and carrot roots from three different irrigation treatments (T_1, T_2 T_{VR} for broccoli and T_1, T_2, T_{CF} for carrot).

Treatment	Actual water depth (mm)	Ascorbic Acid mg / 100 g FW	Carotenoids mg / 100 g FW
Broccoli head			
T_1	394.25 b	13.4459	2.9455
T_2	449.00 a	13.7873	3.0086
T_{VR}	383.00 b	14.4857	3.1056
lsd (P = 0.05)	23.23	3.0094	1.0205
s.e.m	6.71	0.8696	0.2949
Carrot root			
T_1	856.00 b	4.9105	12.5524
T_2	1136.50 a	4.5726	11.8232
T_{CF}	925.75 b	4.2906	12.1376
lsd (P = 0.05)	79.87	0.7767	1.1477
s.e.m	23.08	0.2244	0.3316

Treatment x ascorbic acid and carotenoid, non significant

Broccoli and carrot were harvested on 19 September 2006 and 20 March 2007 respectively. The three irrigation treatments were T_1: 100% Epan; T_2: 150% Epan; and T_{VR}, for broccoli: variable water replacement (VR) to maintain (>=) 11% volumetric soil water content and T_{CF} for carrot: crop factor (CF) multiplied by 100% Epan, and data are mean (n=4), different letters following data within a column indicate a significant difference between means.

6.3.2 Carrot root

Although the magnitude of the differences in ascorbic acid and carotenoids between irrigation treatments for the carrot trial was higher than among irrigation treatments for the broccoli trial, the same results were observed in terms of the effect of different irrigation treatments.

There was no significant difference in ascorbic acid and total carotenoid content among the three irrigation treatments, although the highest ascorbic acid and total carotenoid contents were observed in the carrot root sample from plants which received the 100% Epan treatment; and lowest ascorbic acid and total carotenoid content was observed for carrot plants which received the CF and 150% Epan treatments, respectively (Table 6.3).

6.4 Discussion

The amount of irrigation water applied to the 150% Epan treatment was significantly different from the other treatments. However, there were no treatment effects on the contents of carotenoids or ascorbic acid in broccoli heads and carrot roots.

Many previous studies indicated that some environmental factors including soil moisture might influence the contents of carotenoids (Melédez-Martinez *et al*., 2007; Riggi *et al*., 2008; Rubatzky, 1999) and ascorbic acid (Sorensen, 1999; Toivonen *et al*., 1994 cited in Lee *et al*., 2000). Reducing the irrigation level, tends to increase the carotene content of the carrot root (Rubatzky, 1999). Reduced irrigation levels can increase the content of ascorbic acid in horticultural crops, especially for broccoli and leek (Sorensen *et al*., 1999). Actually, carotenoid compounds are precursors for the formation of the phytohormone abscisic acid (Schwartz *et al*., 2003 cited in Riggi *et al*., 2008). This hormone is involved in plant stress responses, such as drought, salinity and cold and carotenoid biosynthesis (β-carotene) precedes production of abscisic acid (Riggi *et al*., 2008).

The present study showed that the effect of irrigation treatment on broccoli trial, even with 17% lower than the standard industry irrigation level (150% Epan water replacement), did not affect the content of ascorbic acid and carotenoid. This resulted in only small differences among the treatments, i.e. 13.4 - 14.5 mg/100 FW for ascorbic acid and 2.9-3.1 mg/100 FW for carotenoid. The similar results were shown in the carrot trial; with the differences in the amount of irrigation water

applied was evident at 33% from the irrigation standard (150% Epan water replacement) level. The content of ascorbic acid was 4.3-4.9 mg/100 FW and the content of carotenoid was 11.8-12.6 mg/100 FW.

Generally, soil fertility has an effect on the carotene content (Rubatzky, 1999; Sorensen, 1999). Sorensen (1999) revealed that the carotene of carrot roots was positively correlated with the concentration of nitrogen. The decreasing the nitrogen supply slightly decreased the concentration of carotene of carrot roots. Based on the results, there is an indication that the three treatments did not significantly decrease the nitrogen content of the soil on each plot because of leaching.

The irrigation levels used in the present study, between 150% and 100% Epan water replacement, did not affect the contents of ascorbic acid and carotenoid in broccoli heads and carrot roots. The range of irrigation level that from 150% Epan water replacement to less than 100% may be applied to evaluate the more detailed effect of different irrigation levels on the contents of ascorbic acid and carotenoid in broccoli heads and carrot roots. The irrigation levels applied in this present study should be broadening in the further experiment.

In conclusion, the results of this experiment demonstrated that a reduction in the irrigation levels from 150% to 100% Epan water replacement did not affect the contents of ascorbic acid and carotenoid in broccoli heads and carrot roots. It also assumed that the different irrigation water levels of all treatment did not make much difference in the soil characteristics, such as soil water content and soil nitrogen content and further, more severe, treatments may be required to elicit a response.

Chapter 7: Total antioxidant of carrot root

7.1 Introduction

Food nutrient quality is a significant aspect and overall objective of agricultural production, especially fruit and vegetable production suited for human consumption. Numerous studies have identified that the consumption of high quality fruit and vegetables is able to prevent the risk of development of certain diseases and to reduce the aging process (Alasalvar *et al*., 2004; Bahorun *et al*., 2004; Yu *et al*., 2002).

Many fresh fruits and vegetables, such as carrots, are a source of natural antioxidants (Lorenz and Maynard, 1997; Ou *et al*., 2002). Studies specific to antioxidants are becoming increasingly prominent in the literature. For example, research has been developed to observe antioxidants, including vitamins sourced from natural sources, such as fruit and vegetables and their respective influence on the human body's mechanisms to prevent free radical effects (Molyneux, 2004; Ou *et al*., 2002).

The impact of irrigation and fertiliser treatment levels on vegetable yield, quality (shape, size and disease incidence), water use efficiency, physiological responses and nutrient up-take compositions have been previously studied (Babik and Elkner, 2002; El-Shikha *et al*., 2007; Gibberd *et al*., 2000). Further research has observed the effects of pre-harvest factors on post-harvest quality of various vegetables, including the effect of temperature, light intensity and water (Eraslan *et al*., 2007; Riggi *et al*., 2008; Wurr *et al*., 2002).

There is also a magnitude of research available that discusses the effects of pre and post harvest treatments, such as salinity (Eraslan *et al*., 2007) and solar radiation (Zhou and Yu, 2006) on the antioxidant activities of carrots or other vegetables; cooking methods (Zhang and Hamauzu, 2004); drying processes (Uyan *et al*., 2004); chilling storage and modified atmosphere packaging (MAP) (Alasalvar *et al*., 2005). However, it is difficult to find research discussing the influence of irrigation treatments on the antioxidant capacity of carrots or other vegetables.

The diphenylpicrylhydrazyl (DPPH) method is a simple method used to evaluate free radical scavenging capacity (Gil *et al*., 2002). This method is based on the measurement of the reducing ability of the antioxidant toward DPPH (Brand-Williams *et al*., 1995; Prior *et al*., 2005). The trolox-equivalent antioxidant capacity standard curve was used to determine the antioxidant capacity of carrots in this experiment. Other result interpretation parameters determined from the DPPH method are "efficient concentration" (called the EC_{50} value) and anti radical power (APR) (Brand-Williams et al., 1995; Molyneux, 2004).

The aim of this experiment was to determine the influence of three different irrigation levels on total antioxidant capacity of carrot roots.

7.2   Methodology
7.2.1   Location and layout detail

For the detail of this sub heading please refer to sub heading location and layout detail in chapter 5.

7.2.2   Irrigation treatments and experimental design

The irrigation treatments and experimental design can be refered to chapter 3 sub heading 3.2.2. Each treatment replicated has 4 samples for laboratory analysis.

7.2.3   Laboratory analysis

The carrot nutrient quality was analysed by measuring the total antioxidant capacity. Measurements were performed in the Wine Laboratory, located at the Centre of Wine Excellence, Curtin University of Technology, Margaret River, Western Australia.

Determining the total antioxidant capacity (AOC) using the DPPH assay:

Cleaned carrot root samples were stored in a cool room (2 to 3 ^{o}C) then the roots were "topped" and "tailed" whereby a sub-sample was taken from the middle 1/3 of each carrot root.

The sub sample was grated and fixed in liquid nitrogen. The sample was then ground to a fine powder using a mortar and pestle. To avoid water absorption, 0.5 g to 1 g samples of the fine powder were weighed quickly and transferred to a 15 ml centrifuge tube. Each sample was extracted with 5 ml methanol in the centrifuge tube

and spun at 4400 rpm for 10 min. Half ml of supernatant was mixed with 2.5 ml of 75 μM DPPH solution in a 4 ml cuvette. The reading was taken at $\lambda= 517$ nm after 30 min (methanol was used as a reference) (Brand-Williams *et al.*, 1995; Gil *et al.*, 2002; Molyneux, 2004).

To form a standard curve, 0.5 ml of 0, 0.04, 0.1, 0.2, 0.25 and 0.5 mM of trolox solution in methanol was mixed with 2.5 ml of 75 μM DPPH solution. The reading was taken at $\lambda= 517$ nm again, after 30 min. The 0mM trolox was used as a "control". To determine the % DPPH scavenging, EC_{50} and $EC_{50\ sample}$, APR (antiradical power) and total AOC (trolox equivalent antioxidant capacity) concentrations were calculated by:

- The % DPPH scavenging is defined as $Q = 1 – (A0 – AC)/A0$.
  Where A0 is the control value of absorbance (absence of any sample), AC is absorbance for the added sample concentration reading after 30 min (Molyneux, 2004).

- EC_{50} ("efficient concentration" value) is defined as the concentration of substrate that cause a 50% loss of DPPH activity calculated from the calibrated standard curve. The EC_{50} sample is calculated as a concentration at EC_{50}, divided by the concentration value of antioxidant in DPPH solution from the sample after 30 min [(mmol/L)/(mmol/L)](Brand-Williams *et al.*, 1995).

- APR (antiradical power) is defined as: $1/ EC_{50\ sample}$ (Brand-Williams *et al.*, 1995).

- Total AOC (antioxidant capacity) is expressed as μmol TE/g or mmol TE/Kg (Brand-Williams *et al.*, 1995).

7.2.4 Statistical analysis

All data collected were subjected to analysis of variance (ANOVA). Using One-way design randomised block using GenStat Release 8.2 statistical software. Comparison of means of treatments was undertaken using LSD's calculated at P=0.05 (Christensen, 1996; Gomez and Gomez, 1984; McConway, 1999; Payne *et al.*, 2005; Steel and Torrie, 1960).

7.3 Results

The average values of antioxidant analysis for total trolox-equivalent antioxidant capacity, DPPH scavenging and ARP (anti radical power) value were 1.056 μmol TE/g, 44.83% and 0.8789 respectively.

Trolox equivalent antioxidant capacity

The DPPH assay was standardised with trolox solutions (Fig. 7.3). The value of the trolox equivalent antioxidant capacity (TEAC) is a standardized measure of the antioxidant capacity of the sample. The antioxidant capacity of carrot roots from the three irrigation treatments ranged from 1.040 to 1.083 μmol TE/g, respectively. Roots grown with the 100% Epan treatment had the highest antioxidant capacity (1.083 μmol TE/g), followed by the CF (1.045 μmol TE/g) and 150% Epan treatment (1.040 μmol TE/g). The total antioxidant capacity (AOC) recorded from the highest irrigation treatment was significantly different in comparison to AOC at 100% Epan. The AOC from the 100% Epan treatment was 4.2% higher than from 150% Epan treatment. However, there was no significant difference between the 100% Epan and CF treatments, although a 3.6% difference did exist (Table 7.3).
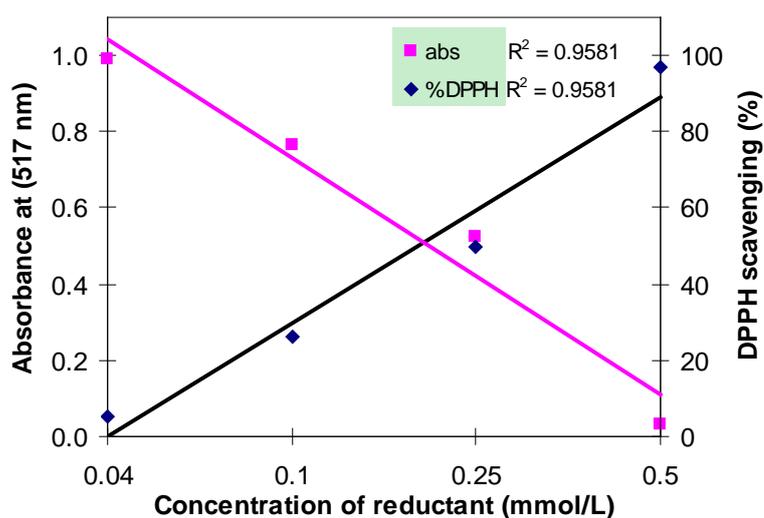

Figure 7.3 The absorbance and percentage DPPH scavenging versus the amount of reductant added.
The graph lines were determined from the standard curve and percentage of DPPH curve. Equations calibrated with trolox. Graph adapted from Blois (1958) in Molyneux (2004).

Percentage of DPPH scavenging and antiradical power (ARP)

Calculating the percentage of DPPH scavenging is the other way to determine the antioxidant activity. DPPH scavenging results ranged from 44.25% to 45.80%. Again, results identified that the highest DPPH scavenging was detected in the carrot root sample extract for carrots grown with the 100% Epan treatment. Although the value from the 100% Epan irrigation treatment was just 1.55% higher than DPPH scavenging at the 150% Epan treatment, it was significant difference between them. Furthermore, despite the DPPH scavenging at the 100% Epan treatment was 1.35% higher than the CF treatments, there was no significant difference identified between the two samples (Table 7.3).

Table 7.3 DPPH scavenging (%), antiradical power (ARP) (dimensionless) and total antioxidant capacity (AOC) (μmol TE/g) of carrot root from three different irrigation treatments (T_1, T_2 and T_{CF}). Carrots were harvested on 20 March 2007.

Treatment	Actual water depth (mm)	Total AOC (μmol TE/g)	DPPH scavenging (%)	ARP
Carrot root				
T_1	856.00b	1.0830a	45.7953a	0.9015a
T_2	925.75b	1.0451ab	44.4458ab	0.8699ab
T_{CF}	1136.50a	1.0395b	44.2478b	0.8653b
lsd (P = 0.05)	79.87	0.0429	1.526	0.0357
s.e.m		0.0124	0.4409	0.0103

The three irrigation treatments were T_1: 100% Epan; T_2: 150% Epan; and T_{CF}: crop factor (CF) multiplied by 100% Epan, APRs are inverse of concentration at EC_{50} divided by the concentration value of antioxidant in DPPH solution from sample at 30 min [1/(mmol/L)/(mmol/L)] and data are means (n=4), different letters following data within a column indicate a significant difference between means (ns = no significant treatment effect).

The same trend was observed in antiradical power (ARP) activity. The ARP values were dimensionless. The highest ARP value obtained was by 100% Epan treatment (0.902) followed by CF (0.870) and 150% Epan treatments (0.865) respectively. Furthermore, the percentage differences among the treatments on ARP values were exactly the same as total antioxidant capacity values. The only significant difference exists between the 100% and 150% Epan treatments (Table 7.3).

7.4 Discussion

The 33% difference between the volume of water applied at the 100% Epan and 150% Epan treatments had a small impact on the nutritive value of carrot roots. The percentage of the DPPH scavenging capacity for roots of plants grown with the 100% Epan treatment was greater than at the 150% Epan treatment by 1.55%. However, the difference was somewhat more prominent (4.2%) when considered on the basis of total antioxidant capacity (AOC) and antiradical power (ARP) activities. Interestingly, the 23% difference between the amounts of water applied at the CF and 150% Epan treatments did not show a significant affect on antioxidant capacity. Likewise, there was significant effect in the antioxidant activities between the 100% Epan and crop factor (CF) irrigation treatments. The amount of water applied at the CF treatment was only 8% higher than it was at the 100% Epan treatment.

Through this experiment, the results reveal that the variation in antioxidant activity values among the same vegetables indicated that this is not only influenced by geographical differences or location, weather conditions, and harvest periods, and cultivars (Alasalvar *et al*., 2005; Ou *et al*., 2002; Pellegrini *et al*., 2003; Singh *et al*., 2007) as previously determined but also by different amounts of irrigation and rainfall

The outcome of this antioxidant analysis differs that of from the ascorbic acid and carotenoid analyses (See chapter 6) which was not sensitive to water availability. Although fruits and vegetables, including carrots, are rich sources of different phytonutrients, such as vitamin C, E and B-carotene, including antioxidant properties (Prior *et al*., 1998 cited in Alasalvar *et al*., 2005), a significant contribution of the antioxidant activity from the fruits and vegetables also comes from the phenolics (Gil *et al*., 2002). The contributions of phenolic compounds to antioxidant activity were much greater than those of vitamin C and carotenoids and it is possible that for the carrots utilized in this experiment the phenolic compounds were more sensitive to the irrigation treatment than the other antioxidant fractions.

For further investigation, to avoid the influence of the differences of the carrot water content between the treatments, it is suggested that an experiment be set up using dry matter as the sample. The removal of sample moisture is aimed at preserving the carrot and increasing the percentage of dry matter sample, resulting in a higher value of antioxidant capacities per unit weight (Cao *et al*., 1996; Uyan *et al*., 2004).

In conclusion, the reduction of the irrigation level treatment from 150% Epan water replacement to 100% Epan water replacement, increased; the percentage of the DPPH scavenging by 1.6%, and the total antioxidant capacity (AOC) and antiradical power (ARP) activities by 4.2%. This increase is significant but modest, further gains may be obtained by investigating genotype x treatment interactions to identify both genotypes with inherently higher antioxidant capacity but also genotypes with increased response to irrigation levels.

Chapter 8: General discussion

This present study demonstrated the potential of reducing irrigation volumes from standard industry levels to maximise crop water use efficiency (WUE). However, the experiments indicated the irrigation treatments on a free draining sandy soil did not affect growth and yield.

8.1 Irrigation system assessments

Sprinkler irrigation systems are particularly suited to use for porous (sandy) soil with high infiltration rates such as the Grey Phase Karrakatta sand (Dechmi *et al*., 2003; Hansen *et al*., 1980; Li and Rao, 2003). A good design, management practice, understanding of crop water requirements and associated irrigation scheduling, can be utilised to improve efficiency of sprinkler irrigation systems (Hansen *et al*., 1980).

On both experiments, the sprinkler irrigation system showed good performance. The distribution uniformity (DU) assessment of the sprinkler irrigation system resulted in values ranging from 85% to 93% with an average of 90%, which was above the acceptable level of 80% (Haman *et al*., 2003). As a high spatial uniformity of water distribution was achieved, there was minimal variation in the average depth of water applied at different points in the plot (Haman and Yeager, 2005; Ley, 2003) equal to about 10% of the target water application volume (Hartz, 1999).

The irrigation water use efficiencies (Eu) of the sprinkler system utilised in both experiments (broccoli and carrot) was high (78% and 95% in the broccoli and carrot trials, respectively) and was not affected by the treatments (Table 3.3.4.). The Eu values exceeded the acceptable level of 75% for sprinkler irrigation systems (Hansen *et al*., 1980).

Water application efficiencies (Ea) in the broccoli experiment were low and differences among the treatments were minimal ranging from 35% to 43%. Numerous rainy days were experienced during the broccoli experiment and accumulated 274 mm of rainfall (i.e., 57%, 58%, and 65% greater than the target volumes for the 100% Epan (T_1), 150% Epan (T_2) and variable water replacement (VR) (T_{VR}) treatments, respectively). Therefore, this experiment is not representative of the treatments as planned, resulting in low water application efficiencies in all treatments.

In contrast, water application efficiencies (Ea) for the carrot experiment were relatively high. The 100% Epan (T_1), 150% Epan (T_2) and Crop Factor (CF) (T_{CF}) treatments had Ea values of 81%, 65% and 78% respectively (Table 3.3.3.). The Ea from the 100% Epan (T_1) and Crop Factor (CF) (T_{CF}) treatments were above the acceptable value of 75% for sprinkler irrigation (Hansen *et al*., 1980). The crops for all treatments consumed close to the same amount of water applied throughout the season. Compared to the 100% Epan and CF treatments, where water applied exceeded water stored by 21%, the low water application efficiency (E_a=65%) on the 150% Epan treatment was affected by the excessive water applied and about 35% of the water applied was lost through to deep percolation (Hill, 2000).

8.2 Broccoli experiment

While the effects of the irrigation treatment on yield and crop water use efficiency (WUE) (irrigation plus rain water) of broccoli were not significant, the WUE when calculated on the basis of irrigation volume alone (WUE_i) did differ among the treatments. In comparison to the 150% Epan treatment, the crop water use efficiency (WUE_i) (minus rainfall) of the 100% Epan and VR treatments increased by an average of 1.5-fold on the dry weight basis yield, and 1.6-fold on a fresh weight basis. The difference in irrigation treatment had no significant impact on, yield, plant growth, diameter of heads and nutritive quality (ascorbic acid and total carotenoid contents) of broccoli heads.

A high WUE_i can reduce the volume of water and cost required for quality broccoli production. This is an important finding as in the context of the crop production strategy employed in this experiment. Frequent irrigation was required during the winter period irrespective of rainfall to ensure high levels of soil water availability. The excess water applications experienced during the rainy, winter season of the broccoli experiment can be reduced by calculating the crop water requirements, based on the previous day's evaporation and predicted rainfall events and amounts. Rainfall events should always be considered as a supplement when water is applied through the irrigation system ('Irrigation Water Management', 1997). Before irrigation water is applied to the site, a decision must be made on the volume of irrigation water applied to the site dependant on water depletion and rainwater. Rainfall between 2.5 to 18.7 mm can be considered effective for crop

requirements to be retained in the root zone ('Irrigation Water Management', 1997; Hartz, 1999).

8.3 Carrot experiment

In the carrot experiment, compared to the standard industry irrigation level (the 150% Epan water replacement), a regulated water deficit from the 100% Epan and CF irrigation level increased the crop water use efficiency (WUE) by 14% and 26% respectively. Also, the reduction of irrigation levels from the 150% Epan water replacement to the CF and 100% Epan water replacements did not affect the yields (carrot roots on a dry weight basis).

Plant growth (height and root length) of the CF treatment was significantly greater than the 100% Epan treatment and the CF treatment was also greater than the 150% Epan treatments for parameters such as leaf length. This result was similar to the previous experiment conducted by Gibberd *et al*. (2003) in that the yield (root fresh weight basis) at the 151% Epan treatment was not different to the 124% Epan treatment, but was different to the 97% Epan treatment. Also, the reduction in irrigation to 124% Epan increased the WUE. The results of this experiment reveal that, with regulated water deficits in irrigation, (lower than standard industry) yields and WUE could be increased (Singh *et al*., 1987; Turner, 1990).

There were no treatment effects on the contents of carotenoid or ascorbic acid for both broccoli or carrot roots. The content of ascorbic acid ranged from 4.3 to 4.9 mg/100 FW, whilst the content of carotenoid ranged from 11.8 to 12.6 mg/100 FW. However, in the antioxidant analysis of carrots, the outcome was different and the treatments impacted on the antioxidant capacity of carrot root tissue. The 100% Epan treatment was greater than at the 150% Epan treatment by 1.55% of DPPH scavenging, and 4.2% in the total antioxidant capacity (AOC) and antiradical power (ARP) activity contents. The outcome of this antioxidant analysis was different from the ascorbic acid and carotenoid analyses as it assumed that although fruits and vegetables, including carrots, are rich sources of different phytonutrients, such as vitamin C, E and B-carotene, including antioxidant properties (Prior *et al*., 1998 cited in Alasalvar *et al*., 2005), the significant difference observed in this experiment might have been derived from other fractions such as the phenolics (Gil *et al*., 2002).

Physiology measurements were performed on the carrot trial over two days. Irrigation treatments had no significant effect on the photosynthesis rate (Pn) during the first day. However, the average of the Pn at the 150% Epan treatment was higher than the Pn at the CF and 100% Epan treatments on the second day. The results confirm Turner's (1990) statement that reductions in the amount of water application will decrease the rate of the photosynthesis. It is also indicated that the rate of photosynthesis of carrots was negatively correlated with the air and canopy temperature. Environmental factors, such as air and canopy temperature, influence the photosynthetic rate of carrots directly or indirectly (Gibberd *et al*., 2003). The leaf photosynthesis rate was high in the morning hours when temperatures were low and this equates to the peak period of assimilation. Similar to the leaf photosynthesis rate, the stomatal conductance rate is influenced by environmental and internal factors, such as light, CO_2 level, temperature and the water status of the plant (Hopkins and Huner, 2004) which in this experiment was mediated by air-to-leaf VPD. For example, on the second day of measurements, the highly irrigated 150% Epan treatment showed a higher stomatal conductance rate than the two lower irrigation level treatments. As demonstrated by Gibberd *et al*. (2003), the variation of the leaf photosynthesis rate is caused by the change of the stomatal opening. Intercellular CO_2 also has the same pattern as the stomatal conductance rate pattern.

There was no treatment effect on the leaf water potential (LWP) over the two-days of physiological measurements. However, the LWP value was negatively correlated with the Pn, VPD and temperature values which is similar to the observations by Gibberd *et al*. (2003).

8.4 Differential soil water stress index/soil water status

Soil water potential is a determinate of the flux of water into the plant. A tensiometer is the primary method utilised to measure the potential soil water holding capacity of a given soil sample associated with the water status in field crops (James *et al*., 1982) and can be used to regulate irrigation scheduling and volume (El-Shikha *et al*., 2007). The differential soil water stress index (DSWSI) was determined by the ratio of soil water potential of all treatments relative to 150% Epan treatment (as a standard industry irrigation level) in an average 0-45 cm depth.

In both the experiments the DSWSI was closer to one. The soil water tension in broccoli and carrot trials ranged from -3.0 to -9.3 kPa and -3.0 to -6.0 kPa, respectively and which is between saturation and field capacity for sandy soils (0 to -10 kPa) (Hansen *et al*., 1980). These results imply that there was no significant difference in soil water tension among all irrigation treatments and different soil depths (Table 4.3.5, Fig. 4.3.2, Table 5.3.4 and 5.3.3). One week before harvesting, the DSWSI in broccoli trial increased as soil water tension became increasingly negative and exceeded the soil field capacity, resulting in stressed soil conditions. The proposed of the soil moisture stress imposed near head maturity in broccoli may have a positive benefit on head color and stem turgor (Wurr *et al*., 2002).

In general, the differential soil water stress index (DSWSI) value from all treatments was relatively stable and close to one. There were no signs of soil water stress in any irrigation treatments in different soil depths in both the experiments.

8.5 Irrigation water requirement/scheduling

The application of irrigation in excess of pan evaporation levels in these experiments resulted in the generation of wastewater (drainage). It is difficult to predict the volume of rainfall and plant water requirements using pan evaporation as rainfall may be experienced after irrigation has been applied to the site. To avoid potential wastewater risks, an alternative irrigation schedule that can be determined using soil moisture monitoring devices should be considered to identify the soil water depletion. The soil water depletion can be determined when the percentage reaches a set level of available soil water within the root zone, based on soil and plant characteristics (El-Shikha *et al*., 2007).

The differential soil water stress index (DSWSI) can also be used to control the irrigation scheduling. When the DSWSI increases, the soil water tension which is compared with standard or control soil water tension, is more negative, exceeding the soil field capacity. This indicates that the soils have started to become stressed and need irrigation.

8.6 Conclusion

This present study indicated an increase in water use efficiency without reducing the yields and crops quality. This increase resulted from the combination of 1) High uniformity of the sprinkler irrigation and application of precise irrigation

schedule, 2) The reduction of irrigation application from 150% Epan replacement (as standard industry level) to not less than 100% Epan and crop factor or variable water replacement treatment, 3) The amount and frequency of the rainfall, and evaporation.

Management and operation of irrigation should be continually assessed and evaluated for the ongoing improvement of irrigation systems and water resource management. This practice can lead to improved water and energy conservation. The results in this study can be applied by horticultural growers in Western Australia, especially for broccoli and carrot. This application will enhance the efficiency of yield production, biomass and product quality, and reduce the cost and the risk of water pollution by using more effective fertiliser.

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Appendix 1: Medina trace element mix

Magnesium sulphate $MgSO_4.7H_2O$	50.5	Kg/ha
Manganese sulphate $MgSO_4.H_2O$	20.0	Kg/ha
Ferrous sulphate $FeSO_4.7H_2O$	18.0	Kg/ha
Borax $Na_2B_4O_7.10H_2O$	18.0	Kg/ha
Copper sulphate $CuSO_4.5H_2O$	18.0	Kg/ha
Zinc sulphate $ZnSO_4. H_2O$	18.0	Kg/ha
Sodium molybdenum $NaMoO4.2H_2O$*	2.0	Kg/ha

*: used for the first crop.

Appendix 2: Table of bio-composition of 100 g fresh raw carrot roots and broccoli heads.

Bio-composition	Carrot (unit/100g)	Broccoli (unit/100g)
	(g)	**(g)**
Moisture	86-89	88.2-91
Protein	0.7-1.1	3.0-4.4
Fat	0.2-0.5	0.4-0.9
Carbohydrates	6.0-10.6	1.8-5.2
Total sugar	5.6	1.5
Crude fiber	1.0-2.4	1.1-2.6
Total ash	0.9-1.1	
	(mg)	**(mg)**
Calcium	27-80	48-103
Iron	0.4-2.2	0.9-1.7
Phosphorus	25-53	66-87
Sodium	35-47	8-27
Potassium	323-341	325-382
Magnesium	9.0-19	22
Cooper	0.02	0.02
Zinc	0.2	0.6
Sulfur		130
Chloride		100
Thiamine	0.04-0.10	0.07-0.10
Riboflavin	0.02-0.06	0.06-0.23
Niacin	0.2-2.5	0.64-0.9
Vitamin C	4-9.3	87-113
Vitamin E		1.3
Vitamin B6	0.15	0.14-0.16
Manganese		0.2
		(μg)
Iodine		2
Folate		90
Carotene	5.33	575
	(IU)	**(IU)**
Vitamin A	1,100-28,129	1,542-2,500

	kcal	(kJ)	kcal	(kJ)
Energy Value	140	124-125	28	137-138

Sources: Lorenz and Maynard (1997); Kotecha *et al*. (1998); Nonnecke (1989); Rangavajhyala *et al*. (1998); Rubatzky (1999).

Appendix 3: Flied experiment layout

	Plot 1		Plot 7	
	Plot 2		Plot 8	
	Plot 3		Plot 9	
	Plot 4		Plot 10	
	Plot 5		Plot 11	
	Plot 6		Plot 12	

☐ = Treatment 1

■ = Treatment 2

☐ = Treatment 3

Appendix 4: Linear regression equations of physiologies correlation on carrot experiment

The linear regression equations at Figure 5.3.6:

Between the vapour pressure deficit (VPD) and photosynthesis (Pn):

$Pn = -5.0246VPD + 26.135$ ($R^2 = 0.33$);

$Pn = -7.367VPD + 32.54$ ($R^2 = 0.36$);

$Pn = -8.198VPD + 30.421$ ($R^2 = 0.63$),

at the 100% Epan, 150% Epan and CF treatments, respectively.

Between vapour pressure deficit (VPD) and leaf water potential (ψ_l):

$\psi_l = -126.53VPD - 901.735$ ($R^2 = 0.069$);

$\psi_l = -280.29VDP - 647.61$ ($R^2 = 0.34$);

$\psi_l = -152.97 VDP - 765.64$ ($R^2 = 0.10$),

at the 100% Epan, 150% Epan and CF treatments, respectively.

Between the leaf water potential (ψ_l) and photosynthesis (Pn):

$Pn = 0.0036\psi_l + 22.263$ ($R^2 = 0.04$);

$Pn = 0.0145\psi_l + 37.055$ ($R^2 = 0.32$);

$Pn = -0.0013\psi_l + 16.585$ ($R^2 = 0.04$),

at the 100% Epan, 150% Epan and CF treatments, respectively.

Between intercellular CO_2 (Ci) and photosynthesis (Pn):

$Pn = -0.0005Ci + 18.366$ ($R^2 = 3E\text{-}05$);

$Pn = 0.0105Ci + 19.436$ ($R^2 = 0.0017$);

$Pn = -0.0165Ci + 20.879$ ($R^2 = 0.0203$),

at the 100% Epan, 150% Epan and CF treatments, respectively.