EFFECT OF WATER APPLICATION AND PLANT DENSITY ON CANOLA (*Brassica napus* L.) IN THE FREE STATE

by

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DECLARATION

I declare that the thesis hereby submitted by me for the Masters of Science in Agriculture degree at the University of the Free State is my own independent work and has not previously been submitted by me to another University/Faculty. I further cede copyright of the thesis in favour of the University of the Free State

Keletso Angelique Seetseng

Signature..........

Date: 2 April 2009

Place: Bloemfontein, South Africa

DEDICATION

I dedicated this thesis to my grandma Otumiseng Nellie Seetseng, who departed this year (23 October) shortly before the completion of this work; she was such a caring and a loving mother. She raised an exquisite family and encouraged me to go to university at a rather critical stage in my upbringing. I just wish she was here to celebrate with me, the achievement we dreamt of on more than one occasion. She left behind so many good memories. Her spirit and zest for life were inspirational to everyone whom she raised and knew her. "Robala ka kagiso mosetsana wa motshweneng, ke ithutile go ka tlala seatla mo go wena". "But, I miss you mama and wish you were somehow near"

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ABSTRACT

Canola serves as a very favorable crop to produce oil world wide. Canola production in South Africa is mainly restricted to the Western Cape Province under winter rainfall conditions. The Protein Research Foundation propagated the production expansion to the central part of South Africa. The semi arid area (Central part of South Africa) is characterized by variable and unreliable summer rainfall. Irrigation is therefore vital for sustainable production of a winter crop like canola. The aim of this study was to establish the crop's plasticity ability, water use, water use efficiency and transpiration coefficient under a range of water application and plant density treatments combinations for the central South Africa.

An experiment with a line source sprinkler irrigation system was conducted near Bloemfontein in the Free State Province. Water applications, excluding 57 mm rain were: W1 = 118 mm, W2 = 176 mm, W3 = 238 mm, W4 = 274 mm and W5 = 363 mm. These water applications were combined with the following planting densities: PD25 = 25plants m^{-2}, PD50 = 50 plants m^{-2}, PD75 = 75 plants m^{-2}, PD100 = 100 plants m^{-2}, PD125 = 125 plants m^{-2}.

Seeds (558 - 4653 kg ha^{-1}) and biomass (1983 - 6733 kg ha^{-1}) yields induced by the treatments proved that canola has a high plasticity. This is because over the full range of water application treatments optimized yields were realized at only one plant density though different for seed (25 plant m^{-2}) and biomass (75 plants m^{-2}) yields. Compensation of yields at lower plant densities resulted from branches and hence pods per plant.

Total evapotranspiration increased linear (r^2 = 0.97) from 245 mm with 118 mm water application (W1) to 421 mm with 363 mm water application (W5) but was not influenced by plant density at all. Water use efficiency confirmed the optimum plant density for fodder production is 75 plants m^{-2} and for seed production is 25 plants m^{-2}. The water use efficiency at these two plant densities were 12.9 kg ha^{-1} mm^{-1} and 9.6 kg ha^{-1} mm^{-1}, respectively.

The β coefficient of canola was constant (2.26) for the full to moderate irrigation regimes (W5 - W3), but not for the low irrigation regimes (W2 - W1). The β coefficient of 2.26 was used to separate the evapotranspiration of the W3 - W5 treatments into evaporation (56%) and transpiration (44%). This method was not suitable to establish the influence of plant density on the two components of evapotranspiration. A transpiration coefficient of 0.0045 was calculated for canola when planted for fodder at an optimum plant density of 75 plants m^{-2} under moderate (W3) to full (W5) irrigation.

Key words: Biomass yield, seed yield, transpiration coefficient, water use, water use efficiency.

UITTREKSEL

Kanola word wêreldwyd gereken as een van die mees belowendste gewasse vir oliesaadproduksie. Die gewas word hoofsaaklik in die Wes-Kaap Provinsie verbou en die Proteiennavorsingstigting is van mening dat dit moontlik ook in die sentrale dele van Suid-Afrika verbou kan word. Die klimaat van die sentrale deel word as halfdroog beskou en word gekarakteriseer deur wisselvallige en onbetroubare somerreënval en baie lae winterreën wat besproeiing noodsaak vir die verbouing van wintergewasse soos kanola. Die doel van die studie was om die plastisiteitsvermoë, waterverbruik, waterverbruiksdoeltreffenheid transpirasie koëffisiënt van kanola in die sentrale deel van Suid-Afrika onder 'n reeks van watertoedienings- en plantdigheidsbehandelingskombinasies te ondersoek.

'n Veldeksperiment met kanola as toetsgewas is onder 'n lynbronsprinkelaar-besproeiingstelsel naby Bloemfontein in die Vrystaat uitgevoer. Die waterbehandelings, uitsluitende die 57 mm reën, het bestaan uit: W1 = 118 mm, W2 = 176 mm, W3 = 238 mm, W4 = 274 mm en W5 = 363 mm. Hierdie water behandelings is met die volgende plantdigthede gekombineer: PD25 = 25 plante m^{-2}, PD50 = 50 plante m^{-2}, PD75 = 75 plante m^{-2}, PD100 = 100 plante m^{-2}, PD125 = 125 plante m^{-2}.

Saad- (558 - 4653 kg ha^{-1}) en biomassaopbrengste (1983 - 6733 kg ha^{-1}) wat deur die behandelings geskep is, het bewys dat kanola oor 'n hoë plastisiteitvermoë beskik. 'n Verdere bewys daarvan is die feit dat oor die volle reeks van watertoedieningsbehandelings optimum opbrengste by slegs een plantestand verkry is, alhoewel dit vir saad (25 plante m^{-2}) en biomassa (75 plante m^{-2}) verskil het. Kompensasie in opbrengste by die lae plantdigthede is veroorsaak deur meer sytakke wat aanleiding gegee het tot meer peule per plant.

Totale evapotranspirasie (ET) het linieër (r^2 = 0.97) van 245 mm met 118 mm watertoediening (W1) na 421 mm met 363 mm watertoediening (W5) toegeneem. Plantdigthede het egter nie die totale ET beïnvloed nie. Die waterverbruiksdoeltreffendheid bevestig dat die optimum plantdigtheid vir voerproduksie 75 plante m^{-2} en vir saadproduksie 25 plante m^{-2} is. Die waterverbruiksdoeltreffendheid by die twee plantdigthede was onderskeidelik 12.9 kg ha^{-1} mm^{-1} en 9.6 kg ha^{-1} mm^{-1}.

Die β koëffisiënt van kanola was konstant (2.26) oor die vol tot matige beperkende besproeiingsbehandelings (W5-W3), maar nie vir die lae besproeiingpeile nie (W2 - W1). Die β koëffisiënt is gebruik om die evapotranspirasie van W3 - W5 behandelings in evaporasie (56%) en transpirasie (44%) te skei. Vanweë die veranderlikheid van die β koëffisiënt by die lae besproeiingspeile was dit nie moontlik om die skeiding in evapotranspirasie vir die behandelings te bereken nie. 'n Transpirasiekoëffisiënt van 0.0045 is vir kanola onder voerproduksie by 'n optimum plantdigtheid van 75 plante m^{-2} by matige (W3) tot volbesproeiingspeile (W5) verkry.

Sleutelwoorde: Biomassaopbrengs, saadopbrengs, transpirasiekoëffisiënt, waterverbruik, waterverbruiksdoeltreffendheid.

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LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Motivation

Canola is an oil seed crop, genetically altered and improved version of rapeseed. Rapeseeds as a group are cool-season annuals of the Cruciferae (mustard) family belonging to the genus Brassica (Murdock *et al.*, 1992). In 1978, the rapeseed industry in Canada adopted the name "canola" to identify these new rapeseed varieties. Canola is genetically low in both erucic acid and glucosinolates and this distinguish it from ordinary rapeseed. The name "canola" is an internationally registered trademark of the Canola Council of Canada. Seeds of canola commonly contain 40% or more of oil which is widely used as cooking oil, salad oil and in making margarine. It is appealing to health conscious consumers because it has the lowest saturated fat content of all major edible vegetable oil (Raymer, 2002). Canola meal is the major by-product resulting from the extraction of oil from seeds and represents about 60% of the original weight of the seed containing 36 to 44% crude protein (Bell, 1995). This meal is therefore used as a constituent in animal feed production. The leaves and stems of canola provide high quality forage because of its low fiber and high protein content and can be milled into animal feed (Wiedenhoeft and Bharton, 1994).

Production of canola in South Africa is currently with a few exceptions restricted to the winter rainfall region of the Western Cape Province. In this region canola is planted sometimes in rotation with wheat. The two crops are of different family which is an advantage in suppression of weeds, pests and diseases. Despite of this advantage, only 11% or less of the 400 000 ha available land in the Western Cape was used annually over the past five seasons for canola production (Table 1.1). During this period the area under canola production decreased from an average of 44 225 ha in the first two season to an average of 32 630 ha in the last two seasons. The reason for this decline is that producers prefer wheat instead of canola due to better market prices and less pest control measures (Personal communication; Prof G.A. Agenburg, Department of Agronomy, University of Stellenbosch, Stellenbosch). However the area planted with either wheat or sunflower decreased.

The contribution of canola to oilcake production in South Africa is quite small, ranging between 6 and 10% in the past three seasons (Table1.1). Oilcake production from either sunflower or canola seems to be insufficient for local demand and therefore importing oilcake is essential. The imported oilcake was 22 144 tons in 2006/2007 and 68 808 tons in 2007/2008. The prediction is that the local demand for oilcake will increase in future, because of the expected increase in consumption of imported oilcake. An increase in oilseed crop production is therefore of great importance to be more self sufficient in oilcake. As canola production is subordinates to sunflower production it seems logical to concentrate on the expansion of the former.

In South Africa like elsewhere in the world, biofuel production will increase. This is because of the need for clean oil that is friendly to the environment. Industries for biofuel production are centered in the extraction of oil from the production of crops as an alternative to non-renewable fossil oil. For instance the production of biodiesel depends heavily on the availability of seed oil produced. The South African government has allocated some money for the introduction of canola production in the Eastern Cape Province. This will serve as an anchor for a biodiesel plant (Khumalo, 2007) which will in future compete with other plants for the production of oilseed crops in addition to plants manufacturing human food and animal feed. It is further motivated that the expansion of oilseed crop production in South Africa is crucial.

Table 1.1 Area planted (ha) with wheat and canola, oilcake produced from sunflower and canola, and oilcake imported over some seasons in South Africa (National Crop Estimates Committee, 2008).

	Area planted (ha)				
CROP	**2003/2004**	**2004/2005**	**2005/2006**	**2006/2007**	**2007/2008**
Wheat	748 000	830 000	805 000	764 800	632 000
Canola	44 200	44 250	40 200	32 000	33 260
	Oil cake produced (ton)			**Oilcake imported (ton)**	
	2005/2006	**2006/2007**	**2006/2007**	**2006/2007**	**2007/2008**
Sunflower	267 120	199 500	178 500	22 144	68 808
Canola	17 270	21 175	14 300	-	-

Based on the above mentioned it is not surprising that Dr De Kock, a representative of the Protein Research Foundation conveyed a few years back to researchers from the ARC-Small grain Institute, Griqualand West Co-operation and UFS-Department of Soil, Crop and Climate Sciences the need for research on canola. He motivated this need that canola may be a good alternative for wheat under irrigation and possibly dryland since the latter is almost the only crop planted in winter by farmers. Dr De Kock emphasized that for successful introduction of canola as an alternative crop for wheat, proper information on agronomic practices like cultivar selection, planting date, plant density, optimum fertilization and irrigation are essential. During the workshop Prof Van Rensburg and Du Preez mentioned that the UFS-Department of Soil, Crop and Climate Sciences is inter alia well-equipped to do research on the interaction of water application and plant density using the line source approach. Research of this nature of canola was generally well supported by attendants since optimization at plant density and water supply is crucial when this oilseed crop is intended for cultivation in the central part of South Africa. This part of South Africa is semi arid and it rain mostly out of growing season for canola because canola is a winter crop. Therefore the expectation is that the growth of this crop will often be constrained by the water availability if not irrigated.

1.2. Objectives

The general objective with this study on canola in the summer rainfall region of South Africa was to establish optimum plant densities for different soil water regimes. Specific objectives were to:

(i). Review literature on canola addressing its agronomic requirements, growth and development, and water use and water use efficiency (Chapter 2).

(ii). Examine the effects of different rates of water application and plant density on yield, yield components and growth parameters of canola to establish the plasticity of the crop (Chapter 3).

(iii). Determine water use and water use efficiency of canola at various rates of water application and plant density (Chapter 4).

(iv). Quantify the transpiration efficiency coefficient of canola over a range of water application levels and plant densities (Chapter 5).

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Canola is not commonly planted in the summer rainfall region of South Africa and as pointed out earlier. Proper knowledge of this crop is lacking in general among agronomists of the Free State region. Therefore some agronomic requirements of canola are reviewed firstly as the baseline information on climate, plant density, fertilization and irrigation. Literature on the growth and development of canola and its yield compensatory mechanisms is dealt with in more detail. Lastly, aspects of canola's water use and water use efficiency is discussed.

2.2. Agronomic requirements

2.2.1. Climate

Studies done by Thurling and Vijendra Das (1977), Mendham *et al.* (1981a), Morrison *et al.* (1990b) and Angadi *et al.* (2003) showed that climate plays a major role in canola production. In areas that have a short growing season, canola has a limited time to express its potential yield plasticity as compared with other regions that have a longer growing season (Mendham and Salisbury, 1995). Yield plasticity of canola therefore varied widely indicating the importance of weather conditions in the determination of optimum plant density (Angadi *et al.*, 2003). Any environmental stress that affects vegetative growth of canola may affect yield and seed composition.

Rainfall: When grown under rainfed, canola fits well in the 450 - 550 mm rainfall zones and it is susceptible to water stress. This is why according to Zang *et al.* (2004) canola production has a slow but steady expansion in southwestern Australia with an annual rainfall of 450 - 700 mm. In semi arid regions, rainfall is imperative in the production of canola to meet the crop's water demand for stress free growth during the season. A shortage of rain during the most susceptible growth stage of canola, namely towards pods filling could lead to a reduction in yield

Temperature: Temperature plays a significant role in the growth and development of canola, as shown by several studies on rapeseeds (Thurling and Vijendras Das, 1977; Mendham *et al.*, 1981b; Morrison *et al.*, 1989). Sidlaukas and Bernotas (2003) cited Mendham *et al.* (1981a), who plotted days to maturity against mean temperature and that resulted in a linear relationship indicating that each degree (^{0}C) rise in temperature gave nearly eight days earlier maturity. Based on various trials in the central part of South Africa Nel (2005) concluded that a mean daily temperature of 18^{0}C during the grain filling stage appears to be the threshold. Mean daily temperature above this threshold resulted in lower seed oil content and yield were limited. He also stated that although canola can survive light frosts, cold periods below -4^{0}C might harm flowers and young pods.

2.2.2. Soils

Canola prefers deep, medium textured soils that are well drained because it does not tolerate poor drainage or flooding conditions that leads to water logging (Canola Council of Canada, 2005). Heavy clay soil and soils that tend to crust, compact or lack of surface soil moisture at planting usually affect canola establishment negatively. A period of four years without canola in rotational systems is recommended for fields that have been infected with sclerotinia white mold or blackleg. Planting of fields infested with garlic and wild mustard also might lead to the contamination of seeds and result in lower seed quality and grade standards, therefore should be avoided (Canola Council of Canada, 2005).

2.2.3. Fertilization

In areas of Victoria, South Australia with less than 450 mm annual rainfall, some farmers choose to use starter fertilizer drilled with the seeds and top dress the crop with urea later. The rates of fertilizer applied depend on the yield targets which mostly depend on the amount of rainfall the crop is likely to receive during the growing season (Department of Primary Industries, 2008). Adequate fertilization is essential for obtaining top canola yields. Nitrogen is the most important fertilizer applied to canola in terms of costs to growers and inadequate or untimely nitrogen application often restricts yield (Hocking and Stapper, 2001). Nitrogen deficiency results in fewer and smaller leaves than when plants are nitrogen sufficient (Medham *et al.,* 1981b). Although canola takes up large amount of nitrogen from the soil, not all of it is removed from the field at harvest. The remaining nitrogen in the canola residues can therefore be mineralized. Nitrogen in residues together with fertilizer nitrogen not taken up, is estimated to be as high as 60% in some instances, and can therefore make a large contribution to the next summer crop.

According to the guidelines of Nel (2005) farmers should apply nitrogen at a rate equivalent to between seven and eight percent of the target seed yield. This is equivalent to between 70 and 80 kg N ha^{-1} for seed yield of 1 ton ha^{-1}. The nitrogen concentration in the seeds amounts to four percent, which implies that for one ton of seeds only 40 kg N ha^{-1} will be removed. He also suggested that if the Bray 1 extractable phosphorus content of a soil exceeds 20 mg kg^{-1}, 7 kg P ha^{-1} should be applied for every ton of seeds expected to be harvested per hectare. In a similar manner he recommended an application of 10 kg K ha^{-1} for each ton of seed to be expected per hectare when the NH_4OH_C exchangeable potassium content of a soil exceeds 80 mg kg^{-1}. The moisture regulating effect of potassium is well documented. In addition, magnesium and sulfur are also essential for oil production and quality when canola is cropped. Therefore care must be taken that the latter two nutrients are sufficient (Department of Primary Industries, 2008).

2.2.4. Planting

Seedbed preparation: A firm, moist and uniform seedbed is recommended of the planting of canola. This kind of seedbed promotes a rapid germination and early uniform stands because it allows a good seed to soil contact and quick water absorption (Canola Council of Canada, 2005). Thomas (1994) observed in field studies that emergence of canola was reduced when seeding was deeper than 30 mm. This is because canola seedling finds it difficult to force their way through a thick soil cover or crust (Canola Growers Association, 2005)

Planting date: A suitable window period for planting of canola depends on prevailing weather conditions and is therefore site specific. In the central part of South Africa such a period must limit the chance of severe frost damage during flowering on the other hand and extreme heat during grain filling on the other hand. Based on these criteria Nel (2005) recommended planting cultivars with a medium growth period from 20 May until 20 June

Hodgson (1979) indicated that due to differences in environments, there is a trade-off between sowing early to avoid end-of-season high temperatures and water deficit, which depresses seed yield and oil concentration. In Southeastern Australia, Taylor and Smith (1992) studied for three years in concession the response of canola sowed in April, May, June, July and August respectively. They concluded that optimum planting dates depend entirely on the weather condition of every season. Row spacing: In Northwest Alberta, Christensen and Drabble (1984) observed greater stand mortality at wider row spacing than narrower row spacing due to excessive water and hence root disease developed. However a greater yield at 15 than 30 cm row spacing was reported in studies conducted by Morrison *et al.* (1990b). This phenomenon was attributed to lower interplant competition that resulted in a greater number of pods per plant and seeds per pod. Plants exhibited higher dry weight per unit area and at certain growth stages, higher leaf area index when grown in row spaced at 15 cm compared to 30 cm.

2.2.5. Irrigation

About any method of irrigation can be used effectively for the production of canola (McCaffery, 2004). However when sprinkler irrigation is employed special precautions and good water management practices are required to reduce the risks of disease infection (Johnson and Croissant, 2006). Water stress results in large yield losses because the leaves wilt and die sooner, causing less branching, pods per plant and seeds per pod. The pods and seeds become smaller. The application of water played a significant role in the accumulation of yield as indicated in Table 2.1. Under dry land, total seed yield obtained was 1042 kg ha^{-1} and increased when irrigation was applied at different growth stages. According to researchers at Agriculture and Agri-Food Canada (2005), the crop responded positively to irrigation at different growth stages and accumulating more yield in the process. The indication is that full irrigation is necessary up to ripening stage. In the report they compiled they indicated that rainfall was not enough and only irrigation kept water availability above 50%.

Table 2.1 Effects of irrigation levels on canola yield (adapted from Agriculture and Agri-Food Canada, 2005).

Irrigation Treatment	**Water (mm)**	**Seed yield (kg ha^{-1})**
No irrigation	0	1042
Irrigate to stem elongation	65	1281
Irrigate to early pod formation	130-195	1747
Irrigate to pod ripening*	260-325	2636

* *First seed turning brown*

The result in Figure 2.1 indicates that when canola was irrigated from the rosette stage until harvest, biomass steadily increases until the end. The total accumulated yield under irrigation was 2554 kg ha^{-1} and the LAI was almost 4.5. On the other hand, biomass accumulated on dry land was not even half of irrigated crop as it was 952 kg ha^{-1} with a LAI of almost 3.

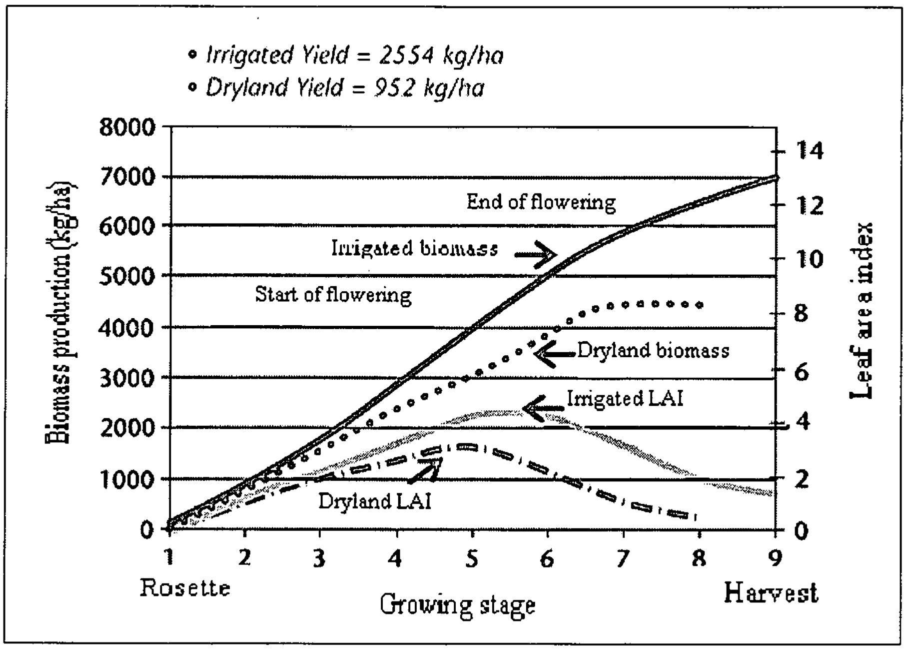


Figure 2.1. Biomass production and Leaf Area Index (adapted from Agriculture and Agri-Food Canada, 2005).

2.2.6. Plant density

Canola is a very flexible plant that can adapt to a wide range of plant densities due to its ability to increase branches resulting in more pods formation. It has therefore the ability to compensate using yield components at different plant densities and this is well documented in several papers (Mendham *et al.* 1981a; Ogilvy, 1984; McGregor, 1987; Leach *et al.*, 1999). Plant density governs yield components and thus the yield of an individual plant (Ozer, 2003). On the contrary, Diepenbrock (2000) showed that plant density is an important factor affecting yield. A uniform distribution of plants per unit area is a prerequisite for yield stability with canola. The ideal plant density is 50 - 70 plants m^{-2} and that is achieved by planting three to four kilo grams of seeds per hectare. However densities of 80 - 100 plant m^{-2} improve the uniformity in maturation but it is important to minimize interplant competition in crops.

2.3. Plant development and growth

2.3.1. Growth stages

Plant development is the progress when a crop grows through the stages of its life cycle. During this process its organs increases in size that coincide with the accumulation of dry matter. Knowledge on plant morphology is therefore crucial in understanding the response of a crop to growing conditions (Thomas, 2001). Such knowledge helps in developing agronomic strategies for better crop management. Stages of development often needs to be quantified and more precisely defined for a crop because it is a useful key for commercial production as it assists in determining the timing of management operations (Boyles *et al.*, 2006). The interaction between development and growth at each stage contributes to the potential and the actual yield of a crop (Mendham and Salisbury, 1995). The five major stages of growth were identified by Thomas (2001) for canola and are listed in Table 2.2. A concise description of each growth stage follows:

Pre-emergence: During germination seed absorbs water and swells, splitting the seed coat and the root grow downward and develop root hairs anchoring the developing seedling. The hypocotyl (stem) grows upward, pushing the cotyledons (seed leaves) through the soil (Boyles *et al.*, 2006).

Seedling: Seedlings of canola emerge four to ten days after planting and develops a short stem and the exposed growing point makes seedlings more susceptible to environmental hazards than wheat. The cotyledon at the top of the hypocotyl expands, turn green and provide nourishment to the plant Seedlings develop its true leaves from four to eight days after emergence (Boyles *et al.*, 2006).

Rosette: The plant establishes a rosette with larger and older leaves but smaller at the base and newer leaves at the center. The stem length remains unchanged as its thickness increases (Boyles *et al.*, 2006).

Table 2.2. Growth stages of canola from vegetative to reproductive stage using a scale developed in Canada (adapted from Thomas, 2001)

Stage of development.	**Description of main raceme.**
0: Pre-emergence	Seeds absorbing water and the formation of seedling roots.
1: Seedling.	Emerging of seedlings above the soil.
2: Rosette.	First true leaf expanded; Second true leaf expanded.
3: Budding.	Flower cluster visible at center of rosette; Lower buds yellowing.
4: Flowering.	First flower opens. Many flowers opened, lower pods elongating. Lower pods starting to fill. Flowering complete, seed enlarging in lower pods.
5: Ripening.	Seeds in lower pods full size, translucent. Seeds in lower pods green; Seeds in lower pods green-brown; Seeds in lower pods yellow or brown; Seeds in all pods brown, plant dead.

Budding: Rising temperatures and lengthening daylight initiate bud formation. A cluster of flower buds become visible at the center of the rosette and rises as the stem become bolts or lengthens rapidly. Leaves attached to the main stem unfold and the cluster of flower buds enlarges as the main stem elongates. Secondary branches develop from buds in the axil of some leaves (Boyles *et al.*, 2006).

Flowering: Flowering begins with the opening of the lowest bud on the main stem or raceme and continues upward, with three to five or more flowers opening each day. Secondary branches begin to flower a few days later. Under favorable growing conditions, flowering of the main stem continues for two to three weeks and full plant height is reached at the peak of flowering stage. High temperatures at flowering will hasten plant development and reduce the time from flowering to maturity. This shortens the time that the flower is receptive to pollen, as well as the duration of pollen release and its viability. The result may be a decrease in the number of pods per plant and the number of seeds per pod, resulting in lower yields. At this stage, the stem and pod walls are the major sources of nutrients for seed growth. Canola plants initiate more flower buds that can develop into productive pods. Only half the flowers that open will develop into productive pods. A plant only maintains the number of pods it can support through photosynthesis under prevailing conditions. The firm green seed has adequate oil and protein to support future germination. Stems and pods turn yellow and become brittle as they dry out. The seed coat turns from green to brown, and seed moisture is lost rapidly. When the seed is completely ripe, it has a dark uniform color (Boyles *et al.*, 2006).

Ripening: Maturation begins as the last flowers fade from the main raceme but flowering continues on secondary racemes for some time. Pods at the base of the main raceme are considerably more developed. Matured pods split easily along the center membrane and the seed is lost by shattering (Boyles *et al.*, 2006). The focus on the development and growth of canola was so far on the above-ground parts of the crop. Knowledge on the development and growth of canola's roots is also important since water and nutrients depend upon them. Secondary roots grow from the taproot in four to eight days after emergence. After establishment, a rapid root growth can be noticed consisting of taproot extension growing vertically and the secondary root growth laterally on the taproot. Roots growth continues until it reaches a maximum rate at the flowering stage. In the absence of constraints the leading roots will penetrate downwards through the soil at an average rate of one centimeter per day reaching ultimately a depth of 1 - 1.5 m. About two-thirds of the total root system length is found in the top 30 cm of the profile. The growth of canola's roots will be affected and delayed when the soil is dry, compacted or waterlogged (Mendham and Salisbury, 1995). Canola is an excellent break crop for wheat, and its effectiveness is thought to be due in part to the suppression of soil-borne cereal pathogens by biocidal compounds released by decayed roots tissues, which reduce disease infection in following crops (Angus *et al.,* 1991; Kirkegaard *et al.,* 1994).

2.3.2. Growth stages and sequential development pattern of yield components

The attainment of characteristic form and function in a crop depends according to Adams (1967) upon the chain of interrelated events. The events are sequential in time, gene related and subjected to the modifying influences of environmental and agricultural forces for example, maize displays an orderly sequence of development of yield components which are ears per plant, number of kernels per row and kernel weight (Leng, 1963; Hatfield *et al.*, 1965). In the case of wheat the development sequence in yield components involves the formation of ears per plant, number of spikelets per ear, number of seeds per spike and seed size or weight (Leng, 1963; Hatfield *et al.*, 1965). The sequential pattern for yield components in sorghum is characterized by the formation of number of panicles per plant, number of seeds per panicles and seed size or weight (Krieg and Lascono, 1990).

Pods forming crops such as navy beans, soybeans, chick peas and rapeseeds display a similar development of their yield components (McGregor, 1987; Bluementhal *et al.*, 1988; Liu *et al.*, 2003). Adams (1967) described the sequential order of development in yield components for navy beans (*Phaseolus vulgaris*) in relation to its growth stage using the diagram presented in Figure 2.2. He stated that the terminal, essential morphological components of yield are the number of pods per plant, or per unit area, the mean number of seeds per pod and the average seed size or weight. The components of yield in most pod forming crops are believed to be genetically independent and the component's correlations are generally near zero or non competitive under non-stressed environments (Clarke and Simpson, 1978; Diepenbrock, 2000; Ball *et al.*, 2001).

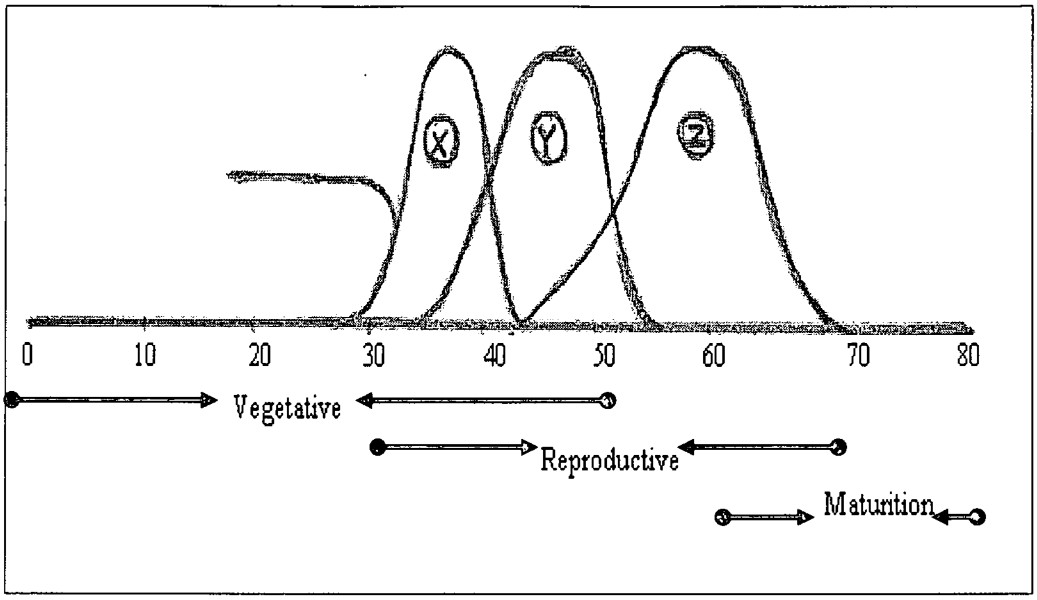


Figure 2.2. Days from emergence to maturity in a sequential pattern for development of yield components and growth stages in navy bean (adapted from Adams, 1967)

2.3.3. Effect of water supply and plant density on yield components

In semi-arid conditions, water supply is regarded as an environmental factor that induces competition among individual plants. Fortunately, the plasticity of a plant enables its organs on alternative pathway in attaining their final maturition. In agriculture where crops are planted in a fix configuration, individual plants respond similar with respect to optimize the available resources. Therefore, Krieg and Lascono (1990) stated that plasticity in seed forming crops is largely determined by the number of seeds per unit area.

The seeds number components comprised of the number of organs (ears, cobs, and panicles) per unit area, the number of seeds per organ and the seed size or weight. These components reflect on the yield attained. Champolivier and Merrien (1996) investigated the effects of water stress on rape seed under controlled glasshouse conditions. They observed that yield and yield components were mainly affected by water shortage occurring from flowering to the end of seed setting stage. Irrigation, according to Clarke (1977) increased branch numbers through lengthening of the flowering period and as a result the number of pods was also increased. Allen and Morgan (1972) reported that the ability of canola to supply assimilates during flowering stage is important in determining the number of pods. During this stage of development, the number of pods is ultimately determined by the survival in number of branches (Diepenbrock, 2000). Irrigation increased seed number through its effect on pod surface area, which resulted in a greater assimilates supply (Clarke and Simpson, 1978). In water stress condition, growth is hindered as the plant loses its leaves quicker and therefore photosynthesis is inefficient. In canola, plant density depends on seeding rates and their physical configuration in plant rows. Morrison *et al.* (1990a) stated that there is often confusion with respect to the concept of "physical" space and the "available" space for plants.

Physical space refers to the volumetric area available for growth and competition among plants for this space rarely occurs (Milthorpe and Moorby, 1974). Plants do compete for available space if affected by competitive stress among individual plants. Competition occurs when a plant require a particular factor necessary for growth or when the immediate supply of the factor is below the combined demand for plants (Milthorpe and Moorby, 1974). These factors are inter alia, light, carbon dioxide, oxygen, and water, nutrients collectively they constitute "available space". According to Donald (1963) plants exhibit extreme plasticity by responding in size and form to the available space. Leach *et al.* (1999) reported that plants grown at high densities had fewer pod-bearing branches, but produces more branches per plant and at low plant densities produce more branches that carry fertile pods.

Canola establishes plasticity to maintain seed yield across a wide range of plant densities. Due to this ability of the crop Thurling (1974) found a positive correlation between seed yield and pods per plant, regardless of plant density, there were more branches per plant, confirming that a reduction in plant density significantly increases branching and the number of pods per plant. In support, Angadi *et al.* (2003) concluded that the number of pods per plant was the most important factor responsible for yield compensation, while seeds per pod and seed weight did not significantly contribute to yield compensation. Morrison *et al.* (1990a) showed with a rapeseed field in southern Manitoba that 15 cm row spacing out performed 30 cm row spacing. Plants grown in the 15 cm rows had a greater dry matter weight and leaf area index than plants grown in 30 cm spaced rows. However, they recorded higher crop growth and net assimilation rates at lower (1.5 and 3.0 kg ha^{-1}) than higher (6 and 12 kg ha^{-1}) seeding rates Similarly in the Western Cape, 17 cm row resulted in higher yields than 34 cm, and a seeding rate of 3 kg ha^{-1} out-yielded a seeding rate of 7 kg ha^{-1} (De Villiers and Agenbag, 2007).

Clarke and Simpson (1978) investigated the plasticity of seed with regard to both water application and plant density. A negative relationship was found between an increased plant stand and branches per plant, pods per plant and seeds per pod were observed at all three irrigation regimes. Adams (1967) stated that it is often more advantageous to possess a buffered yield system. Therefore negative correlations should be expected almost as a regular feature of development. The number of seeds per pod and thousand seed weight were both lower on the bottom branches than on the main stem and this was due to pods formed at a greater depth in the canopy where light might be a limiting factor for photosynthesis,. They concluded that yield of rapeseed per unit area was a function of number of pods per unit area, number of seeds per pod and weight per seed. The study of Clarke and Simpson (1978) showed clearly that the number of pods per unit area increased with higher seeding rates, although number of pods per plant declined. There was no compensation between number of pods per plant and number of seeds per pod.

2.4. Water use and water use efficiency

2.4.1. Water use

In semi-arid areas water is ussually the most important production limiting factor. Thus the basic principle that should be used to manage the soil water balance ensuring minimum water losses under dryland an even irrigation in order to increase the amount of water that can be transpired. The soil water balance in its simplest form for the growing season of an annual crop like canola is as follows (Hensley *et al.*, 1997):

$$\Delta S = (P + I) - (R + D + E + T) \qquad 2.1$$

Where : ΔS = change in soil water content over a specific soil depth (mm); over the growing season

P = precipitation (mm)

I = irrigation (mm)

T = transpiration (mm)

E = evaporation from the soil (mm)

R = runoff (mm)

D = deep drainage (mm)

Supply of water through either precipitation or irrigation and the effect thereof on canola was discussed earlier (See section 2.2.5 and 2.3.3) and hence not repeated here.

Runoff: This process reduces the amount of water available for plants to transpire. The amount of water loss by runoff depends on rainfall intensity, slope of the land, hydraulic conductivity of the soil, initial water content of the soil, land use and land cover. It was stated by Bennie *et al.* (1998) that if surface storage is neglected, surface runoff during a rainy storm normally starts to take place when the rainfall intensity exceeds the infiltration rate of the soil. This statement is confirmed by results from various long-term runoff trials (Haylett, 1960; Du Plessis and Mostert, 1965; Bennie *et al.*, 1994) conducted under dryland condition in the summer rainfall region of South Africa.

Drainage: Howell *et al.* (1998) stated that the amount of rainfall exceeding 600 mm per year goes almost entirely into drainage. This might be the case in bare soils, but drainage depends heavily on whether the root zone water content exceeds the drained upper limit (DUL). DUL is regarded as the highest field measured water content of a soil after it has been thoroughly wetted and allowed to drain under the influence of gravity forces until drainage becomes practically negligible (Ratliff *et al.*, 1983). Normally it is when the water content of a soil profile decreases at about 0.1 - 0.2% of its water content per day. The process is exclusively controlled by the water holding capacity of the root zone. DUL depends on soil texture, organic matter content, porosity and the thickness of each horizon in a soil profile which constitute the specified rooting depth (Boedt and Laker, 1985). The presence of a crop complicates drainage, because plants can transpire at a significant rate if the water is above DUL, provided that the oxygen does not reach levels that influence respiration negatively. Therefore Hattingh (1993) introduced the crop modified upper limit (CMUL) to describe water uptake above DUL and in the presence of a crop. The determination of the DUL and CMUL is very important as it plays a role in establishing plant available water (PAW). The difference between either DUL or CMUL and the lower limit (LL) is regarded as representing PAW. LL is regarded as the lowest field measured water content of a soil profile after the crop has stopped extracting water and experience severe water stress (Ratliff *et al.*, 1983; Van Rensburg, 1988). The lower limit depends on the depth and density of the roots, ramification, atmospheric evaporative demand, unsaturated hydraulic conductivity and water retention of each soil horizon within the rooting zone and drought resistance of the crop (Hensley and De Jager, 1982).

Evapotranspiration: This is the amount of water lost from a soil through two processes simultaneously, namely evaporation from the soil surface and transpiration from the plants canopy. Factors to consider when assessing evapotranspiration are inter alia air temperature, humidity, wind speed, ground cover, plant density and soil water content (Hatfield *et al.*, 2001; Johnson and Croissant, 2006; Unger *et al.*, 2006). The effect of soil water content on ET is conditioned primarily by the magnitude of the atmospheric water deficit and the type of soil. ET is also determined by the soil water content and the ability of the soil to conduct water to the roots. On the other hand, too much water will result in water logging which will damage the roots and limit root water uptake by inhibiting respiration (Canola Council of Canada, 2008). The crop type, variety and development stage should be considered when assessing evapotranspiration from crops grown in large, well-managed fields (Taylor and Smith, 1992; Bennie *et al.*, 1997). Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different ET levels in different types of crops under identical environmental conditions. Not only the type of crop, but also the crop development, environment and management should be considered when assessing transpiration (Unger *et al.*, 2006).

Evapotranspiration under standard conditions (ET) refers to the evaporating demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions (Angus and Van Herwaarden 2001) The contribution of evaporation and transpiration to ET over the growing season of an annual crop will change on account of soil coverage. Evaporation will be the major contributor during early growth stages. During later growth stages transpiration will be the major contributor (Angus and Van Herwaarden 2001). Evapotranspiration can be used interchangeably with water use under conditions where the other water losses (runoff and drainage) and gains (rain and irrigation) are known. French and Schultz (1984) presented results of field experiments with canola by graphing grain yields against water use, from sowing to harvesting. The approach had a remarkable acceptance among canola growers and advisers in the variable rainfall environment as an indication of whether the crop yield was limited by the water supply or some other factors. Results revolved from research from Agriculture and Agri-Food Canada (2005) on water use, yield components and seed yield of canola grown under rainfed, low irrigation and high irrigation are given in Table 2.3. All parameters increased on account of better water supply from rainfed to low irrigation, and from low irrigation to high irrigation.

Table 2.3. Water use, yield components and seed yield of canola under rainfed, low irrigation and high irrigation (adapted from Agriculture and Agri-Food Canada, 2005).

	Water use (mm)	**Branches plant^{-1}**	**Pods plant^{-1}**	**Seeds pod^{-1}**	**Seed weight g 100^{-1}**	**Seed yield (kg ha^{-1})**
Rain fed	210	3.5	48	15.2	3.09	922
Low irrigation	282	3.9	54	18.9	3.22	1537
High irrigation	369	4.0	61	20.3	3.48	2463

2.4.2. Water use efficiency

The general understanding amongst crop and soil scientists that water use efficiency (WUE) refers to the ratio of biomass or seed yield to evapotranspiration (Angus and Van Herwaarden, 2001). Nielsen (1996) reported that canola exhibits a linear response of seed yield to water use with approximately 7.73 kg ha^{-1} of seeds produced for every mm of water used. He stated however, that this efficiency depends heavily on the timing and intensity of water stress as was found by Jonhson *et al.* (1996). They reported values of WUE ranging from 8.3 to 11.4 kg ha^{-1}mm^{-1}. Using the water use and seed yield data given in Table 2.3 values of WUE were 4.39 kg ha^{-1}mm^{-1} for rainfed, 5.45 kg ha^{-1}mm^{-1} for low irrigation and 6.67 kg ha^{-1}mm^{-1} for high irrigated canola. Canola is least sensitive during its vegetative stage of development and hence will not affect the WUE as in the case where water stress occurs during the grain-filling stage (Nielsen, 1996).

CHAPTER 3

INFLUENCE OF WATER APPLICATION AND PLANT DENSITY ON PLASTICITY OF CANOLA (*Brassica napus* L.)

3.1. Introduction

Canola can exhibit extreme plasticity by responding in size and form to available space (Morrison *et al.*, 1990a; Angadi *et al.*, 2003; Ozer, 2003). Available space in this context does not refer to the physical or volumetric space between plants, but rather to the competition amongst plants to acquire water, nutrients, light, carbon dioxide, oxygen etc. (Milthorpe and Moorby, 1974). Several papers on rape seed suggested that yield and yield components are affected by water application (Dembriska, 1970; Champolivier and Merrien, 1996) and plant density (Leach *et al.*, 1999; Momoh and Zhou, 2001; Ozer, 2003). Champolivier and Merrien (1996) investigated the effects of water stress on oilseed rape using pot experiments. They concluded that yield and yield components are mainly affected when water shortage occurring from flowering to the end of seed set. A yield reduction of 48% was observed when only 37% of the full water requirement was supplied. The number of seeds per plant was the main yield component affected; seed weight was reduced under water stress from the stage when the pods were swollen until the seed coloring stage.

Rao and Mendham (1991) observed that full irrigation increased seed yield of canola on account of more productive pods per plant and seeds per pod in comparison to a single irrigation. Clarke and Simpson (1978) found under field conditions with canola that irrigation scarcely affected the number of branches per plant, but increased the number of pods per plant, number of seeds per pod and the 1000 seed weight. Yield was positively correlated with 1000 seeds weight. The ultimate goal of plant density trials is to obtain the optimum seed density for a production system associated with specific climate and soil combinations. Plant density is one of the most important agronomic tools to modify competition amongst plants to ensure sustainable yields in semi-arid environments. Yield component analysis provides the scientific basis to explain yield variation, while plant growth analysis measures the effects of these competitive relationships (Morrison *et al.*, 1990b). They reported that the number of pods per plant was strongly affected by the plant density of canola.

Field trials with canola in Saskatoon by Clarke and Simpson (1978) revealed that the number of branches per plant, pods per plant and seeds per pod decreased as plant density increased. They are of opinion that the availability of assimilates may have been better in the low plant density treatments due to more photosynthetic surface per plant. Maximal crop growth in terms of biomass production tended to occur at a later stage in low than high density planted canola, thus coinciding with the flowering stage. Reported optimum plant density varies greatly, e.g. 4.5 - 6.5 kg ha^{-1} in Canada (Downey *et al.*, 1974) and 20 kg ha^{-1} in Sweden (Ohlsson, 1974). The objective of this trial was to examine the effects of varying water application and plant density rates on yield, yield components and growth parameters of canola to establish the plasticity of this crop.

3.2. MATERIALS and METHODS

3.2.1. Description of field experiment

Experimental site: The study was conducted on the experimental farm of the Department of Soil, Crop and Climate Sciences of the University of Free State. This farm is located in the Kenilworth area, about 15 km northwest of Bloemfontein. The trial was done on a soil that classified as Bainsvlei form of the Amalia family (Soil Classification Working, 1991). It occurs on the footslope and has a straight, northern slope of less than 1%. Some properties of this deep, apedal, eutrophic soil relevant to the study were extracted from records of Van Rensburg (1996) and are summarized in Table 3.2. The silt-plus-clay content increase gradually over depth from 13% in the Ap horizon to about 30% at 2 m in the C-horizon. Generally, the soil has a high infiltration and good internal drainage. Several irrigation studies on crops were conducted on the soil. The reports indicated that the soil can be regarded as a high potential soil, with no apparent physical, chemical and biological constraints.

Table 3.1. Some morphological and chemical characteristics of the Bainsvlei Amalia soil (Van Rensburg, 1996)

	Horizon*			
Morphological characteristics	**Ap**	**B1**	**B2**	**C**
Depth (m)	0 - 0.35	0.35 - 1.18	1.18 - 1.40	1.40 - 3.00
Texture class	Fine sand	Fine sandy loam	Fine sandy clay loam	Fine sandy clay loam
Structure	Apedal, massive	Coarse, weak, prismatic	Apedal, massive	Course, strong, angular blocky
Color	Red brown: (5YR4/4)	Red brown: (5YR5/6)	Brown: (10YR4/6)	Yellow orange: (10YR6/4)
Chemical characteristics				
P (Bray 1) (mg kg^{-1})	7.8	2.4	2.1	1.8
Ca (NH_4OA_c) (mg kg^{-1})	112	68	422	564
Mg (NH_4OAc) (mg$_c$ kg^{-1})	98	60	298	318
K (NH_4OAc) (mg$_c$ kg^{-1})	70	27	106	164
pH (H_2O)	6.2	6.5	5.9	5.7

*Ap = Orthic A, B1 = Red apedal B, B2 = Soft plinthic B; C = Weathered mudstone

Experimental design: A split plot design with five water application rates as main treatments (W1, W2, W3, W4 and W5) and five plant densities (PD25, PD50, PD75, PD100 and PD125) as sub treatments was used (Figure 3.1). All treatment combinations were replicated four times as blocks. This approach has its origin in the line source sprinkler irrigation method proposed by Hanks (1976) and as applied by Van Rensburg et al. (1995). With this method the water application rate decreases approximately linear perpendicular from lateral on both sides, W5 to W1.

Block 1

W1PD50	W1PD100	W1PD75	W1PD25	W1PD125
W2PD125	W2PD25	W2PD50	W2PD75	W2PD100
W3PD100	W3PD50	W3PD25	W3PD125	W3PD75
W4PD75	W4PD125	W4PD100	W4PD50	W4PD25
W5PD25	W5PD75	W5PD125	W5PD100	W5PD50

Block 2

W1PD25	W1PD50	W1PD100	W1PD75	W1PD125
W2PD75	W2PD125	W2PD25	W2PD50	W2PD100
W3PD125	W3PD100	W3PD50	W3PD25	W3PD75
W4PD50	W4PD75	W4PD125	W4PD100	W4PD25
W5PD100	W5PD25	W5PD75	W5PD125	W5PD50

x----x----x-----x-----x-----x----x------x-----x----x-----x----Line source----x-----x-----x----x----x-----x------x-----x-----x----x

W5PD100	W5PD25	W5PD75	W5PD125	W5PD50
W4PD50	W4PD75	W4PD125	W4PD100	W4PD25
W3PD125	W3PD100	W3PD50	W3PD25	W3PD75
W2PD75	W2PD125	W2PD25	W2PD50	W2PD100
W1PD25	W1PD50	W1PD100	W1PD75	W1PD125

Block 3

W5PD25	W5PD75	W5PD125	W5PD100	W5PD50
W4PD75	W4PD125	W4PD100	W4PD50	W4PD25
W3PD100	W3PD50	W3PD25	W3PD125	W3PD75
W2PD125	W2PD25	W2PD50	W2PD75	W2PD100
W1PD50	W1PD100	W1PD75	W1PD25	W1PD125

Block 4

Figure 3. 1. Layout showing water application (W5 - W1 not randomized) with a single line source experiment (Hanks, 1976) as the main treatment and plant density (PD25 - PD125 fully randomized) as sub treatments

Water application: 30 H Rain Bird sprinklers were attached on the lateral with 1.5 m high rises (diameter = 20 mm) at 6 m intervals. The operating pressure was set at 350 kPa throughout the season. It was not always possible to irrigate at wind speeds lower than the specified 3 m s^{-1}. Water applications were therefore measured with rain gauges installed just above the canopy in all water treatments per block. The perpendicular distances of the rain gauges from the lateral were 11.93 m, 9.36 m, 6.93 m, 4.57 m and 2.63 m for W1 to W5 treatments, respectively. As shown in Table 3.2 total irrigation amounted to 118 mm for W1, 176 mm for W2, 238 mm for W3, 294 mm for W4 and 363 mm for W5

Plant density: The plant rows were fixed at 0.3 m intervals. Three plant rows were used to represent a plot which was 10.4 m long. The middle row corresponded with the distances of the rain gauges installed perpendicular to the lateral. Thus, the area of an individual plot amounted to 9.4 m^2. After germination plants were hand thinned to densities of: 25 plants m^{-2} at PD25, 50 plants m^{-2} at PD50, 75 plants m^{-2} at PD75, 100 plants m^{-2} at PD100 and 125 plants m^{-2} at PD125.

Agronomic practices: Before the onset of the experiment, the area was used for commercial wheat production. After the summer fallow period, fertilizers were mechanically broadcasted at a rate of 170 kg N ha^{-1} as LAN and 60 kg P ha^{-1} as single super phosphate. Thereafter the area was ploughed to a depth of 0.25 m and then disk ploughed to smooth the soil surface. A rotovator was used to prepare the seedbed. The canola cultivar Outback was planted on 7 June 2005 with a modified Bramley wheat planter at a seeding rate of 6.2 kg ha^{-1}. Climate data was obtained from an automatic weather station that is managed by the ARC-Institute for Soil, Climate and Water on the experimental farm.

3.2.2. Measurements on plants

Plants were sampled five times during the growing season from an area of 0.5 m^2 in each plot, viz. on day 70 (15 August), 88 (2 September), 102 (16 September), 116 (30 September) and 130 (14 October) after planting. These plants were cut close to the soil surface and the leaves were removed for the determination of their leaf area with a Licor (model Li 3000) leaf area meter. After leaf area determination the leaves together with the remaining parts of the plants sampled from a plot were oven dried at 70°C and then weighted to obtain biomass yield. Plant height was measured *in situ* with a tape-measure in all plots for block 1 on day 87 and 109 after planting. Photos were taken during plants measurements.

A day before final harvest (2 November), 20 plants per plot were removed to determine yield components comprising of the branches per plant, pods per plant and seed weight per plant. The final harvest per plot was done on an area of 6 m^2 by cutting the plants just above the soil surface. Four of these plants were used to measure the diameter and length of their main stems. The length of the main stems was measured with a ruler, while the diameter of the stems was calculated by dividing their area, measured with the mentioned leaf area meter by the length. All plants harvested from 6 m^2 of a plot were dried for six weeks in a glasshouse at a temperature of 34°C, where after the seeds were separated from the pods by hand. The weight of seeds and biomass were recorded.

3.2.3. Processing of data

Leaf area index (LAI = Leaf area/Soil area) and harvest index (HI = Seed yield/Biomass yield) were firstly calculated. Then analyses of variance were done at a confidence level of 5% with the NCSS 2000 statistical package (Hintze, 1998) on all parameters except plant height. The treatment means evolved from these analyses were then subjected to regression analyses with Excel of the Microsoft Office package, using the polynomial equations. Plot means of plant height were also regressed.

3.3. RESULTS and DISCUSSION

Only the results from the regression analyses will be presented and discussed. These relationships illustrate the effect of plant density on the yield, yield components and growth parameters of canola for each water application treatment, except for the biomass recorded over the growing season. The latter was related to days after planting (DAP) for every plant density regardless of the water application treatments for reasons given later. Data from the analyses of variance is summarized in appendices and reference to it will be made occasionally. However, notice must be taken firstly of the environmental conditions prevailed during the field experiment in comparison with long-term data.

3.3.1. Environmental conditions

Before the onset of the experiment a preliminary assessment on the suitability of the climate for the cultivation of canola was made using long-term climate data from a nearby agro-meteorological station at Glen Agricultural Institute (Table 3.2). According to the long-term evaporation and rainfall the aridity index is 0.25, which confirms the semi-arid climate of the area (Schulze and McGee, 1978). The assessment also showed that the thermal growing season is long enough to support the sustainable growth of canola (results not shown). It also indicated that the monthly mean rainfall during the growing season is insufficient for the full water requirement of the crop. Therefore, appropriate soil water conservation measures such as summer fallow was introduced to conserve water before the planting of canola can resume.

Irrigation was also introduced as a strategy to improve water supply to the plants in the 2005 season as explained in Section 3.2.1. The crop received between 118 mm and 363 mm of irrigation over the range of water treatments from W1 to W5 (Table 3.2). No irrigation was intended at W1 but it was caused by wind that disturbed the application pattern of the line source irrigation system. This is unfortunately one of the major disadvantages of the technique. Additional to the irrigation, the crop received a total of 57 mm of water in the form of rain, which was far less than the long-term mean of 97 mm. The distribution of rain over the growing season was poor as almost a third of the rain fell in October. Evaporation during the winter months of 2005 was generally lower than the corresponding long-term value of 753 mm. The winter season was perceived to be generally warmer than normal as indicated by the higher maximum, minimum and average temperatures in comparison with the long-term values.

Table 3.2. Long-term climate data from a nearby meteorological station at Glen Agriculture Institute (adapted from Botha *et al.,* 2003), and climate data (supplied by ARC-ISCW, 2006) and measured irrigation at experimental site in 2005.

Parameter		June	July	Aug	Sept	Oct	Total for crop's season	Annual means
Precipitation (mm)	**Long-term**	9	8.1	11.6	19.3	49	97	543
	2005	23.3	0.6	4.9	0.4	27.9	57	-
Evaporation (mm)	**Long-term**	81.9	93.5	140.6	197.5	239.1	753	2198
	2005	81	89.9	120.9	153	173.6	618.4	-
Max. temperature (^{0}C)	**Long-term**	17.9	17.8	20.6	24.4	25.4	21.2	24.8
	2005	19.5	20.3	21.8	26.5	26.9	22.8	-
Min. temperature (^{0}C)	**Long-term**	-1.1	-1.6	0.9	5.2	9.2	2.5	7.5
	2005	3.1	2.8	4.2	7.9	11.6	6.0	-
Average temperature (^{0}C)	**Long-term**	8.2	8.1	10.7	14.8	17.5	11.9	16.2
	2005	11.3	11.6	13.0	17.2	19.3	14.5	-
Irrigation								
W1		20	3	30	54	11	118	-
W2		34	5	37	72	28	176	-
W3		53	7	46	88	44	238	-
W4		62	10	57	105	60	294	-
W5		75	13	78	113	84	363	-

3.3.2. Yield response

The yield response of canola to plant density for each water application treatment is displayed in Figure 3.2 as seed yield (a), biomass yield (b) and harvest index (c). Coefficients of determination for the polynomial equations are 0.98 - 0.99 for seed yield, 0.58 - 0.91 for biomass yield and 0.74 - 0.98 for harvest index. Most of these equations can be therefore regarded as representative of the water application-plant density induced response. The response curves for seed yield were generally similar in shape, except for W5 that has a steeper initial decline with increased plant density. All five curves showed a maximum yield at PD25, where after it gradually declines with a further increase in plant density to PD125 (Figure 3.2a). Thus, the optimum yields obtained for PD25 with the means given were 1564, 1004, 2485, 3146 and 4653 kg ha^{-1} of seeds at the W1, W2, W3, W4 and W5 treatments, respectively (Appendix 3.1b).

The shape of the response curves for biomass yield, differ from that for seed yield. They gradually increase from PD25 and peak at PD75 and then decline towards PD125 (Figure 3.1b). Thus, 75 plants m^{-2} seems to be the optimal density for all the water treatments. The mean biomass yields obtained at this plant density were 3150, 3875, 4083, 5341 and 6733 kg ha^{-1} for W1 to W5, respectively (Appendix 3.1a).

The harvest index curves decline from PD25 to about PD75, where after they either increase slightly or flatten towards PD125. All five curves showed almost a similar variation in harvest index over plant densities, especially W3 to W5. This phenomenon can be attributed to the line source sprinkler irrigation system used. Treatments W2 to W4 received irrigation amounts proportional to W5 and special measures were taken to ensure the plants in W5 were not subject to water stress (See Chapter 4 for further details). Due to the proportional water application that coincides with low rainfall during the growing season, the canola was subject to water stress in W2 to W4.

Canola plants developed stress in the W1 to W4 treatments according to the water deficit induced by them in relation to W5. Hence, the plants adapted to the weekly irrigations by producing seed in a close relation to dry biomass. Several experiments with oilseed rape species have demonstrated that water stress from flowering to the end of seed set is determinant of the final yield (Richards and Thurling, 1978a; Champolivier and Merrien, 1996). The harvest index of W4 and W5 varied between 0.4 and 0.6 over all plant density treatments. In comparison, the harvest index of W1 varied between 0.2 and 0.4 over all plant densities, indicating water stress developed during the reproductive growth stage. In this treatment most of the stored water from the summer fallow was probably used during the vegetative growth stage.

The harvest index values evolved from this study were considerably higher than those reported by Richards and Thurling (1978a) for various rapeseed species and cultivars produced in Western Australia. Their values varied between 0.16 and 0.22, while that of Rao and Mendham (1991) varied between 0.28 and 0.33 in Tasmania. On the other hand, Mendham *et al.* (1984) reported that very high yields of 5500 kg ha^{-1} are possible in Tasmanian. Apparently the winters in Tasmania are not cold enough to prevent growth, and spring and early summer give moderate temperatures and hence a long period for seed development at favorable radiation levels.

3.3.3. Yield component analysis

The response of three yield components of canola, viz. branches per plant (a), pods per plant (b) and seed weight per plant (c) to plant density for each water application treatment is depicted in Figure 3.3. Coefficients for determination for the polynomial equations are 0.96 - 0.99 for branches per plant, 0.50 - 0.93 for pods per plant and 0.75 - 0.97 for seed weight per plant. The response curves for the number of branches per plant have similar shapes. They indicate a gradual decline in the number of branches per plant with an increase in plant density from PD25 to PD75. At higher plant densities (PD100 and PD125) the number of branches per plant remained almost constant. For pods per plant, the shape of the curves for W1, W2 and W3 are almost similar, showing no response to plant density. Greater responses were obtained in the W4 and W5 treatments, especially at low to moderate plant densities. In these two treatments pods per plant declined sharply from PD25 to PD75 and then stabilize.

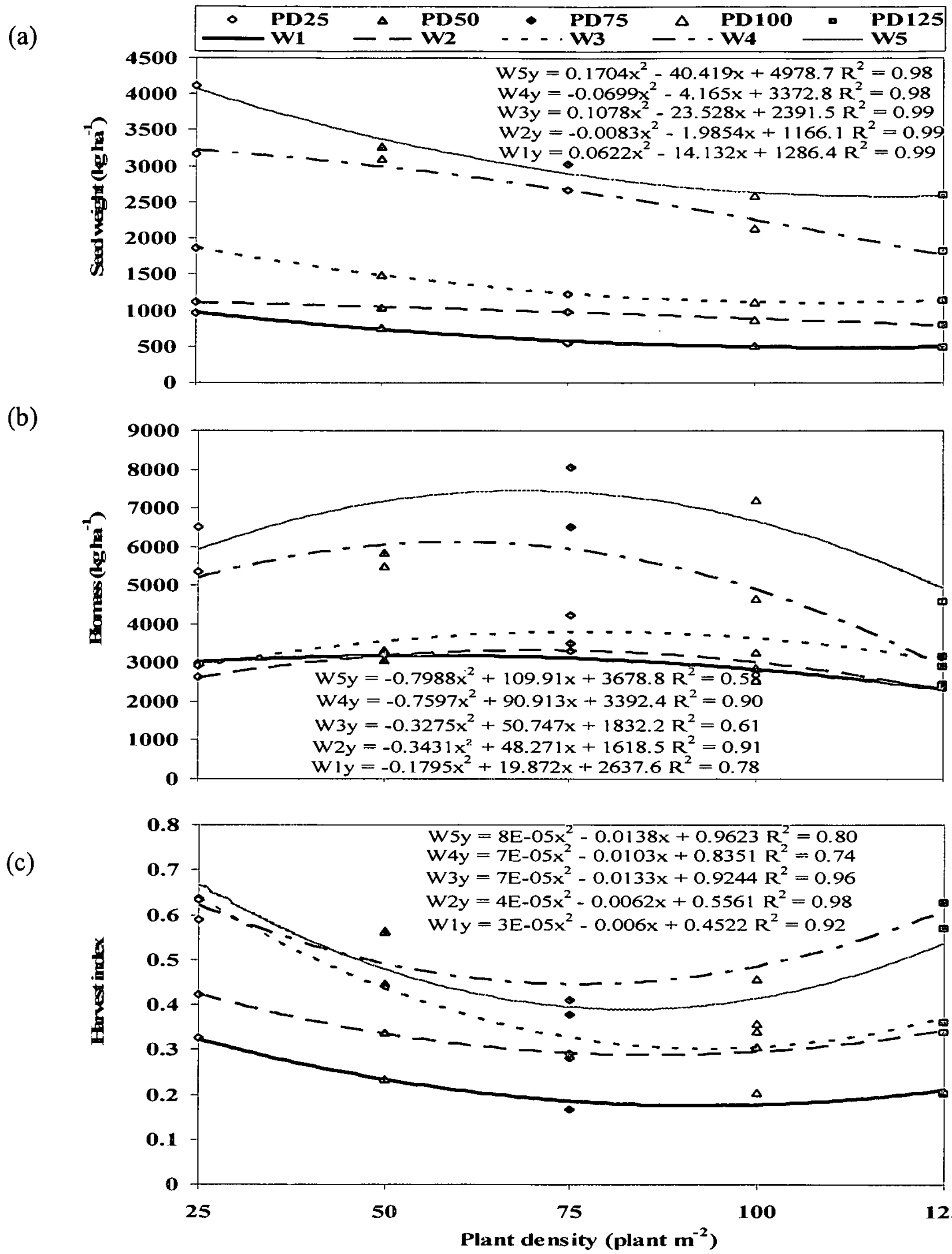


Figure 3.2. Effect of plant density on the seed yield (a), biomass yield (b) and harvest index (c) of canola for each water application treatment. Analyses of variance, data presented in Appendix 3.1a-c.

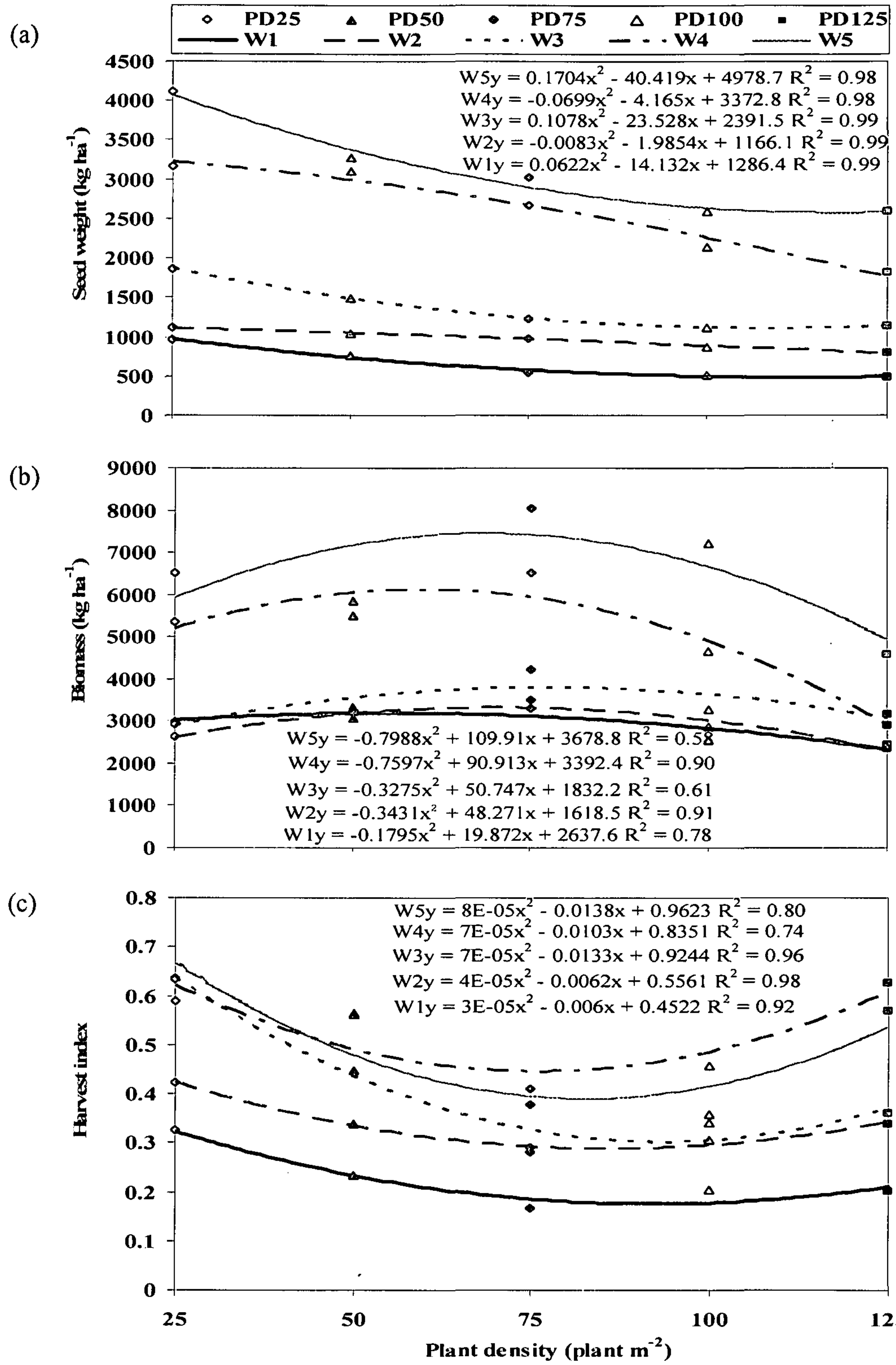


Figure 3.3. Effect of plant density on the seed yield (a), biomass yield (b) and harvest index (c) of canola for each water application treatment. Analyses of variance, data presented in Appendix 3.1a-c.

The shapes of the response curves for seed weight per plant were almost similar, indicating a decrease in seed weight per plant with an increase in plant density. However, the curves showed a prominent interaction between water treatments and low to moderate plant density levels (PD25 - PD75). The results also indicated that seed weight per plant generally increases with an increase in water application over all plant density treatments.

In order to obtain better insight how yield components influence yield the equations given in Figure 3.3 were used to calculate for every water application treatment the branches per plant, pods per plant and seed weight $plant^{-1}$ at PD25 and PD75. The mean seed weight per pod was calculated using the calculated values of the latter two yield components. Only the data on the branches per plant, pods per plant and mean seed weight per pod is presented in Table 3.3.

The crop's ability to compensate for environmental variation is eminent from the yield component data in Table 3.3. Plant density induced major changes with respect to the number of branches per plant. The plants from PD25 produced between 13 and 62% more branches per plant than the plants from PD75. At PD25 branching was enhanced by the W4 and especially W5 treatments. These trends created a sound base for pods to form on the branches in PD25 over the entire water application range. In fact the number of pods per plant was 15 to 123% more in PD25 than PD75. Higher water application boosted the number of pods per plant in PD25.

This is especially evident in the W4 and W5 treatments where PD25 outperformed PD75 with about 120%. The ability of canola to adjust is illustrated by the mean seed weight per pod. At PD25 mean seed weight remains almost constant from W1 to W3 and then drops. The mean seed weight per pod of the lower water application treatments W1 and W2 is larger in PD25 than PD75. The difference amounts to 76% for W1 and 276% for W2. This was accomplished through heavier seed weight per pod because it was the parameter measured and seeds were not counted.

Table 3.3. Calculated yield components of canola for all water application treatments at the two plant densities that performed best

Water application treatments	Branches plant^{-1}		Pods plant^{-1}		Mean seed weight pod^{-1} (g pod^{-1})	
	PD25	PD75	PD25	PD75	PD25	PD75
W1	34	21	44	32	0.0659	0.0375
W2	36	26	54	47	0.0759	0.0202
W3	35	31	68	47	0.0676	0.0632
W4	37	32	132	59	0.0442	0.0457
W5	43	35	174	78	0.0464	0.0477

Several studies showed that rapeseed species and cultivars are able to compensate in seed number and weight, especially where water application and plant density treatments led to an increase in the surface area of pods (Rao and Mendham, 1991). The ability of rape seed to compensate through its branches per plant, pods per plant and seed number or weight per pod is well documented (Clarke and Simpson, 1978; Morrison *et al.*, 1990a; Mendham and Salisbury, 1995; Momoh and Zhou, 2001; Angadi *et al.*, 2003; Ozer, 2003).

3.3.4. Growth parameter analysis

Dryland (W1): Biomass growth curves for the period 70 - 130 DAP were determined for each plant density (PD25 - PD125) at various water treatments (W1 - W5) and results were presented in Figure 3.4. These curves show that plant density led to biomass accumulation in a distinct pattern and trend, namely PD125 > PD100 > PD75 > PD50 > PD25. This is surprising because in most crops, ultra high plant density tends to reduce biomass accumulation relative to optimum or sub-optimum plant density (Unger *et al.*, 2006). The reduction in biomass yield at the ultra high densities is generally attributed to high LAI, which leads to high transpiration rates that cause early replenishment of the stored water. Under these circumstances, crop water stress can develop at critical growth stages which cause lower biomass accumulation (Bennie *et al.*, 1997).

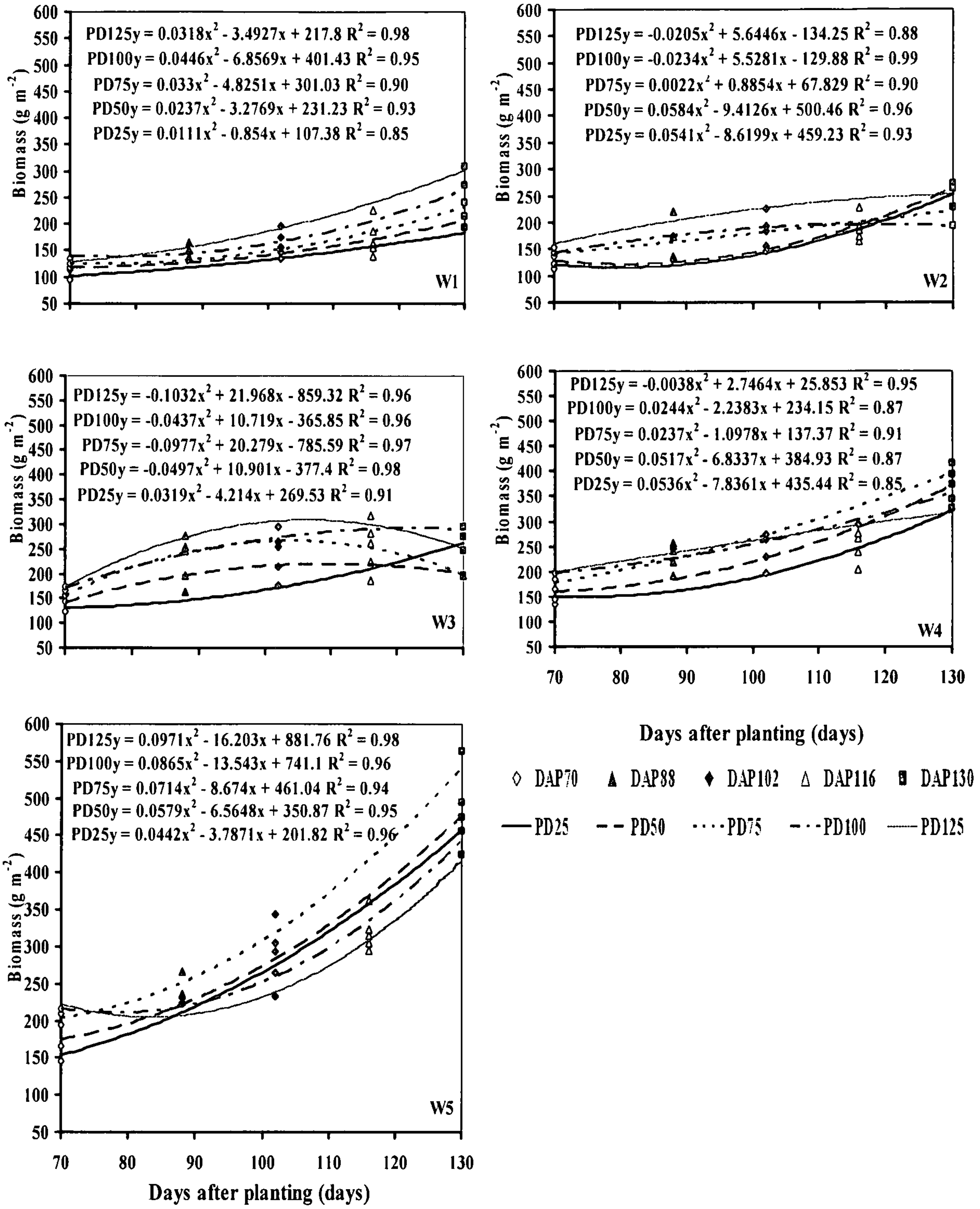


Figure 3.4. Biomass of canola on day 70, 88, 102, 116 and 130 after planting for every plant density treatment regardless of the water application treatments. Analyses of variance, data presented in Appendix 3.3a-e

Ultra high plant densities (PD100 and PD125) caused the LAI to decline relatively to the low (PD25 and PD50) and optimum plant density (PD75) during the period 88 to 102 DAP (Figure 3.5). According to Mendham and Salisbury (1995), extended leaf area duration may be of value to build up reserves before flowering, because the photosynthetic role of leaves is mainly lost after flowering. Major (1977) showed that leaf area declines sharply during flowering, but was largely replaced by stem and then pod area.

Deficit irrigation (W2-W4): Plants in these treatments received only a fraction of the full irrigation that amounts 363 mm in W5, viz. 81% for W4, 66% for W3 and 48% for W2 and for those values rain is not considered (Table 3.2). This strategy force plants to make use of stored water in the root zone. If the water source becomes insufficient to meet the crop water demand plant water stress develops, which eventually manifested in poorer growth (Van Rensburg *et al.*, 1995). The phenomenon is observed in the biomass accumulation of canola in W2, W3 and W4 from 70 to 130 DAP (Figure 3.4). There is generally a gradual decrease of biomass with a decline in irrigation level from W4 to W2 as presented in the set of photos displayed in Figures 3.6 and 3.7. The weekly irrigation frequency employed, allowed plants to adapt for deficit irrigation regimes, which strengthened the gradual decrease in biomass over time. This was also observed in a line source experiment with maize, groundnuts, wheat and peas by Bennie *et al.* (1997).

The changes in the growth parameters during the growing season, especially biomass accumulation, demonstrates that plant density created competition amongst plants for essential resources for growth. Generally, biomass of the W2 - W4 treatments increased with increased plant density into the reproductive phase until about 116 DAP (Figure 3.4). Biomass accumulation continues slightly longer in the lower than higher plant density treatments. This phenomenon can probably attribute towards the way plants used stored water during the season. The LAI of plants tended to be greater in the higher than lower plant density treatments, especially on 70 and 88 DAP for the W2 and W3 treatments (Figure 3.5). LAI of the W2 to W3 treatments varied from 0.3 to 0.9 on day 70 and from 0.5 to 2.2 on day 88 after plant. Clarke and Simpson (1978) reported a positive relationship between LAI and growth rate of canola until the LAI reached 3. Higher leaf areas provide greater surfaces for evaporation and hence greater transpiration rates which poses a risk of depleting plant available water faster in the early growth stages and induces water stress later in the more critical growth stages (Van Rensburg, 1996). This probably happens later in the season with the plants of the high density treatments in W2 and W3. On 102 DAP LAI varied between 1.1 and 3.1 for the W2 to W4 treatments, but with the difference that plants of the lower plant density treatments generally outgrow that of the higher plant density treatments. This agrees with the findings of Momoh and Zhou (2001), who observed a decrease in leaf area with an increase in plant density. The reduction of biomass by higher plant densities could be attributed to higher senescence and lower leaf production. Hay and Walker (1989) reported that closer spacing of plants was associated with initial larger and more rapidly growing leaf canopies, but the effect was short lived because later leaves were smaller and senescence of the leaf canopy was faster. This also correspond with the results of Mendham *et al.* (1981b) and Yang (1996), who reported greater leaf area in lower plant densities later in the season.

Another feature of canola is the formation of branches and pods in the upper part of canopy from 87 to 109 DAP. The LAI decreased sharply after day 108 and reached low values that varied between 0.2 and 0.6 on day 116 and between 0.1and 0.3 on day 130 (Figure 3.5). Major (1977) also showed that leaf area declines sharply during flowering and that the photosynthetic role was largely replaced by branch and pod areas. As mentioned earlier Mendham and Salisbury (1995) are of opinion that extended leaf area duration, may be of value to build up reserves before flowering since the photosynthetic role of leaves is greatly reduced after flowering.

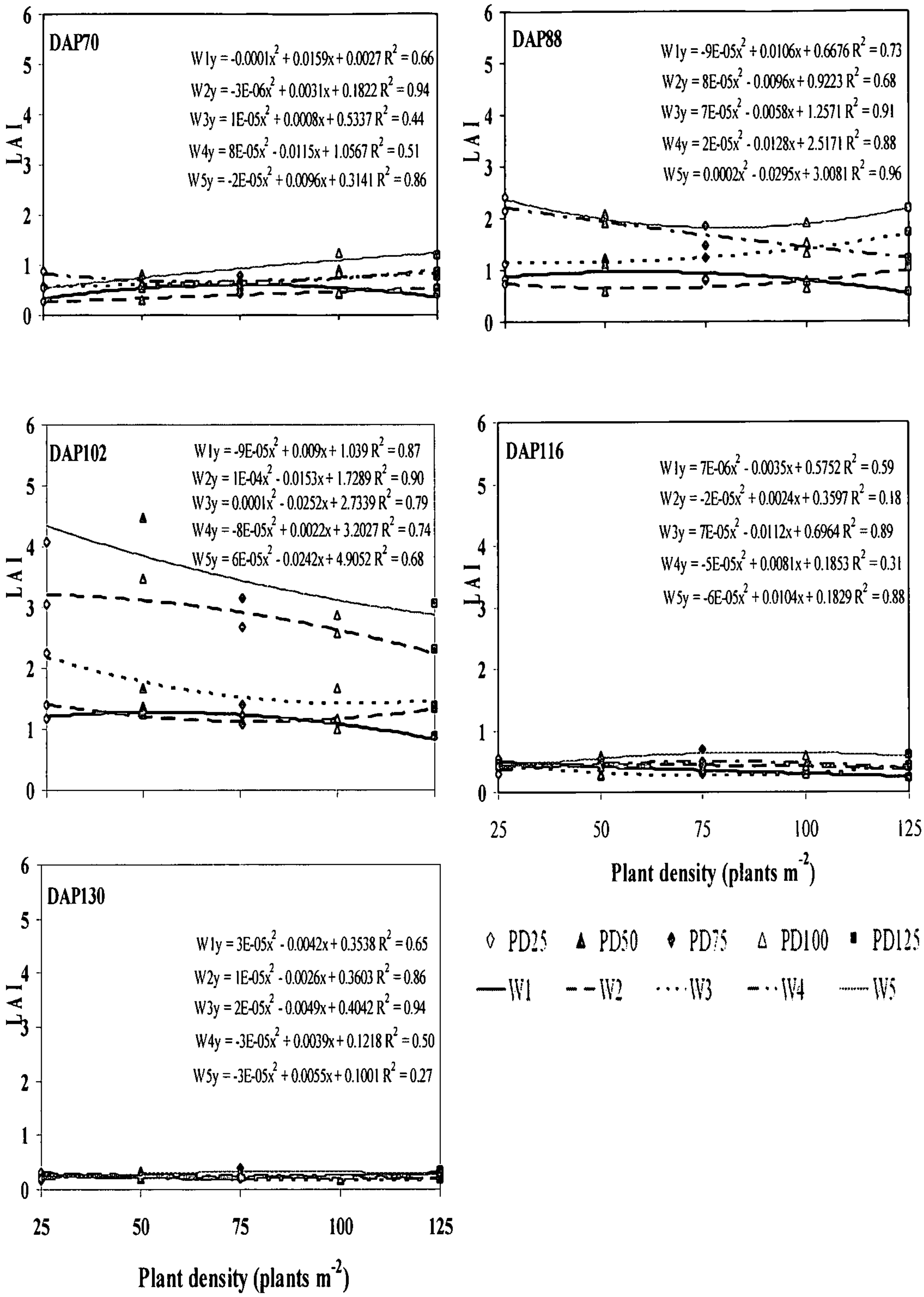


Figure 3.5. Effect of plant density on the leaf area index of canola on day 70, 88, 102, 116 and 130 after planting for each water application treatment. Analyses of variance, data presented in Appendix 3.4.a-e

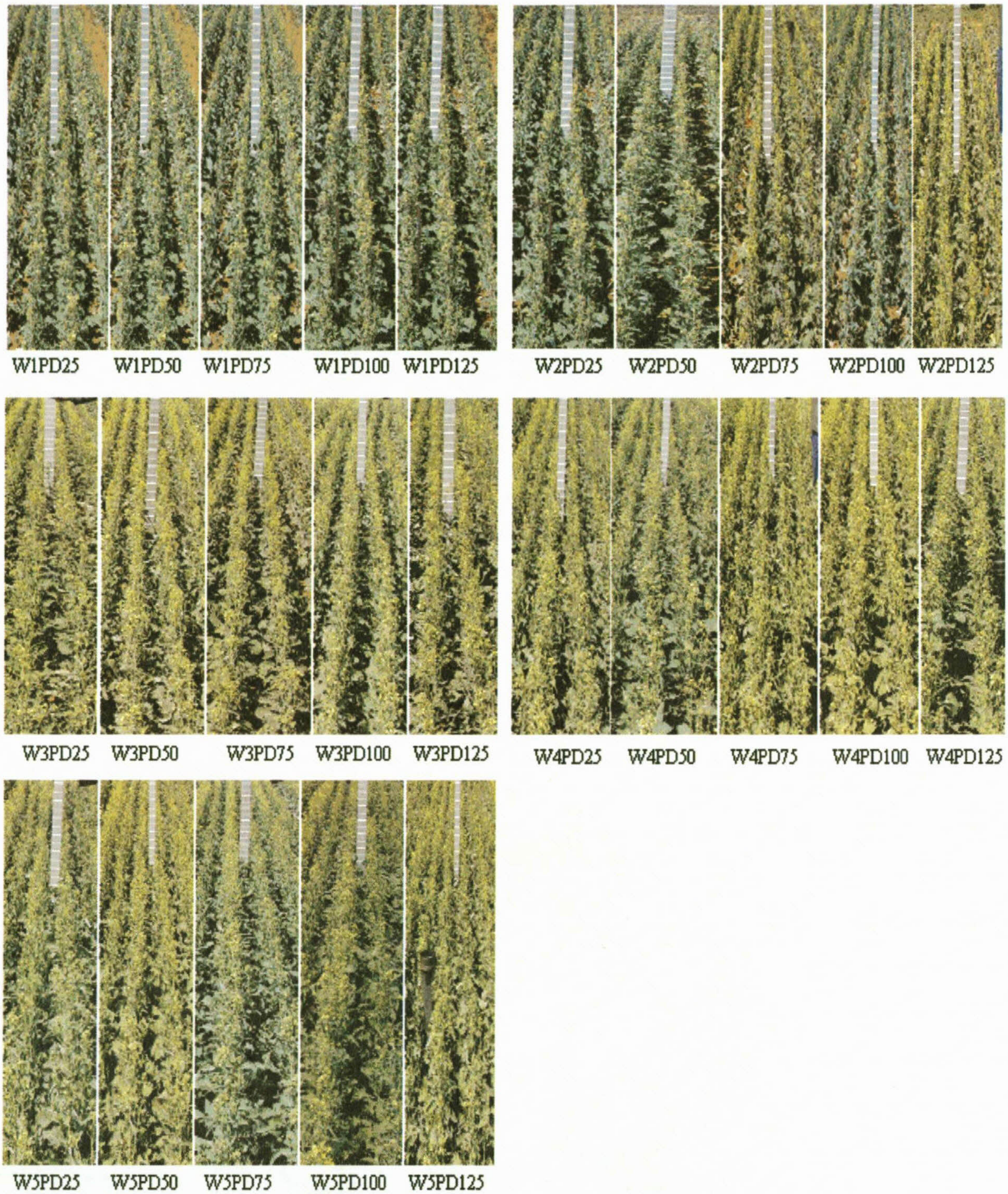


Figure 3.6. Effect of plant density on canopy appearance and plant height of canola on day 87 after planting for each water application treatment.

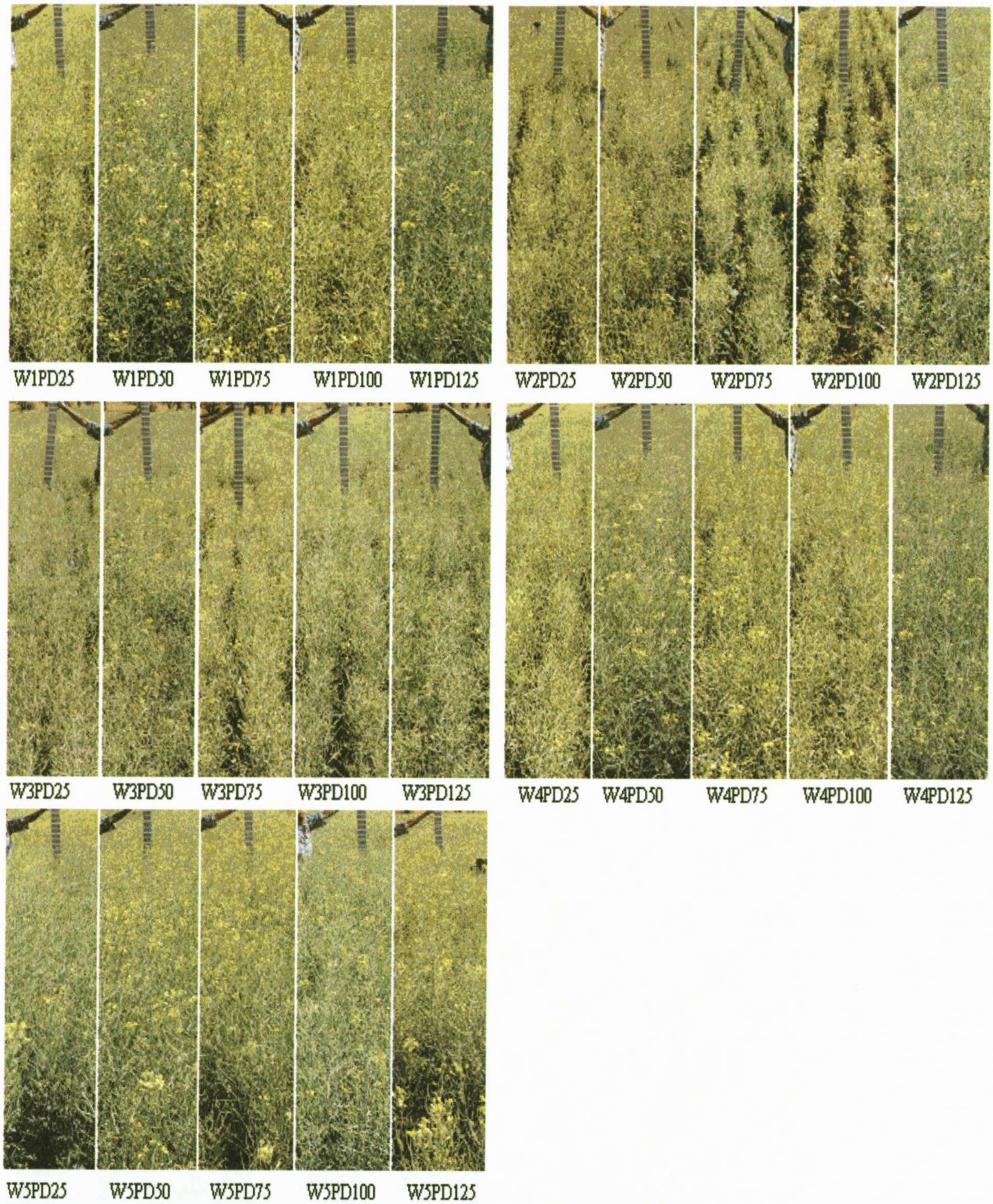


Figure 3.7. Effect of plant density on canopy appearance and plant height of canola on day 109 after planting for each water application treatment.

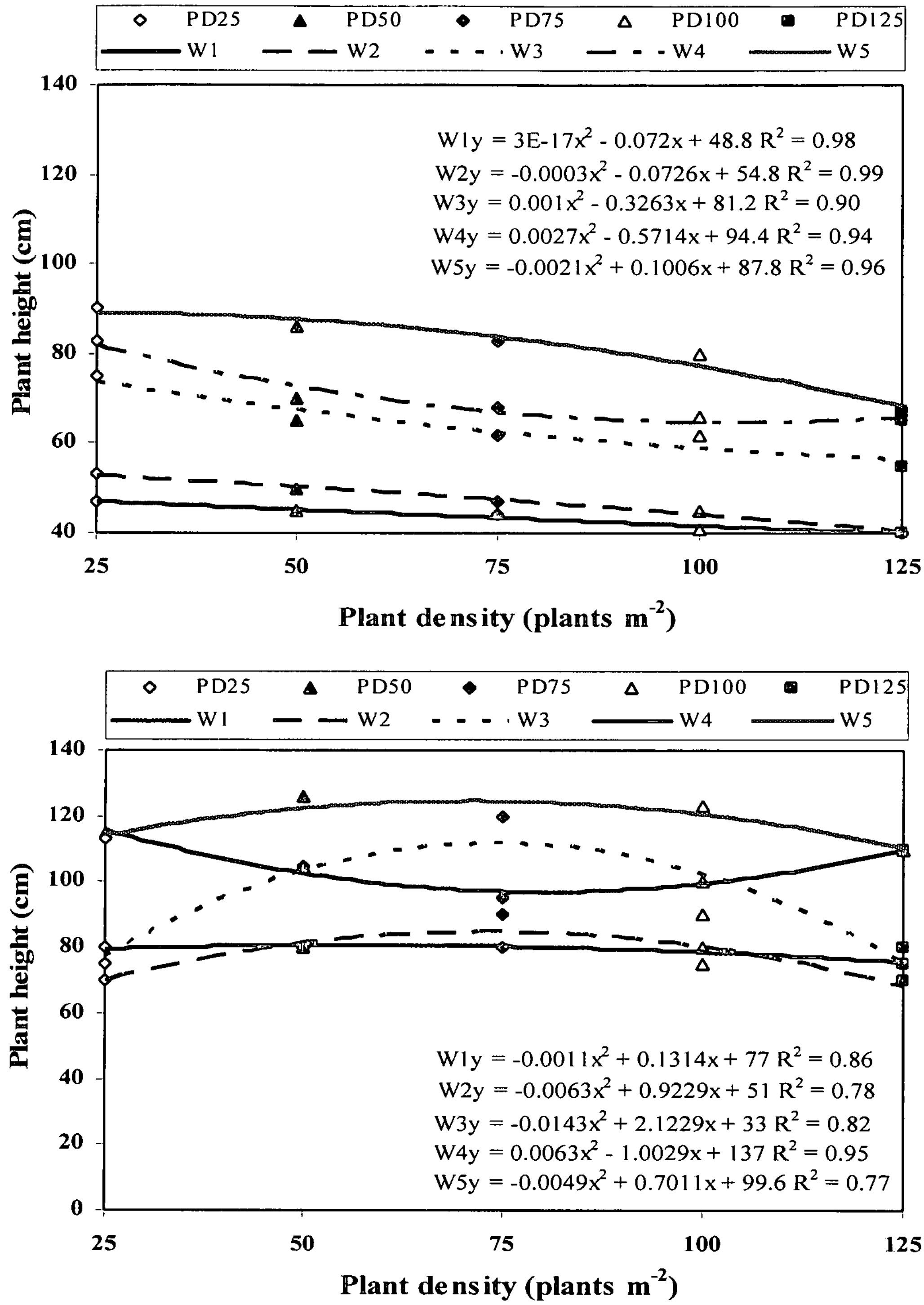
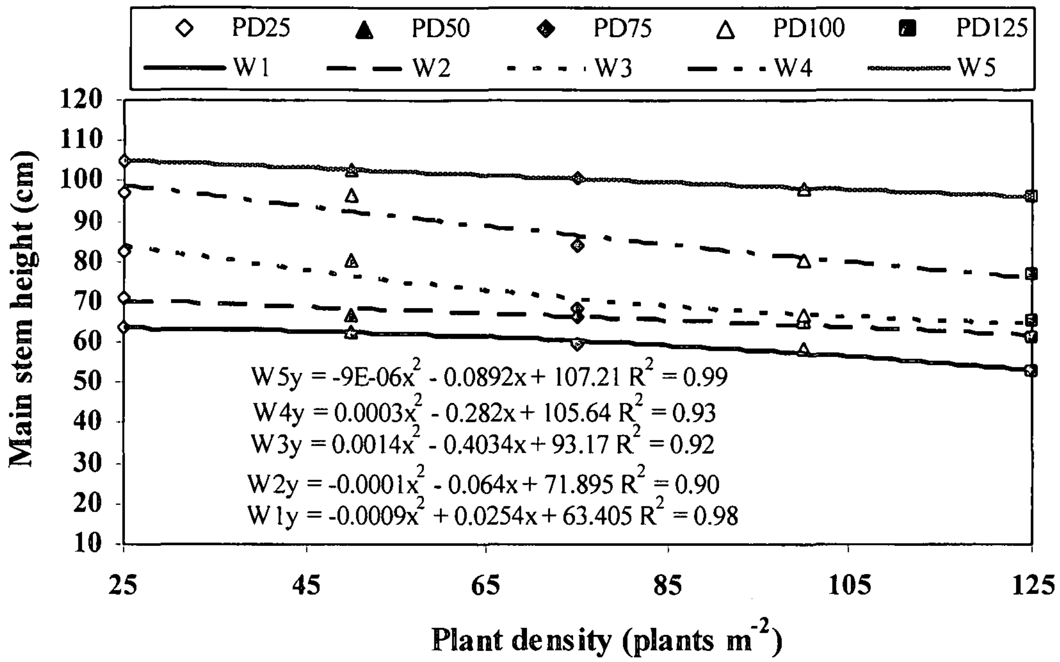


Figure 3.8. Effect of plant density and water application on plant height, at 87 (a) and 109 (a) days after plant



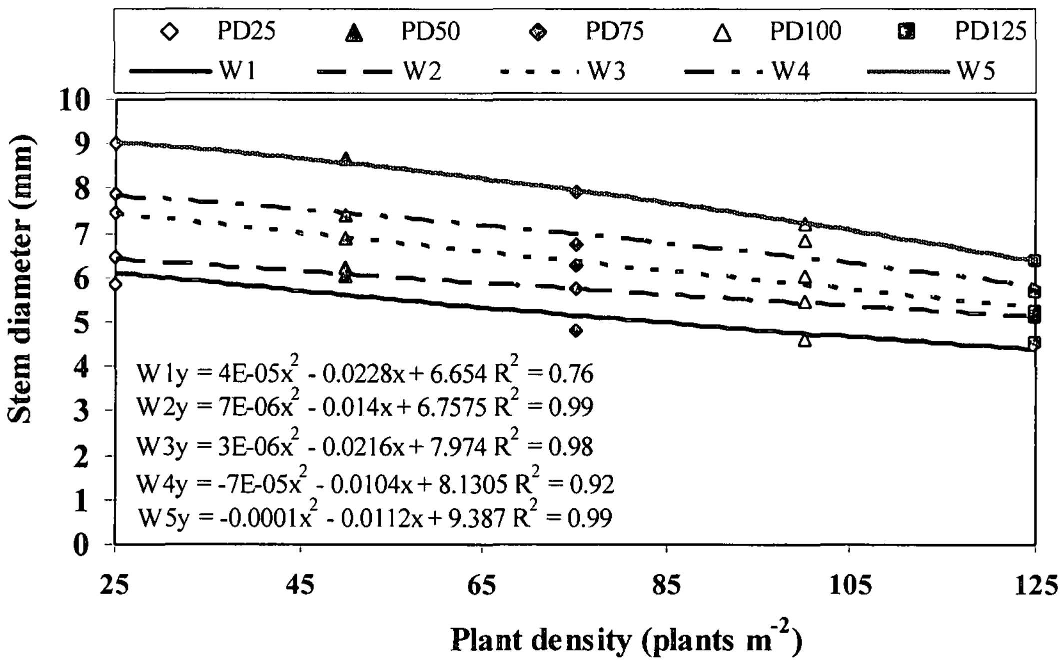


Figure 3.9. Effect of plant density on the main stem height (a) and diameter (b) for canola at harvest for each water application treatment. Analyses of variance, data presented in Appendix 3.5.

Full irrigation (W5): This treatment met the water requirements of a crop because it had no signs of water stress at any stage of the growing season. Judged by the growth parameters, this was probably the case. Strong proof for this argument was found when comparing the biomass accumulation in W5 and other water application treatments and without exception there were larger accumulation than that of other water application treatments. Likewise, this is also true for LAI (Figure 3.5) and plant height (Figures 3.6 and 3.7).

Plant density influenced the general growth pattern of canola in W5. Until 70 DAP accumulation of biomass, exhibit a similar pattern as in the other water application treatments, namely increasing with increased plant density (Figure 3.4). This pattern changed towards day 88 after planting and there after when biomass accumulation of PD125 and also that of PD100 to a lesser extent slowed down relative to the other plant density treatments. During this period PD75 performed the best with respect to accumulation of biomass.

In plant density treatments associated with W5 LAI increased almost linearly from planting to reach a maximum on 102 DAP and then decreased sharply towards harvesting on 130 DAP (Figure 3.5). Noteworthy is that LAI varied on 70 DAP from 0.5 in PD25 to 1.2 in DP125. This trend is reversed on 102 DAP in that LAI ranged from 4.1 in PD25 to 3.1 in PD125. On 116 and 130 DAP LAI of all plant density treatments were almost similar.

On 87 DAP, plant height in W5 decreased almost linear from 90 cm in PD25 to 70 cm in PD125 (Figure 3.6). The plants in all five plant density treatments grow taller as the season progressed but not to the same extent. As results of this, on 109 DAP plants were highest in PD75, viz. 130 cm (Figure 3.7).

In other water application treatments the upper part of the canopy changed from 37 to 109 DAP. It is due to the formation of branches and pods as illustrated by the photos in figures 3.6 and 3.7. These branches and pods partially played the photosynthetic role of the leaves that decline after flowering (Major, 1977).

Despite of vigorous growth the plants did not lodge over significant areas in the experiment. Lodging was considered as a risk because the canopy appears top heavy as most of the pods were carried in the upper third of it. This trend becomes greater with an increase in water application, because canopy height increased accordingly. This manifested in the length of the main stems at harvest (Figure 3.8a). The reason why the plants did not lodge at the high water application treatments was probably due to a larger diameter of the main stems that strengthen the plants (Figure 3.8b). This figure shows that the diameter of the main stems at harvest increased from W1 to W5 and decreased from PD25 to PD125. Thus, an increase in plant density might increase the risk of lodging under severe wind conditions. Researchers of Agriculture and Agri-Food of Canada (2005) reported that canola could reach a height of 175 cm on average, which can enhance the risk of lodging. They stated that the thickness of the stems increases when plant density decreases and plants are therefore less prone to lodging at lower plant densities.

3.4. CONCLUSIONS

An experiment with a line source sprinkler irrigation system was conducted to measure the effects of five water application treatments. Treatments were (W1 = 175 mm, W2 = 233 mm, W3 = 295 mm, W4 = 351 mm and W5 = 420 mm) and five plant density treatments (PD25 = 25 plants m^{-2}, PD50 = 50 plants m^{-2}, PD75 = 75 plants m^{-2}, PD100 = 100 plants m^{-2} and PD125 = 125 plant m^{-2}) on the yield, yield components and growth parameters of canola.

The seed and biomass yields induced by the water application and plant density treatments confirmed the plasticity of canola, and revealed important information on production aspects relevant to the central parts of South Africa. Plasticity was best demonstrated by the fact that only one plant density (PD25 for seeds production and PD75 for biomass) is required to obtain optimum yields over the full range of water application treatments. However, the optimum plant density differed for seed and biomass yields. For seed yield it was 25 plants per m^2 and for biomass yield it was 75 plants per m^{-2}. Seed yield varied from 558 - 4653 kg ha^{-1} and biomass from 1983 - 6733 kg ha^{-1}. The yield component analysis provided insight on how canola compensated for differences in plant density. Over all water application treatments plants from the PD25 treatment formed between 13 and 62% more branches than plants from the PD75 treatment. This created more potential sites for pod formation. Plants from the PD25 treatment formed between 15 and 123% more pod plants from the PD75 treatment over all water application treatments.

The accumulation of biomass increased with higher water applications for all plant densities treatments. Biomass accumulation also increased with higher plant densities for all water application treatments. This trend continues to 130 days after planting (harvesting) in the dryland treatment (W1) but reversed from 116 days after planting (ripening) in the deficit irrigation treatments (W2 - W4) and 88 days after planting (flowering) in the full irrigation treatment (W5). LAI showed almost similar trends as biomass with regard to the water application and plant density treatments.

The structure of canola's canopy changed noticeably from 87 to 109 days after planting. During the flowering period a large number of branches and pods formed in the upper third of the canopy. Almost simultaneously the plants start to lost leaves as there was a sharp decrease in LAI between 102 and 116 days after planting. Despite a strong decline in leaf area, plants maintained a relative high biomass accumulation rate until the end of the season, suggesting that the branches and pods also contributed to photosynthetic material. Plant height varied between 0.5 and 1.3 m at the end of the season and the response was mainly attributed towards the water application treatments. Despite vigorous growth and top heavy plants they did not lodge over significant areas in the experiment. The reason why the plants did not lodge at high water applications is probably due to larger diameters of the main stems that strengthen the plants. An increase in plant density reduced the main stem diameter of the plants, which might increase the potential for lodging.

CHAPTER 4

WATER USE AND WATER USE EFFICIENCY OF CANOLA (*Brassica napus L.*) AS AFFECTED BY WATER APPLICATION AND PLANT DENSITY

4.1. Introduction

Knowledge of water use (evapotranspiration) on field crops is of crucial importance to farmers, advisers, managers and water user associations (WUA). Farmers need information for planning weekly and seasonal water budgets at farm level. WUA needs this information for balancing the supply and demand of water at a scheme level. On the other hand, both crop water use (CWU) and water use efficiency (WUE) depend entirely on how the crop interacts with climate, soil and irrigation systems (Bennie, 1995). The canopy and root attributes related to the supply and demand of water are constantly improved through research and the application of new technologies (Unger *et al.*, 2006). The areas of improvement are strongly related to improved plant material and technical advance agronomical practices such as cultivation techniques, fertilizer application, weed and pest control, selection of optimum planting dates and the use of optimum plant densities (Van Rensburg, 1988; Petersen *et al.*, 2006; Schlegel and Grant, 2006).

Against this background, it is necessary to review the water use of crops from time to time as was done by the Orange-Riet WUA. They used a team of experts to revise water use for crops produced in the area. This team recommended that wheat used on average 625 mm, maize 782 mm, sunflower 588 mm, cotton 830 mm, peanuts 680 mm, soybeans 449 mm and potatoes 698 mm (Department of water affairs and forestry, 2004). Another feature that is evident from the list of irrigated crops reviewed in the Orange-Riet WUA area is the lack of diversity in winter crops. Winter crops are mainly limited to wheat and peas. This phenomenon is not restricted to the Orange-Riet WUA, but is experienced in all the irrigation schemes of the central part of South Africa. There is a need to introduce through research alternatives crops that can fit into the bio-physical and socio-economical conditions of the farmers. It can be used as a cash crop to reduce nitrogen leaching because of its high capacity to take up nitrates from the soil (Malagoli *et al.*, 2005). Introducing canola in rotation helps to reduce pests and weeds in wheat and *vice versa*. The expansion of canola production from the Western Cape to the central part of South Africa can lead to an increase in the production of biofuel and edible healthy oil.

Research on CWU and WUE of canola is lacking, both local and international. Walton *et al.* (1999) reported that total water use varies from 160 to 180 mm in semi arid zones and in humid areas were rainfall range from 400 to 500 mm. According to Tesfamariam (2004) who conducted field trials in Pretoria, water use of canola ranged from 238 mm to 438 mm for the water stressed treatments in 2002 and from 552 mm to 709 mm 2003 for the water unstressed treatments. Nielsen (1996) reported for the semi-arid zone of north-east Colorado a WUE of 7.73 kg seed ha^{-1} mm^{-1}.

In canola, high plant density supports a dense cover of flowers and then pods which quickly shade out leaves whereas at lower density the fewer flowers may allow leaf area to expand further and persist longer. Any strategy that increases the rate of the canopy closure should increase the proportion of transpiration relative to evaporation and thereby increase dry weight production and seed yield (Morrison *et al.*; 1990b). The objectives of this chapter were therefore to: (i) determine the daily crop water use for canola under full irrigation in semi-arid conditions, (ii) investigate how the seasonal water use and water use efficiency of canola was affected by water application regimes and plant density, and (iii) optimize plant density for different water regimes.

4.2. MATERIALS and METHODS

In achieving the mentioned objectives a relevant data from the experiment described in Section 3.2 was used. This experiment was done with a line source sprinkler irrigation system to establish the effects of five water application treatments (W1 = 118 mm, W2 = 176 mm, W3 = 238 mm, W4 = 274 mm and W5 = 363 mm) and five plant density treatments (PD25 = 25 plants m^{-2}, PD50 = 50 plants m^{-2}, PD75 = 75 plants m^{-2}, PD100 = 100 plants m^{-2} and PD125 = 125 plants m^{-2}) on yield response, yield components and growth parameters of canola. Details regarding experiment description, plant measurements and data processing were presented in Chapter 3. However, some details on the quantification of the soil water balance follow since no information on it was given earlier.

4.2.1. Soil water balance of full irrigation regime

Evapotranspiration: This component was calculated on a weekly basis with the water balance equation (Equation, 4.1) using only the W5PD75 treatment, which represented a full irrigation regime.

$$ET = (-\Delta W) + P + I - D - R \qquad 4.1$$

Where ET = evapotranspiration (mm)

-ΔW = change in soil water content (mm)

P = precipitation (mm)

I = irrigation (mm)

D = drainage (mm)

R = runoff (mm)

Change in soil water content: Two neutron access tubes were installed to a depth of 2 m in each of the four replicates the W5PD75 treatment which was located adjacent to the lateral. Volumetric soil water content was indirectly measured with a neutron water meter weekly. The measurements were done at a depth interval of 300 mm up to 1800 mm.

Precipitation: Water applications were measured with rain gauges installed in all the water treatments per block. Measurements were taken just above the canopy on a weekly basis.

Irrigation: Irrigation was done weekly to refill soil water deficits. Soil water deficit was calculated as the difference between drain upper limit (DUL) and actual total water content of the root zone.

Drainage: The concept of crop modified upper limit (CMUL) as described by Hattingh (1993) was used to calculate drainage. Actual soil water content was never above the CMUL values, indicating that drainage was neglected.

Runoff: The application rate of the irrigation system was lower than the soil's final infiltration rate. This final was measured with a double ring infiltrometer and was mathematically described with a power function ($r^2 = 0.98$):

$$y = 1.1835x^{-0.9973} \qquad 4.2$$

Where x = cumulative time (minute)

y = infiltration rate (cm min^{-1})

Using Equation 4.2 the final infiltration rate calculated after 45 min was 0.022 cm min^{-1} or 13.2 mm h^{-1}. The maximum application rate of the line source irrigation system was 6.25 mm h^{-1}, and hence drainage was assumed to be zero. Runoff during rain events was never observed and also assumed to be zero.

4.2.2. Total water use of all water regimes

Total water use was calculated for all plots with Equation 4.1 from soil water contents measured gravimetrically at the start and the end of the growing season (Data summarized in Appendix 4.2). Soil samples were collected in triplicate for 300 mm intervals to 1800 mm depth. The gravimetric soil water contents were converted to volumetric soil water contents using bulk densities measured with the core method as described by Blake and Hartge (1986). Bulk density values were 1.67 g cm^{-3} for 0 - 300 mm; 1.65 g cm^{-3} for 300 - 600 mm; 1.6 g cm^{-3} for 600 - 900 mm; 1.66 g cm^{-3} for 900 - 1200 mm and 1.69 g cm^{-3} for 1200 - 1500 mm.

4.2.3. Calculations

Crop factor: The crop factor (Cf) was calculated as follows:

$$Cf = ETa/ETo \qquad 4.3$$

Where ETa = actual evapotranspiration (mm)

ETo = reference crop evapotranspiration (mm)

Water use efficiency: Either biomass or seed yield at harvesting was used to estimate the water use efficiency (WUE) of canola.

$$WUE = Y/ET \qquad 4.4$$

Where Y = biomass or seed yield (kg ha^{-1})

4.3. RESULTS and DISCUSSION

4.3.1. Water use

4.3.1.1. Daily water use in full irrigation regime

The mean soil water content (SWC) measured during the growing season in the W5-PD75 treatment is presented in Figure 4.1. Irrigation amounted to 363 mm and rainfall to 57 mm (Table 3.3). SWC was never above CMUL and therefore drainage was assumed to be negligibly low. The lower limit (LL) of plant available water (PAW) was derived from the mean SWC of all W1 treatments at the end of the season. The results indicated that SWC was never below LL and as a result the crop probably never experienced water stress. Instead, 64.5 mm was left in the profile at harvest as indicated in Figure 4.1.

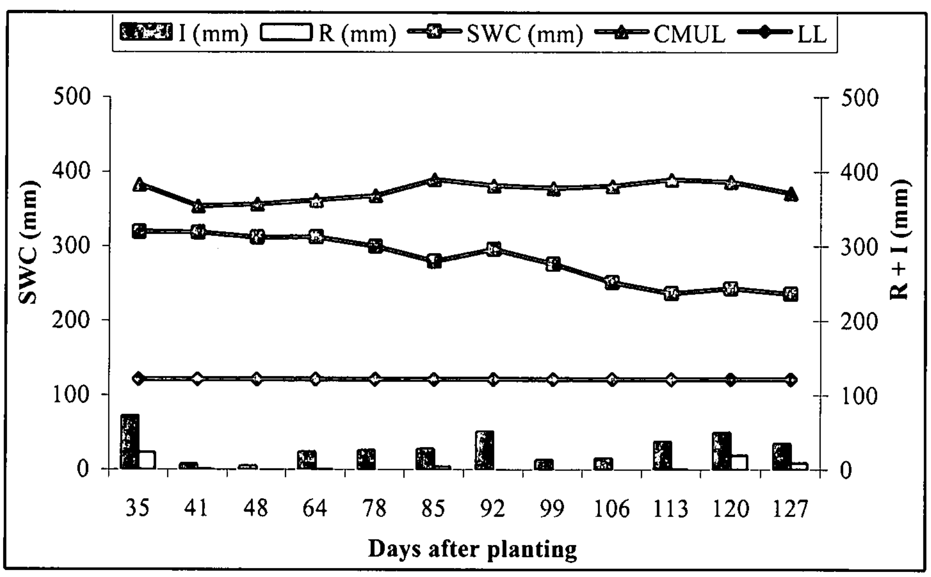


Figure 4.1. Mean soil water content (SWC) of the root zone during the growing season in the W5-PD75 treatment, relative to the crop modified upper limit (CMUL) and the lower limit (LL) of plant available water (data is summarized in Appendix 4.1).

Mean daily ET_0 was regressed against days after planting using a third order polynomial function and the results is depicted in Figure 4.2. It was assumed that ET increased linearly from 0 - 1.15 mm day^{-1} at 48 DAP. The measured ET over this period amounted to 55.4 as indicated in Table 4.1. From 48 DAP towards the polynomial function reflected an increase to approximately 100 after DAP. From 100 to 110 days after planting ET peaks at about 6.5mm day^{-1}. Thereafter ET decreased rapidly towards harvesting. High temperatures in the last two weeks of the growing season probably accelerated the ripening of the crop.

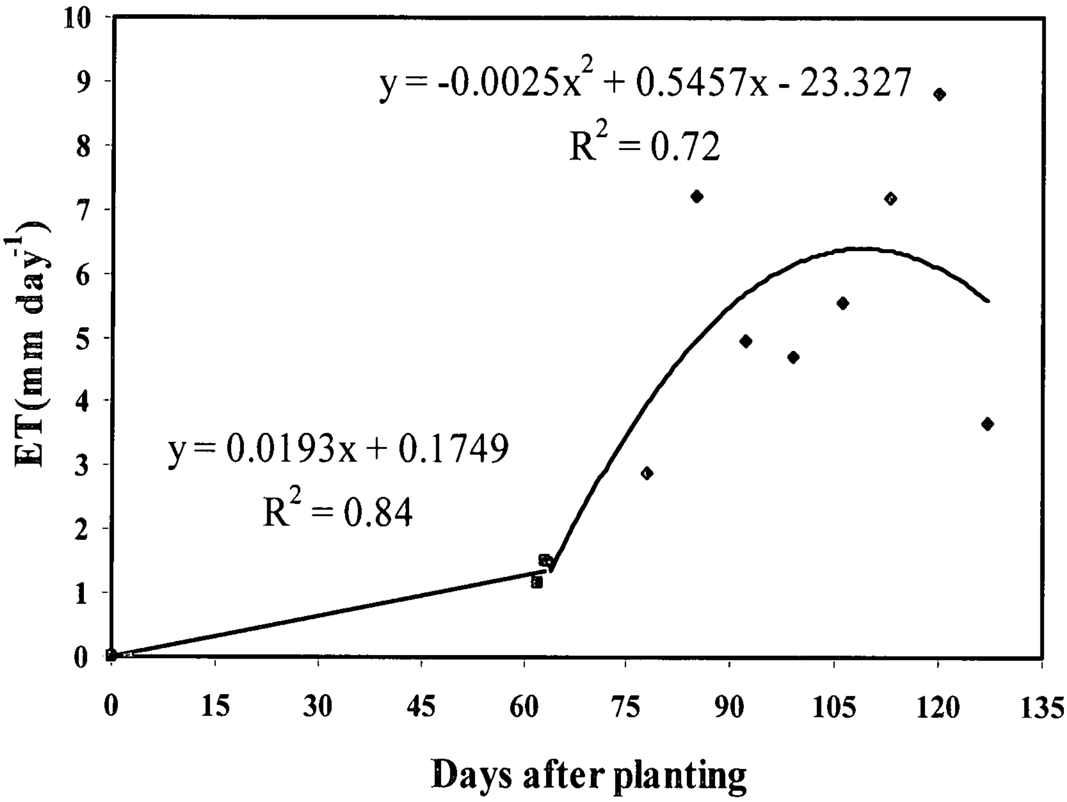


Figure 4.2. Relationship between mean daily ET and days after planting for the W5 - PD75 treatment (data summarized in Appendix 4.1)

The polynomial function presented in Figure 4.2 was used to estimate daily ET values for appropriate days after planting. Those values were used to calculate the crop factor for 7 day intervals with Equation 4.3 using corresponding reference evaporation (Eo) values (Table 4.1). The crop factor remained 0.4 until 62 - 69 days after planting and then increased gradually to 0.9 at 118 - 125 days after planting. Crop factors are popular among farmers as they use it in deciding on how much water to apply at a particular growth stage.

Table 4.1. Calculated crop factor for canola over seven days intervals during the growing season, except for the first 48 days.

Period	**ΣEo(mm)**	**ΣETo (mm)**	**Eo (mm day^{-1})**	**ETo (mm day^{-1})**	**Cf**
0-48*	125.0	55.4	2.6	1.2	0.4
48-55	125.0	55.4	17.9	7.9	0.4
55-62	125.0	55.4	17.9	7.9	0.4
62-69	186.4	78.8	26.6	11.3	0.4
69-76	249.1	119.2	35.6	17.0	0.5
76-83	375.4	169.6	53.6	24.2	0.5
83-90	415.8	204.3	59.4	29.2	0.5
90-97	455.0	237.3	65.0	33.9	0.5
97-104	493.4	276.1	70.5	39.4	0.6
104-111	534.1	326.3	76.3	46.6	0.6
111-118	580.3	388.1	82.9	55.4	0.7
118-125	444.2	413.8	63.5	59.1	0.9

*Actual measured values as reported in the Appendix 4.1

4.3.1.2. Total water use of all water and plant density treatment combinations

The mean total ET for every water application treatment and plant density treatment are summarized in Table 4.2. Only the water application treatments influenced total ET significantly. This illustrates firstly, that canola responded vigorously to irrigation as can be seen in the slope of the strong linear relationship ($r^2 = 0.97$) between ET and irrigation amounts. Irrigation varied from 118 mm at W1 to 363 mm at W5. This is typical for cool season crops under high vapor pressure deficits conditions. Canola poses a strong growth response to temperature and has the ability to maintain growth despite cool temperatures during winter months (Loomis, 1983). The mean total ET increased from 245 mm at W1 to 429 mm at W5. Secondly, total ET is not a good indicator for evaluating a crop's response to plant density. Van Rensburg (1996) also showed with maize and wheat that total ET was not a good indicator of agronomic practices such as nitrogen rates.

Table 4.2. Mean (SD) total evapotranspiration (mm) of canola as influenced by every water application and plant density, treatment combination.

Plant density treatment	**Water application treatments (mm)**					
	W1	**W2**	**W3**	**W4**	**W5**	
	Mean (SD)	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**
PD25	247 (13.7)	299 (4.6)	353 (8.3)	419 (13.5)	432 (18.2)	350 (78.7)
PD50	248 (9.8)	299 (10.2)	352 (8.7)	419 (15.7)	426 (16.8)	371 (54.5)
PD75	244 (13.5)	299 (5.6)	352 (11.4)	418 (13.8)	427 (17.0)	348 (78.0)
PD100	244 (11.0)	297 (4.5)	352 (9.0)	418 (16.1)	428 (10.4)	348 (78.6)
PD125	244 (7.7)	298 (10.2)	352 (10.8)	415 (15.6)	431 (14.5)	348 (78.7)
Mean	245 (2.0)	299 (0.9)	352 (0.7)	418 (1.4)	429 (2.6)	353 (10.2)
$LSD_{t\leq 0.05}$W			10.8*			
$LSD_{t\leq 0.05}$PD			ns			
$LSD_{t\leq 0.05}$W* PD			ns			

SD = standard deviation; *= significant, ns = denote not significant, $P \geq 0.05$

4.3.1.3. Water use efficiency

As shown in Table 4.3 both water application and plant density treatment significantly influenced WUE in terms of biomass production. Accordingly, WUE showed a parabolic type of response to plant density, viz. it increased from 9.3 kg ha^{-1} mm^{-1} at PD25 to 12.7 kg biomass ha^{-1} mm^{-1} at PD75, where after it decreased to 8.3 kg ha^{-1} mm^{-1} at PD125. Except for W1, WUE's increased with higher water applications from 8.3 kg ha^{-1} mm^{-1} at W2 to 12.1 kg ha^{-1} mm^{-1} at W5. Grey (1995) reported an optimum water use efficiency of 18 kg biomass ha^{-1} mm^{-1} which is the highest compared to values reported in literature, that are generally used in the industry

Table 4.3. Mean (SD) water use efficiency (kg ha^{-1} mm^{-1}) of canola in terms of biomass production as influenced by every water application and plant density, treatment combination

Plant density treatments	Water application treatment (mm)					Mean (SD)
	W1	W2	W3	W4	W5	
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	
PD25	9.3 (0.62)	6.9 (0.92)	8.1 (0.48)	9.1 (0.78)	11.9 (0.94)	9.3 (1.94)
PD50	11.0 (1.20)	9.5 (1.56)	8.8 (0.45)	9.2 (0.79)	12.5 (1.37)	10.4 (1.74)
PD75	14.1 (0.93)	10.3 (0.28)	11.0 (2.19)	12.1 (1.54)	15.3 (2.35)	12.9 (2.54)
PD100	12.0 (1.81)	8.4 (0.88)	8.8 (0.99)	9.4 (1.47)	11.3 (1.01)	10.0 (1.62)
PD125	9.6 (0.69)	6.7 (1.57)	7.8 (1.76)	7.8 (1.31)	9.8 (1.02)	8.3 (1.32)
Means	11.2 (2.44)	8.3 (1.58)	8.9 (1.25)	9.5 (1.57)	12.1 (2.02)	10.2 (1.71)
$LSD_{t\leq0.05}$W	1.1*					
$LSD_{t\leq0.05}$PD	1.1*					
$LSD_{t\leq0.05}$W*PD	ns					

SD = standard deviation ; * = significant; ns = not significant, $P \geq 0.05$

In terms of seed production, WUE was significantly influenced by the water application and plant density treatments and their interaction (Table 4.4). WUE varied from 2.0 kg ha^{-1} mm^{-1} at W1-PD125 to 11.3 kg ha^{-1} mm^{-1}. A WUE of 7.7 kg ha^{-1} mm^{-1} was observed by Nielsen (1996). Grey (1995) reported WUE values that ranged between 10 to 12 kg ha^{-1} mm^{-1}. WUE's calculated from the data of Taylor *et al.* (1991) ranged from 7 to 14 kg ha^{-1} mm^{-1}. This is a clear indication that WUE of canola varies between regions and requires further research.

Table 4.4. Mean (SD) water use efficiency (kg ha^{-1} mm^{-1}) of canola in terms of seed production as influenced by every water application and plant density, treatment combination.

Plant density treatment	Water application treatment (mm)					Mean (SD)
	W1	W2	W3	W4	W5	
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	
PD25	3.9 (0.22)	5.9 (0.01)	7.5 (0.14)	7.5 (0.97)	11.3 (0.63)	7.2 (2.72)
PD50	3.0 (0.13)	5.5 (0.00)	5.8 (1.92)	7.5 (0.31)	7.7 (0.30)	5.9 (1.90)
PD75	2.3 (0.13)	4.0 (0.00)	5.5 (0.19)	5.7 (0.19)	7.1 (0.29)	4.9 (1.83)
PD100	2.1(0.10)	3.3 (0.00)	5.2 (0.13)	5.1 (0.16)	6.0 (0.16)	4.3 (1.59)
PD125	2.0 (0.07)	2.4 (0.01)	4.7 (0.13)	4.4 (0.17)	6.01 (0.19)	3.9 (1.68)
Means	2.7 (0.80)	4.2 (1.47)	5.7 (1.06)	6.0 (1.41)	7.6 (2.18)	5.2 (1.33)
$LSD_{t\leq0.05}$W			0.4*			
$LSD_{t\leq0.05}$PD			2.12*			
$LSD_{t\leq0.05}$W*PD			1.28*			

SD = standard deviation; * = significant; ns = not significant at $P \leq 0.05$

4.3.1.4. Optimizing plant density for different water regimes

Canola is produced for either fodder or oil. As shown in the previous section, plant density influenced WUE in terms of biomass yield. Therefore, ET for a specific plant density was regressed against biomass yields (Figure 4.3) and seed yield (Figure 4.4), irrespective of the water application treatment. The regression line of biomass yield was forced through the origin but not that of seed yield. In the case of biomass, yield varied with r^2 from 0.87 at PD25 to 0.92 at PD100 and PD125. WUE for biomass as indicated by the slope of the regression lines had increased by 4.51 kg ha^{-1} mm^{-1} at PD75 with PD75 > PD50 > PD100 > PD25 > PD125. In the case of seed yield r^2 varied from 0.78 at PD125 to 0.87 at PD50 and WUE for seed increased by 4.2 kg ha^{-1} mm^{-1} at PD25. WUE for seeds decreased as follows: PD25 > PD50 > PD75 > PD100 > PD125.

The trend observed here with WUE support those reported on yield response in Section 3.2.1, namely that biomass increased with higher plant density to a level where it started declining. According to Van Averbeke and Marais (1992), the seed yield of maize had a similar trend. McGregor (1987) reported a reduction in biomass yield of rapeseed at high plant densities even though a specific density was not mentioned, but the result was attributed to the high competition among plants. Results from this study showed that canola has a huge compensatory capacity at low plant density. This is consistent to the findings of Ali *et al.* (1996) who reported that low plant density caused an increase in number of branches per plant. Similarly, Taylor and Smith (1992) reported a consistent increase in the number of seeds per pod as plant density decreased

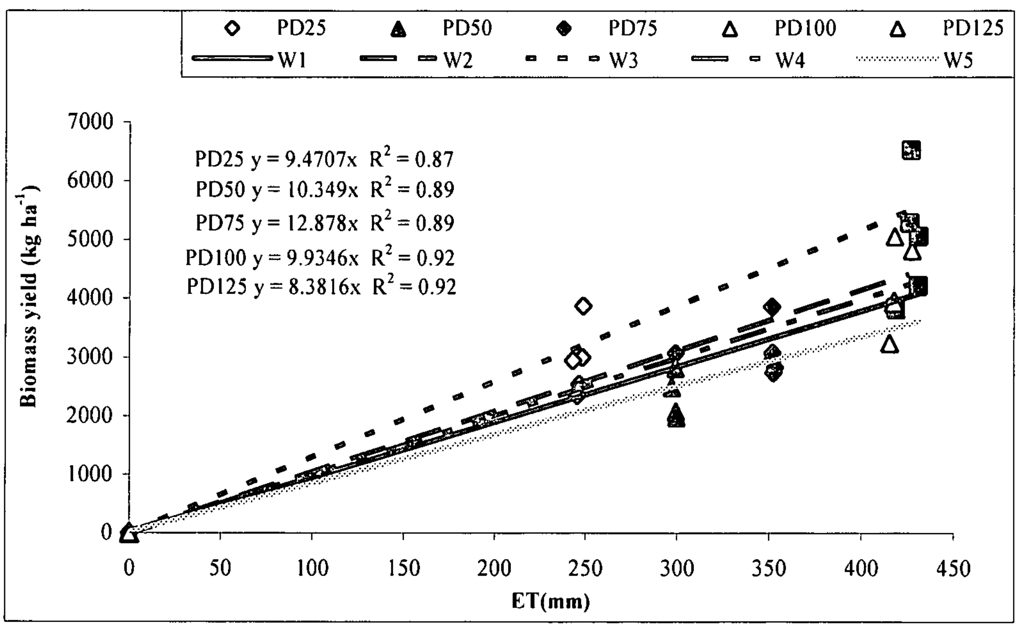


Figure 4.3. Relationships between biomass yield and total evapotranspiration for each plant density irrespective of the water application.

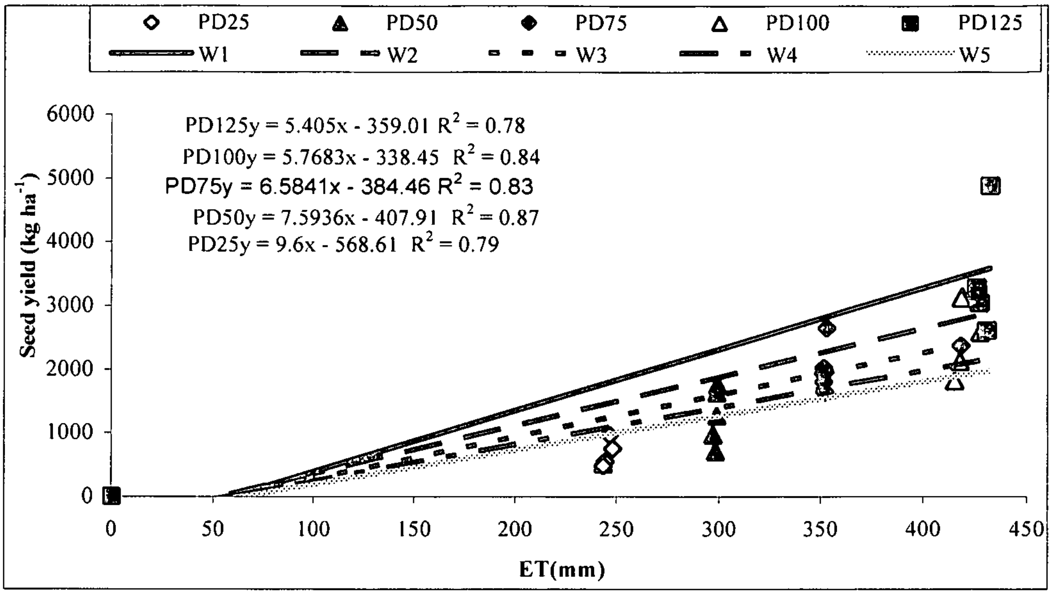


Figure 4.4. Relationships between seed yield and total evapotranspiration for each plant density irrespective of the water applications.

4.4. CONCLUSION

The daily ET of canola was measured under a full irrigation regime.Daily ET was not measured on regular basis at the plant establishing period (0 - 48 DAP) and hence the ET rates were assumed to be linear over the period. Successfully over the rest of the growing season with a polynomial equation ($r^2 = 0.72$). This equation predicted a maximum water use of 6.9 mm day^{-1} on 110 days after planting. The crop factor increased gradually from 0.4 on day 48 and peaked at 0.9 on day 111. Total ET increased linear ($r^2 = 0.97$) from 245 mm at a 118 mm water application to 429 mm at 363 mm water application, but was not influenced at all by plant density. Based on WUE it was found that the optimum plant density for fodder production was 75 plants m^{-2} and for seed production it was 25 plants m^{-2} irrespective of water application

CHAPTER 5

EFFECT OF WATER APPLICATION AND PLANT DENSITY ON THE – TRANSPIRATION EFFICIENCY OF CANOLA (*Brassica napus l.*)

5.1. Introduction

The challenge in computing the transpiration coefficient (m) of a crop, as indicated in Equation 5.1, relates to the difficulty of separating transpiration (T) from the actual evapotranspiration (ETa) under field conditions. Transpiration is most accurate when determined in weighing lysimeters or in containers where the surface of the soils is treated to prevent actual evaporation (Ea) from the soil surface. The kind of experiments were used by De Wit (1958) to prove that the biomass yield (Ybm) is related to transpiration on account of the simultaneous import of CO_2 and export of water through the stomata during photosynthesis.

$$Ybm = m\ T/Eo \qquad 5.1$$

Tanner and Sinclair (1983) suggested that variability due to climate could be further reduced by replacing the reference crop evaporation (Eo) with the Bierhuizen and Slatyer (1965) atmospheric water vapor pressure deficit:

$$Ybm = m\ T/(e^{*}-e) \qquad 5.2$$

Where:

e^* = saturated vapor pressure for air at a given temperature (kPa)

e = ambient or actual vapor pressure at that temperature (kPa)

These findings as well as those of Gregory (1988) and Monteith (1988) stimulated world wide research into field crop water relations. Most crop water related field studies in South Africa reported a linear relationship between seed yield (kg ha^{-1}) and water use (mm), expressed as ET (Bennie *et al.* 1988; Van Rensburg *et al.*, 1995; Van Rensburg, 1996; Bennie *et al.*, 1997). These relationships were used in the planning and management of irrigation at farm and scheme level (Bennie *et al.*, 1988; Bennie, 1995). Despite wide use of the water production functions, the approach was criticized due to the inherent empirical nature of the relationships. Stewart *et al.* (1977) as cited by Hanks (1983) suggested that the relationship should rather be expressed relative to the maximum ET and yield of a particular region as indicated in Equation 5.3:

$$1-(Ya/Ym) = \beta\,[1-ETa/ETm] \qquad 5.3$$

Where:

Ya = actual biomass yield (kg ha^{-1})

Ym = maximum biomass yield (kg ha^{-1})

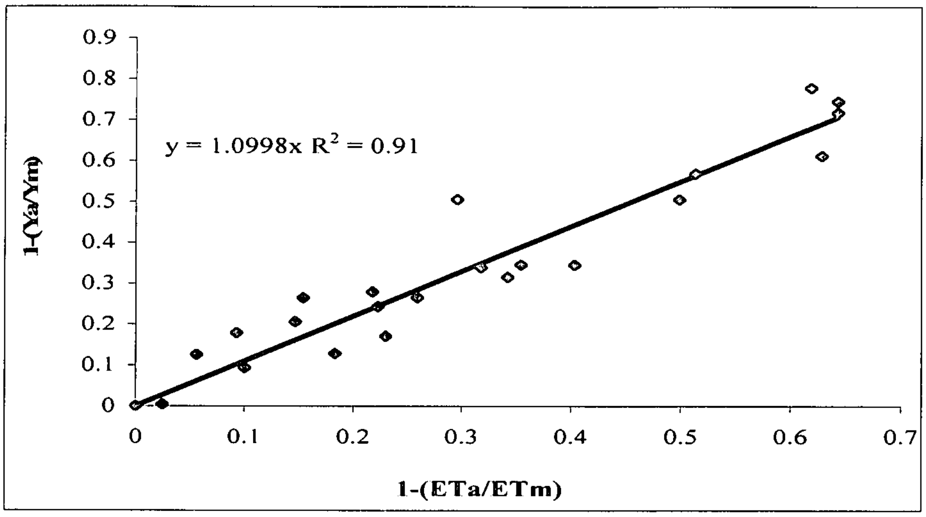
ETa = actual evapotranspiration (mm)

ETm = maximum evapotranspiration (mm)

β = slope of the relationship between

The slope of the relationship (β coefficient) is regarded as a crop response factor and it was generally agreed that the β coefficient is less empirical than the crop production function (Doorenbos and Kassam, 1979; Hanks and Rasmussen, 1982). Strydom (1998) applied Equation 5.3 to determine the β coefficient for both peas and potatoes using irrigation experiments conducted under a line source irrigation system near Bloemfontein. He found that the β coefficient for peas and potatoes were 1.1 and 1.58, respectively (Figure 5.1). These linear relationships imply that the β coefficient of a crop is constant over a wide range of ET's as induced by the line source irrigation system.

(a)



(b)

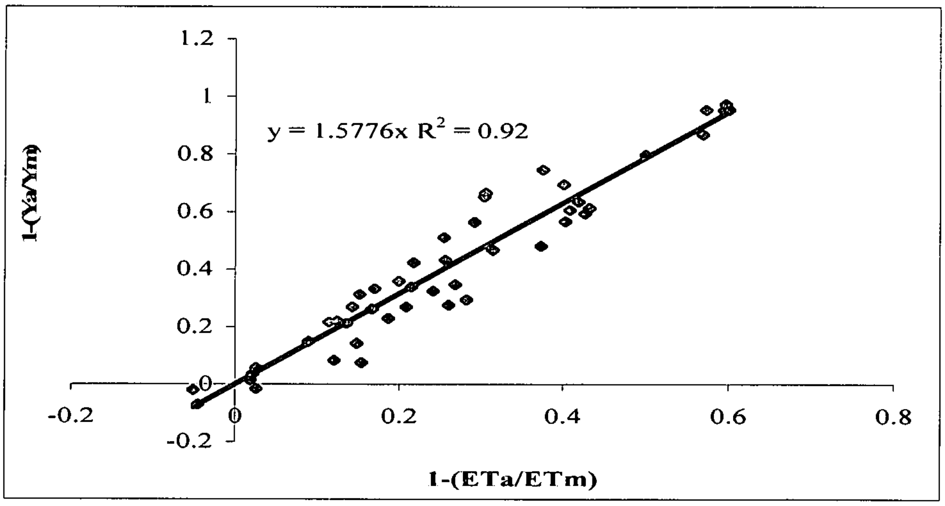


Figure 5.1. The β coefficient for (a) peas and (b) potatoes as indicated by the slope of the linear relationships (modified from Strydom, 1998).

The objectives of this chapter were therefore to: (i) establish the influence of water application and plant density on the β coefficient of canola, and (ii) use the β coefficient in separating Es and T from actual ET.

5.2. MATERIALS and METHODS

In achieving the mentioned objectives relevant data from the experiment described in Section 3.2 and 4.2 was used. This experiment was done with a line source sprinkler irrigation system comprising of five water application treatments (W1 = 118 mm, W2 = 176 mm, W3 = 238 mm, W4 = 274 mm and W5 = 363 mm) and five plant density treatments (PD25 = 25 plants m^{-2}, PD50 = 50 plants m^{-2}, PD75 = 75 plants m^{-2}, PD100 = 100 plants m^{-2} and PD125 = 125 plants m^{-2}). Details regarding experiment description, plant measurements, water measurements and data processing are therefore not repeated here. Only details on the calculations are given here.

5.2.1. Determination of the β coefficient

The relative final biomass yield, namely the ratio of actual yield (Ya) to maximum yield (Ym) was calculated per plant density treatment, irrespective of water application treatments. Maximum biomass yields used were 3279, 3606, 4477, 3453 and 2905 kg ha^{-1} for the PD25, PD50, PD75, PD100 and PD125 treatments, respectively. Similarly, the relative ET was calculated as the ratio of the actual evapotranspiration (ETa) to the maximum evaptranspiration (ETm) per plant density treatment, irrespective of water application treatments. The ETm's were 446, 440, 438, 436 and 445 mm for the PD25, PD50, PD75, PD100 and PD125 treatments, respectively. Relative yield deficits [1-(Ya/Ym)] were then regressed against relative ET deficits [1-(ETa/ETm)] for each plant density treatment, over all water application treatments.

5.2.2. Separation of evapotranspiration into evaporation and transpiration

ETa was separated into Ea and T by applying Equations 5.4 and 5.5 as suggested by Hanks (1992):

$$Ea = [1 - (1/\beta)]\ ETa \qquad 5.4$$

$$T = ETa - Ea \qquad 5.5$$

5.2.3. Estimation of the transpiration coefficient

The transpiration coefficient (m) was calculated with Equation 5.2, which requires data on vapor pressure deficit. The Penman-Monteith equation was used to estimate the vapor pressure deficits (e^*-e) as indicated in Appendix 5.1 (Allen *et al.*, 1998). These inputs were obtained from the standard automatic meteorological station at the experimental site.

5.3. RESULTS and DISCUSSION

5.3.1. Effect of water application and plant density on the β coefficient

The relationships between relative yield deficits and relative ET deficits for each plant density over all water application treatments are displayed in Figure 5.2. Based on the general shape of the curves, crop response was similar amongst plant density treatments. Therefore all data were combined and was best described by a single polynomial function showing two distinct phases (Figure 5.3). The first phase covering the 0 - 0.18 relative ET scale is linear and the second phase covering the 0.18 - 0.42 relative ET scale non-linear. This implies a change in the β coefficient of canola with a gradient in water application and is therefore contrasting to the findings of Strydom (1998) with peas and potatoes (Figure 5.1). The first phase (β coefficient = 2.26) reflected full to moderate irrigation regimes (W5 - W3) while the second phase reflected moderate to sub-optimum irrigation regimes (W3 - W1). Improved transpiration efficiency under water stress conditions is well described by Parameswaren *et al.* (1981) and Onken & Wendt (1989). They observed in wheat and sorghum studies that restricted water supply conditions increased the m-value (Equation 5.1) of both crops. McCree *et al.* (1990) and Nobel (1999) attributed the increase in m-value to (i) an improved conversion efficiency of photosynthate to biomass on account of greater starch production under severe water supply conditions and (ii) a proportionately greater effect of partial stomatal closure on flux of water compared to that of CO_2. The fact that the β coefficient of canola was affected by the amount of irrigation is in agreement with the general conclusion that the m-value (Equations 5.1 and 5.2) can be affected by a number of cultural practices, such as tillage, fertilization and plant density (De Wit, 1958, Boukar *et al.*, 1996). The β coefficient of canola in phase one seems very high when compared to that of other crops. For example, Bennie *et al.* (1997) reported β coefficients of 1.26, 1.30, 1.37, 1.25 and 1.52 for wheat, maize, groundnuts, peas and potatoes, respectively. Canola is a C3 plant and according to Tanner and Sinclair (1983) its transpiration efficiency should not differ largely from other C3 plants such as wheat and barley. The reason for this is that these plants use a similar photosynthetic pathway. After reviewing a large number of papers on the m-value, Unger *et al.* (2006) stated that the relationship between yield and ET remains a ratio and many environmental and cultural factors can influence it.

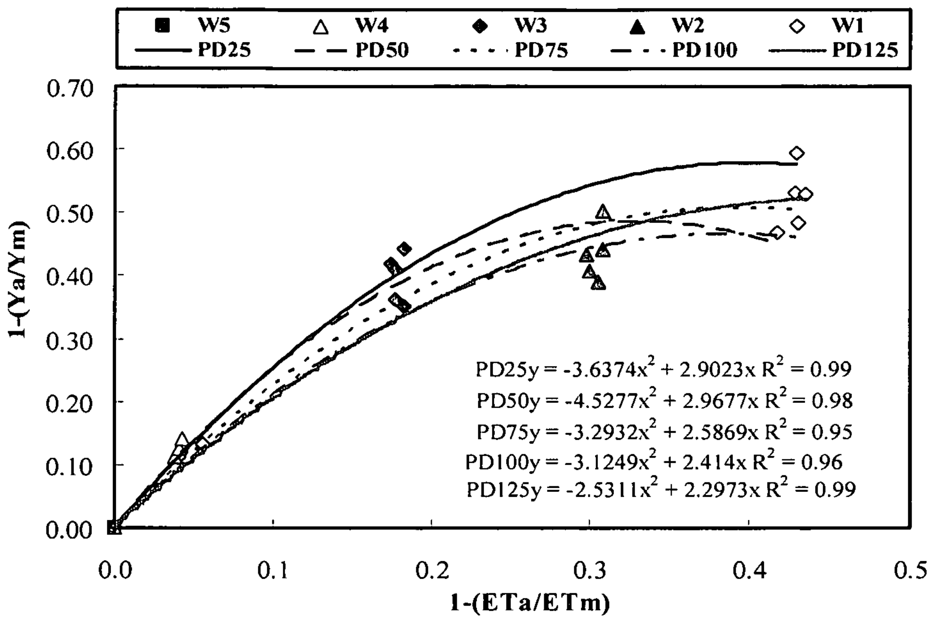


Figure 5.2. Relationships between relative yield deficits (1-Ya/Ym) and evapotranspiration deficits (1-ETa/ETm) for each plant density over all water application treatents.

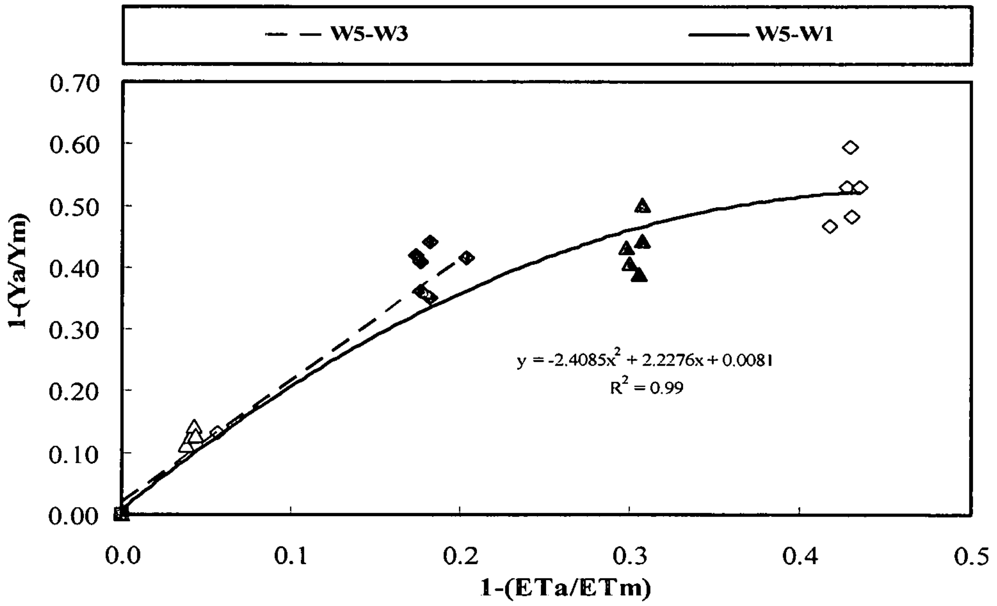


Figure 5.3. Relationship between relative yield deficits (1-Ya/Ym) and relative evapotranspiration deficits (1-ETa/ETm) for the combined plant density treatments (PD25 - PD125) over all water treatments.

5.3.2. Separation of evapotranspiration into evaporation and transpiration

It is clear from Equations 5.3, 5.4 and 5.5 that the separation of evapotranspiration (ET) into its components of evaporation and transpiration (T) requires a β coefficient. As described in previous section a β coefficient was established for the W5 - W3 treatments but not for W2 and W1 treatments. Therefore, only results on the separation of ET for the former treatments are presented in Table 5.1. Over all plant densities estimated T varied between 187 and 190 mm in W5, between 183 and 184 mm in W4 and a constant 155 mm in W3. On average for the W3 - W5 and PD25 - PD125 treatment combination the contribution of Ea and T to ET were 56% and 44%, respectively. It can be concluded that this method for separating ET into Ea and T was not suitable in establishing the influence of plant density on the two components. The β coefficient represents optimum conditions and will probably be more suitable to separate Ea and T once the optimum plant density is known as in the case of PD75 for biomass yield.

Table 5.1. Separation of evapotranspiration (ETa) for the water application (W3 - W5) and plant density (PD25 - PD125) treatment combinations into evaporation (Ea) and transpiration (T) using the estimated β coefficient.

Water application (mm)	Parameters (mm)	Plant density					
		PD25	PD50	PD75	PD100	PD125	Mean
W5	ETa	432	426	427	428	431	429
	Ea	242	239	239	240	241	240
	T	190	187	188	188	190	189
W4	ETa	419	419	418	418	415	418
	Ea	235	235	234	234	232	234
	T	184	184	184	184	183	184
W3	ETa	353	352	352	352	352	352
	Ea	198	197	197	197	197	197
	T	155	155	155	155	155	155

5.3.3. Transpiration coefficient

The relationship between biomass yield and transpiration per unit vapor pressure deficit at optimum plant density (PD75) moderate (W3) to full (W5) irrigation is presented in Figure 5.4. Biomass yield increased linear with an increase in transpiration per unit vapor pressure deficit ($r^2 = 0.56$). The transpiration coefficient or m-value of canola under these particular conditions is therefore 0.0045 g water kPa^{-1} biomass kg^{-1}.

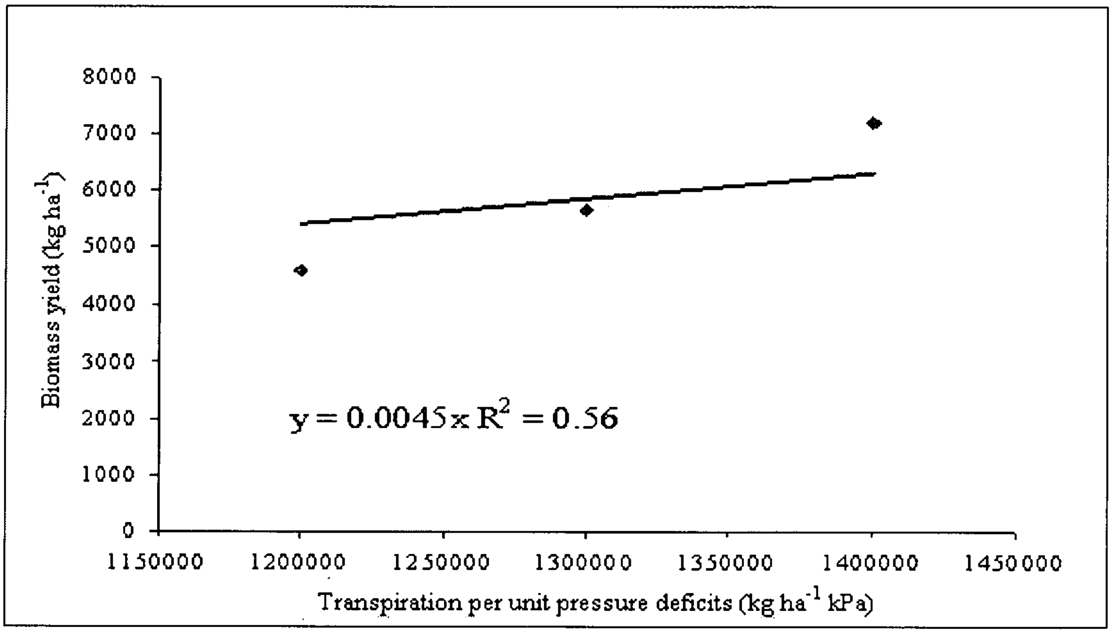


Figure 5.4. Relationship between biomass yield and transpiration per unit vapor pressure deficits kPa at optimum plant density treatment (PD75) with moderate (W3) to full (W5) irrigation.

5.4. CONCLUSION

The β coefficient of canola changed with a gradient in water application. It was constant for the full to moderate irrigation regimes (W5 - W3), but not for the moderate to sub-optimum irrigation regimes (W3 - W1). No obvious explanation can be given for this phenomenon since with other crops like peas and potatoes the β coefficient was constant over the full range of irrigation regimes. The β coefficient was used therefore to separate the ET of only the W3 - W5 treatments into Ea and T. This method was not at all suitable to determine the influence of plant density on the two components of ET. A transpiration coefficient of 0.0045g water kPa^{-1} biomass kg^{-1} was estimated for canola when planted for fodder, viz. an optimum plant density of 75 plants m^{-2} that coincides with moderate to full irrigation.

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

Insufficient available water is usually the limiting factor in crop production. Irrigation is therefore vital for sustainable production in the semi arid regions for winter crops like canola. The study therefore aimed at establishing the crop's ability to plasticity, its water use and water use efficiency and transpiration coefficient under a range of water application (W1 = 118 mm, W2 = 176 mm, W3 = 238 mm, W4 = 274 mm and W5 = 363 mm) and plant density : PD25 = 25 plants m^{-2}, PD50 = 50 plants m^{-2}, PD75 = 75 plants m^{-2}, PD100 = 100 plants m^{-2} and PD125 = 125 plants m^{-2}.treatment combination. Irrigation at the crop,s growing season was 57 mm and it was not included in the total water applied at different levels.

The yield of seeds (558 - 4653 kg ha^{-1}) and biomass (1983 - 6733 kg ha^{-1}) were induced by the water application and plant density treatments showing the capacity of canola to plasticity. The ability to yield compensation was best illustrated at the full irrigation treatment and the optimum seed yields was observed at 25 plant m^{-2} and biomass at 75 plants m^{-2}. Compensation of yields at lower plant densities was a result from number of branches $plant^{-1}$ and therefore the number of pods $plant^{-1}$.

The daily ET of canola under full irrigation increased exponential from 48 days after planting and peaked (6.9 mm day^{-1}) on day 110 before it decreased towards harvesting at 130 days after planting. Total ET increased linear (r^2 = 0.97) from 245 mm with 118 mm water application (W1) to 421 mm with 363 mm water application (W5) but was not influenced by plant density at all. Based on WUE, the optimum plant density for fodder production is 75 plants m^{-2} and for seed production is 25 plants m^{-2}. At these two plant densities WUE was 12.9 kg ha^{-1} mm^{-1} and 9.6 kg ha^{-1} mm^{-1}, respectively. Coefficient of

2.26 was used to separate the ET's of the W5 - W3 treatments into Es (56%) and T (44%). This method was not suitable to determine the influence of plant density on the two components of ET. A transpiration coefficient of 0.0045 was estimated for canola when planted for fodder at an optimum plant density of 75 plants m^{-2} that coincides with the moderate (W3) to full (W5) irrigation regimes.

Therefore, until proven different, 75 plants m^{-2} for fodder production and 25 plant m^{-2} for seed production are recommended, irrespective of the amount of irrigation. Further studies are however warrant to establish whether these recommended plant densities are universal to other cultivars, planting dates and fertilization rates for example. Other aspects requiring more investigation are inter alia the amount of water needed for optimum yield and the growth stages susceptible for water stress.

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APPENDICES

Appendix 3.1a Analysis of variance and the means of biomass (kg ha^{-1}) for different water applications (W1 - W5) and plant densities (PD25 - PD125)

ANOVA

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Power Alpha (0.05)**
W	4	1.016984E+08	2.542461E+07	73.44	0.000000*	1.000000
PD	4	3.143274E+07	7858185	22.70	0.000000*	1.000000
W X PD	16	4151137	259446.1	0.75	0.735040 ns	0.416816
S	75	2.59662E+07	346216			
Total (Adjusted)	99	1.632485E+08				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	**W2**	**W3**	**W4**	**W5**	**Mean**
PD 25	2375	2600	2900	4239	5388	3500.4
PD 50	3050	3108	3175	4266	5291	3778
PD 75	3150	3875	4083	5341	6733	4636.4
PD100	2491	2941	3075	3941	5329	3555.4
PD125	1983	2350	2737	3241	4216	2905.4
Mean	2609.8	2974.8	3194	4205.6	5391.4	3675.12

$LSD_{(t,0.05)}$ Water 5.07

$LSD_{(t,0.05)}$ PD 28.17

$LSD_{(t,0.05)}$ Water X PD 20.48

Appendix 3.1b Analysis of variance and means of seed yield (kg ha^{-1}) for different water applications (W1 - W5) and plant densities (PD25 - PD125)

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha (0.05)
W	4	8.33645E+07	2.084112E+07	320.40	0.000000*	1.000000
PD	4	1.731596E+07	4328991	66.55	0.000000*	1.000000
W X PD	16	5260338	328771.1	5.05	0.000001*	0.999964
S	75	4878574	65047.64			
Total(Adjusted)	99	1.108194E+08				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	W2	W3	W4	W5	Mean
PD 25	1564	1004	2485	3146	4653	2570.4
PD 50	1412	821	2143	3115	3273	2152.8
PD 75	1026	655	1754	2443	3036	1782.8
PD 100	858	606	1626	2124	2577	1558.2
PD 125	653	558	1514	1815	2604	1428.8
Mean	1102.6	728.8	1904.4	2528.6	3228.6	1898.6

$LSD_{(t,0.05)}$ Water 4.6

$LSD_{(t,0.05)}$ PD 2.1

$LSD_{(t,0.05)}$ Water X PD 2.3

Appendix 3.1c Analysis of variance and means of harvest index for different water applications (W1 - W5) and plant densities (PD25 - PD125)

ANOVA

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Power Alpha(0.05)**
W	4	2.627057	0.6567641	111.99	0.000000*	1.000000
PD	4	1.935738	0.4839345	82.52	0.000000*	1.000000
W X PD	16	0.2837493	1.773433E-02	3.02	0.000633*	0.990646
S	75	0.4398358	5.864478E-03			
Total (Adjusted)	99	5.28638				
Total	100					

*= Significant at 0.05 (5%): ns = non-significant

	W1	**W2**	**W3**	**W4**	**W5**	**Mean**
PD 25	0.5	0.6	0.7	0.8	0.8	0.7
PD 50	0.3	0.5	0.7	0.8	0.6	0.5
PD 75	0.2	0.4	0.4	0.5	0.5	0.4
PD 100	0.2	0.4	0.6	0.6	0.5	0.4
PD 125	0.2	0.3	0.6	0.6	0.7	0.5
Mean	0.2	0.4	0.6	0.6	0.6	0.5

$LSD_{(t,0.05)}$ Water 0.0

$LSD_{(t,0.05)}$ PD 0.0

$LSD_{(t,0.05)}$ Water X PD 0.0

Appendix 3.2a Analysis of variance and means of branches per plant for different water applications (W1 - W5) and plant densities (PD25 - PD125)

ANOVA

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Power Alpha(0.05)**
W	4	2177.316	544.329	1534.33	0.000000*	1.000000
PD	4	1675.781	418.9453	1180.90	0.000000*	1.000000
W X PD	16	295.863	18.49144	52.12	0.000000*	1.000000
S	75	26.6075	0.3547667			
Total(Adjusted)	99	4175.567				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	**W2**	**W3**	**W4**	**W5**	**Means**
PD 25	34.4	35.4	35.5	37.3	42.7	37.0
PD 50	24.6	31.1	32.2	34.6	39.3	32.3
PD 75	21.8	25.8	30.8	31.9	35.2	29.1
PD 100	21.0	21.2	28.5	30.7	34.4	27.2
PD 125	19.6	19.5	23.1	29.0	36.4	25.5
Means	24.3	26.6	30.0	32.7	37.6	30.2

$LSD_{(t,0.05)}$ Water 0.2

$LSD_{(t,0.05)}$ PD 0.2

$LSD_{(t,0.05)}$ Water X PD 0.2

Appendix 3.2b Analysis of variance and means of pods per plant for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha(0.05)
W	4	52963.09	13240.77	48.45	0.000000*	1.000000
PD	4	34572.48	8643.121	31.63	0.000000*	1.000000
W X PD	16	27609.3	1725.581	6.31	0.000000*	0.999999
S	75	20494.91	273.2655			
Total (Adjusted)	99	135639.8				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	W2	W3	W4	W5	Means
PD 25	46.9	55.2	141.2	141.2	183.3	113.6
PD 50	28.1	49.6	66.4	66.4	92.3	60.6
PD 75	37.2	47.5	68.7	68.7	89.6	62.3
PD 100	32.9	46.8	58.6	58.6	68.1	53.0
PD 125	33.6	40.8	53.9	53.9	63.7	49.2
Means	35.7	48.0	77.8	77.8	99.4	67.7

$LSD_{(t,0.05)}$ Water 1.2

$LSD_{(t,0.05)}$ PD 0.9

$LSD_{(t,0.05)}$ Water X PD 1.7

Appendix 3.2c Analysis of variance and means of seeds weight per plant (g) for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Power Alpha(0.05)**
W	4	124.9834	31.24585	1401.16	0.000000*	1.000000
PD	4	136.0954	34.02385	1525.73	0.000000*	1.000000
W X PD	16	37.6346	2.352163	105.48	0.000000*	1.000000
S	75	1.6725	0.0223			
Total (Adjusted)	99	300.3859				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	**W2**	**W3**	**W4**	**W5**	**Mean**
PD 25	3.05	4.42	4.65	6.03	8.10	5.25
PD 50	1.87	1.47	3.28	3.90	5.40	3.18
PD 75	1.01	1.32	2.63	1.72	4.39	2.21
PD 100	1.51	1.11	2.90	3.50	2.70	2.35
PD 125	1.01	1.73	3.07	1.60	3.54	2.19
Mean	1.69	2.01	3.30	3.35	4.82	3.04

$LSD_{(t,0.05)}$ Water 0.0

$LSD_{(t,0.05)}$ PD 0.0

$LSD_{(t,0.05)}$ Water X PD 0.0

Appendix 3.a Analysis of variance and means of biomass (g m^{-2}) on day 70 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Power Alpha(0.05)**
W	4	56481.69	14120.42	48.39	0.000000*	1.000000
PD	4	34773	8693.25	29.79	0.000000*	1.000000
W X PD	16	4102.244	256.3902	0.88	0.595132 ns	0.492476
S	75	21886.05	291.814			
Total (Adjusted)	99	117243				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	**W2**	**W3**	**W4**	**W5**	**Mean**
PD 25	95.1	113.8	123.2	135.2	144.8	122.4
PD 50	113.5	123.0	143.2	144.1	166.1	138.0
PD 75	118.6	136.0	154.9	163.7	193.5	153.3
PD 100	135.7	142.6	165.1	185.5	208.5	167.5
PD 125	124.8	153.2	173.9	196.2	216.0	172.8
Mean	117.5	133.7	152.0	164.9	185.8	150.8

$LSD_{(t,0.05)}$ Water 1.2

$LSD_{(t,0.05)}$ PD 0.9

$LSD_{(t,0.05)}$ Water X PD 0.6

Appendix 3.4b Analysis of variance and means of biomass (g m^{-2}) on day 88 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125)

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha(0.05)
W	4	141350.1	35337.53	361.30	0.000000*	1.000000
PD	4	46521.43	11630.36	118.91	0.000000*	1.000000
W X PD	16	27159.27	1697.455	17.36	0.000000*	1.000000
S	75	7335.46	97.80614			
Total (Adjusted)	99	222366.3				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	W2	W3	W4	W5	Mean
PD 25	133.9	135.6	163.1	192.4	225.0	170.0
PD 50	136.9	133.5	195.2	219.8	234.9	184.0
PD 75	145.2	174.1	246.7	255.5	266.1	217.5
PD 100	151.7	173.5	254.6	251.7	236.4	213.6
PD 125	166.0	221.9	276.4	242.4	226.4	226.6
Mean	146.7	167.7	227.2	232.3	237.8	202.3

$LSD_{(t,0.05)}$ Water 1.9

$LSD_{(t,0.05)}$ PD 1.1

$LSD_{(t,0.05)}$ Water X PD 1.7

Appendix 3.4c Analysis of variance and means of biomass (g m^{-2}) on day 102 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha(=0.05)
W	4	215965.2	53991.29	4673.7	0.000000*	1.000000
PD	4	43928.39	10982.1	950.66	0.000000*	1.000000
W X PD	16	61059.77	3816.236	330.35	0.000000*	1.000000
S	75	866.4075	11.5521			
Total (Adjusted)	99	321819.7				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	W2	W3	W4	W5	Mean
PD 25	135.3	145.5	175.2	197.9	293.9	189.5
PD 50	146.1	154.2	214.2	230.4	304.1	209.8
PD 75	156.4	182.9	254.6	273.1	343.8	242.1
PD 100	173.7	193.2	265.1	264.2	265.2	232.3
PD 125	195.4	224.4	293.7	274.8	233.0	244.3
Mean	161.4	180.0	240.5	248.0	288.0	223.6

$LSD_{(t,0.05)}$ Water 2.3

$LSD_{(t,0.05)}$ PD 1.1

$LSD_{(t,0.05)}$ Water X PD 2.5

Appendix 3.4d Analysis of variance and means of biomass (g m^{-2}) on day 116 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha(0.05)
W	4	275014	68753.5	917.10	0.000000*	1.000000
PD	4	55257.96	13814.49	184.27	0.000000*	1.000000
W X PD	16	44309.2	2769.325	36.94	0.000000*	1.000000
S	75	5622.645	74.9686			
Total (Adjusted)	99	380203.8				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

	W1	W2	W3	W4	W5	Mean
PD 25	138.85	164.85	185.55	203.7	315.5	201.69
PD 50	155.55	174.95	224.35	239.925	322.85	223.525
PD 75	163.45	186	262.8	292.65	362.65	253.51
PD 100	187.05	193.85	282.95	266.425	305	247.055
PD 125	225.65	228.35	317.1	275.6	294.6	268.26
Mean	174.11	189.6	254.55	255.66	320.12	238.808

$LSD_{(t,0.05)}$ Water 2.6

$LSD_{(t,0.05)}$ PD 1.2

$LSD_{(t,0.05)}$ Water X PD 2.1

Appendix 3.4e Analysis of variance and means of biomass (g m^{-2}) on day 130 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha(0.05)
Water	4	925499.8	231375	6950.98	0.000000*	1.000000
PD	4	4180.35	1045.087	31.40	0.000000*	1.000000
W X PD	16	143159.4	8947.46	268.80	0.000000*	1.000000
S	75	2496.5	33.28667			
Total (Adjusted)	99	1075336				
Total	100					

*= Significant at 0.05 (5%); ns = non-significant

	W1	W2	W3	W4	W5	Mean
PD25	192.9	263.9	273.3	343.4	475.0	309.7
PD50	213.6	272.5	196.8	394.3	494.6	314.4
PD75	241.5	228.1	195.7	414.8	562.4	328.5
PD100	273.1	193.4	294.5	373.2	455.4	317.9
PD125	308.4	261.9	245.8	325.5	423.9	313.1
Mean	245.9	244.0	241.2	370.2	482.3	316.7

$LSD_{(t,0.05)}$ Water 5.4

$LSD_{(t,0.05)}$ PD 4.9

$LSD_{(t,0.05)}$ Water X PD 2.0

Appendix 3.5a. Analysis of variance and means of leaf area index on day 70 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha (0.05)
W	4	3.606074	0.9015185	89.57	0.000000*	1.000000
PD	4	1.054114	0.2635285	26.18	0.000000*	1.000000
W X PD	16	1.693066	0.1058166	10.5	0.000000*	1.000000
S	75	0.75485	1.006467E-02			
Total (Adjusted)	99	7.108104				
Total	100					

*= Significant at 0.05 (5%); ns = non-significant

	W1	W2	W3	W4	W5	Mean
PD 25	0.3	0.3	0.6	0.9	0.5	0.5
PD 50	0.6	0.3	0.6	0.6	0.8	0.6
PD 75	0.6	0.4	0.5	0.7	0.8	0.6
PD 100	0.4	0.5	0.9	0.9	1.3	0.8
PD 125	0.4	0.5	0.8	0.8	1.2	0.7
Mean	0.5	0.4	0.7	0.8	0.9	0.6

$LSD_{(t,0.05)}$ Water 0.0

$LSD_{(t,0.05)}$ PD 0.0

$LSD_{(t,0.05)}$ Water X PD 0.0

Appendix 3.5b. Analysis of variance and means of leaf area index on day 88 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Power Alpha (0.05)**
W	4	24.85627	6.214067	66.74	0.000000*	1.000000
PD	4	0.691966	0.1729915	1.86	0.126726 ns	0.439771
W X PD	16	4.996614	0.3122884	3.35	0.000196*	0.995865
S	75	6.983525	9.311367E-02			
Total (Adjusted)	99	37.52837				
Total	100					

*= Significant at 0.05 (5%); ns = non-significant

	W1	**W2**	**W3**	**W4**	**W5**	**Mean**
PD 25	0.8	0.7	1.1	2.2	2.4	1.4
PD 50	1.1	0.6	1.2	2.1	1.9	1.4
PD 75	0.8	0.8	1.2	1.5	1.9	1.2
PD 100	0.8	0.7	1.3	1.5	1.9	1.2
PD 125	0.6	1.0	1.7	1.2	2.2	1.3
Mean	0.8	0.8	1.3	1.7	2.1	1.3

$LSD_{(t,0.05)}$ Water 0.0

$LSD_{(t,0.05)}$ PD 0.0

$LSD_{(t,0.05)}$ Water X PD 0.0

Appendix 3.5c. Analysis of variance and means of leaf area index on day 102 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha(0.05)
W	4	88.2269	22.05672	1259.59	0.000000*	1.000000
PD	4	8.011706	2.002927	114.38	0.000000*	1.000000
W X PD	16	6.164124	0.3852578	22.00	0.000000*	1.000000
S	75	1.313325	0.017511			
Total (Adjusted)	99	103.716				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant

PD	W1	W2	W3	W4	W5	Mean
PD 25	1.2	1.4	2.2	3.1	4.1	2.4
PD 50	1.4	1.3	1.7	3.5	4.5	2.5
PD 75	1.2	1.1	1.4	2.7	3.2	1.9
PD 100	1.0	1.2	1.7	2.6	2.9	1.9
PD 125	0.9	1.3	1.4	2.3	3.1	1.8
Mean	1.1	1.3	1.7	2.8	3.5	2.1

$LSD_{(t,0.05)}$ Water 1.81

$LSD_{(t,0.05)}$ PD 16.51

$LSD_{(t,0.05)}$ Water X PD 0.52

Appendix 3.5d. Analysis of variance and means of leaf area index on day 116 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Power Alpha(0.05)**
W	4	0.588406	0.1471015	609.54	0.000000*	1.000000
PD	4	0.071946	0.0179865	74.53	0.000000*	1.000000
W X PD	16	0.765964	4.787275E-02	198.37	0.000000*	1.000000
S	75	0.0181	2.413333E-04			
Total (Adjusted)	99	1.444416				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant LSD(0.05t) = 41.73

	W1	**W2**	**W3**	**W4**	**W5**	**Mean**
PD 25	0.5	0.4	0.5	0.3	0.4	0.4
PD 50	0.3	0.4	0.3	0.6	0.5	0.4
PD 75	0.4	0.5	0.3	0.4	0.7	0.5
PD 100	0.3	0.3	0.3	0.4	0.6	0.4
PD 125	0.2	0.4	0.4	0.4	0.6	0.4
Mean	0.4	0.4	0.4	0.4	0.6	0.4

$LSD_{(t,0.05)}$ Water 0.0

$LSD_{(t,0.05)}$ PD 0.0

$LSD_{(t,0.05)}$ Water X PD 0.0

Appendix 3.5e. Analysis of variance and means of leaf area index on day 130 after planting for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Power Alpha(0.05)**
W	4	0.07241	0.0181025	9051.25	0.000000*	1.000000
PD	4	0.04729	0.0118225	5911.25	0.000000*	1.000000
W X PD	16	0.22375	1.398437E-02	6992.19	0.000000*	1.000000
S	75	0.00015	0.000002			
Total (Adjusted)	99	0.3436				
Total	100					

* = Significant at 0.05 (5%); ns = non-significant LSD(0.05t) = 37.99

	W1	**W2**	**W3**	**W4**	**W5**	**Mean**
PD25	0.3	0.3	0.3	0.2	0.2	0.2
PD50	0.2	0.3	0.2	0.3	0.3	0.3
PD75	0.3	0.2	0.2	0.3	0.4	0.3
PD100	0.2	0.2	0.2	0.2	0.2	0.2
PD125	0.3	0.2	0.2	0.2	0.3	0.2
Mean	0.2	0.2	0.2	0.2	0.3	0.2

$LSD_{(t,0.05)}$ Water 0.0

$LSD_{(t,0.05)}$ PD 0.0

$LSD_{(t,0.05)}$ Water X PD 0.0

Appendix 3.5a Analysis of variance and means of main stem diameter (mm) at harvest for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha (0.05)
W	4	82.89252	20.72313	40.27	0.000000*	1.000000
PD	4	49.43538	12.35884	24.02	0.000000*	1.000000
W X PD	16	5.566034	0.3478771	0.68	0.808303ns	0.373246
S	75	38.59515	0.514602			
Total (Adjusted)	99	176.4891				
Total	100					

*= Significant at 0.05 (5%); ns = non-significant

	W1	**W2**	**W3**	**W4**	**W5**	**Mean**
PD25	5.9	6.4	7.5	7.9	9.0	7.3
PD50	6.2	6.0	6.9	7.4	8.7	7.0
PD75	4.8	5.7	6.3	6.7	7.9	6.3
PD100	4.6	5.5	6.0	6.8	7.2	6.0
PD125	4.5	5.1	5.2	5.7	6.4	5.4
Means	5.2	5.8	6.4	6.9	7.8	6.4

$LSD_{(t,0.05)}$ Water 0.0

$LSD_{(t,0.05)}$ PD 0.0

$LSD_{(t,0.05)}$ Water X PD 0.0

Appendix 3.5b Analysis of variance and means of main stem height (cm) at harvest for different water applications (W1 - W5) and plant densities (PD25 - PD125).

ANOVA

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power Alpha (0.05)
W	4	21928.75	5482.188	85.12	0.000000*	1.000000
PD	4	966.3679	241.592	3.75	0.007768*	0.773682
W X PD	16	2229.431	139.3394	2.16	0.013512*	0.936385
S	75	4830.35	64.40466			
Total (Adjusted)	99	29954.9				
Total	100					

*= Significant at 0.05 (5%); ns = non-significant

	W1	W2	W3	W4	W5	Mean
PD25	63.7	65.4	82.6	96.4	105.0	82.6
PD50	62.5	61.1	80.2	76.5	98.1	75.7
PD75	52.7	66.8	65.2	80.3	102.8	73.5
PD100	59.7	71.0	66.6	97.3	96.0	78.1
PD125	58.3	66.5	68.2	83.9	100.5	75.5
Mean	59.4	66.2	72.5	86.9	100.5	77.1

$LSD_{(t,0.05)}$ Water 51.62

$LSD_{(t,0.05)}$ PD 3502.02

$LSD_{(t,0.05)}$ Water X PD 181.61

Appendix. 4.1. Water balance report data for W5-PD75 tratment

Water treat-ments	Surface treat ments	Soil depth intervals (mm)	Days after planting															
			Volumetric water content mm mm^{-1}															
			1		35			41			48			64			78	
				Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave
W5	Rep 1	0-300	0.120	0.161	0.174	0.168	0.160	0.174	0.167	0.119	0.139	0.129	0.119	0.139	0.129	0.092	0.111	0.101
		300-600	0.168	0.245	0.256	0.251	0.242	0.257	0.250	0.243	0.255	0.249	0.243	0.255	0.249	0.208	0.219	0.213
		600-900	0.201	0.222	0.249	0.236	0.221	0.256	0.239	0.224	0.250	0.237	0.224	0.250	0.237	0.208	0.225	0.216
		900-1200	0.204	0.226	0.225	0.225	0.232	0.229	0.230	0.238	0.231	0.234	0.238	0.231	0.234	0.227	0.240	0.234
		1200-1500	0.164	0.163	0.181	0.172	0.169	0.178	0.173	0.191	0.183	0.187	0.191	0.183	0.187	0.205	0.212	0.209
		1500-1800		0.170	0.224	0.197	0.168	0.224	0.196	0.173	0.226	0.199	0.173	0.226	0.199	0.185	0.238	0.211
		Total wc-1800(mm)		356.22	392.91	374.6	357.7	395.4	376.6	356.4	385.0	370.7	356.4	385.0	370.7	337.0	373.3	355.2
		Total wc-1500(mm)	257.1	305.16	325.71	315.4	307.2	328.2	317.7	304.6	317.2	310.9	304.6	317.2	310.9	281.6	302	291.8
		I (mm)				75			8			5			24			26
		P(mm)				23.3			0.6			0			0.6			0.1
		CMUL(mm)				348.4			345.9			356.8			354.7			372
		D_p (mm)				0			0			0			0			0
		ET_d (mm day^{-1})				1.18			1.06			1.69			1.54			3.227
		ET_p(mm)				39.97			6.34			11.8			24.6			45.18
		∑D (mm)				0			0			0			0			0
		∑ I (mm)				75			83			88			112			138
		∑ P(mm)				23.3			23.9			23.9			24.5			24.6
		∑ ETmm				39.97			46.3			58.1			82.7			127.9
		Eo mm day^{-1}				2.54			2.78			3.02			3.84			7.07
		Eo(p)mm				86.50			16.65			21.17			61.48			98.97
		∑ Eo(p)mm				86.5			103.2			124.3			185.8			284.8
		CF				0.46			0.38			0.56			0.40			0.46

Appendix. 4.1. Water balance report data for W5-PD75 continues….

Water treat-ments	Surface treat ments	Soil depth intervals (mm)	Days after planting: Volumetric water content mm mm^{-1}															
			1	35			41			48			64			78		
				Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave
	Rep 2	0-300	0.115	0.158	0.171	0.164	0.153	0.184	0.169	0.148	0.119	0.133	0.149	0.119	0.134	0.090	0.105	0.097
		300-600	0.140	0.249	0.248	0.249	0.245	0.245	0.245	0.248	0.242	0.245	0.258	0.242	0.250	0.221	0.231	0.226
		600-900	0.195	0.226	0.236	0.231	0.228	0.228	0.228	0.238	0.228	0.233	0.238	0.228	0.233	0.230	0.248	0.239
		900-1200	0.215	0.237	0.236	0.236	0.243	0.239	0.241	0.240	0.245	0.243	0.240	0.245	0.243	0.243	0.241	0.242
		1200-1500	0.190	0.193	0.195	0.194	0.193	0.207	0.200	0.217	0.205	0.211	0.217	0.205	0.211	0.221	0.210	0.216
		1500-1800		0.171	0.186	0.179	0.176	0.187	0.182	0.215	0.180	0.198	0.215	0.180	0.198	0.231	0.224	0.228
		Total wc-1800(mm)		370.32	381.45	375.89	371.5	386.6	379	391.9	365.6	378.7	395.1	365.6	380.4	371	377.8	374.4
		Total wc-1500(mm)	256.50	318.99	325.59	322.3	318.6	330.5	324.6	327.3	311.6	319.5	330.6	311.6	321.1	301.7	310.5	306.1
		I (mm)				75			8			5			23			28
		P(mm)				23.3			0.6			0			0.6			0.1
		CMUL(mm)				343.54			345.8			353.2			352			370.9
		D_p (mm)				0			0			0			0			0
		ET_d (mm day^{-1})				0.96			1.053			1.445			1.372			3.08
		ET_p(mm)				32.51			6.32			10.12			21.95			43.11
		∑D (mm)				0			0			0			0			0
		∑ I (mm)				75			83			88			111			139
		∑ P(mm)				23.3			23.9			23.9			24.5			24.6
		∑ ET(mm)				32.51			38.83			48.95			70.9			114
		Eo mm day^{-1}				2.54			2.78			3.02			3.84			3.62
		Eo(p)				86.5			16.65			21.17			61.48			50.62
		∑ Eo(p)				86.5			103.1			124.3			185.8			236.4
		CF				0.38			0.38			0.48			0.36			0.85

Water treatment	Surface treat-. ment	Soil depth (mm)	Days after planting Volumetric water content (mm mm^{-1})															
			1	35			41			48			64			78		
				Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave
W5	Rep 3	0-300	0.121	0.151	0.149	0.150	0.149	0.148	0.148	0.111	0.120	0.115	0.111	0.120	0.115	0.093	0.096	0.095
		300-600	0.171	0.237	0.261	0.249	0.236	0.257	0.247	0.258	0.234	0.246	0.258	0.234	0.246	0.214	0.211	0.212
		600-900	0.181	0.225	0.231	0.228	0.230	0.233	0.231	0.234	0.230	0.232	0.234	0.230	0.232	0.215	0.215	0.215
		900-1200	0.180	0.226	0.228	0.227	0.228	0.230	0.229	0.231	0.234	0.233	0.231	0.234	0.233	0.233	0.218	0.225
		1200-1500	0.195	0.196	0.201	0.199	0.199	0.203	0.201	0.206	0.204	0.205	0.206	0.204	0.205	0.203	0.211	0.207
		1500-1800		0.154	0.163	0.158	0.172	0.168	0.170	0.168	0.196	0.182	0.168	0.196	0.182	0.218	0.209	0.214
		Total wc-1800(mm)		356.88	369.63	363.3	364.1	371.5	367.8	362.4	365.6	364	362.4	365.6	364	352.8	347.9	350.4
		Total wc-1500(mm)	254.40	310.83	320.79	315.8	312.5	321.2	316.8	312	306.7	309.3	312	306.7	309.3	287.3	285.2	286.2
		I (mm)				75			8			5			24			29
		P(mm)				23.3			0.6			0			0.6			0.1
		CMUL(mm)				346.50			350.1			358.2			354.7			375.4
		D_p (mm)				0			0			0			0			0
		ET_d (mm day^{-1})				1.09			1.3			1.8			1.538			3.7
		ET_p(mm)				36.89			7.58			12.52			24.6			52.17
		$\sum$D (mm)				0			0			0			0			0
		$\sum$ I (mm)				75			83			88			112			141
		$\sum$ P(mm)				23.3			23.9			23.9			24.5			24.6
		$\sum$ ET(mm)				36.89			44.47			56.99			81.59			133.8
		Eo mm day^{-1}				2.54			2.78			3.02			3.84			3.62
		Eo(p)				86.50			16.65			21.17			61.48			50.62
		$\sum$ Eo(p)				86.50			103.1			124.3			185.8			236.4
		CF				0.43			0.46			0.59			0.6			0.9

Water treatments	Surface treatments	Soil depth (mm)	Days after planting: Volumetric water content mm mm^{-1}															
			1	35			41			48			64			78		
				Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave
	Rep 4	0-300	0.125	0.136	0.164	0.150	0.142	0.142	0.142	0.116	0.101	0.108	0.116	0.101	0.109	0.081	0.112	0.097
		300-600	0.169	0.261	0.254	0.257	0.258	0.245	0.251	0.244	0.253	0.248	0.244	0.253	0.248	0.227	0.257	0.242
		600-900	0.179	0.234	0.232	0.233	0.234	0.229	0.231	0.232	0.227	0.230	0.232	0.227	0.230	0.247	0.242	0.244
		900-1200	0.181	0.220	0.226	0.223	0.224	0.209	0.217	0.229	0.228	0.229	0.229	0.228	0.229	0.229	0.243	0.236
		1200-1500	0.191	0.206	0.197	0.201	0.210	0.206	0.208	0.209	0.214	0.211	0.209	0.214	0.211	0.231	0.232	0.231
		1500-1800		0.187	0.154	0.170	0.188	0.188	0.188	0.188	0.193	0.190	0.188	0.193	0.190	0.223	0.226	0.225
		Total wc-1800(mm)		373.11	367.95	370.5	376.7	365.4	371	365.2	364.7	365	365.2	364.7	365	371.1	393.7	382.4
		Total wc-1500(mm)	253.46	316.98	321.84	319.4	320.3	309	314.6	308.9	306.8	307.9	308.9	306.8	307.9	304.2	325.8	315
		I (mm)				75			8			5			22			28
		P(mm)				23.3			0.6			0			0.6			0.1
		CMUL(mm)				343.43			363.4			356.7			352.7			354
		D_p (mm)				0			0			0			0			0
		ET_d (mm day^{-1})				0.95			2.23			1.68			1.41			1.50
		ET_p(mm)				32.351			13.4			11.75			22.59			20.95
		∑D (mm)				0			0			0			0			0
		∑ I (mm)				75			83			88			110			138
		∑ P(mm)				23.3			23.9			23.9			24.5			24.6
		∑ ET(mm)				32.35			45.75			57.5			80.09			101
		Eo mm day^{-1}				2.54			2.78			3.02			3.84			3.62
		Eo(p)				89.04			16.65			21.17			61.48			50.62
		∑ Eo(p)				89.04			105.7			126.9			188.3			239
		CF				0.36			0.80			0.56			0.37			0.41

R1W5	Days after plant																				
	Volumetric water content mm mm^{-1}																				
Soil depth	85			92			99			106			113			120			127		Ave
interval	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	
0-300	0.09	0.10	0.10	0.11	0.17	0.14	0.15	0.12	0.13	0.08	0.10	0.09	0.07	0.09	0.08	0.19	0.18	0.18	0.09	0.07	0.08
300-600	0.20	0.19	0.20	0.22	0.20	0.21	0.17	0.16	0.17	0.17	0.19	0.18	0.16	0.17	0.16	0.16	0.18	0.17	0.20	0.18	0.19
600-900	0.21	0.24	0.23	0.22	0.23	0.22	0.16	0.16	0.16	0.16	0.19	0.17	0.15	0.16	0.16	0.18	0.19	0.18	0.20	0.19	0.20
900-1200	0.24	0.24	0.24	0.21	0.20	0.21	0.18	0.19	0.18	0.19	0.21	0.20	0.18	0.18	0.18	0.18	0.18	0.18	0.20	0.20	0.20
1200-1500	0.22	0.21	0.21	0.24	0.16	0.20	0.19	0.18	0.19	0.17	0.21	0.19	0.16	0.16	0.16	0.18	0.20	0.19	0.24	0.23	0.24
1500-1800	0.23	0.24	0.23	0.23	0.18	0.21	0.18	0.20	0.19	0.18	0.24	0.21	0.18	0.22	0.20	0.18	0.23	0.21	0.23	0.24	0.24
Total wc-1800(mm)	356.67	364.59	361	370	341.5	355.7	310.1	301	305.6	282.5	341.67	312	270.9	292.02	281.5	320.6	348.4	334.5	351.3	335.4	343.4
Total wc-1500(mm)	288.51	293.88	291	301.4	287	294.2	256.3	240.3	248.3	227.7	268.68	248	216.3	227.19	221.7	265.9	278.1	272	281.7	263.3	272.5
I (mm)			28			51			13			15			38			50			35
P(mm)			4.2			0			0			0			0.4			19			8.9
CMUL(mm)			381			389.7			394.5			363			396.8			367.68			387.34
D_p(mm)			0			0			0			0			0			0			0
ET_d (mm day^{-1})			4.7			6.9			8.41			2.16			9.264			2.6786			6.20
ET_p(mm)			33			48.03			58.87			15.1			64.85			18.75			43.4
∑D (mm)			0			0			0			0			0			0			0
∑ I (mm)			163			214			227			242			280			330			365
∑ P(mm)			24.6			24.6			24.6			24.6			25			44			52.9
∑ ET(mm)			161			209			268			283			348			366			410
Eo mm day^{-1}			4.42			6.26			5.6			3.99			7.063			4.85			5.88
Eo(p)			30.9			44			39			28			49			34			41.18
∑ Eo(p)			482			526			565			593			643			677			41.18
CF			1.06			1.10			1.50			0.54			1.31			0.55			1.05

R2W5	Days after planting Volumetric water content mm mm^{-1}																				
Soil depth	85			92			99			106			113			120			127		
interval	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave
0-300	0.08	0.07	0.08	0.14	0.14	0.14	0.19	0.15	0.17	0.10	0.10	0.10	0.09	0.08	0.08	0.19	0.18	0.18	0.07	0.07	0.07
300-600	0.18	0.17	0.18	0.16	0.16	0.16	0.18	0.17	0.17	0.19	0.18	0.19	0.17	0.18	0.17	0.20	0.23	0.21	0.11	0.10	0.11
600-900	0.19	0.20	0.19	0.23	0.20	0.22	0.16	0.16	0.16	0.18	0.16	0.17	0.17	0.19	0.18	0.15	0.19	0.17	0.19	0.21	0.20
900-1200	0,23	0.22	0.22	0.22	0.22	0.22	0.19	0.19	0.19	0.21	0.20	0.20	0.19	0.19	0.19	0.22	0.24	0.23	0.18	0.18	0.18
1200-1500	0.19	0.21	0.20	0.18	0.19	0.19	0.19	0.18	0.19	0.20	0.18	0.19	0.20	0.21	0.20	0.19	0.24	0.21	0.21	0.21	0.21
1500-1800	0.19	0.22	0.20	0.17	0.19	0.18	0.23	0.19	0.21	0.23	0.22	0.23	0.22	0.25	0.23	0.24	0.11	0.18	0.22	0.23	0.23
Total wc-1800(mm)	317.73	325.56	321.6	329.19	330.1	329.7	343.1	313.3	328.2	335.7	313.5	324.6	308	328.4	318.5	353	354	353.5	291.8	302.82	297
Total wc-1500(mm)	260.19	260.61	260.4	278.94	273.4	276.2	273.3	256.3	264.8	267.4	246.39	257	242.8	254.55	248.7	282.4	319.53	301	226.4	232.53	229
I (mm)			24			52			14			15			30			48			36
P(mm)			4.2			0			0			0			0.4			19			8.9
CMUL(mm)			399.8			383.1			374.8			372			384.6			362			360.2
D_p (mm)			0			0			0			0			0			0			0
ET_d (mm day^{-1})			10.56			5.17			3.62			3.27			5.52			2.10			1.95
ET_p(mm)			73.89			36.22			25.37			22.9			38.65			14.70			116.39
∑D (mm)			0			0			0			0			0			0			0
∑ I (mm)			163			215			229			244			274			322			358
∑ P(mm)			24.6			24.6			24.6			24.6			25			44			52.9
∑ ET(mm)			187.9			224.1			249.5			272			311			325.7			339.37
Eo mm day^{-1}			4.419			4.26			5.6			5.99			5.063			4.85			2.18
Eo(p)			30.93			29.82			39.2			41.9			35.44			33.95			8.88
∑ Eo(p)			482.2			512.1			551.3			593			628.6			662.6			671.44
CF			0.153			1.21			0.65			0.55			1.09			0.43			1.53

R3W5 Soil depth interval	Days after plant																				
	Volumetric water content mm mm-1																				
		85			92			99			106			113			120			127	
	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave
0-300	0.08	0.07	0.08	0.17	0.20	0.19	0.07	0.18	0.13	0.07	0.08	0.08	0.08	0.07	0.07	0.16	0.11	0.14	0.10	0.11	0.11
300-600	0.19	0.22	0.21	0.19	0.20	0.19	0.16	0.22	0.19	0.15	0.22	0.18	0.19	0.20	0.19	0.13	0.20	0.17	0.15	0.17	0.16
600-900	0.20	0.22	0.21	0.21	0.20	0.20	0.23	0.19	0.21	0.16	0.20	0.18	0.18	0.19	0.18	0.12	0.15	0.13	0.15	0.15	0.15
900-1200	0.21	0.23	0.22	0.23	0.21	0.22	0.21	0.22	0.21	0.17	0.22	0.20	0.20	0.19	0.20	0.16	0.10	0.13	0.15	0.16	0.15
1200-1500	0.21	0.22	0.21	0.23	0.22	0.22	0.23	0.21	0.22	0.17	0.22	0.19	0.20	0.19	0.20	0.14	0.11	0.13	0.16	0.15	0.15
1500-1800	0.21	0.23	0.22	0.23	0.22	0.23	0.21	0.22	0.22	0.19	0.22	0.21	0.22	0.21	0.21	0.07	0.09	0.08	0.16	0.15	0.16
Total wc-1800(mm)	331.5	359	345	376.3	373.7	375	336.3	369.8	353	273.4	347	310	320	313.2	317	234.4	230.9	232.7	260.7	267.8	264.3
Total wc-1500(mm)	267.3	290.2	279	307.9	306.6	307	272.5	302.8	288	215.3	280.7	248	256	250.6	253	214.3	203.6	208.9	212.8	221.8	217.3
I (mm)			28			50			13			15			36			49			34
P(mm)			4.2			0			0			0			0.4			19			8.9
CMUL(mm)			385			371			381			393			380			409.6			382
D_p (mm)			0			0			0			0			0			0			0
ET_d (mm day^{-1})			5.67			3.07			4.66			7.81			4.47			16.03			4.94
ET_p(mm)			39.7			21.5			32.6			54.6			31.3			112.2			34.55
$\sum$D (mm)			0			0			0			0			0			0			0
$\sum$ I (mm)			142			192			205			220			256			305.2			339.2
$\sum$ P(mm)			24.6			24.6			24.6			24.6			25			44			52.9
$\sum$ ET(mm)			173			195			228			282			313			425.7			460.2
Eo mm day^{-1}			4.42			4.26			5.6			5.99			5.06			9.85			5.88
Eo(p)			30.9			29.8			39.2			41.9			35.4			68.95			41.18
$\sum$ Eo(p)			267			297			336			378			414			482.7			523.8
CF			1.28			0.72			0.83			1.30			0.88			1.63			0.84

R4W5 Soil depth interval																					
	Days after planting																				
	Volumetric water content (mm mm^{-1})																				
	85			92			99			106			113			120			127		
	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave
0-300	0.08	0.1	0.09	0.13	0.15	0.14	0.15	0.13	0.14	0.08	0.1	0.09	0.07	0.1	0.09	0.15	0.11	0.13	0.08	0.09	0.09
300-600	0.23	0.18	0.21	0.24	0.19	0.21	0.23	0.24	0.23	0.22	0.17	0.19	0.17	0.16	0.16	0.13	0.12	0.13	0.16	0.17	0.17
600-900	0.24	0.21	0.23	0.24	0.22	0.23	0.21	0.2	0.21	0.2	0.16	0.18	0.16	0.17	0.17	0.14	0.08	0.11	0.16	0.17	0.17
900-1200	0.24	0.2	0.22	0.24	0.2	0.22	0.22	0.2	0.21	0.2	0.17	0.19	0.17	0.17	0.17	0.21	0.11	0.16	0.16	0.17	0.17
1200-1500	0.22	0.21	0.22	0.23	0.21	0.22	0.22	0.21	0.22	0.2	0.18	0.19	0.16	0.16	0.16	0.19	0.04	0.11	0.16	0.17	0.16
1500-1800	0.23	0.21	0.22	0.21	0.2	0.21	0.22	0.22	0.22	0.22	0.19	0.2	0.19	0.18	0.18	0.11	0.12	0.12	0.18	0.17	0.18
Total wc-1800(mm)	374	335	355	385	351	368	376	363	370	335	291	313	275	283	279	278	178	228	272	282	277
Total wc-1500(mm)	305.7	272	289	321.4	290	306	309.2	296.1	303	270.8	233.9	252	219	229.6	224	243.4	140.82	192.1	219.1	229.8	224.5
I (mm)			25			50			12			12			38			50			35
P(mm)			4.2			0			0			0			0.4			19			8.9
CMUL(mm)			393			381			363			396			397			407.2			356.3
D_p(mm)			0			0			0			0			0			0			0
ET_d (mm day^{-1})			7.91			4.73			2.16			8.9			9.47			14.48			1.649
ET_p(mm)			55.4			33.1			15.1			62.3			66.3			101.4			11.55
∑D (mm)			0			0			0			0			0			0			0
∑ I (mm)			160			210			222			234			272			322			357
∑ P(mm)			24.6			24.6			24.6			24.6			25			44			52.9
∑ ET(mm)			156			190			205			267			333			434.5			446.1
Eo mm day^{-1}			4.42			8.26			5.6			5.99			6.06			6.85			5.88
Eo(p)			30.9			57.8			39.2			41.9			42.4			47.95			41.18
∑ Eo(p)			270			328			367			409			451			499.3			540.43
CF			1.79			0.57						1.49			1.56			2.11			0.28

Appendix 4.2. Soil water balance data for all water application (W1 - W5) and plant density (PD25 - PD125) treatment combinations

Drainage = 0; Runoff = 0

REP			ΔSWCb	ΔSWCend	ΔW	P	I	ET
1	W1	PD25	257.1	201.00	-56.10	52.9	121	230.00
1	W1	PD50	257.1	195.00	-62.10	52.9	121	236.00
1	W1	PD75	257.1	204.00	-53.10	52.9	121	227.00
1	W1	PD100	257.1	199.00	-58.10	52.9	121	232.00
1	W1	PD125	257.1	195.00	-62.10	52.9	121	236.00
1	W2	PD25	257.1	190.00	-67.10	52.9	178	298.00
1	W2	PD50	257.1	199.00	-58.10	52.9	178	289.00
1	W2	PD75	257.1	192.00	-65.10	52.9	178	296.00
1	W2	PD100	257.1	194.00	-63.10	52.9	178	294.00
1	W2	PD125	257.1	200.00	-57.10	52.9	178	288.00
1	W3	PD25	257.1	200.00	-57.10	52.9	240	350.00
1	W3	PD50	257.1	202.00	-55.10	52.9	240	348.00
1	W3	PD75	257.1	204.00	-53.10	52.9	240	346.00
1	W3	PD100	257.1	206.00	-51.10	52.9	240	344.00
1	W3	PD125	257.1	210.00	-47.10	52.9	240	340.00
1	W4	PD25	257.1	178.00	-79.10	52.9	305	437.00
1	W4	PD50	257.1	175.00	-82.10	52.9	305	440.00
1	W4	PD75	257.1	179.00	-78.10	52.9	305	436.00
1	W4	PD100	257.1	176.00	-81.10	52.9	305	439.00
1	W4	PD125	257.1	178.00	-79.10	52.9	305	437.00
1	W5	PD25	257.1	269.00	11.90	52.9	365	406.00
1	W5	PD50	257.1	272.00	14.90	52.9	365	403.00
1	W5	PD75	257.1	272.50	15.40	52.9	365	402.50
1	W5	PD100	257.1	262.00	4.90	52.9	365	413.00
1	W5	PD125	257.1	264.00	6.90	52.9	365	411.00

Appendix 4.2. continues....

Drainage = 0; Runoff = 0

REP			**ΔSWCb**	**ΔSWCend**	**ΔW**	**P**	**I**	**ET**
2	W1	PD25	256.5	175.00	-81.50	52.9	117	251.40
2	W1	PD50	256.5	172.00	-84.50	52.9	117	254.40
2	W1	PD75	256.5	170.00	-86.50	52.9	117	256.40
2	W1	PD100	256.5	178.00	-78.50	52.9	117	248.40
2	W1	PD125	256.5	179.00	-77.50	52.9	117	247.40
2	W2	PD25	256.5	193.00	-63.50	52.9	177	293.40
2	W2	PD50	256.5	195.00	-61.50	52.9	177	291.40
2	W2	PD75	256.5	191.00	-65.50	52.9	177	295.40
2	W2	PD100	256.5	194.00	-62.50	52.9	177	292.40
2	W2	PD125	256.5	195.00	-61.50	52.9	177	291.40
2	W3	PD25	256.5	199.00	-57.50	52.9	233	343.40
2	W3	PD50	256.5	201.00	-55.50	52.9	233	341.40
2	W3	PD75	256.5	204.00	-52.50	52.9	233	338.40
2	W3	PD100	256.5	197.00	-59.50	52.9	233	345.40
2	W3	PD125	256.5	194.00	-62.50	52.9	233	348.40
2	W4	PD25	256.5	187.00	-69.50	52.9	291	413.40
2	W4	PD50	256.5	184.00	-72.50	52.9	291	416.40
2	W4	PD75	256.5	192.00	-64.50	52.9	291	408.40
2	W4	PD100	256.5	194.00	-62.50	52.9	291	406.40
2	W4	PD125	256.5	191.00	-65.50	52.9	291	409.40
2	W5	PD25	256.5	221.00	-35.50	52.9	358	446.40
2	W5	PD50	256.5	231.00	-25.50	52.9	358	436.40
2	W5	PD75	256.5	229.47	-27.03	52.9	358	437.93
2	W5	PD100	256.5	234.00	-22.50	52.9	358	433.40
2	W5	PD125	256.5	222.00	-34.50	52.9	358	445.40

Appendix 4.2. continues......

Drainage = 0; Runoff = 0

REP			ΔSWCb	ΔSWCend	ΔW	P		
3	W1	PD25	254.4	181.00	-73.40	52.9	116	242.30
3	W1	PD50	254.4	179.00	-75.40	52.9	116	244.30
3	W1	PD75	254.4	183.00	-71.40	52.9	116	240.30
3	W1	PD100	254.4	186.00	-68.40	52.9	116	237.30
3	W1	PD125	254.4	185.00	-69.40	52.9	116	238.30
3	W2	PD25	254.4	185.00	-69.40	52.9	180	302.30
3	W2	PD50	254.4	180.00	-74.40	52.9	180	307.30
3	W2	PD75	254.4	190.00	-64.40	52.9	180	297.30
3	W2	PD100	254.4	187.00	-67.40	52.9	180	300.30
3	W2	PD125	254.4	183.00	-71.40	52.9	180	304.30
3	W3	PD25	254.4	191.00	-63.40	52.9	241	357.30
3	W3	PD50	254.4	188.00	-66.40	52.9	241	360.30
3	W3	PD75	254.4	185.00	-69.40	52.9	241	363.30
3	W3	PD100	254.4	194.00	-60.40	52.9	241	354.30
3	W3	PD125	254.4	193.00	-61.40	52.9	241	355.30
3	W4	PD25	254.4	194.00	-60.40	52.9	292	405.30
3	W4	PD50	254.4	197.00	-57.40	52.9	292	402.30
3	W4	PD75	254.4	193.00	-61.40	52.9	292	406.30
3	W4	PD100	254.4	195.00	-59.40	52.9	292	404.30
3	W4	PD125	254.4	199.00	-55.40	52.9	292	400.30
3	W5	PD25	254.4	212.00	-42.40	52.9	339.2	434.50
3	W5	PD50	254.4	222.00	-32.40	52.9	339.2	424.50
3	W5	PD75	254.4	217.28	-37.12	52.9	339.2	429.22
3	W5	PD100	254.4	219.00	-35.40	52.9	339.2	427.50
3	W5	PD125	254.4	215.00	-39.40	52.9	339.2	431.50

Appendix 4.2. continues….

Drainage = 0; Runoff = 0

REP			ΔSWCb	ΔSWCend	ΔW	P	I	ET
4	W1	PD25	253.5	160.00	-93.50	52.9	116	262.40
4	W1	PD50	253.5	165.00	-88.50	52.9	116	257.40
4	W1	PD75	253.5	169.00	-84.50	52.9	116	253.40
4	W1	PD100	253.5	166.00	-87.50	52.9	116	256.40
4	W1	PD125	253.5	170.00	-83.50	52.9	116	252.40
4	W2	PD25	253.5	170.00	-83.50	52.9	167	303.40
4	W2	PD50	253.5	165.00	-88.50	52.9	167	308.40
4	W2	PD75	253.5	166.00	-87.50	52.9	167	307.40
4	W2	PD100	253.5	172.00	-81.50	52.9	167	301.40
4	W2	PD125	253.5	164.00	-89.50	52.9	167	309.40
4	W3	PD25	253.5	183.00	-70.50	52.9	239	362.40
4	W3	PD50	253.5	188.00	-65.50	52.9	239	357.40
4	W3	PD75	253.5	187.00	-66.50	52.9	239	358.40
4	W3	PD100	253.5	182.00	-71.50	52.9	239	363.40
4	W3	PD125	253.5	180.00	-73.50	52.9	239	365.40
4	W4	PD25	253.5	175.00	-78.50	52.9	288	419.40
4	W4	PD50	253.5	179.00	-74.50	52.9	288	415.40
4	W4	PD75	253.5	172.00	-81.50	52.9	288	422.40
4	W4	PD100	253.5	173.00	-80.50	52.9	288	421.40
4	W4	PD125	253.5	180.00	-73.50	52.9	288	414.40
4	W5	PD25	253.5	221.00	-32.50	52.9	357	442.40
4	W5	PD50	253.5	223.00	-30.50	52.9	357	440.40
4	W5	PD75	253.5	224.46	-29.04	52.9	357	438.94
4	W5	PD100	253.5	227.00	-26.50	52.9	357	436.40
4	W5	PD125	253.5	228.00	-25.50	52.9	357	435.40

Appendix 5.1. Determination of vapor pressure deficit (e*-e) for the separation of Ea and T

Month	YEAR	DOY	Actual Date	Tmax	Tmin	Tmean	Determine Δ (kPa)	Y	RHx	RHn	e^0(Tmax)	e^0(Tmin)	e_a (kPa)	e_s (kPa)	e*-e
June	2005	152	1	18.86	2.26	10.6	0.09	0.06	83.40	25.86	2.16	0.71	0.57	1.44	0.86
	2005	153	2	22.57	1.32	11.9	0.09	0.06	76.40	19.40	2.73	0.67	0.52	1.70	1.18
	2005	154	3	25.71	5.77	15.7	0.11	0.06	79.60	29.70	3.31	0.92	0.86	2.12	1.26
	2005	155	4	24.07	6.63	15.4	0.11	0.06	92.50	42.13	2.98	0.97	1.08	1.98	0.90
	2005	156	5	16.86	0.1	8.5	0.08	0.06	92.40	36.16	1.91	1.00	0.81	1.45	0.65
	2005	157	6	22.04	2.36	12.2	0.09	0.06	83.30	28.38	2.64	0.72	0.67	1.68	1.01
	2005	158	7	23.45	7.47	15.5	0.09	0.06	76.40	24.74	2.90	1.04	0.75	1.97	1.21
	2005	159	8	18.37	2.81	10.6	0.09	0.06	68.90	17.38	2.10	0.75	0.44	1.42	0.98
	2005	160	9	13.6	-0.03	6.8	0.07	0.06	71.90	17.65	1.55	1.00	0.50	1.27	0.78
	2005	161	10	17.48	0.68	9.1	0.08	0.06	55.93	15.92	2.00	0.98	0.43	1.49	1.06
	2005	162	11	20.44	0.95	10.7	0.09	0.06	59.26	18.37	2.38	0.97	0.50	1.67	1.17
	2005	163	12	22.13	10.33	16.2	0.12	0.06	75.60	23.07	2.64	1.25	0.78	1.95	1.17
	2005	164	13	11.74	-0.52	5.6	0.06	0.06	68.90	20.33	1.38	1.02	0.49	1.20	0.71
	2005	165	14	14.69	-3.2	5.7	0.06	0.06	91.40	25.79	1.68	1.12	0.73	1.40	0.67
	2005	166	15	16.34	-2.65	6.8	0.07	0.06	91.80	67.06	1.91	1.10	1.15	1.50	0.36
	2005	167	16	18.46	-1.04	8.7	0.08	0.06	93.10	39.04	2.10	1.04	0.89	1.57	0.67
	2005	168	17	20.39	1.62	11.0	0.09	0.06	84.30	27.58	2.38	0.69	0.62	1.53	0.91
	2005	169	18	21.4	3.23	12.3	0.09	0.06	79.90	23.71	2.56	0.77	0.61	1.67	1.06
	2005	170	19	21.73	3.86	12.8	0.10	0.06	84.80	11.88	2.60	0.80	0.49	1.70	1.21
	2005	171	20	20.51	0.96	10.7	0.09	0.06	88.10	30.89	2.41	0.97	0.80	1.69	0.89
	2005	172	21	21.14	1.41	11.3	0.09	0.06	77.70	29.27	2.49	0.95	0.73	1.72	0.99
	2005	173	22	15.87	9.58	12.7	0.10	0.06	78.10	37.04	1.79	0.72	0.61	1.25	0.64
	2005	174	23	16.77	7.2	12.0	0.09	0.06	81.80	28.07	1.91	0.78	0.59	1.34	0.76
	2005	175	24	19.22	7.31	13.3	0.10	0.06	86.60	21.60	2.20	0.78	0.57	1.49	0.91
	2005	176	25	21.35	5.5	13.4	0.10	0.06	84.10	30.13	2.45	0.82	0.72	1.64	0.92
	2005	177	26	21.73	6.82	14.3	0.10	0.06	82.10	29.90	2.60	0.79	0.71	1.70	0.98
	2005	178	27	17.25	4.97	11.1	0.09	0.06	70.30	27.71	1.94	0.84	0.56	1.39	0.83
	2005	179	28	17.15	0.56	8.9	0.08	0.06	65.79	22.35	1.94	0.98	0.54	1.46	0.92
	2005	180	29	21.35	3.27	12.3	0.09	0.06	83.50	33.06	2.53	0.89	0.79	1.71	0.92
	2005	181	30	22.3	4.07	13.2	0.10	0.06	89.20	36.90	2.69	0.87	0.88	1.78	0.89

July	2005	182	1	18.84	4.74	11.8	0.09	0.06	84.20	14.60	2.16	0.85	0.51	1.51	0.99
Month	YEAR	DOY	Actual Date	Tmax	Tmin	Tmean	Determine Δ (kPa)	γ	RHx	RHn	e^0(Tmax)	e^0(Tmin)	e_a (kPa)	e_s (kPa)	e*-e
July	2005	183	2	17.09	0.29	8.7	0.08	0.06	73.70	18.15	1.94	0.99	0.54	1.46	0.92
	2005	184	3	19.51	2.12	10.8	0.09	0.06	66.39	12.91	2.27	0.93	0.45	1.60	1.14
	2005	185	4	19.03	4.95	12.0	0.09	0.06	45.46	14.34	2.20	0.84	0.35	1.52	1.17
	2005	186	5	16.6	4.93	10.8	0.09	0.06	63.00	13.21	1.88	0.84	0.39	1.36	0.97
	2005	187	6	17.81	5.5	11.7	0.09	0.06	65.56	18.52	2.03	0.82	0.46	1.43	0.97
	2005	188	7	18.21	4.5	11.4	0.09	0.06	67.73	18.02	2.10	0.85	0.48	1.48	1.00
	2005	189	8	19.57	2	10.8	0.08	0.06	62.46	20.20	2.27	0.93	0.52	1.60	1.08
	2005	190	9	18.88	1.83	10.4	0.08	0.06	71.50	23.32	2.16	0.94	0.59	1.55	0.96
	2005	191	10	19.63	1.79	10.7	0.09	0.06	89.80	35.48	2.27	0.94	0.82	1.60	0.78
	2005	192	11	19.85	0.7	10.3	0.08	0.06	63.86	15.57	2.30	0.98	0.49	1.64	1.15
	2005	193	12	21.95	2.39	12.2	0.09	0.06	72.80	28.23	2.60	0.92	0.70	1.76	1.06
	2005	194	13	21.05	2.74	11.9	0.09	0.06	79.60	34.57	2.56	0.91	0.80	1.74	0.93
	2005	195	14	19.43	2.18	10.8	0.08	0.06	81.00	41.65	2.23	0.93	0.84	1.58	0.74
	2005	196	15	19.18	3.45	11.3	0.09	0.06	87.60	30.31	2.20	0.89	0.72	1.54	0.82
	2005	197	16	19.69	2.21	11.0	0.09	0.06	82.60	29.98	2.30	0.92	0.73	1.61	0.89
	2005	198	17	19.1	2.12	10.6	0.09	0.06	82.10	22.88	2.20	0.93	0.63	1.56	0.93
	2005	199	18	21.26	3.98	12.6	0.10	0.06	66.54	15.59	2.53	0.87	0.49	1.70	1.21
	2005	200	19	22.15	2.25	12.2	0.09	0.06	45.64	15.03	2.64	0.92	0.41	1.78	1.37
	2005	201	20	18.94	0.26	9.6	0.08	0.06	66.42	24.34	2.16	0.99	0.59	1.58	0.98
	2005	202	21	17.6	1.6	9.6	0.08	0.06	80.80	11.66	2.00	0.94	0.50	1.47	0.97
	2005	203	22	18.7	-1.82	8.4	0.08	0.06	72.20	24.14	2.16	1.07	0.65	1.62	0.97
	2005	204	23	22.74	2.03	12.4	0.09	0.06	88.00	57.52	2.77	0.93	1.21	1.85	0.64
	2005	205	24	24.15	4.6	14.4	0.10	0.06	86.10	43.66	2.98	0.85	1.02	1.92	0.90
	2005	206	25	25.44	5.23	15.3	0.11	0.06	82.30	37.86	3.22	0.83	0.95	2.02	1.07
	2005	207	26	23.93	3.46	13.7	0.10	0.06	84.90	22.98	2.94	0.88	0.71	1.91	1.20
	2005	208	27	20.01	2.03	11.0	0.09	0.06	72.70	21.32	2.34	0.93	0.59	1.63	1.05
	2005	209	28	21.15	2.78	12.0	0.09	0.06	73.10	27.46	2.49	0.91	0.67	1.70	1.02
	2005	210	29	22.29	2.89	12.6	0.10	0.06	80.90	20.27	2.69	0.90	0.64	1.79	1.16
	2005	211	30	22.72	4.94	13.8	0.10	0.06	84.30	23.34	2.77	0.84	0.68	1.80	1.13

	2005	212	31	22.36	2.68	12.5	0.10	0.06	87.30	26.03	2.69	0.91	0.75	1.80	1.05
	2005	213	1	22.6	2.82	12.7	0.10	0.06	68.03	17.72	2.77	0.90	0.55	1.84	1.28
August	**YEAR**	**DOY**	**Actual Date**	**Tmax**	**Tmin**	**Tmean**	**Determine Δ (kPa)**	**γ**	**RHx**	**RHn**	**e^0(Tmax)**	**e^0(Tmin)**	**e_a (kPa)**	**e_s (kPa)**	**e*-e**
	2005	214	2	22.49	5.09	13.8	0.10	0.06	76.80	21.26	2.69	0.84	0.61	1.76	1.15
August	2005	215	3	18.28	-1.13	8.6	0.08	0.06	61.79	21.06	2.10	1.04	0.54	1.57	1.03
	2005	216	4	23.34	3.04	13.2	0.10	0.06	73.30	32.05	2.85	0.90	0.79	1.87	1.09
	2005	217	5	22.73	7.12	14.9	0.11	0.06	80.50	38.06	2.77	0.78	0.84	1.77	0.93
	2005	218	6	23.69	7.87	15.8	0.11	0.06	64.50	30.10	2.94	0.76	0.69	1.85	1.16
	2005	219	7	25.09	8.96	17.0	0.12	0.06	68.24	28.81	3.17	0.73	0.71	1.95	1.24
	2005	220	8	25.34	8.83	17.1	0.12	0.06	68.47	16.99	3.22	0.74	0.53	1.98	1.45
	2005	221	9	11.62	4.52	8.1	0.07	0.06	68.59	24.30	1.38	0.85	0.46	1.12	0.66
	2005	222	10	14.99	2.03	8.5	0.08	0.06	72.80	16.19	1.68	0.93	0.47	1.30	0.83
	2005	223	11	19.03	-0.13	9.5	0.08	0.06	64.53	15.93	2.20	1.00	0.50	1.60	1.10
	2005	224	12	23.07	4.7	13.9	0.10	0.06	52.84	12.15	2.81	0.85	0.39	1.83	1.43
	2005	225	13	23.81	0.86	12.3	0.09	0.06	46.87	12.05	2.85	0.97	0.40	1.91	1.51
	2005	226	14	27.11	2.58	14.8	0.11	0.06	54.82	27.06	3.57	0.91	0.73	2.24	1.51
	2005	227	15	18.19	5.53	11.9	0.09	0.06	86.50	19.74	2.16	0.82	0.57	1.49	0.92
	2005	228	16	20.8	-0.82	10.0	0.08	0.06	59.00	15.83	2.45	1.03	0.50	1.74	1.24
	2005	229	17	18.06	2.24	10.2	0.08	0.06	52.75	16.36	2.06	0.92	0.41	1.49	1.08
	2005	230	18	15.81	-2.88	6.5	0.07	0.06	47.39	16.26	1.79	1.11	0.41	1.45	1.04
	2005	231	19	22.52	0.27	11.4	0.09	0.06	58.84	14.93	2.73	0.99	0.49	1.86	1.36
	2005	232	20	25.16	3.03	14.1	0.10	0.06	71.00	17.19	3.17	0.90	0.59	2.04	1.44
	2005	233	21	21.54	12.07	16.8	0.12	0.06	91.50	30.70	2.56	0.66	0.70	1.61	0.92
	2005	234	22	21.98	9.06	15.5	0.11	0.06	86.30	20.40	2.60	0.73	0.58	1.67	1.09
	2005	235	23	18.76	-1.77	8.5	0.08	0.06	59.97	11.92	2.16	1.07	0.45	1.62	1.17
	2005	236	24	22.37	2.13	12.3	0.10	0.06	40.49	11.98	2.69	0.93	0.35	1.81	1.46
	2005	237	25	23.46	5.51	14.5	0.11	0.06	44.79	7.02	2.85	0.82	0.28	1.84	1.55
	2005	238	26	23.82	1.31	12.6	0.10	0.06	39.47	11.75	2.94	0.95	0.36	1.95	1.59
	2005	239	27	16.99	0.67	8.8	0.08	0.06	59.53	9.63	1.91	0.98	0.38	1.44	1.06
	2005	240	28	23.85	2.34	13.1	0.10	0.06	55.48	10.89	2.94	0.92	0.42	1.93	1.51
	2005	241	29	25.69	10.69	18.2	0.13	0.06	80.60	17.55	3.31	0.69	0.57	2.00	1.43

	2005	242	30	27.27	14.37	20.8	0.15	0.06	57.90	12.38	3.62	0.62	0.40	2.12	1.71
	2005	243	31	27.78	9.38	18.6	0.13	0.06	49.29	13.54	3.73	0.72	0.43	2.22	1.79
September	**YEAR**	**DOY**	**Actual Date**	**Tmax**	**Tmin**	**Tmean**	**Determine Δ (kPa)**	**γ**	**RHx**	**RHn**	**e^0(Tmax)**	**e^0(Tmin)**	**e_a (kPa)**	**e_s (kPa)**	**e^*-e**
	2005	244	1	18.3	1.83	10.1	0.08	0.06	52.39	12.91	2.10	0.94	0.38	1.52	1.14
	2005	245	2	23.23	2.8	13.0	0.10	0.06	44.06	13.28	2.85	0.91	0.39	1.88	1.49
	2005	246	3	26.46	5.99	16.2	0.12	0.06	59.16	16.92	3.41	0.81	0.53	2.11	1.58
	2005	247	4	26.62	5.06	15.8	0.11	0.06	49.71	12.98	3.51	0.84	0.44	2.18	1.74
	2005	248	5	18.94	2.3	10.6	0.09	0.06	65.74	27.22	2.16	0.92	0.60	1.54	0.94
	2005	249	6	23.1	1.57	12.3	0.10	0.06	53.24	17.25	2.83	0.95	0.50	1.89	1.39
	2005	250	7	21.59	9.04	15.3	0.11	0.06	46.14	15.36	2.56	0.73	0.37	1.65	1.28
	2005	251	8	23.94	4.46	14.2	0.10	0.06	51.84	15.62	2.94	0.85	0.45	1.90	1.45
	2005	252	9	28.48	8.31	18.4	0.13	0.06	89.30	53.73	3.84	0.75	1.37	2.29	0.93
	2005	253	10	31.17	10.92	21.0	0.15	0.06	94.40	32.89	4.50	0.69	1.06	2.59	1.53
	2005	254	11	30.89	10.09	20.5	0.15	0.06	82.50	23.74	4.43	0.71	0.82	2.57	1.75
	2005	255	12	30.95	8.68	19.8	0.14	0.06	61.18	29.40	4.52	0.74	0.89	2.63	1.74
	2005	256	13	32.38	12.34	22.4	0.16	0.06	64.85	11.82	6.82	0.66	0.62	3.74	3.12
	2005	257	14	27.87	12.18	20.0	0.15	0.06	34.75	11.55	3.73	0.66	0.33	2.19	1.86
	2005	258	15	29.44	11.58	20.5	0.15	0.06	53.43	12.92	4.06	0.67	0.44	2.37	1.93
	2005	259	16	30.23	10.32	20.3	0.15	0.06	59.26	19.21	4.30	0.70	0.62	2.50	1.88
	2005	260	17	30.34	10.5	20.4	0.15	0.06	70.40	10.80	4.30	0.70	0.48	2.50	2.02
	2005	261	18	30.76	9.34	20.1	0.15	0.06	56.01	19.81	4.43	0.72	0.64	2.58	1.94
	2005	262	19	31.24	11.65	21.4	0.15	0.06	57.32	9.64	4.78	0.67	0.42	2.72	2.30
	2005	263	20	30.96	8.48	19.7	0.14	0.06	80.50	10.06	4.43	0.75	0.52	2.59	2.06
	2005	264	21	30.2	7.9	19.1	0.14	0.06	53.08	22.17	4.30	0.76	0.68	2.53	1.85
	2005	265	22	27.57	9.29	18.4	0.13	0.06	61.70	33.61	3.67	0.73	0.84	2.20	1.36
	2005	266	23	30.9	12.02	21.5	0.16	0.06	83.20	23.84	4.43	0.66	0.80	2.55	1.74
	2005	267	24	30.89	8.83	19.9	0.14	0.06	65.47	11.46	4.43	0.74	0.49	2.58	2.09
	2005	268	25	22.44	10.42	16.4	0.12	0.06	35.74	10.13	2.69	0.70	0.26	1.69	1.43
	2005	269	26	23.31	6.59	15.0	0.11	0.06	54.40	8.74	2.85	0.79	0.34	1.82	1.48
	2005	270	27	17.57	5.22	11.4	0.09	0.06	77.60	11.33	2.00	0.83	0.44	1.42	0.98
	2005	271	28	18.79	5.27	12.0	0.09	0.06	67.32	12.09	2.16	0.83	0.41	1.50	1.09

	2005	272	29	22.69	4.11	13.4	0.10	0.06	86.10	33.34	2.77	0.87	0.83	1.82	0.98
	2005	273	30	25.02	9.61	17.3	0.12	0.06	72.80	22.74	3.17	0.72	0.62	1.94	1.32
	2005	274	1	28.63	6.99	17.8	0.13	0.06	74.20	13.31	3.95	0.78	0.55	2.37	1.81
	YEAR	**DOY**	**Actual Date**	**Tmax**	**Tmin**	**Tmean**	**Determine Δ (kPa)**	**γ**	**RHx**	**RHn**	**e^0(Tmax)**	**e^0(Tmin)**	**e_a (kPa)**	**e_s (kPa)**	**e*-e**
October	2005	275	2	25.22	6.47	15.8	0.11	0.06	80.80	26.76	3.22	0.80	0.75	2.01	1.25
	2005	276	3	29.24	4.39	16.8	0.12	0.06	73.10	15.16	4.07	0.86	0.62	2.46	1.84
	2005	277	4	27.58	10.23	18.9	0.13	0.06	52.16	9.67	3.67	0.70	0.36	2.19	1.83
	2005	278	5	19.81	11.13	15.5	0.11	0.06	43.90	9.96	2.30	0.68	0.26	1.49	1.23
	2005	279	6	21.05	10.06	15.6	0.11	0.06	65.37	18.37	2.49	0.71	0.46	1.60	1.14
	2005	280	7	25.66	11.03	18.3	0.13	0.06	30.34	9.60	3.49	0.69	0.27	2.09	1.82
October	2005	281	8	22.15	9.54	15.8	0.11	0.06	89.90	46.36	2.75	0.72	0.96	1.74	0.77
	2005	282	9	24.45	4.79	14.6	0.11	0.06	92.60	13.64	3.03	0.84	0.60	1.94	1.34
	2005	283	10	30.97	12.35	21.7	0.16	0.06	59.87	9.37	4.43	0.66	0.40	2.54	2.14
	2005	284	11	32.46	15.83	24.1	0.18	0.06	43.42	10.72	4.82	0.59	0.39	2.71	2.32
	2005	285	12	29.13	12.78	21.0	0.15	0.06	49.99	9.23	4.13	0.65	0.35	2.39	2.03
	2005	286	13	28.16	8.92	18.5	0.13	0.06	41.31	7.61	3.82	0.73	0.30	2.28	1.98
	2005	287	14	30.14	13.77	22.0	0.16	0.06	54.46	8.64	3.34	0.63	0.32	1.98	1.67
	2005	288	15	29.21	15.35	22.3	0.16	0.06	83.30	20.19	4.07	0.60	0.66	2.33	1.67
	2005	289	16	28.35	14.97	21.7	0.16	0.06	53.13	12.25	3.84	0.60	0.40	2.22	1.82
	2005	290	17	27.17	14.08	20.6	0.15	0.06	48.10	11.05	3.86	0.62	0.36	2.24	1.88
	2005	291	18	28.4	15.55	22.0	0.16	0.06	43.16	11.02	3.84	0.59	0.34	2.21	1.87
	2005	292	19	22.14	13.46	17.8	0.13	0.06	45.58	9.86	2.56	0.63	0.27	1.60	1.33
	2005	293	20	25.99	10.5	18.2	0.13	0.06	61.87	7.48	3.31	0.70	0.34	2.00	1.67
	2005	294	21	24.79	8.58	16.7	0.12	0.06	36.63	8.70	3.12	0.74	0.27	1.93	1.66
	2005	295	22	28.26	9.68	19.0	0.14	0.06	43.86	7.25	3.84	0.72	0.30	2.28	1.98
	2005	296	23	32.82	14.19	23.5	0.17	0.06	29.01	9.67	4.96	0.62	0.33	2.79	2.46
	2005	297	24	31.59	16.16	23.9	0.17	0.06	32.31	8.97	4.62	0.58	0.30	2.60	2.30
	2005	298	25	25.04	7.85	16.4	0.12	0.06	35.53	7.21	3.17	0.76	0.25	1.96	1.72
	2005	299	26	27.66	8.51	18.1	0.13	0.06	46.68	12.19	3.73	0.74	0.40	2.23	1.83
	2005	300	27	29.75	13.58	21.7	0.16	0.06	54.38	16.92	4.18	0.63	0.53	2.41	1.88
	2005	301	28	21.95	15.1	18.5	0.13	0.06	54.94	11.96	2.60	0.60	0.32	1.60	1.28

	2005	302	29	19.73	14.27	17.0	0.12	0.06	60.31	12.42	2.30	0.62	0.33	1.46	1.13
	2005	303	30	26.48	14.18	20.3	0.15	0.06	55.11	16.88	3.41	0.62	0.46	2.01	1.56
	2005	304	1	29.35	15.11	22.2	0.16	0.06	51.38	16.95	4.06	0.60	0.50	2.33	1.83
	2005	305	2	32.03	15.21	23.6	0.17	0.06	53.25	9.70	4.76	0.60	0.39	2.68	2.29
November	2005	306	3	33.26	15.23	24.2	0.18	0.06	34.75	7.75	5.10	0.60	0.30	2.85	2.55
	2005	307	4	30.07	13.12	21.6	0.16	0.06	29.84	4.17	5.03	0.64	0.20	2.84	2.63
	2005	308	5	27.29	13.24	20.3	0.15	0.06	20.61	8.14	3.62	0.64	0.21	2.13	1.91
	2005	309	6	24.27	7.58	15.9	0.11	0.06	55.93	20.31	3.03	0.77	0.52	1.90	1.38
	2005	310	7	23.59	9.11	16.4	0.12	0.06	84.90	41.43	2.90	0.73	0.91	1.81	0.90
	2005	311	8	20.84	5.62	13.2	0.10	0.06	86.60	38.76	2.45	0.82	0.83	1.64	0.80
	2005	312	9	24.54	6.22	15.4	0.11	0.06	94.90	25.21	3.08	0.80	0.77	1.94	1.17
	2005	313	10	28.97	9.82	19.4	0.14	0.06	81.60	18.11	3.95	0.71	0.65	2.33	1.68