Modelling the soil water balance of canola *Brassica napus* L (Hyola 60)

by

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ABSTRACT

Soil Water Balance (SWB) is a generic crop growth and irrigation-scheduling model. It improves on traditional methods of irrigation scheduling using evaporative demand by mechanistically and dynamically, quantitatively considering the soil–plant-atmosphere continuum. However, it needs specific crop growth parameters, which are not readily available for canola. The objective of this study was to determine crop growth parameters specific to canola and to identify the effect of water stress at different stages of growth on seed and oil yield. The study was conducted on the experimental farm of the University of Pretoria, South Africa, under a rain shelter during 2002 and in an open field during 2003. Weather data were recorded with an automatic weather station, phenological stages monitored frequently and growth analyses carried out every two weeks. Soil water content was measured with a neutron water meter weekly during 2002 and once every five days during 2003. Fractional interception of PAR was also measured with a sunfleck ceptometer. Specific crop parameters including specific leaf area, the leaf stem partitioning parameter, maximum rooting depth and thermal time requirements for crop development were generated from field measurements. These data form the backbone for accurate mechanistic simulations of the soil-water balance. The model was successfully calibrated and evaluated, proving its potential to be used as a generic crop irrigation-scheduling tool. Highest seed and oil yield was harvested from the unstressed treatment and lowest from the treatment stressed during the flowering stage.

> And the LORD God took the man, and put him into the garden of Eden to dress it and to keep it. (Gen 2:15)
>
> If any would not work, neither should he eat. (2 Thes. 3:10)

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a	Campbell's coefficient of the log-log water retention function
ADL	Allowable depletion level
Alt	Altitude (m)
a_n	Leaf absorptance of near infrared radiation
a_p	Leaf absorptance of photosynthetically active radiation
a_s	Leaf absorptance of solar radiation
b	Slope of the log-log water retention function
canola	Canada oil low acid
CDM	Canopy dry matter (kg)
CDM_i	Canopy dry matter daily increment (kg)
D	Index of agreement of Willmott
DAP	Days after planting
DM	Dry matter production (kg m^{-2})
DM_i	Daily increment of total dry matter (kg m^{-2})
Dr	Drainage (mm)
DWR	Vapour pressure deficit corrected dry matter water ratio (Pa)
dz	Soil layer thickness (m)
E	Actual evaporation (mm)
e_a	Actual (atmospheric) vapour pressure (kPa)
E_c	Radiation conversion efficiency (kg MJ^{-1})
EHRD	Eritrean Human Resource Development
$EMDD$	Emergence day degrees (d ^{o}C)
e_s	Saturated vapour pressure (kPa)
ET	Evapotranspiration (mm = kg m^{-2})
ETo	FAO reference evapotranspiration (mm d^{-1})
f	Layer root fraction
FAO	Food and Agricultural Organization of the United Nations (Rome, Italy)
FI	Fractional interception of solar radiation

FI_{evap}	Fractional interception of solar radiation by photosynthetically active and senesced leaves
FI_{trans}	Fractional interception of radiation by photosynthetically active leaves
FI_{PAR}	Fractional interception of photosynthetically active radiation
FI_{solar}	Fractional interception of solar radiation
$FLDD$	Day degrees at end of vegetative growth (d ^{o}C)
f_r	Fraction of dry matter partitioned to roots
g	gravitational acceleration (9.8 m s^{-2})
GDD	Growing day degrees (d ^{o}C)
GDD_i	Growing day degrees daily increment (d ^{o}C)
H_C	Crop height (m)
H_{Cmax}	Maximum crop height (m)
HDM	Harvestable dry matter (kg m^{-2})
HDM_i	Harvestable dry matter daily increment (kg m^{-2})
I	Irrigation amount (mm)
I_c	Amount of precipitation intercepted by the canopy (mm)
K	Canopy radiation extinction coefficient
K_{bd}	Canopy extinction coefficient of ‘black’ leaves for diffuse radiation
Kc_b	Basal crop coefficient.
Kc_{max}	maximum value of the FAO crop factor (Kc) following rain or irrigation
K_{PAR}	Canopy extinction coefficient of photosynthetically active radiation
K_s	Canopy extinction coefficient of total solar radiation
LAD	Leaf area duration
LAI	Leaf area index (m^{2} m^{-2})
$LAIage_i$	Age of leaf area index generated on day “i”
LAI_i	Leaf area index daily increment (m^{2} m^{-2})
LDM	Leaf dry matter (kg m^{-2})
LDM_i	Leaf dry matter daily increment (kg m^{-2})
$Loss$	Soil water loss by transpiration (volumetric soil water content)
MAE	Mean absolute error

MaxLeafAge	Day degrees for leaf senescence (d ^{o}C)
MTDD	Maturity day degrees (d ^{o}C)
N	Number of observations
NIR	Near infrared radiation (0.7 – 3 µm)
NWM	Neutron water meter
NEWSWB	New soil water balance model
P	Precipitation (mm)
P_a	Atmospheric pressure for a given altitude (kPa)
PAR	Photosynthetically active radiation (0.4 – 0.7 µm)
PART	Stem-leaf partitioning parameter (m^{2} kg^{-1})
PE	Potential evaporation (mm)
PET	Potential evapotranspiration (mm)
psilm	Minimum leaf water potential (kPa or J kg^{-1})
PT	Potential transpiration (mm)
PWP	Permanent wilting point
P_0	Standard atmospheric pressure at sea level (101.3 kPa)
R	Runoff (mm)
RD	Root depth (m)
RDM	Root dry matter (kg m^{-2})
RDM_i	Root dry matter daily increment (kg m^{-2})
RD_{max}	Maximum root depth (m)
Rg	Specific gas constant for dry air (286.9 J kg^{-1} K^{-1})
RGR	Root growth rate (m^{2} kg$^{-0.5}$)
RH_{max}	Daily maximum relative humidity (%)
RH_{min}	Daily minimum relative humidity (%)
RMSE	Root mean square error
rpf	Reproductive partitioning fraction
R_s	Solar radiation (MJ m^{-2} day^{-1} or W m^{-2})
r^2	Coefficient of determination
S.a.	Sinno anno (no date)
SDM	Stem dry matter (kg m^{-2})

SDM_i	Stem dry matter daily increment (kg m^{-2})
SI	Stress index
SLA	Specific leaf area (m^2 kg^{-1})
SWB	Soil Water Balance model
SWD	Soil water deficit (mm = kg m^{-2})
T	Actual transpiration (mm = kg m^{-2})
T_a	Air temperature $T_a = T_d$ (^oC)
T_{avg}	Daily average air temperature (^oC)
T_b	Base temperature (^oC)
$T_{cut\text{-}off}$	Cut-off temperature (^oC)
TDM	Top dry matter (kg m^{-2})
TDMstart	Top dry matter at emergence (kg m^{-2})
Tlo	Temperature for optimum light-limited crop growth
T_{max}	Daily maximum air temperature (^oC)
T_{min}	Daily minimum air temperature (^oC)
T_o	Standard air temperature at sea level (293 K)
TransDD	Day degrees of transition period from vegetative to reproductive growth (d ^oC)
Transl	Factor determining translocation of dry matter from stem to grain
Tr_{max}	Maximum transpiration rate (mm day^{-1})
T_w	Wet bulb air temperature (^oC)
U	Wind speed (m s^{-1})
U_2	Wind speed measured at 2 m height (m s^{-1})
U^*	Dimensionless root uptake rate
VPD	Vapour pressure deficit (Pa)
wsf	Water stress factor
WUE	Water use efficiency (kg ha^{-1} mm^{-1})
Y	Yield (kg ha^{-1})
LAIy	Leaf area index of senesced leaves
z	Soil depth (m)

α	Adiabatic lapse rate (K m^{-1})
ΔS	Change in soil water storage (mm = kg m^{-2})
Δt	Duration (days)
γ	Psychrometer constant (kPa ^{o}C^{-1})
θ	Volumetric soil water content (m^{3} m^{-3} or m m^{-1})
θ_{fc}	Volumetric soil water content at field capacity (m^{3} m^{-3} or m m^{-1})
θ_{pwp}	Volumetric soil water content at permanent wilting point (m^{3} m^{-3} or m m^{-1})
θ_{sat}	Volumetric water content at saturation (m^{3} m^{-3} or m m^{-1})
ρ_w	Water density (Mg m^{-3} or kg m^{-3})
ρ_b	Bulk density (Mg m^{-3} or kg m^{-3})
σ	Stefan-Boltzmann constant (5.6697×10^{-8} W m^{-2} K^{-4})
Ψ_{avg}	Root weighted average soil matric potential (J kg^{-1} or kPa)
Ψ_{fc}	Soil matric potential at field capacity (J kg^{-1} or kPa)
Ψ_{lm}	Leaf water potential at maximum transpiration (J kg^{-1} or kPa)
Ψ_m	Soil matric potential (J kg^{-1} or kPa)
Ψ_{pwp}	Soil matric potential at permanent wilting point (J kg^{-1} or kPa)
Ψ_x	Xylem water potential (J kg^{-1} or kPa)

CHAPTER 1

GENERAL INTRODUCTION

Canola is the third most important source of plant oil in the world after soybean and palm oil (Sovero, 1997). It is also an excellent rotation crop to control cereal diseases, pests and weeds. It has a good stable yield, which requires normal farm equipment. It grows in areas that receive more than 300 mm of rain, well-drained soil with a good potential for growing wheat, relatively free of broad leaf weeds, and residues of broad leaf herbicides. However, care needs to be taken not to plant in areas where it has grown consecutively for the last three seasons (Grombacher and Nelson, 1996). Production of canola is recently expanding in the Western Cape of South Africa. It does have also the potential to grow in Eritrea, because mustard, which is of the same family, grows well on the highlands. The Eritreans use the leaves at its young age as cabbage and after maturity the seeds are used for the preparation of spices.

Canola seed yield and percentage oil content by mass increases with the amount of water it receives. Water stress during the flowering stage has a severe impact both in the seed yield and percentage oil content. Therefore in seasons, with low or no rainfall at all, the crop needs to be supported by irrigation. However, the availability of water for irrigation is becoming scarce due to low rainfall as well as an increase in the demand of water for all industrial, domestic, municipal and other activities. So good irrigation water management practices are required to get promising yield with good water use efficiency. This can be facilitated by quantifying crop water requirement accurately.

Commercial and subsistence farmers are able to get optimal yield by applying the right amount of water at the right time using efficient irrigation scheduling methods. However, most farmers in South Africa and all farmers in Eritrea do not use irrigation scheduling to increase water use efficiency. Instead they depend on the experience gained over time to determine how much and when to irrigate so as to get the highest yield without taking prior consideration to water use efficiency. According to Steyn (1997) some of the reasons for South African farmers not making use of irrigation scheduling techniques is the failure to appreciate a net benefit from irrigation scheduling, and the lack of reliable and user-friendly irrigation scheduling techniques.

The aim of irrigation water management is to know how much and when to apply water to the crop. The best method of estimating crop water use is that of direct measurement. Reliable soil water content measurements could be carried out *in-situ*; however, this is tedious and impractical, especially on commercialised large farms. Other methods such as the A – pan and crop factor method consider atmospheric demand as the only way to predict water use, and it is also based on the idea that crop development relies only on calendar time. However, crop development is mainly influenced by thermal time in addition to other elements such as water supply and evaporative demand (Steyn, 1997).

There are also other approaches, one of which is integrating the soil – plant – atmosphere mechanistically using models. Philip (1966) refers to the combined description of the soil, plant and atmosphere as the soil-plant-atmosphere continuum. Modelling has been largely used for research to understand the interaction between different factors as well as to develop and test new ideas. The availability of computers with large capacities made the use of modelling possible to analyse complex systems found in nature (Ahuja and Nielsen, 1990).

According to Ahuja and Nielsen (1990), models are able to be used in the field of soil water for designing an irrigation system for uniform application of water or for soil water conservation practices. Furthermore, they mentioned the possibility of using models to simulate the entire soil-plant-atmosphere continuum on a daily basis for decision on irrigation, fertigation or pesticide application. Models could be deterministic (with unique results for a given set of data) or stochastic (which can accommodate spatial variability to quantify degree of uncertainty). Ritchie and Johnson (1990) further classified deterministic models into mechanistic and functional models. According to them, mechanistic models are based on dynamic rate concepts, whereas functional models are based on capacity factors and consider processes in a more simple way thereby reducing the input required.

Models for soil water budgeting differ in their complexity, input requirement and degree of accuracy (Kruse, Ells and Mcsay, 1990; Larsen, 1984). In order to be commercially available and usable, they need to be user friendly with reliable accuracy of simulation. SWB is a mechanistic, real time, generic crop soil water balance irrigation scheduling model, which has a user-friendly interface. It is based on the improved generic crop version of the New Soil Water Balance (NEWSWB) model (Annandale, Benadé, Jovanovic, Steyn and Du Sautoy, 1999). Simulations from SWB are helpful to accurately manage irrigation scheduling, predicting yields and irrigation water requirements in different regions.

As SWB is a generic crop growth and irrigation scheduling model, specific parameters for each crop need to be determined. One of the approaches for the determination of specific crop growth parameters is to conduct field trials. Specific crop parameters for different crops have been determined and are being used by the model (Jovanovic and Annandale, 2000). However, specific crop parameters of canola were not determined.

The objectives of the dissertation are:

a. To determine the specific parameters so as to simulate the crop growth of canola mechanistically.
b. To calibrate the Soil Water Balance model for canola and evaluate it by using independent data.
c. To estimate the water requirements and the effect of water stress at different development stages on seed and oil yield.

CHAPTER 2

LITERATURE REVIEW

2.1 Canola

Canola is a herbaceous plant that produces small, round, black, brown or yellow coloured seeds. The word canola is given to genetically selected and nutritionally superior rapeseed that has oil with less than 2% erucic acid and less than 30 µmol g^{-1} aliphatic glucosinulates. It belongs to the *Cruciferae* (*Brassicaceae*) family (Downey, 1997). This family has about 375 genera and 3200 species, including cabbage, cauliflower, broccoli, brussels sprouts, turnip, various mustards and weeds (Willis, 1973). The name *Crucifer* is derived based on the arrangement or alignment of flower petals, which are diagonally opposite to each other in the form of a cross. *Brassica napus* belongs to a group of six genetically related species, namely: *Brassica nigra* (black mustard), *Brassica oleracea* (eg. cabbage), *Brassica rapa* or *Brassica campestris* (eg. field mustard), *Brassica carinata* (Abyssinian mustard derived by ancient crossing of *B. nigra* and *B. oleracea*), *Brassica juncea* (eg. Indian mustard, derived from old world crosses of *B. nigra* and *B. rapa*) and *Brassica napus* (derived from ancient crosses between *B. oleracea* and *B. compestris*) (Robbelen, Downey and Ashri, 1989).

Many *Brassica* species have been under cultivation since prehistoric times for their edible roots, stems, leaves, buds, flowers and seeds. Rapeseed is closely related to other *Brassica* species such as cabbage, cauliflower, kale, as well as brown and oriental mustard. The *Cruciferae* family also contains a host of weed species, which are difficult to control with herbicides in canola plantations due to their close genetic relationship. Examples are stinkweed, shepherd's-purse, flix weed, ball mustard, warm seed mustard, hare's-ear mustard and common peppergrass (Thomas, 2001a).

Generally both air and soil temperatures greatly influence canola plant growth and productivity. The threshold temperature (or base temperature) of canola below which little significant plant growth occurs is 5 °C. It is a relatively cool season crop, which grows best above 12 ^{o}C and below 30 ^{o}C. The optimum temperature for maximum canola development and growth is estimated at just over 20 ^{o}C (Thomas, 2001d).

2.1.1 History

Production of rapeseed has a long history as far back as 3000 years ago in India. Ancient Sanskrit literature dating back to 1500 BC was found in India, which mentioned about *Brassica rapa*, implying that it has been known in that area since that time. In addition *Brassica juncea* has been found in archaeological sites dating back to 2300 BC. Production of rapeseed also has a long history in China because the name rapeseed was already recorded 2500 years ago. *Brassica rapa*, which is believed historically to have the widest distribution of *Brassica* oilseeds, was distributed 2000 years ago from northern Europe to China and Korea, with the primary centre of diversity in the Himalayan region. *Brassica napus* probably was under production since the Middle Ages. It was introduced to Asia in the 19th century. The germplasm in China and Japan was developed by the cross breeding of European *Brassica napus* and the indigenous *Brassica rapa* cultivars (Sovero, 1997). At present, China, Canada, India, and northern Europe are the leading producers of this crop (Downey, 1997).

Production of rapeseed in Canada began in 1942 on a few hectares. At that time it was grown to compensate for the rape oil supplies which used to come from Europe for the war effort, where rape oil was used as a lubricant. It has a better quality than other oils in clinging to water and steam washed metal surfaces. The crops were well adapted to the climate in Canada. After some modifications in handling and harvesting techniques, the crop area expanded under guaranteed price support, until the development of the diesel engine, which led to the price falling. This happened because of the replacement of steam engines by diesel engines, which started to use other motor oils. However, another market was opened in Japan, where this oil was considered the preferential oil for deep fat frying (Downey, 1997).

On the other hand, the low fatty acid composition of rapeseed oil attracted the attention of Canadian and European nutritionists. This motivated them to identify low erucic acid varieties. The first low erucic acid *Brassica napus* and *Brassica campestris* varieties were released in 1968 and 1971 consecutively. In 1970 nutritionists confirmed that low erucic acid rapeseed oil is nutritionally better than the original high erucic acid oil types. This led Canada to grow 1.62 million hectares of low erucic acid varieties within two years. Further modification has resulted in the development of *Brassica napus* varieties with low linolenic contents of less than 3% and the possibility of raising the level of the polyunsaturated fatty acid (linoleic) to 30% or more. Identification of the glucosinulate free *B. napus* cultivar "Browski" from Poland, led to its incorporation into high yielding varieties of *B. napus*. It is due to this improvement of the oil that the word "canola" is used instead of rapeseed (Downey, 1997).

2.1.2 Seedbed preparation and planting methods

Canola has very small seeds, therefore proper seedbed preparation is required for effective emergence. After disking, the land must be harrowed properly to get a well packed and firm soil, which is necessary to ensure appropriate planting depth and good seed contact with soil. In addition, it is better to carry out both the tillage operation and planting within a week so as to kill the weeds and invert the moist soil to the planting depth (15 – 25 mm) (Grombacher and Nelson, 1996).

Vigorous winter canola plants result when sowing earlier than winter wheat. However, it should not be too early because it will make the crop more susceptible to flea beetles at emergence. In the northern hemisphere growing regions, where the temperatures are cold such as in Canada, planting too early may also decrease establishment rate of the crop because of low soil temperatures. On the other hand, late planting may expose the small plant to winter cold and death. Planting spring canola when soil temperature is 10^{o} C or more gives the best yield. Planting very late may also result in yield decline due to high summer temperatures (Grombacher and Nelson, 1996).

Planting could be carried out either by a grain drill or broadcast spreader. Grombacher and Nelson (1996) argue that double disc openers are better than hoe-type openers because of their improved precision in seed placement. Hoe-type openers are more desirable in rough fields. It is necessary to use a harrow, roller, or a cultipacker with the teeth rose (protruded out) to incorporate the seed after broadcasting.

As far as the seed rate is concerned, trials conducted on irrigated canola by Canada-Saskatchewan Irrigation Diversification Center (CSIDC) in Canada, showed 3 to 6 kg ha^{-1} seeding rates are sufficient for high yields. Yield was not influenced by row spacing ranging from 16 to 48 cm. Both trails conducted by CSIDC (2000b) and Leach, Stevenson, Rainbow and Mullen (1999) showed the effect of high plant density in reducing the number of pods per plant as well as dry matter per plant. Moreover, they observed that at very high densities, 1000 seed mass was increased.

2.1.3 Weed, disease, and insect pest management

Canola has a dense canopy, which enables it to compete well with several weeds. However, it is advisable to clear the field of weeds before planting. Use of herbicides such as fluazifop-butyl (Fusilade 2000) and glyphosate (Roundup), together with tillage is best to control infestation of perennial weeds. Trifluralin (Treflan) can also be used for both spring and winter canola, however, it doesn’t control wild oats (*Avena fatua L.*). Canola is sensitive to broad-leaf herbicides (Grombacher and Nelson, 1996).

In addition to weeds the production of canola can also be reduced by different diseases. These diseases include *Sclerotinia sclerotiorum* (White mould or stem rot), which is promoted by excess nitrogen fertiliser, high plant density, high humidity and high innoculant levels. According to Grombacher and Nelson (1996) this could be controlled by rotating with non-host crops, deep ploughing, and use of certified seed free of *Sclerotinia.* Based on the studies conducted at CSIDC the following recommendations are made. During high rainfall years stopping irrigation ahead of the budding stage could reduce *Sclerotinia* stem rot. Since *Sclerotinia* is aggravated in a lodged crop, both lodging and *Sclerotinia* could be reduced by using lower seeding rates (Canada-Saskatchewan Irrigation Diversification Centre, 2000a). Black spot, *Alternaria brassicae* and *A. raphani*, could be controlled by using disease free certified seed, a one in four year rotation and by controlling weedy mustards and volunteer canola. *Fusarium* and *Pythium* *sp*. and *Rhizoctonia solani* cause seed rots, seedling blights, and root rots. Seed rot can be controlled by Captan seed treatment and all the others can be controlled by crop rotation with non-host crops. Ploughing and a one in four year rotation can also control stem canker or black leg, which is caused by *Phoma lingum* (Grombacher and Nelson, 1996).

Insects can also contribute to a decline in canola yield besides weeds and diseases. Some of the insects which damage canola are flea beetles, cabbage seed pod weevils, grasshoppers, cabbageworms and aphids. Flea beetle is not problematic after the seedling stage and canola is very tolerant to this pest, unless the weather is hot and dry. Cabbage seedpod weevil is a major pest of winter canola and Dipel can control it. Heavy infestation by grasshoppers and cabbageworms can also reduce yields (Grombacher and Nelson, 1996). Aphids can also be controlled using a systemic insecticide registered against aphids.

2.1.4 Harvesting and storage

A combine harvester with a reel head could be used for harvesting. When direct harvesting is a problem because of humidity or weed infestation, swathing can be carried out. The level of seed moisture should be 30% or lower before swathing. Threshing should start when seed moisture is 10% or lower. Too early swathing may result in green seed, with lower oil content and higher seed moisture. On the other hand too late swathing leads to excessive shattering (Grombacher and Nelson, 1996). The next step after threshing if seed is not directly taken for processing, is storage.

When storing canola the seed moisture and temperature should be taken into account. For long-term storage seed moisture should not exceed 8%, but if the seed is stored below 6% moisture it will be susceptible to damage in handling. When drying, the temperature should not exceed 40^{o} C because it can alter the seed oil composition as well as prevent germination (Grombacher and Nelson, 1996).

2.1.5 Soil fertility and plant water use

Soil fertility improves the water use efficiency of plants. Plants grown on fertile soils use water efficiently and as a result they produce a deep and large root system. According to Thomas (2001b) sufficient soil fertility results in an increased duration of the leaves, which enhances the supply of food for pod and seed development, in the later stage. Once pod formation has started, nitrogen translocates from the leaves to the pods, because the pods start to photosynthesise themselves. However, if the soil has enough nitrogen to supply both the pods and the leaves the life of the leaves is extended. On the other hand, Thomas (2001b) observed that low fertility soils demanded more water to produce a kg of dry matter compared to fertile soils.

2.1.6 Soil water requirements of canola

Water requirements of canola depend on the growth stage and climatic condition of the area (Thomas, 2001b). During the first stages of growth it demands little water. Water requirement increases with vegetative and root growth until flowering, which is the peak water use period. Water use decreases as the crop ripens. Canola's peak water use during hot and dry weather conditions is expected to reach 8 mm per day or more. An increase in the temperature and windiness of an area increases the water use of canola. However, when air is moist, and the days are cloudy, water use is low (Thomas, 2001b).

Data from research results at the United States Department of Agriculture (USDA) Central Great Plains Research Station reveals that canola is able to extract water down to a soil depth of 180 cm. However, most of the water is extracted from the 0 to 120 cm soil layer. In addition the study showed that canola has a linear response of seed yield to water use (Nielsen, 1997).

2.1.7 Effect of soil water on canola growth performance

Sufficient soil water is required to ensure a good germination rate of canola seed. Studies at the Melfort Research Station by Agriculture and Agri-Food Canada showed that clay soils that have better water storage capacities gave better and quicker emergence compared to sandy loam soils with lower water storage capacities. In this study low emergence of seeds was observed for both soil textures at 50% of water between field capacity and wilting point depleted. This implies that seed sown on dry soil will have a poor germination rate. Therefore, sufficient soil water should be maintained in the soil pores. This helps seeds absorb water, thus enhancing their germination rate. A dry or loose seedbed exposes the soil water to evaporation leading to lower germination rates unless it rains, because the seeds are small and are planted at shallow depth. It is therefore of great importance to maintain the soil water above 50% of water between field capacity and wilting point in order to achieve good germination rates (Thomas, 2001c). The presence of sufficient soil water enhances root growth and leaf area. It helps plants keep their leaves for a longer time, lengthens the flowering period, and improves the proliferation of branches for each plant and at the same time it increases the number of flowers (Thomas, 2001c).

2.1.8 Effect of water stress timing on canola seed yield and oil content

Research results from the USDA Central Great Plains Research Station during 1993 and 1994 showed that water stress timing has an effect on the yield of canola. Similarly studies conducted at this station showed that oil content increased from 37% to 44% with an increase in the level of irrigation. Higher yield was recorded for treatments without water stress and stress during the vegetative growth stage in both years. Lowest yield was recorded for the treatment with water stress at the seed filling stage during 1993 and at the flowering stage during 1994. The cause for the lowest seed yield harvest from the treatment with water stress during the seed filling stage during 1993 was the reduction in the number of branches per plant, number of pods per branch, and smaller seeds. The reason for lowest seed yield during 1994 from the treatment with stress during the flowering stage was the reduction in the number of branches per plant (Nielsen, 1997).

2.2 Irrigation

Successful irrigation sites were observed in history along the four major river basins namely the Nile in Egypt around 6000 B.C., the Tigris and Euphrates in Mesopotamia around 4000 B.C., the Yellow river in China around 3000 B.C. and the Indus river in India around 2500 B.C. Irrigation was introduced in Mexico and South America by the Maya and Inca civilizations 2000 years ago. Other historical irrigation sites include the 3000 year old tunnels of Iran for diverting water from the mountains to the valley and the 2000 year old tank in SriLanka, which are still in use today, as well as the second and third century dams in Japan. Successful irrigation contributed to the development of many early civilizations by providing a more stable supply of food and fibre and by supporting a higher population density. However, the lack of good management has resulted in the failure of some civilizations because of water logging, soil salinity and the absence of co-operation among people in the development and operation of the irrigation scheme (Hoffman, Howell and Solomon, 1992).

During 1990, 18% of cultivated land in the world was irrigated. However, it supplied one third of the world's food supply. The rate of irrigated land expansion from 1950 to 1980 was more than 3% per year. It declined to less than 1% per year around 1990. The main reason was the increase in the inputs of production, which came parallel with improved irrigation such as large amounts of fertilizer, herbicides, insecticides and other inputs. In addition the increase in the price of petroleum, which was the main energy source for irrigation, played its own role (Higgins, Dielman and Abernethy, 1987).

2.3 Irrigation water management

Veihmeyer and Hendrickson (1927) forwarded the concept that soil water, which is held in the range of field capacity to permanent wilting point, is equally available to plants. However, Richards and Wadleigh (1952), proved that the availability of soil water to plants decreases with decreasing soil water content ahead of the soils permanent wilting point and at the same time this can result in water stress and growth hindrance to a greater or lesser extent. This variability of the availability of soil water with variation in the soil water content shows the necessity for irrigation water management, to make the best use of water so as to attain an optimal yield.

Hoffman *et al.* (1992) described the primary objective of irrigation water management as the management of production systems for profit without compromising the environment. Irrigation scheduling, which is the determination of when and how much to irrigate, is one of the main irrigation water management methods. Different people have different understanding of irrigation scheduling. For instance, the answer of the traditional irrigator to the question of when and how much to irrigate, is: Irrigate when the available soil water is actually consumed and irrigate the root zone to refill it to field capacity (Hillel, 1990).

However, the modern concept of irrigation water management perceives the soil – plant – atmosphere to be an interrelated system, often referred to as the soil – plant – atmosphere continuum (SPAC), in which all the processes are interdependent. This concept considers that the availability of soil water is not only governed by the soil, but is also a function of the plant and climate (Hillel, 1990). According to Gardner (1960) and Huck and Hillel (1983), the rate of water uptake relies on the capacity of the roots to absorb water from the soil in contact with it, and the capacity of the soil to provide and allow water to move toward the roots at a rate adequate to fulfil transpiration and growth requirements. The above factors also rely on:

i. The features of the plant (rooting density, depth of roots, rate of root extension and the physiological ability of the plant to support its essential functions for some time even while its own water potential decreases).
ii. The characteristics of the soil (hydraulic conductivity and water retention) and,
iii. Weather condition, which ordains the rate of transpiration (Hillel, 1990).

2.4 Irrigation scheduling

Irrigation scheduling is the term applied to denote the timing and amount of water application (Hillel, 1990). Irrigation can be scheduled based on the soil water status, the plant or the weather (Heermann, Martin, Jackson and Stegman, 1990).

2.4.1 Soil water status

The soil water status method is used to determine the soil water reserve of the root zone after irrigation so as to know the allowable depletion level (predetermined depletion level the irrigator calculates). Once the soil has reached that level, the irrigator calculates the amount required to refill the root zone reservoir to the desired level, which could be to field capacity (Campbell and Campbell, 1982).

The prerequisites for the management of soil water status in the root zone are to know rooting depth and density of the given plant grown under irrigation. The rooting depth of plants vary from species to species and at the same time within a given species it varies with the growth stage. During their emergence stage, annual crops have very shallow roots, which extend both laterally and vertically with time. The lateral growth is hindered when it comes in contact with the roots of other plants, and vertical growth, which is the major direction of root extension, continues until it stops growing due to environmental, physiological or genetic factors (Hillel, 1990).

The volume of soil encompassing the root zone determines the volume of soil water reservoir potentially available to the plants. Continuous root depth determination at different growth stages on different types of soil is of great significance. It helps to determine the amount of irrigation water required during a given stage of growth and get an indication for the seasons to come under similar environmental and planting situations (Hillel, 1990). Soil water content determination could be carried out either using on-site measurement methods, or in a laboratory.

Generally, accurate soil water content determination could be carried out using on-site measurement methods. There are different methods and instruments of measuring soil water content, namely: the gravimetric method, neutron soil water meter, gamma ray attenuation and time dimension reflectometry (TDR). Soil water tension could also be measured using tensiometers, pressure plates, thermal conductivity, electrical resistance, the filter paper method and thermocouple psychrometers. The gravimetric method entails taking soil samples from a field using an auger or core sampler and drying it in the oven at 105 °C for 12 to 24 hours to determine the loss in mass of water from the sample. However, this method is laborious, time consuming, destructive and it gives soil water content by mass. As a result the soil bulk density needs to be determined in order to get the corresponding volumetric water content of the soil (Campbell and Mulla, 1990).

The neutron water meter is a non-destructive method of soil water measurement. It gives a representative reading (counts) of volumetric soil water content in a representative soil volume. This measurement could be carried out frequently at the same position. TDR is also a non-destructive method, which allows frequent measurement of soil water in a given place. It has a specific advantage, namely that is the calibration curve is not affected by change in the texture of the soil, salinity, bulk density, temperature or organic matter content and it provides a rapid way of estimating soil volumetric water content. However, they have some drawbacks. First of all they are expensive in addition to that the neutron water meter needs great care when being used because it emits radioactive waves, which have health hazards if used negligently (Campbell and Mulla, 1990).

Tensiometers are also useful instruments in determining the tension or matric potential of soil water. If properly installed and maintained, it is very useful in predicting when plants might begin to experience stress. The drawbacks of these instruments are the need for correct installation, continuous supervision and servicing, as well as, the need for retention curves to be developed for a specific site so as to determine how much to irrigate (Campbell and Mulla, 1990).

The benefits, which a farmer should get from irrigation scheduling in arid and semi-arid areas, are energy and water conservation. However, the soil water status method doesn’t really tell us when to irrigate. Therefore, it doesn’t save energy in such a way that we have to check at a regular interval. The interval might be to early or to late depending on the prevailing weather condition. If there was very high atmospheric demand during the interval the crops might have already suffered some stress. This will influence the final yield. Otherwise, if checked now and then, time and energy will also not be saved. In addition to that this method doesn’t take into consideration the root depth with time so as to irrigate the root zone only in order save water and energy. Therefore scheduling based on only the soil factor may result in committing big errors.

2.4.2 Plant water status

There are some traditional and scientific methods of detecting plant water status. The traditional way is direct visual investigation (examination). A skilful farmer who knows his crops very well can identify the water status of his crops easily by visual observation of the wilting leaves. There are also some scientific methods of detecting the plant water status such as; leaf water potential, stomatal resistance, canopy temperature (Phene, Reginato, Itier and Tanner, 1990), crop water stress index (Jackson, 1982), cell enlargement and canopy growth, relative leaf water content, plant organ diameter (Phene *et al*., 1990), photosynthesis rate, absissic acid (ABA) hormone (Campbell and Turner, 1990), leaf osmotic potential (Campbell, 1990) and sap flow (Steinberg, Van Bavel and MacFarland, 1989). However, plant water status depends not only on water availability but also to a larger extent on large diurnal atmospheric condition variations. This method does not tell us how much water to add. In addition it is not easy to detect the threshold plant water value, which shows the beginning of yield reduction (Theodore, 1990). In addition the instruments are expensive and complex (Jovanovic, Annandale and Stirzaker, 2002). Therefore scheduling based on only the plant water status may lead to big error.

2.4.3 The atmosphere

Meteorologically triggered evapo-transpirational demand over time could be used to determine the irrigation requirement. The evaporation of water from a pan was thought to integrate the effects of radiation, temperature, wind and humidity in a single simple measurement. However, the albedo, roughness and resistance of a pan differ markedly from that of a crop. The crop also has stomates that close at night, whilst pan evaporation can be appreciable, especially on windy nights. The pan also stores quite a bit of heat, and evaporation rate is influenced by how full or empty the pan is. Despite its shortcomings, the Penman formula or its derivatives can be used as an irrigation-scheduling criterion in certain conditions and is better than no scheduling at all. It can be used with locally calibrated crop coefficients and well-equipped weather station under careful supervision of the weather station and data collection (Hillel, 1990).

Another agro-meteorological method is the standardized form of the Penman – Monteith equation that uses the energy balance of a reference grass surface to estimate the evaporative demand. This method calculates the evaporative demand from measured solar radiation, air temperature, wind speed and humidity. The underlying logic behind this method is radiation supplies the energy for evaporation, the humidity or vapour pressure influences the driving force and wind influences the resistance to this vapour loss (Allen, Pereira, Raes and Smith, 1998). However, it doesn't take into consideration the soil and plant factors, which greatly influence the plant available soil water. The amount of plant available soil water in a given soil layer depends on the texture, structure and organic matter of the soil as well as distribution of the plant roots. Therefore scheduling based on only the atmospheric demand may lead to big errors.

The overlying explanations on the soil water status, the plant water status or climate show the inadequacy of using one of them as an irrigation scheduling method. This calls for a mechanistically integrated system, which includes the soil water status, the atmospheric demand, and the plant. The development of computers has made it possible to integrate the soil water status, the plant water status and the climate using models, as a result improving the accuracy of irrigation scheduling.

2.5 Models

Crop systems are complex in nature. This complexity makes the use of growth models significant in simulating the real system. There are different types of mathematical models used in crop production. Addiscot and Wagnet (1985) classified models as deterministic or stochastic, mechanistic or functional and rate or capacity type. They explained deterministic models as models that generate a specific result for a specific set of events and are related to a certain degree of uncertainty. However, stochastic models accommodate spatial variability and quantify the degree of uncertainty caused due to spatial variability of the mediating processes. Stochastic models generate an uncertain result for they encompass one or more random variables with a related probability distribution.

Ritchie and Johnson (1990) classified deterministic models into mechanistic or functional. Mechanistic models are based on dynamic rate concepts and basic processes. Functional models are based on capacity factors, and deal with processes in a simplified way. The main difference between functional and mechanistic models is on their role either as research or management tools. Mechanistic models are mainly used as research tools because they are very helpful in understanding the integrated systems of nature. However, functional models require less input and this makes them handy to be used for management purposes. They are broadly used and are validated independently.

Models can also be classified based on the factors they include. Penning de Vries, Jansen, Ten Berge and Bakema (1989) classified crop growth models into four levels based on the factors they include. Level one crop growth models, respond only to weather variables, mainly temperature and solar radiation and they simulate potential yield of a crop without water stress, lack of nutrients and without other constraints. Level two crop growth models include a soil water balance and the influence of soil water deficit on the growth of the crop and yield. Level three crop growth models include the availability of nitrogen in the soil and the effect of adding nitrogen fertilizer on the growth and yield of crops. In addition, they include the interaction between nitrogen, water and weather factors. Level four models include the remaining stress factors like pests and nutrients other than nitrogen.

According to Jones and Ritchie (1990) level two crop growth models which include the crop, soil, weather, and management components are significant for irrigation management decision-making. The Soil Water Balance model (SWB) can be classified as a level two-crop growth model with the features it has at this time.

2.6 The SWB model

SWB is a generic crop growth and irrigation scheduling model, which carries out simulation using two types of crop models:

a. A mechanistic crop growth model to calculate crop growth and soil water balance.

b. FAO type crop factor model to calculate the soil water balance but it doesn't simulate dry matter production mechanistically (Annandale *et al*., 1999).

The soil water balance of canola was simulated using the mechanistic crop growth model of the SWB therefore this paper will explain only the mechanistic part of the SWB model.

2.6.1 Mechanistic crop growth model

SWB uses soil, weather and crop units to carry out crop growth and water balance simulations mechanistically. The role of each unit is described below.

a) Weather unit

Carries out the calculation of extraterrestrial radiation (MJ m^{-2} day^{-1}), vapour pressure deficit (kPa), net radiation (MJ m^{-2} day^{-1}), FAO reference evapo-transpiration (mm day^{-1}) and potential evapotranspiration (mm day^{-1}) (Annandale *et al*., 1999). The extraterrestrial solar radiation is calculated using the Eq. 2.1

$$R_a = \left[\frac{118.08\, D_{rel}}{\pi \left[\omega_s \sin(Lat) \sin(Dec) + \sin(\omega_s) \cos(Lat) \cos(Dec) \right]} \right] \qquad 2.1$$

The constant 118.08 represents the solar constant in MJ m^{-2} day^{-1}

D_{rel} is relative distance of the earth from the sun, a function of DOY:

$$D_{rel} = 1 + 0.033 \cos\left(\frac{2\pi\, DOY}{365} \right) \qquad 2.2$$

ω_s is sunset hour angle (rad), a function of latitude and solar declination (*Dec*):

$$\omega_s = ar\cos\left[-\tan\left(Lat\right)\tan\left(Dec\right)\right] \tag{2.3}$$

For the Southern hemisphere, solar declination is computed as follows

$$Dec = -0.409\sin\left(\frac{2\pi}{365\,DOY - 1.39}\right) \tag{2.4}$$

Saturated vapour pressure (e_s) in kPa is calculated using Eq. 2.5. Allen *et al*. (1998) mention that using mean air temperature instead of the daily maximum and minimum temperatures underestimates the saturated vapour pressure, and a result; this underestimates vapour pressure deficit and potential evapo-transpiration (*PET*).

$$e_s = 0.611\exp\left[\frac{17.27\ T_a}{T_a + 237.3}\right] \tag{2.5}$$

T_a is air temperature.

SWB calculates e_a either from measured maximum (RH_{max}) and minimum relative humidity (RH_{min}) (Eq. 2.6) or from measured dry bulb (T_a) and wet bulb temperature (T_w) (Eq. 2.7).

$$e_a = \left[\frac{\left[e_s\left(T_{\min}\right)RH_{\max} + e_s\left(T_{\max}\right)RH_{\min}\right]}{2}\right] \tag{2.6}$$

$$e_a = e_s\left(T_w\right) - \left[0.0008\ \left(T_a - T_w\right)P_a\right] \tag{2.7}$$

P_a is atmospheric pressure in kPa and is calculated using Eq. 2.8

$$P_a = P_o\left[\frac{(T_o - \alpha Alt)}{T_o}\right]^{g/(\alpha Rg)} \qquad 2.8$$

P_o is standard atmospheric pressure at sea level (101.3 kPa), T_o is standard temperature at sea level (293 K), α is adiabatic lapse rate in K m^{-1} for saturated air assumed to be 0.0065 K m^{-1}, Alt is altitude in m, g is gravitational acceleration (9.8 m s^{-2}) and Rg is specific gas constant for dry air (286.9 J kg^{-1} K^{-1}).

Vapour pressure deficit is calculated using Eq. 2.9

$$VPD = \left[\frac{[e_S(T_{\max}) + e_S(T_{\min})]}{2}\right] - e_a \qquad 2.9$$

T_{max} is maximum daily temperature in ^{o}C, T_{min} minimum daily temperature in ^{o}C,

The net radiation (R_n) required for the calculation of Penman-Monteith ETo is computed by using Eq. 2.10.

$$R_n = R_{ns} - R_{nl} \qquad 2.10$$

R_{nl} is long-wave net radiation in MJ m^{-2} day^{-1} and R_{ns} is short-wave net radiation in MJ m^{-2} day^{-1}. Considering the albedo of the reference crop as 0.23, R_{ns} is calculated as:

$$R_{ns} = 0.77\, R_s \qquad 2.11$$

R_s is solar radiation in MJ m^{-2} day^{-1}(input value from weather data).

$$R_{nl} = f_c \varepsilon \sigma \left(T_{\max}^4 + T_{\min}^4\right)^{0.5} R_a \qquad 2.12$$

R_a is extraterrestrial radiation in MJ m^{-2} day^{-1}.

f_c is the cloudiness factor and is computed by Eq. 2.13.

$$f_c = \left[\frac{1.35\,R_s}{(R_{so} - 0.35)} \right] \qquad 2.13$$

R_{so} is the short wave radiation during bright sunshine in MJ m^{-2} day^{-1}.

$$R_{so} = 0.75\ R_a \qquad 2.14$$

The value 0.75 shows the maximum clear sky transmissivity of the atmosphere and ε is the clear sky emissivity of the earth's surface:

$$\varepsilon = 0.34 - 0.14\ e_a^{0.5} \qquad 2.15$$

σ is the Stefan-Boltzmann constant (5.67 × 10^{-8} W m^{-2} k^{-4}) (Annandale *et al*., 1999).

SWB calculates Penaman-Monteith ETo as to the procedures recommended by Smith *et al.* (1996).

$$ETo = \left[\frac{\left[0.408\Delta(R_n - G) + \gamma \frac{900}{(T_{avg} + 273)} U_2 (e_s - e_a) \right]}{\left[\Delta + \gamma (1 + 0.34 U_2) \right]} \right] \qquad 2.16$$

Δ is the slope of the saturation vapour pressure curve in kPa ^{o}C^{-1}

$$\Delta = \left[\frac{4098\, e_s}{(T_a + 237.3)^2} \right] \qquad 2.17$$

G is the soil heat flux in MJ m^{-2} day^{-1} and is calculated from today's (DOY) and yesterday's ($DOY\text{-}1$) average air temperature (T_{avg})

$$G = 0.38\left[T_{avg}(DOY) - T_{avg}(DOY-1)\right] \tag{2.18}$$

T_{avg} is the average of the maximum and minimum temperatures and γ is the psychrometer constant in kPa ^{o}C^{-1} and is calculated as:

$$\gamma = \left[\frac{0.00163P_a}{\lambda}\right] \tag{2.19}$$

λ is latent heat of vapourization in MJ kg^{-1} and is calculated as:

$$\lambda = \left(2.501 - 2.361 \times 10^{-3}\right) T_{avg} \tag{2.20}$$

U_2 is wind speed measured at 2m height in m s^{-1}. It is weather data input value. If not available SWB assumes an average U_2 of 2 m s^{-1}.

The potential evapotranspiration, which is used in the soil unit to determine the actual transpiration and evaporation, is calculated as a function of the reference evapotranspiration and Kc_{max}.

$$PET = ETo\ Kc_{max} \tag{2.21}$$

Kc_{max} is the maximum value for the FAO crop coefficient (Kc) after rain or irrigation. Details on how to calculate it are found in Allen *et al.* (1996).

b. Crop unit

The crop unit of SWB model calculates crop phenology, dry matter production and partitioning.

i. Crop phenology

Growing day degrees (*GDD*) in d ^{o}C is computed from average daily air temperature (T_{avg}) as shown in Eq. 2.22 after (Monteith, 1977):

$$GDD = (T_{avg} - T_b)\ \Delta t \tag{2.22}$$

T_b is base temperature in ^{o}C (crop specific parameter) and Δt is time interval (one day).

If average daily temperature is below the base temperature, the growing day degrees for that specific day (GDD_i) is set to 0. A value of 5 ^{o}C, recommended by Thomas (2001d), was used for T_b of canola. Thermal time is accumulated every day as long as the average temperature (T_{avg}) is higher than the T_b, and it doesn't exceed the optimum temperature. If $T_{avg} > T_{cutoff}$ then:

$$GDD_i = T_{cut\text{-}off} - T_b \tag{2.23}$$

Where $T_{cut\text{-}off}$ is an optimal temperature for crop development in ^{o}C (crop specific parameter).

The succession of phonological stages is simulated using day degree requirements for emergence (EMDD), completion of vegetative growth (FLDD), transition period between vegetative and reproductive growth (TransDD) and maturity (MTDD) (Annandale *et al.*, 1999).

ii. Dry matter production

SWB calculates the daily crop dry matter increment from net canopy photosynthesis of the leaves either in direct proportion to transpiration corrected for vapour pressure deficit developed after Tanner and Sinclair (1983) (Eq. 2.24) or radiation limited growth, developed after Monteith (1977) (Eq. 2.25) (Annandale *et al.*, 1999). It then uses the lower of the two.

$$DM_i = \left[\frac{DWR}{VPD}\right] T \qquad 2.24$$

DM_i is daily dry matter increment in kg m $^{-2}$, VPD is vapour pressure deficit in Pa, DWR is dry matter – water ratio in Pa and T is actual calculated daily crop transpiration in mm or kg m^{-2}.

VPD is computed using Eq. 2.9. Hatfield and Fuchs (1990) described evapo-transpiration as the combined loss of water from the soil and plant surface.

Tanner and Sinclair (1983) showed that transpiration is directly proportional to the mean vapour pressure deficit (VPD) between the atmosphere and the crop as shown in Eq. 2.24. According to Howell, Cuenca and Solomon (1990), the vapour pressure deficit of a crop (VPD_c) is approximately equal to the vapour pressure deficit of the atmosphere (VPD_a). In addition, they elaborated that $VPD_c > VPD_a$ for crops growing in humid and sub humid areas, without any stress, and where the canopy temperature is higher than air temperature. However, in arid and semi arid climates, where the air temperature is often higher than canopy temperature, $VPD_c < VPD_a$. SWB considers that $VPD_a = VPD_c$ (Annandale *et al.*, 1999).

The radiation limited dry matter production computation by SWB is done using Eq. 2.25.

$$DM_i = E_c T_f \, FI_{transp} \, R_S \qquad 2.25$$

E_c is radiation conversion efficiency of crop canopy under radiation limited growth in kg MJ^{-1} (Monteith, 1977), T_f temperature factor for radiation-limited crop growth (upper limit is set at 1, when $T_{avg} > T_{lo}$, it is calculated using Eq. 2.26, FI is fraction of incident solar radiation intercepted by the green, transpiring canopy and R_s total solar radiation in MJ m^{-2} day^{-1}

$$T_f = \left[\frac{\left(T_{avg} - T_b\right)}{\left(T_{lo} - T_b\right)} \right] \qquad 2.26$$

T_{lo} is temperature of optimum light limited growth (^{o}C)

According to Annandale *et al*. (1999), SWB uses Eq. 2.27 to explain the transmission of a beam of solar radiation through the plant canopy in the same way as Bouguer's law.

$$FI = 1 - e^{-K\ LAI} \qquad 2.27$$

K is canopy extinction coefficient for solar radiation calculated using field measurements of LAI and FI (crop specific parameter). The value of FI was calculated using field measurements of photosynthetically active radiation (PAR) (K_{PAR}). However, the SWB model uses total solar radiation (K_s) after Monteith (1977). Therefore Eq. 2.28 was used to convert K_{PAR} to K_s.

$$K_s = K_{bd}\sqrt{a_s} \qquad 2.28$$

K_{bd} is canopy radiation extinction coefficient for 'black' leaves with diffuse radiation (calculated using Eq. 2.29), a_s is leaf absorptance of solar radiation (calculated using Eq. 2.30), a_p is leaf absorptance of PAR (assumed to be 0.8) and a_n is leaf absorptance of near infrared radiation (0.7 – 3 μm) (assumed to be 0.2 after Goudriaan (1977)).

$$K_{bd} = \left[\frac{K_{PAR}}{\sqrt{a_p}} \right] \qquad 2.29$$

$$a_s = \sqrt{a_p\, a_n} \qquad 2.30$$

In addition, they used K for the prediction of radiation limited dry matter production, as well as for partitioning ET into evaporation from the soil surface and crop transpiration by calculating the parameters shown in Eqs. 2.31 and 2.32 (Annandale *et al.*, 1999).

$$FI_{transp} = 1 - e^{(-K\,LAI)} \qquad 2.31$$

$$FI_{evap} = 1 - e^{[-K\,(LAI - LAIy)]} \qquad 2.32$$

$LAIy$ is leaf area index of senesced (yellowed) leaves, FI_{transp} is the amount of intercepted solar radiation by the canopy, which is used for the determination of transpiration and dry matter production and FI_{evap} is fractional interception of radiation by photosynthetically active and senesced leaves.

iii. Dry matter partitioning

According to Annandale *et al*. (1999), SWB partitions the dry matter produced primarily to the reproductive sinks after flowering, then to the roots followed by leaves and finally into stems. It calculates root daily dry matter increment using Eq. 2.33.

$$RDM_i = f_r\, DM_i \qquad 2.33$$

f_r is fraction of dry matter partitioned to roots (set to 0 once maximum root depth is reached). Maximum rooting depth is a crop specific parameter) and RDM_i is root dry matter daily increment in kg m^{-2}.

It also calculates daily canopy (CDM_i), leaf (LDM_i) and stem (SDM_i) dry matter increments using Eqs. 2.34, 2.35 and 2.37 respectively (Annandale *et al.*, 1999).

$$CDM_i = (1 - f_r)\, DM_i \qquad 2.34$$

$$LDM_i = f_l \, CDM_i \qquad 2.35$$

f_l is fraction of canopy dry matter partitioned into leaves (calculated using Eq. 2.36)

$$f_l = \left[\frac{1}{(1 + PART\,CDM)^2} \right] \qquad 2.36$$

$PART$ is stem leaf partitioning factor (crop specific parameter)

$$SDM_i = CDM_i - LDM_I \qquad 2.37$$

According to Annandale *et al*. (1999), harvestable dry matter daily increment (HDM_i) is added to CDM_i so as to incorporate grain dry matter into CDM. Under water stress conditions assimilate partitioning is affected. Water stress conditions are simulated when the calculated daily water stress index is lower than the threshold (crop specific parameter). The stress index (SI) is calculated in the soil unit as the ratio between actual and potential transpiration. In such situations of water stress the daily leaf dry matter increment is partitioned half to roots and the remaining half to stems (Eqs. 2.38 and 2.39). Finally, the canopy dry matter is computed using Eq. 2.40. In conditions, where the plant root system has reached the maximum root depth, the fraction of dry matter partitioned to the roots is set to 0, and partitioning of the daily leaf dry matter increment will be fully diverted into stems (Eq. 2.41). As a result LDM_i will be 0, and one stress day is accumulated (Annandale *et al*., 1999).

$$RDM_i := RDM_i + \left(\frac{LDM_i}{2} \right) \qquad 2.38$$

$$SDM_i := SDM_i + \left(\frac{LDM_i}{2} \right) \qquad 2.39$$

$$CDM_i := CDM_i + \left(\frac{LDM_i}{2}\right) \qquad 2.40$$

$$SDM_i := SDM_i + LDM_i \qquad 2.41$$

iv. Leaf area

According to Annandale *et al.* (1999), SWB calculates a daily leaf area increment (LAI_i) after emergence using Eq. 2.42. The leaf area index (*LAI*) at a specific time is computed as the sum of LAI_i values. This shows the photosynthetically active canopy or green leaf area, which plays the main role for transpiration and dry matter production.

$$LAI_i = LDM_i\,SLA \qquad 2.42$$

SLA is the specific leaf area in m^2 kg^{-1} (specific crop parameter, calculated using Eq. 2.43)

$$SLA = \left(\frac{LAI}{LDM}\right) \qquad 2.43$$

LDM is leaf dry matter in kg m^{-2} soil area.

SWB takes into consideration leaf ageing to determine senescing leaves as they stop their contribution to dry matter production. This is done by tracking each individual day's $LAIage_i$. The age (in d °C) of each day's leaf area increment is kept track of from the day it was generated. Once the LAI_i reaches the maximum age (crop specific parameter), it is classified as leaf area of yellow or dead leaves ($LAIy_i$). This results in the reduction of the green leaf area index by $LAIy_i$ at the same time increasing the leaf area index of senesced leaves by the same amount, so as estimate shading of the soil for the evaporation calculation in the Soil unit of SWB. SWB simulates premature leaf senescence and ageing under water deficit conditions using Eqs. 2.44 and 2.46. The upper limit of the water stress factor (*wsf*) is set to 2 (Annandale *et al.*, 1999).

$$WSF = \left(\frac{1}{SI}\right) \tag{2.44}$$

SI is water stress index (calculated using Eq. 2.45)

$$SI = \left(\frac{T}{\left(FI_{transp}PET\right)}\right) \tag{2.45}$$

$$LAIage_i = wsf\ GDD_i \tag{2.46}$$

v. Root growth

SWB computes root depth using Eq. 2.47

$$RD = RGR\ \left(RDM\right)^{0.5} \tag{2.47}$$

RD is root depth in m, RGR is root growth rate in m^2 kg$^{-0.5}$ and RDM is root dry matter in kg m^{-2}.

RD is required in the computation of transpiration in the Soil unit of SWB. Estimation of root depth for the SWB calibration was conducted from the weekly neutron probe readings. It was assumed as the depth from which 90% of soil water was depleted every week (Annandale *et al.*, 1999).

vi. Harvestable dry matter

During the commencement of the flowering stage, initial harvestable dry matter (HDM) of the crop is calculated using Eq. 2.48 (Annandale *et al.*, 1999).

$$HDM = Transl\ SDM \tag{2.48}$$

Transl is factor determining translocation of dry matter from stem to grain (Crop specific parameter).

SWB computes daily harvestable dry matter increment and reproductive partitioning fraction (*rpf*) during the flowering stage using Eqs. 2.49 and 2.50 respectively.

$$HDM_i = rpf\ DM_i \tag{2.49}$$

$$rpf = \left[\frac{(GDD - FLDD)}{TransDD}\right] \tag{2.50}$$

rpf is reproductive partitioning fraction, *FLDD* is day degrees at the end of vegetative growth and *Trans DD* is day degrees of transition period from vegetative to reproductive growth.

The variable *rpf* ranges from 0 (for a crop which has not yet flowered) to 1 (for crops whose dry matter production is fully partitioned to the reproductive portion) (Annandale *et al.*, 1999).

c. Soil unit

According to Annandale *et al.*, (1999) the soil unit simulates the movement of water in the soil profile so as to determine its availability to plants. SWB uses either a cascading or finite difference approach to simulate the movement of water in a soil profile. The cascading approach was used to simulate the soil water balance of canola. Therefore, only the cascading approach is described in this section. According to Annandale *et al.* (1999), SWB partitions the soil profile into different layers with their own physical properties, namely: soil matric potential Ψ_m (J kg^{-1}), volumetric soil water content θ (m m^{-1}), volumetric water content at field capacity θ_{fc} (m m^{-1}), volumetric water content at permanent wilting point θ_{pwp} (m m^{-1}), Campbell's "*a*" and "*b*" parameters of the log-log water retention function, and bulk density ρ_b (Mg m^{-3}).

According to Annandale *et al*. (1999), the SWB model reads the initial values of θ, θ_{fc}, θ_{pwp}, and ρ_b during the initialisation procedure for soil water parameters of each soil layer. It then calculates θ_{sat} and Campbell's "*a* " and "*b*" coefficients using Eqs. 2.51, 2.52, and 2.53 respectively. It also recalculates θ_{pwp} for the specific crop to determine the lower limit of crop water uptake (which varies for each crop because of the variation in the average leaf water potential at maximum transpiration rate) and air-dry volumetric soil water content (θ_{ad}) using Eqs. 2.54 and 2.55 (Annandale *et al*., 2000).

$$\theta_{sat} = 1 - \left(\frac{\rho b}{2.65} \right) \tag{2.51}$$

2.65 Mg m^{-3} is the average density of soil particles.

$$a = \exp\left[\ln\left(-\psi_{pwp} \right) + b \ln\left(\theta_{pwp} \right) \right] \tag{2.52}$$

Ψ_{pwp} is the soil matric potential at permanent wilting point in kPa (J kg^{-1}) and Ψ_{fc} is the soil matric potential at field capacity in kPa (J kg^{-1}).

$$b = \left[\frac{\ln\left(\frac{\psi_{pwp}}{\psi_{fc}} \right)}{\ln\left(\frac{\theta_{fc}}{\theta_{pwp}} \right)} \right] \tag{2.53}$$

$$\theta_{pwp} = \exp\left[\frac{-\ln\left(\frac{-3\psi_{lm}}{2a} \right)}{b} \right] \tag{2.54}$$

Ψ_{lm} is the leaf water potential at maximum transpiration rate in kPa (J kg^{-1})

$$\theta_{ad} = 0.3\ \theta_{pwp} \tag{2.55}$$

θ_{ad} is used to set the lower limit for evaporative loss from the top soil layer.

The SWB model computes transpiration from the irrigation and precipitation water remaining after satisfying the demands for interception, runoff, percolation below root zone and evaporation (Annandale *et al*., 1999).

According to Annandale *et al.* (1999), the SWB model calculates interception when there is precipitation or sprinkler irrigation is used. The amount of water intercepted is computed by multiplying the canopy storage of the crop (crop specific parameter) with fractional interception of radiation by photosynthetically active and senesced leaves (FI_{evap}). FI_{evap} is computed using Eq. 2.32. The amount of precipitation (P) or irrigation (I) reaching the soil surface is then reduced by the amount of water intercepted.

The amount of water, which reaches the soil surface from precipitation, sprinkler and flood irrigation, is checked if it can trigger runoff. Runoff is assumed to be 0 if Eq. 2.56 is satisfied (Annandale *et al*., 1999).

$$P + I \leq 0.2\ S \tag{2.56}$$

S is runoff curve number (an input parameter showing the storage of surface in mm).

If the sum of precipitation and irrigation is found to be greater than 20% of S, runoff is computed using Eq. 2.57, which is adopted from Stewart Woolhiser, Wischmeir, Caro and Frere (1976).

$$R = \left[\frac{(P + I - 0.2\,S)^2}{(P + I + 0.8\,S)} \right] \tag{2.57}$$

The amount of water lost as runoff using Eq. 2.57 is subtracted from the irrigation and/or precipitation reaching the soil surface. The remaining water is left for infiltration and redistribution (Annandale *et al*. 1999).

According to Annandale *et al.* (1999), the SWB model calculates soil water redistribution in a profile on days when precipitation or irrigation occurs following infiltration or when drainage (Dr) occurs. It distributes soil water starting from the top layer downwards and it also updates soil water content for each layer on a daily basis. Soil water deficit to field capacity (SWD) is then computed using Eq.2.58 and Dr using Eq. 2.59.

$$SWD = (\theta_{fc} - \theta)\,\rho_w\,dz \qquad 2.58$$

θ is volumetric water content of the given layer in m^3 m^{-3} or in m m^{-1}, ρ_w is density of water (1000 kg m^{-3}) and dz is thickness of the soil layer in m.

$$Dr = Df\,(\theta - \theta_{fc})\,\rho_w\,dz + D_i \quad \text{only if} \quad (\theta > \theta_{fc}) \qquad 2.59$$

In times when the amount of water added for a given soil layer is greater than ($\theta_{sat} - \theta$), θ is set to θ_{sat}. D_i then will be reduced by ($\theta_{sat} - \theta$) $\rho_w\,dz$. However, if the amount of water added is less than ($\theta_{sat} - \theta$) for that given layer θ is increased by ($D_i/(\rho_w\,dz)$) and D_i is set 0 for the next layer. Df is drainage factor (soil input parameter) and can be determined for each field using Eq. 2.60.

$$Df = \left[\frac{\left(\theta^{t1} - \theta^{t2}\right)}{\left(\theta^{t1} - \theta_{fc}\right)}\right] \qquad 2.60$$

θ^{t1} and θ^{t2} are volumetric water contents of a given soil layer at times $t1$ and $t2$.

The SWB model partitions the PET calculated in the weather unit into potential evaporation (PE) and potential transpiration (PT) by calculating canopy radiant interception from simulated leaf area, as recommended by Ritchie (1972). PE and PT are the upper limits, which occur when the atmospheric demand is limiting. When the supply of water is limiting, soil water evaporation is simulated by relating evaporation rate to water content of the surface soil layer. The SWB model assumes the loss of water due to evaporation only from the upper soil layer. It uses Eq. 2.61 adopted from Reddy (1983) to calculate *PE*.

$$PE = (1 - FI_{evap})\ PET \qquad 2.61$$

According to Campbell (1985), evaporation takes place at a potential rate until θ_{pwp} is reached; however, if the water content is decreased below θ_{pwp} evaporation is supply limited and is computed using Eq. 2.62.

$$E = PE\left[\frac{(\theta - \theta_{ad})}{(\theta_{pwp} - \theta_{ad})}\right]^2 \qquad 2.62$$

In situations where the calculated θ is below θ_{ad}, θ is taken as equal to θ_{ad} and E is computed using Eq. 2.63 (Annandale *et al.*, 1999).

$$E = (\theta - \theta_{ad})\ \rho_w\ dz \qquad 2.63$$

SWB computes soil water loss through transpiration on days when the fractional interception of photosynthetically active leaves (FI_{trans}) and root depth (RD) are greater than 0. Ψ_m of the modeled soil water content is computed on a daily basis using Eq. 2.64 (Annandale *et al.,* 1999).

$$\Psi_m = a\ \theta^{-b} \qquad 2.64$$

The SWB model uses a dimensionless solution to the water potential based water uptake equation, which is developed after Campbell and Norman (1998). This was proved to work very well in the field both under well watered and stressed conditions by Annandale *et al.* (2000). SWB computes transpiration (*Loss*) using Eq. 2.65 for each layer in the soil profile (Annandale *et al.* 2000).

$$Loss\,(Trans) = \left[\frac{\left[\dfrac{FI_{transp}\, Tr_{\max}\, f\left(\psi_x - \psi_m\right)}{\left(0.67\psi_{lm}\right)} \right]}{\left(\rho_w dz\right)} \right] \qquad 2.65$$

Tr_{max} is maximum transpiration rate in mm day^{-1}, f is layer root fraction and ψ_x is xylem water potential in kPa or J kg^{-1}. Detailed description of the above-mentioned variables could be found in Annandale *et al.* (2000).

2.6.2 FAO model

SWB uses the FAO based crop factor model in the absence of specific crop growth parameters determined using weather, soil and growth analysis data. The FAO based crop factor procedure is combined with the mechanistic SWB model to calculate evaporation and transpiration separately using the same weather and soil units. However, the crop factor model does not simulate the effect of water stress on canopy size (Jovanovic and Annandale, 1999).

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental data

Field experiments were conducted at the Hatfield Experimental Farm, Pretoria, South Africa. This area is situated at an elevation of 1327 m above sea level, latitude of 25° 45ʹ S and longitude of 28° 16ʹ E. It has an average annual rainfall of 670 mm, mainly during the months of October to March (Annandale *et al.*, 1999). The soil of the experimental site had a clay content of 26 – 37% and a pH in water of 6.2 – 6.7. The experiment conducted both during 2002 and 2003 had four treatments as shown in Figure 3.1. A panoramic view of the experiment is shown in Figure 3.2.

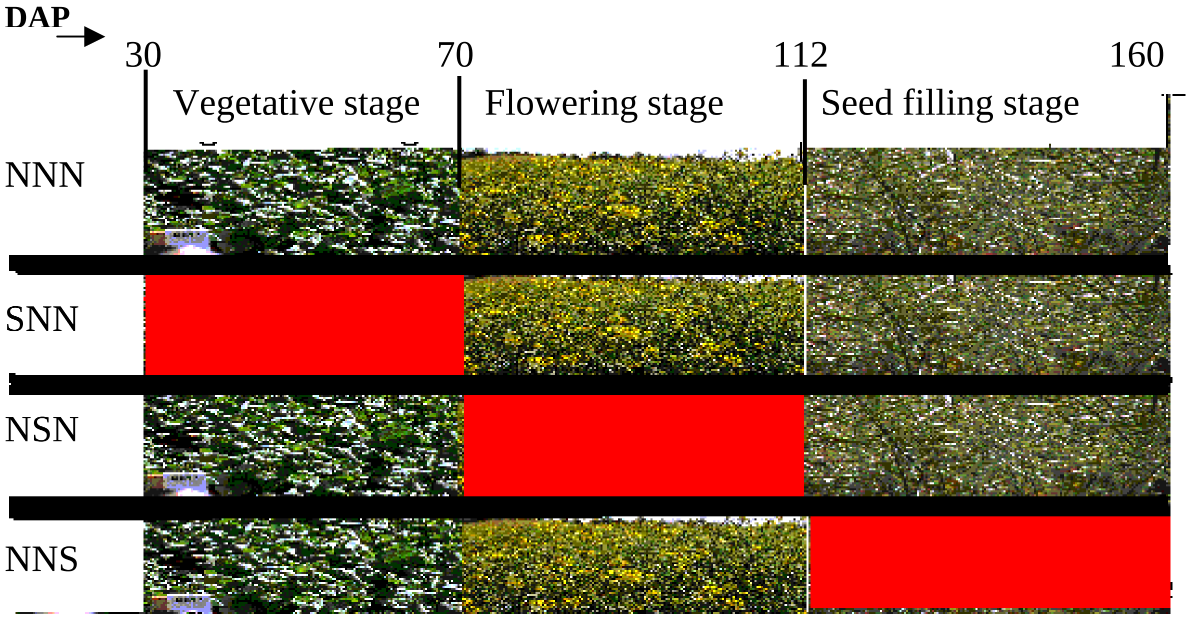

Figure 3.1 Four irrigation water stress treatments being applied at different growth stages

DAP stands for days after planting. The treatment NNN stands for non-stressed treatment (plants being irrigated throughout the growing season), SNN stands for the treatment stressed during the vegetative growth stage (plants not irrigated from 30 to 70 DAP). NSN stands for the treatment stressed during the flowering stage (plants not irrigated from 70 to 112 DAP) and NNS showing the treatment stressed during the seed filling stage (plants not irrigated from 112 to 161 DAP). The three letters indicate the irrigation regime applied for the three phenological stages mentioned in Figure 3.1 namely: vegetative, flowering and seed filling stages whereby N stands for non-stressed and S stands for stress. The area of each experimental unit was 10 m^2 in 2002 and 42 m^2 in 2003. The layout of the experimental plots was based on a randomised block design in 2002 and completely randomised design in 2003.

Sprinkler irrigation was used for one month until the crop was established. This was then replaced by drip irrigation to irrigate individual plots once a week, depending on the soil water deficit to field capacity, except the stress plots. The drippers used were pressure compensated having a delivery rate of 2.3 $l\ h^{-1}$ at a pressure range of 100-150 kPa. The lateral spacing between the dripper lines was 0.62 m and the distance between the drippers in the line was 0.3 m. Irrigation timing was controlled using a solenoid for each treatment based on the time set on the automatic control unit during 2002, whilst manual control was used during 2003.

Soil water deficit measurements were made using a neutron water meter model 503 DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA) that was calibrated for the site (calibration procedure and data are shown in APPENDIX B). The profile was irrigated to field capacity based on the deficit readings for the non-stressed treatments. Water use (ET) in mm and water use efficiency (WUE) in kg ha^{-1} mm^{-1} was calculated using Eqs. 3.1 and 3.2.

$$ET(Loss) = I + P - Dr - \Delta S - R \qquad 3.1$$

I stands for irrigation in mm, P is precipitation in mm, Dr is drainage in mm [assumed to be negligible], ΔS is change in soil water storage in mm and R is runoff in mm [assumed to be negligible].

$$WUE = \left(\frac{Y}{ET}\right) \quad 3.2$$

Y is yield in kg ha^{-1}.

Figure 3.2 Panoramic view of canola experimental layout (winter 2002)

The agronomic practices listed in Table 3.1 were applied to the experiment. The field was ploughed with a disc plough and rotavated to create suitable conditions for good soil – seed contact. Low grain yields were achieved during 2002, mainly due to water deficit and partly due to low nitrogen fertilizer application. Therefore, a relatively greater amount of fertilizer was applied during 2003 at different development stages based on the study conducted by Dreccer, Schapendonk, Slafer and Rabbinge (2000). Weeding was conducted manually during the course of the trial. Infestation of aphids was controlled by spraying Methomyl and Aphicide during both 2002 and 2003. The quality of irrigation water used and the textural and chemical analysis of the soil at the experimental site are displayed in Tables A2 - A4 of APPENDIX A.

Table 3.1 Agronomic practices applied (Winters of 2002 and 2003)

Activities			**Year**	
			2002	**2003**
Land preparation			Ploughed with disc plough, rotavated	Ploughed with disc plough, rotavated
Date of planting			23rd May	21st May
Depth of planting			20 to 40 mm	20 to 40 mm
Row spacing			0.15 m	0.15 m
Seeding rate			5.3 kg ha^{-1}	5.3 kg ha^{-1}
Fertilizer applied	N	During planting	33.33 kg ha^{-1}	60 kg ha^{-1}
		Vegetative stage	-	40 kg ha^{-1}
		Flowering stage	-	100 kg ha^{-1}
	P	During planting	50 kg ha^{-1}	45 kg ha^{-1}
		Vegetative stage	-	40 kg ha^{-1}
		Flowering stage	-	-
	K	During planting	66.67 kg ha^{-1}	60 kg ha^{-1}
		Vegetative stage	-	40 kg ha^{-1}
		Flowering stage	-	-

Growth analysis was conducted every two weeks and the samples were taken from an area of 0.5 m^2 during both 2002 and 2003. The size of the experimental unit was small during 2002 and therefore the samples for growth analysis could not be replicated.

The water stress treatment during the vegetative stage commenced after crop emergence (30 days after planting). The first set of samples for growth analysis was taken 8 days after the commencement of the stress treatments. The samples taken from the plots were partitioned into stems, leaves and pods. Fractional interception of Photosynthetically Active Radiation (PAR) was measured using a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA), and leaf area was measured using an LI 3100 belt driven leaf area meter (LiCor, Lincoln, Nebraska, USA). In addition, weather data was collected from an automatic weather station located about 500 m from the experimental site. The automatic weather station consisted of an LI 200X pyranometer (LiCor, Lincoln, Nebraska, USA) for measuring solar radiation, an electronic relative humidity and temperature sensor installed in a Gill screen, an electronic cup anemometer (MET ONE, Inc. USA) to measure wind speed, an electronic rain gauge (RIMCO, R/TBR tipping bucket rain gauge, Rauchfuss instruments division, Australia) and a CR 10X data-logger (Campbell Scientific inc., USA). All of the above data were monitored and recorded every 10 seconds with the CR 10X data logger. The logged data was downloaded once in a month using a laptop computer.

Leaf area index was calculated from the leaf area and ground area from which the samples were taken. The leaves, stems and pods were dried separately for two days at 70^o C for dry matter determination. Top dry matter was calculated as the sum of leaf, stem, and pod dry matters. During the flowering and grain filling stages, the number of pods was counted, and after harvest, 1000 seed mass and yield for each treatment was measured. Dry mass of seeds was also determined by drying the seeds at 70 ^{o}C in an oven for two days. Harvesting of the pods took place manually after they changed to a brownish colour. Finally, they were threshed manually in a plastic bag. Seed quality was assessed visually, as well as from the percentage of oil extract using a hexane extraction.

3.2 Model parameter description and determination

3.2.1 Input parameters and data needed by SWB

The SWB model requires specific crop parameters as well as management, weather and soil data as an input to run both the Growth and FAO models (Annandale *et al*., 1999).

Specific crop parameters

1. Canopy extinction coefficient for solar radiation (K);
2. Dry matter: water ratio (DWR) in kPa;
3. Radiation use efficiency (E_c) in kg MJ^{-1};
4. Base temperature (T_b) in ^{o}C;
5. Optimum temperature (Tlo) in ^{o}C;

vi. Maximum temperature ($T_{cut\text{-}off}$) in ^{o}C;
vii. Thermal time: emergence (*EMDD*) in d ^{o}C;
viii. Thermal time: reproductive phase (*FLDD*) in d ^{o}C;
ix. Thermal time: maturity (*MTDD*) in d ^{o}C;
x. Thermal time: transition (*TransDD*) in d ^{o}C;
xi. Thermal time: leaf senescence in (*MaxLeafAge*) in d ^{o}C;
xii. Leaf water potential at maximum transpiration rate (*psilm*) in kPa or J kg^{-1};
xiii. Maximum transpiration rate (Tr_{max}) in mm d^{-1};
xiv. Specific leaf area (*SLA*) in m^{2} kg^{-1};
xv. Leaf stem partitioning factor (*PART*) in m^{2} kg^{-1};
xvi. Total dry matter at emergence (*TDMstart*) in kg m^{-2};
xvii. Root fraction (f_r);
xviii. Stem translocation (*Transl*);
xix. Root growth rate (*RGR*) in m^{2} kg $^{-0.5}$;
xx. Maximum canopy height (H_{Cmax}) in m, and
xxi. Stress index (*SI*).

Soil data:

i. Runoff curve number in mm;
ii. Matric potential at field capacity and permanent wilting point in kPa or J kg^{-1};
iii. Maximum drainage rate in mm d^{-1} and drainage factor;
iv. Soil layer:
    - Thickness in m;
    - Volumetric soil water content at field capacity and permanent wilting point in m m^{-1};
    - Initial volumetric water content in m m^{-1}, and
    - Bulk density in Mg m^{-3} of each layer.

Crop data:

i. Model type;
ii. Name of the crop;

iii. Planting date;
iv. Starting date of the simulation;
v. Weather ID;
vi. Area of the field in ha;
vii. Irrigation timing options (amount in mm, interval in days, depletion in %);
viii. Irrigation system (type and design details), and
ix. Management (root zone or profile).

Weather data:

i. Latitude (^{o}N or ^{o}S);
ii. Hemisphere;
iii. Wind speed in m s^{-1} and its height of measurement;
iv. Maximum and minimum daily temperature in ^{o}C;
v. Solar radiation in MJ m^{-2} d^{-1};
vi. Precipitation in mm, and
vii. Maximum and minimum relative humidity in % or vapour pressure in kPa or else dry and wet bulb temperatures in ^{o}C.

3.2.2 SWB parameter determination

The specific crop growth parameters of canola determined for the simulation of growth and water use in SWB include dry matter water ratio, growth day degrees at different stages, stem to grain translocation, minimum leaf water potential at maximum transpiration rate, specific leaf area, leaf stem partitioning parameter, maximum crop height and root depth.

Minimum water potential is the minimum leaf water potential at maximum transpiration rate under optimal soil water supply conditions. This was measured for canola using a pressure bomb by cutting a healthy mature leaf from the plant under optimal water supply during 10:00 to 14:00 on a day of high atmospheric demand. Maximum crop height and root depth were also measured from a healthy growing matured plant with a tape, which has reached the maximum possible size, and *DWR* is computed using Eq. 3.3 (Annandale *et al*., 1999).

$$DWR = \left[\frac{(DM\,VPD)}{ET} \right] \qquad 3.3$$

DM is dry matter measured at harvest time in kg, *VPD* is seasonal average vapour pressure deficit in Pa computed using Eq. 2.9 and *ET* is seasonal crop evapotranspiration in mm calculated using Eq. 3.1.

Radiation use efficiency is the slope of a regression line forced through the origin in a graph of dry matter as a function of the daily cumulative product of fractional interception of solar radiation and solar radiation. This was not done for canola because the ceptometer was out of order during 2002. Therefore the value for radiation use efficiency was adopted from Morison *et al.* (1995); Anderson *et al* (1996). Similarly, canopy extinction coefficient is also an exponential function, which is determined from a graph of fractional interception of solar radiation as a function of leaf area index. Detailed description is found in Annandale *et al.* (1999). As mentioned earlier the ceptometer was out of order therefore, the canopy extinction coefficient for canola was adopted from Gabriel, Denoroy, Gosse, Justes and Andersen (1998); Menddahm *et al.* (1981).

Specific leaf area was computed by dividing leaf area by the corresponding leaf dry matter and was averaged for the season as shown in Appendix C Table C.1, as it showed variation during the growing season (Appendix C, Figure C.1). Furthermore, the leaf-stem partitioning parameter was determined for canola by averaging the leaf partitioning parameters for all the water stress treatments as shown in Appendix C (Figure C.2). The leaf-stem partitioning parameter is the slope of the regression line that is forced through the origin in a graph of *[(SLA CDM) / LAI) – 1]* as a function of *CDM*. On the other hand, growing degrees days for the different stages of growth are computed using Eqs 2.22 and 2.23.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Leaf area index

Leaf area index is the leaf area of the plants per unit ground area. Leaf area index of canola for the growing season of winter 2002 and 2003 are shown in Figures 4.1 and 4.2 respectively.

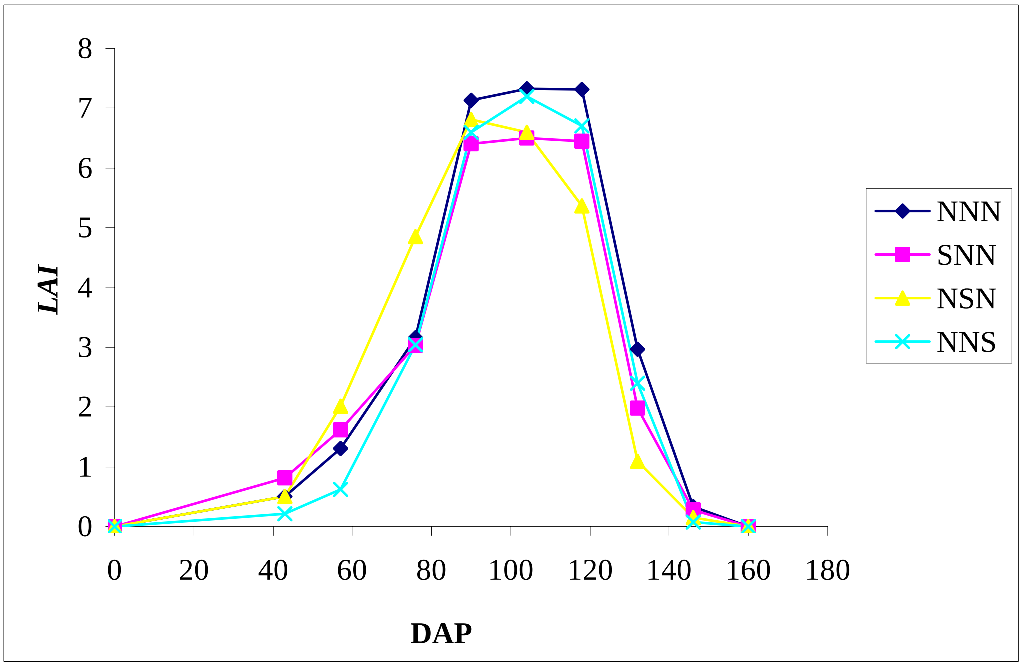

Figure 4.1 Leaf area index of different irrigation regimes (Winter 2002)

Both during 2002 and 2003 the leaves for the treatment without water stress grew vigorously (Figure 4.3), and retained highest leaf area index throughout the growing season. However, for the treatment with stress during the vegetative growth stage it started wilting (Figure 4.4) with the onset of stress. Although the treatment with stress during the vegetative stage had the highest leaf area index before the commencement of stress during both 2002 and 2003, it declined to the lowest level with the application of stress. Nevertheless, some leaves recovered with the resumption of irrigation during the transition period from the vegetative to flowering stage. This shows that canola is a strongly indeterminate crop. Although this crop is indeterminate the SWB model was able to simulate both the crop growth and soil water status very well (Figures 4.23 – 4.24).

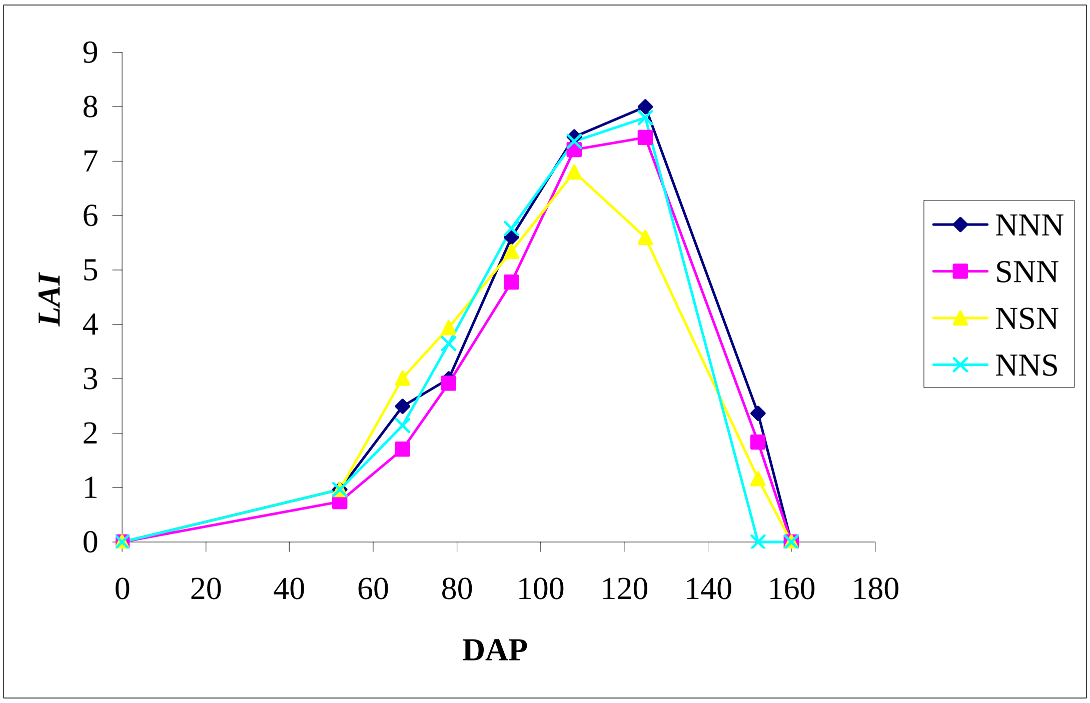

Figure 4.2 Leaf area index of different irrigation regimes (Winter 2003)

Figure 4.3 Vigorous growth of leaves during the vegetative stage of NNN (Winter 2002)

Figure 4.4 Wilting leaves of SNN (photo taken at the same time as **Figure 4.3)**

Treatments stressed during the flowering stage (NSN) had the highest leaf area index similar to the non stressed treatment (NNN); However, three weeks after the application of stress, it dropped to the lowest level and remained there until the middle of the seed filling in both years. On the other hand, the treatment with stress during the grain filling stage (NNS) showed a rapid loss of leaf area. This variation shows the sensitivity of leaf area to water stress in different stages.

The presence of sufficient plant available soil water throughout the growing season helps plants to maintain higher leaf water potentials and at the same time increases the period over which the canopy remains functional. According to Evans (1972), leaf area duration *LAD*, is the integral of leaf area index with respect to time, and therefore takes into account both the duration and extent of photosynthetic tissue, but not the rate of photosynthesis per unit leaf area. *LAD* is calculated using Eq. 4.1.

$$LAD = \left[\frac{\left(LAI_2 + LAI_1 \right)}{2} \right] \times \left(t_2 - t_1 \right) \ (m^2\, m^{-2}\, days) \qquad 4.1$$

The availability of sufficient soil water, especially during the flowering and seed filling stages, helps the crop maintain a higher leaf area for a longer period. This provides the crop with more assimilates, resulting in increased partitioning to harvestable dry matter. Therefore, the source (leaf area) definitely has a greater impact on the yield factor of the treatments when the source is limiting. Evans, Wardlaw and Fischer (1975) point out that in most situations 90 to 95% of the carbohydrates in the seed are derived from photosynthesis during the seed filling stage. In this experiment, the variation in *LAD* after flowering accounted for 97% of the variation in yield as shown in Figure 4.5. This supports the expectations of Evans *et al*. (1975) and is in agreement with work done on wheat by Annandale, Hammes and Nel (1984). These authors expect a close correlation between *LAD* and yield after anthesis under conditions where *LAI* reaches its peak before anthesis and progressively falls with stress. Therefore, in situations where the source is limiting, it is of great significance to keep the canopy cover as large as possible for as long as possible by providing sufficient water and nutrients throughout the growing season, especially during the flowering and seed filling stages, so as to get a good harvest.

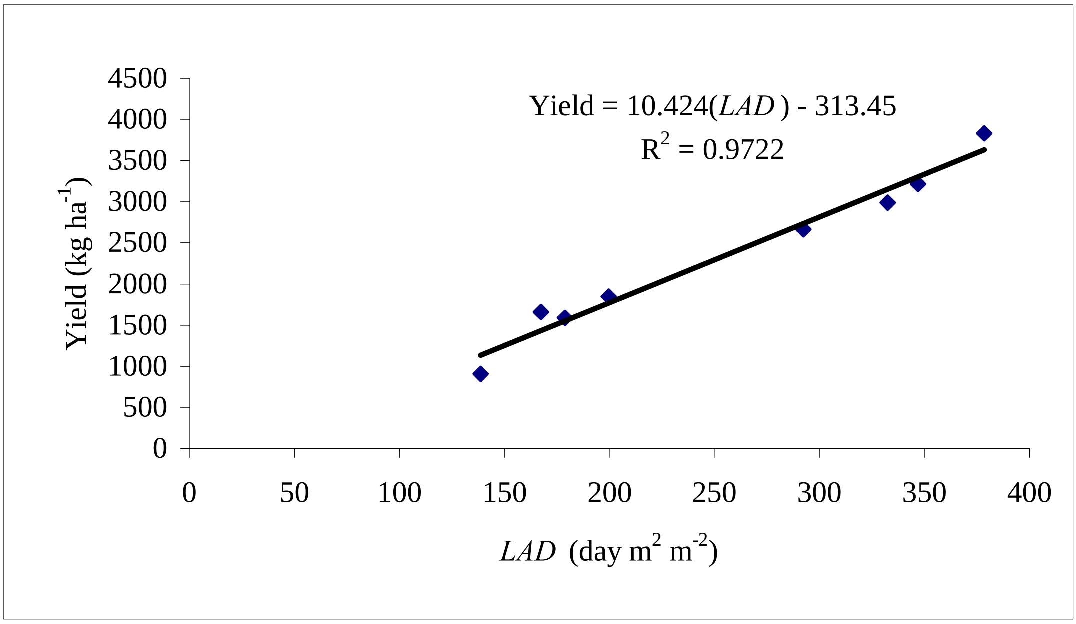

Figure 4.5 Linear relationship between *LAD* after commencement of flowering and seed yield (2002 and 2003)

Write, Morgan and Jessop (1996) explain the effect of water stress on the water potential of leaves very clearly. According to them, leaf water potential is physically related to vapour pressure deficit and soil water potential. A higher soil water potential improves the availability of soil water to plants, which helps them to maintain higher leaf water potentials, and as a result develop greater leaf areas.

As mentioned earlier canola is an indeterminate crop. This was clearly observed for the treatment with water stress during the flowering stage, which showed the blossoming of new flowers and delay in the senescence of leaves after the recommencement of irrigation during the early pod formation period (Figure 4.6). Highest leaf area index, and highest water use was observed during the flowering stage of all treatments; Consequently, leaf area growth was most restricted when stress was applied at that stage of growth. This agrees well with the study conducted by Nielsen (1997).

Meanwhile, leaf senescence was enhanced after the formation of pods in all the treatments. According to Sinclair and de Wit (1975), the main reason for the facilitation of leaf senescence in crops after the formation of pods is that pods become a sink for nitrogen and induce translocation of N from leaves and stems. This does not stop photosynthesis in the vegetative parts, but reduces its efficiency and accelerates senescence because of a N deficiency. Gabrielle, *et al.* (1998) added the following explanation about the facilitation of leaf senescence in canola after the commencement of pod formation. The formation of pods shades the underlying leaves and as a result the radiation available to these leaves is reduced and leaf senescence hastened.

For all treatments the pods dried two weeks after full defoliation of the plants. However, this occurred one week earlier for the treatment with stress in the seed filling stage.

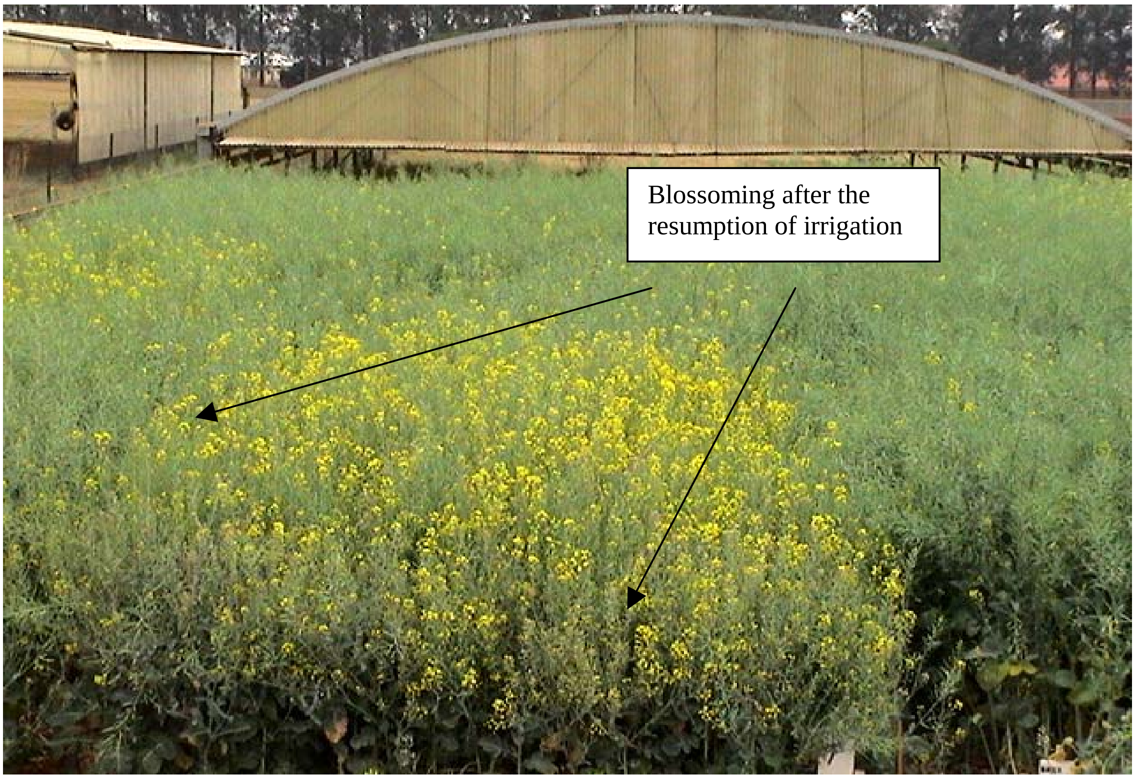

Figure 4.6 Blossoming of new flowers after resumption of irrigation NSN

4.2 *Phenology*

According to Daniel, Scarisbrick and Smith (1986), phenological development of winter oilseed rape is an important aspect of the yield formation process because the time of flowering depends on the combined effect of photoperiod and temperature. However, the SWB model doesn't simulate photoperiodism. Therefore, the effect of photoperiod on the growth and yield of canola needs to be assessed by conducting research in areas with different daylight hours than Pretoria. The recorded thermal time requirement of canola in growing day degrees, using a base temperature of 5 ^{o}C from the date of planting. is shown in Table 4.1. (Weather data is presented in APPENDIX A, Tables A6 and A7)

Table 4.1 Thermal time recorded for completion of canola phenological stages (Winter 2002)

Growth stage	Thermal time in day degrees from planting (^oC)
Emergence stage	77
Vegetative stage	527
Transition stage (from vegetative to flowering stage)	727
Flowering stage	997
Grain filling stage	1742

4.3 Total above ground dry matter accumulation

An increase in dry matter accumulation over time was observed in all treatments for both experiments conducted during 2002 and 2003 as shown in Figures 4.7 and 4.8.

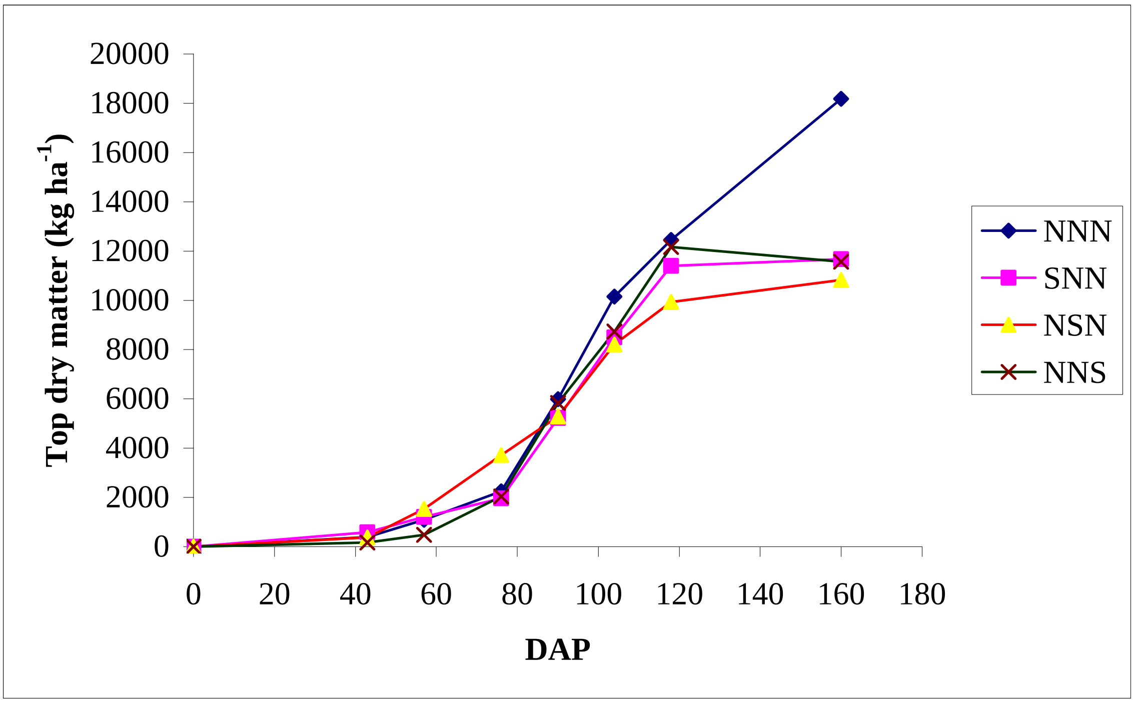

Figure 4.7 Top dry matter accumulation (Winter 2002)

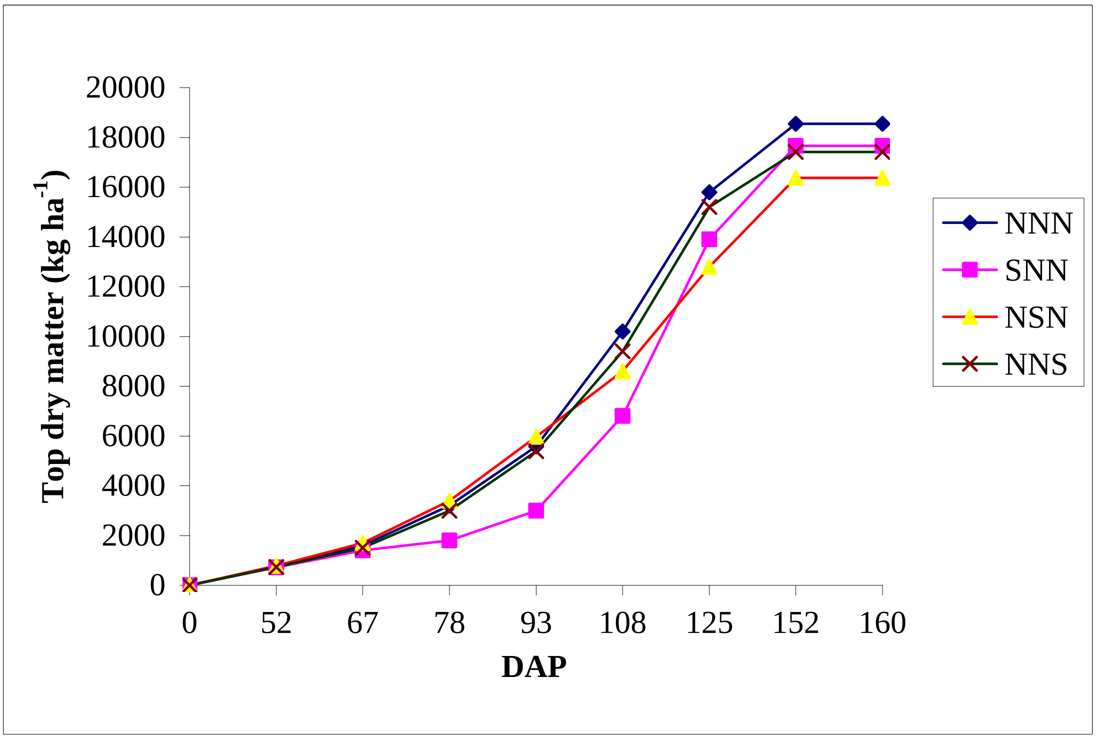

Figure 4.8 Top dry matter accumulation (Winter 2003)

Well-watered canola accumulated dry matter at a faster rate than the water stressed treatments, to ultimately reach a higher final mass. This confirms that the strongly growing crop had a much larger photosynthetic factory. According to Sinclair (1984), leaf area (photosynthetic factory) determines the percentage of solar radiation intercepted by a crop and therefore has a predominant influence on crop growth.

Water deficit during the vegetative stage resulted in reduction of top dry matter, which recovered somewhat with the resumption of irrigation in later growth stages. However, water stress during the flowering stage resulted in the decline of the *LAI* (due to wilting and senescing of leaves) followed by abortion and dropping of flowers, as well as pods, both contributing to a rapid reduction in top dry mass. Therefore, it is of great significance to supply the plant with sufficient water during the sensitive stages of growth (mainly flowering and to some extent seed filling) so as to enlarge the leaf area, which contributes to the enhancement of both top and harvestable dry matter. Abortion of the early-formed flowers was common for all treatments. Only a few of the flowers that first appeared formed pods. Most pod formation took place from the later formed flowers.

The amount of water transpired (*T*) was regressed against dry matter produced over time for NNN (Figure 4.9). Direct measurement of *T* was not done. Instead it was obtained from the SWB model simulation, because the simulated *ET* was similar to that measured and no measurements of transpiration were made. The results show that the quantity of dry matter produced for every mm of water transpired was higher during the vegetative and flowering stages than the seed filling stage. This agrees very well with the explanation given by Tanner and Sinclair (1983). According to them, if the composition of the dry matter changes from hexose sugar to more proteins and lipids, dry matter accumulation per unit water use will be reduced. Similarly, studies conducted by Penning de Vries (1975) show that 1 g of hexose produced by photosynthesis can be used either to produce 0.83 g of carbohydrates, 0.4 g of proteins (assuming a nitrate source of N) or 0.33 g of lipids. Canola is an oil crop and dry matter partitioned to seed during the seed filling stage is mostly converted to proteins and oils, as 30 – 45% of the mass of canola seed is oil. Although normalization for atmospheric evaporative demand was attempted by dividing transpiration by seasonal vapour pressure deficit as shown in Figure 4.10, the correlation was not improved compared to that without such normalization. This can be seen in Figure 4. 9 for NNN. In this study, the amount of water transpired to produce a unit mass of top dry matter during the seed-filling stage of NNN was 2.63 times that needed during the vegetative and flowering stages. This ratio decreased with the application of stress during the different growth stages.

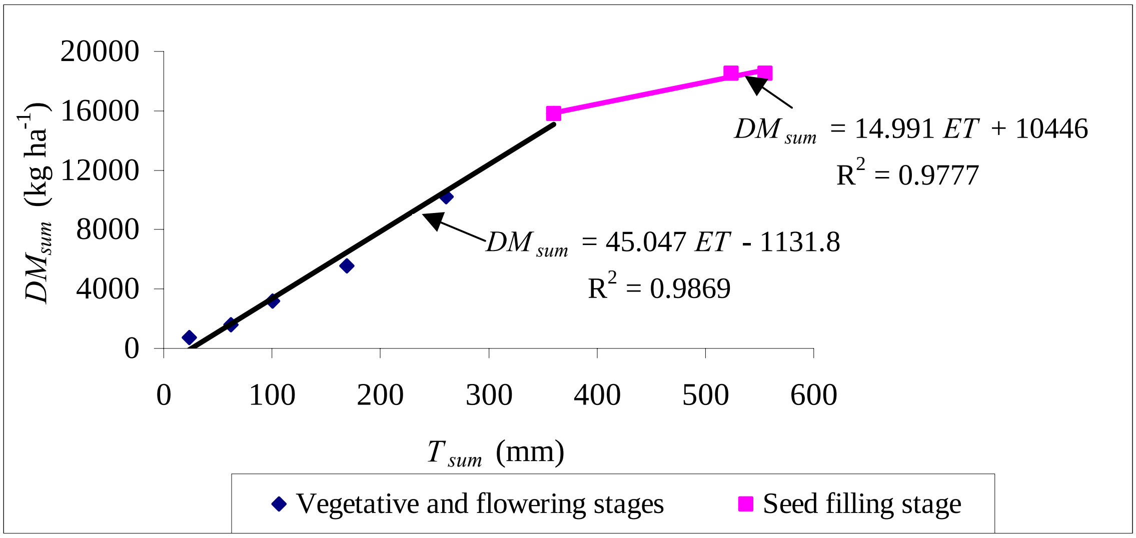

Figure 4.9 Relationship between cumulative transpiration (T_{sum}) and cumulative dry

matter (DM_{sun}). Slopes represent DWR in the vegetative and flowering stage (black line) and seed filling stage (red) (treatment NNN, 2003)

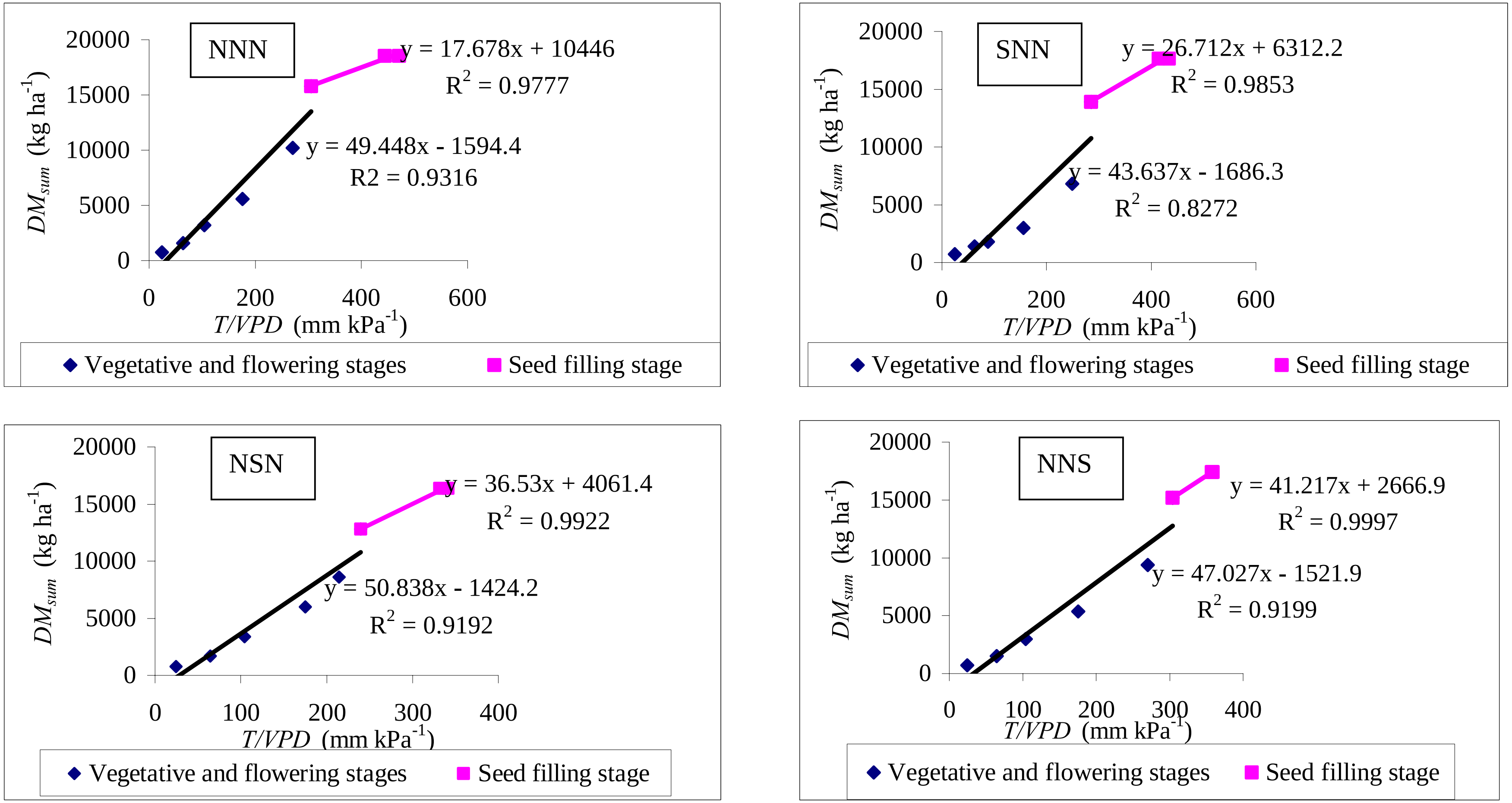

Figure 4.10 Comparison of *VPD* corrected dry matter: transpiration ratio during the vegetative and flowering stages, to that of the seed filling stage for treatments NNN, SNN, NSN and NNS

4.4 Seed yield

Both during winter 2002 and 2003, highest seed yield was harvested for the treatment without water stress, followed by the treatment with stress during the vegetative stage (Figure 4.11).

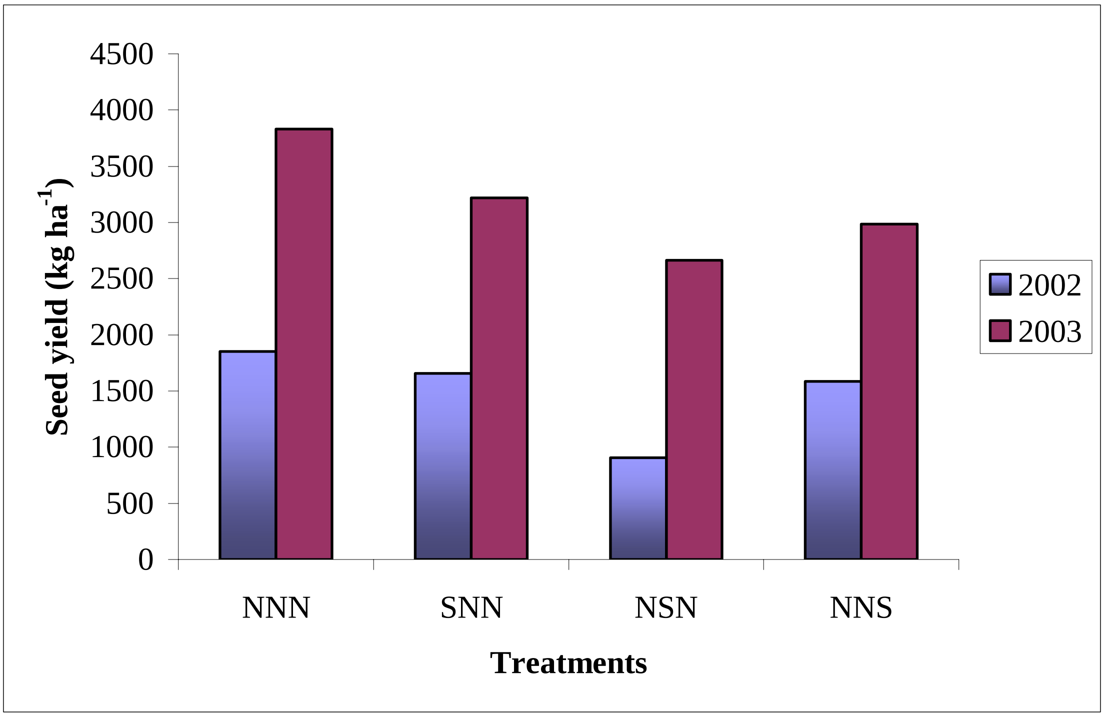

Figure 4.11 Seed yield of all treatments (Winters of 2002 and 2003)

Highest seed yield was harvested from the treatment with no stress due to larger leaf area development, and prolonged duration. The larger photosynthetic factory developed during the growing season was able to supply enough assimilates to support flowering, and the formation of pods, which bear seeds. Similar results were observed on studies conducted in the Canadian Out Look area. According to Thomas (2001c), studies conducted in this area showed the role of adequate soil water in the enhancement of root growth and leaf area. In addition, it helped plants to retain their leaves longer, elongated the flowering period, increased the number of branches per plant as well as number of flower forming pods, seeds per pod, seed mass and seed yield. On the other hand, the influence of water stress on the reduction of yield was observed in all stressed treatments for the studies conducted in Canada, which is similar to this study. However, in the current study, the effect of stress was most crucial for the treatment with stress during the flowering stage. This was because of water stress (Figure 4.12 and Figure 4. 13) at the sensitive stage of growth during which the plant demands more water. This stress resulted in the reduction of maximum possible leaf area.

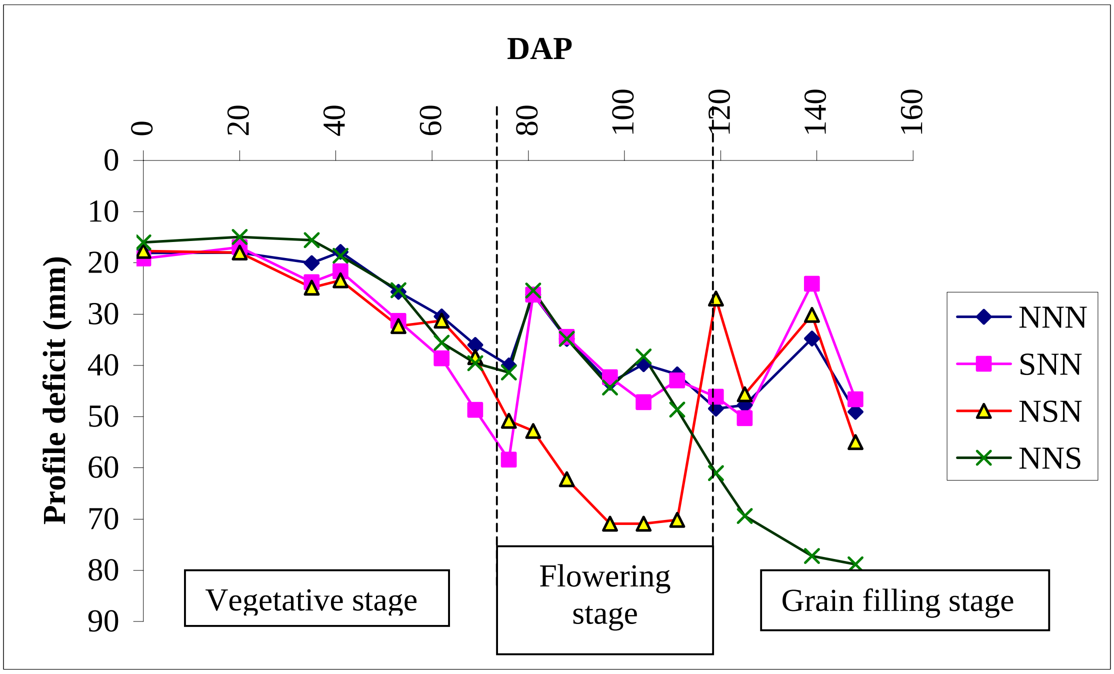

Figure 4.12 Profile water deficit (Winter 2002)

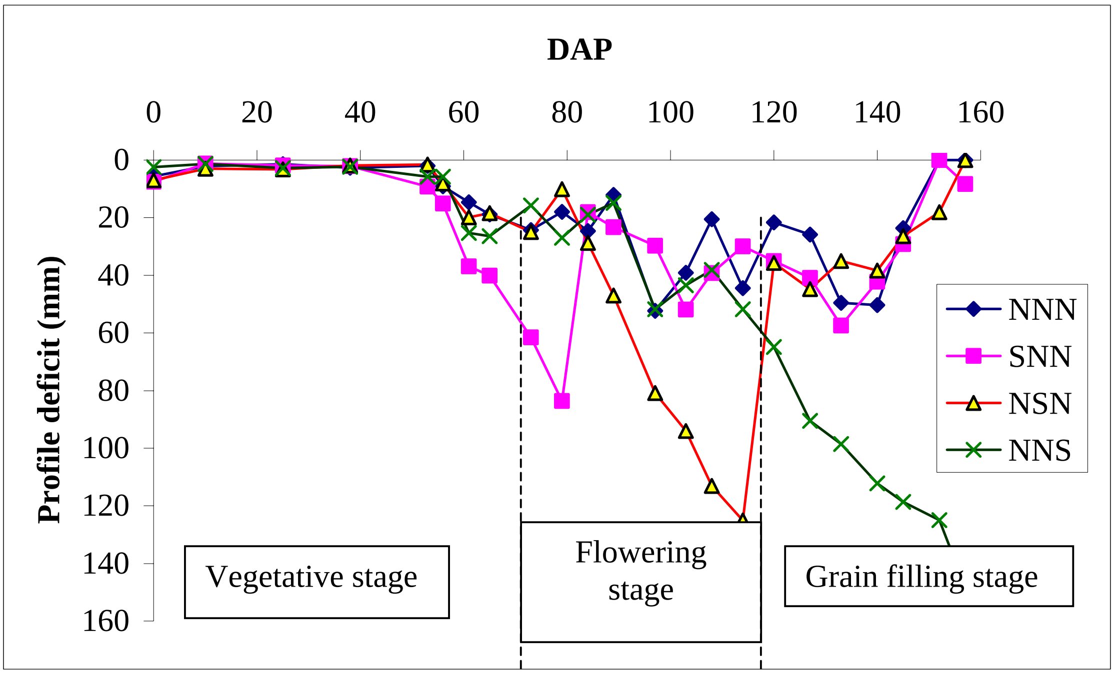

Figure 4.13 Profile water deficit (Winter 2003)

Stress during the flowering stage (NSN), which caused rapid senescence of most leaves, was followed by the dropping of flowers (Figure 4.14). Dropping of flowers inevitably led to a reduction in the total number of pods (Figure 4.15), which bear seeds, and as a result the final yield was reduced. The blossoming of new flowers observed with the resumption of irrigation did never replace the number of dropped flowers. This is similar to what was experienced by Thomas (2001c). According to him, soil water deficit during the flowering to ripening stages results in large yield reductions because of the rapid wilting and death of leaves, causing reduction in branching, number of pods per plant, pod length, seed size and number of seeds per pod.

Figure 4.14 Wilting and dropping of flowers from NSN

The resumption of irrigation after water stress during the flowering stage was accompanied by delayed pod ripening (Figure 4.16) compared to the non-stressed treatment (Figure 4.17).

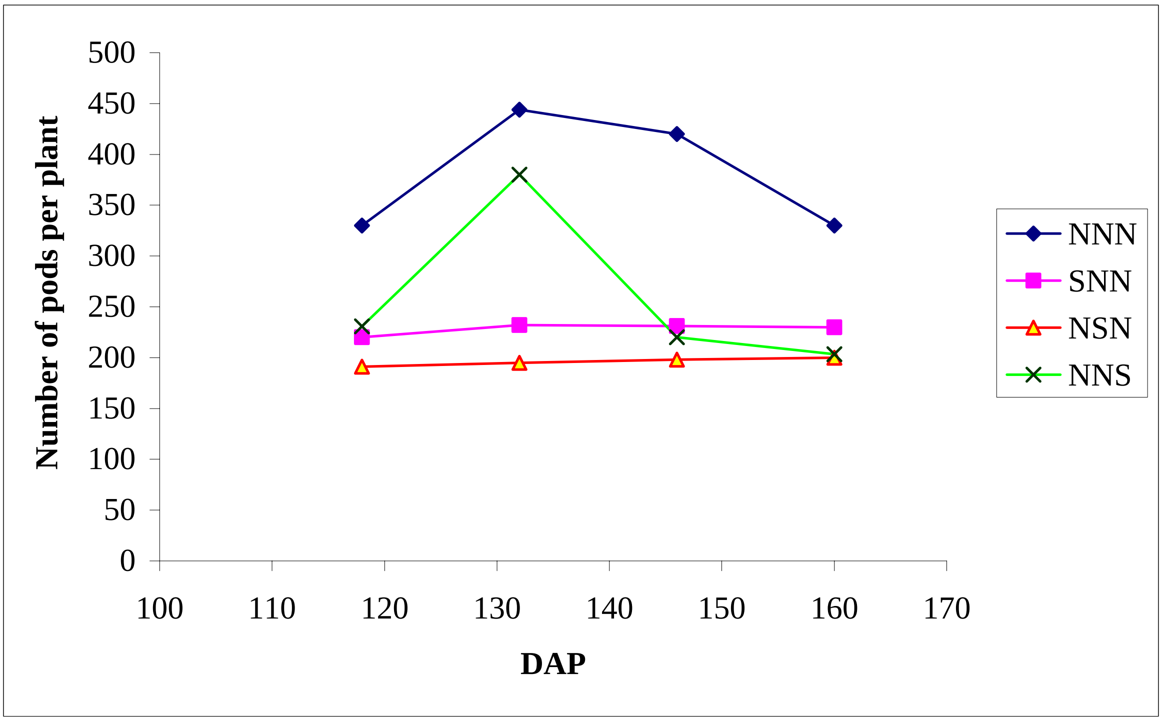

Figure 4.15 Number of pods per plant (Winter 2002)

Figure 4.16 Delayed pod ripening of NSN

Figure 4.17 Timely pod ripening of NNN (Photo taken at the same time as **Figure 4.16)**

The amount of water used (*ET*) was regressed against yield for all treatments applied in both years to see the correlation between the amount of water used (without correction factor) and the corresponding yield harvested (Figure 4.18). In addition to that, vapour pressure deficit corrected water use is regressed against yield in Figure 4.19 to see if the correction factor added (*VPD*) after Tanner and Sinclair (1983) can improve the correlation between water use and yield. The results show that there is very high correlation between the amount of water use and yield. The non-corrected water use versus yield graph shows that water use accounted for 97% of the variation in yield. Where as the corrected water use versus yield showed that 90% of the variation in yield was accounted to water use. This variation in yield due to variation in water use took effect by influencing the leaf area duration as mentioned earlier in section 4.1. The expectation was to get the best correlation between water use and yield from the vapour pressure deficit corrected water use; unfortunately it was not. The graph with correction factor on water use shows that 9.6 kg ha^{-1} is produced for every mm of water after the first 242.8 mm of water used. However, according to the graph without correction factor 6.1 kg ha^{-1} is produced for every mm of water used after the first 242.8 mm of water used.

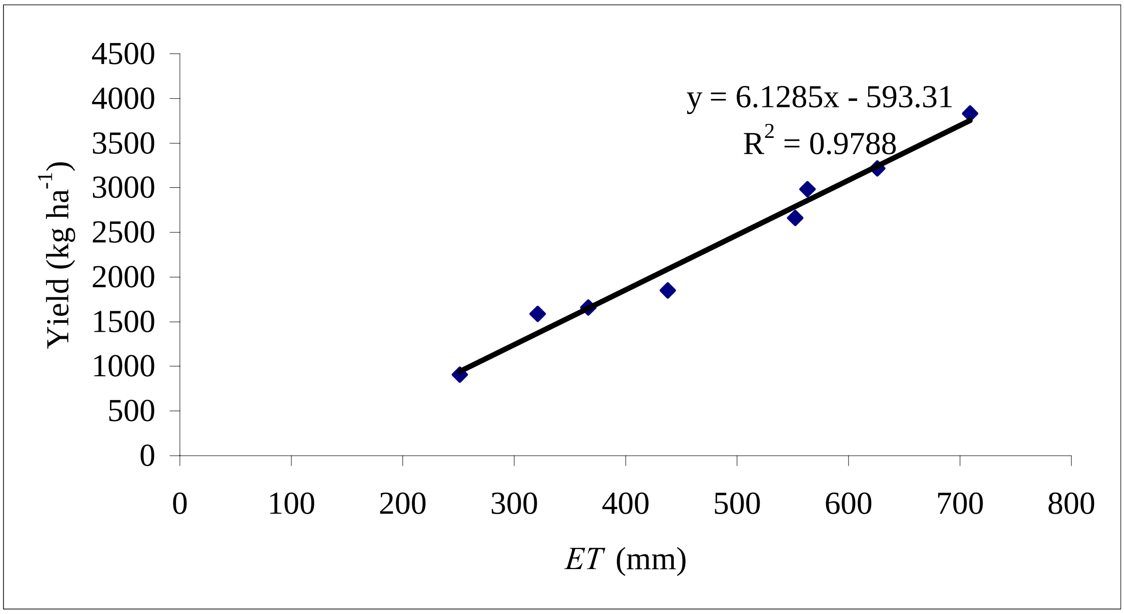

Figure 4.18 Relationship between water use and yield of all treatments in both years

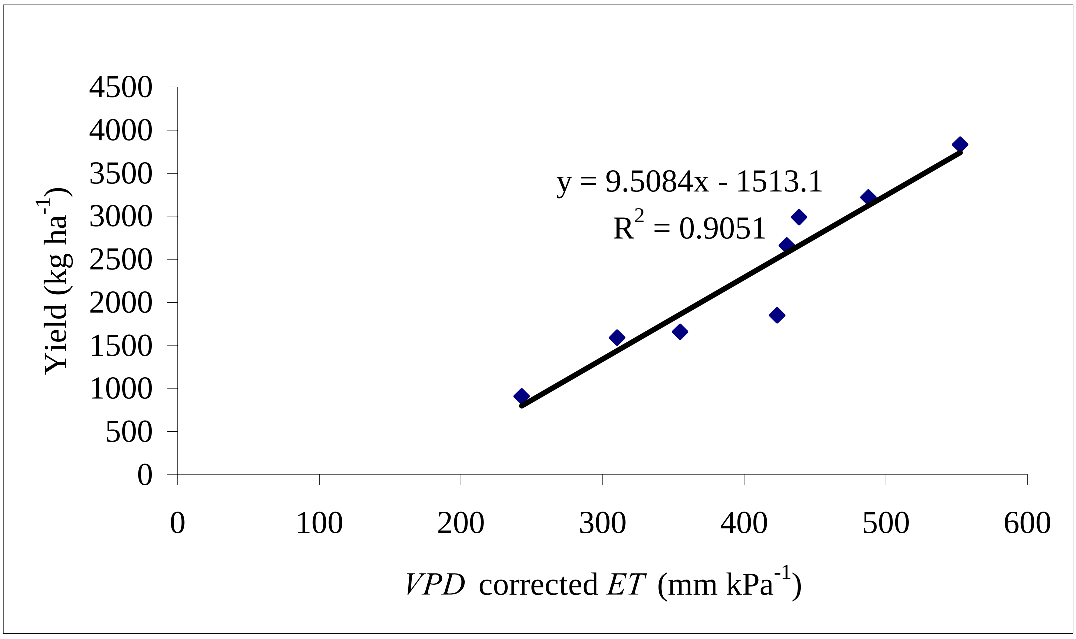

Figure 4.19 Relationship between vapour pressure deficit corrected water use and yield of all treatments in both years

Lowest yield was harvested for the treatment stressed during the flowering stage in both years. In 2002 the lowest seed yield was 908 kg ha^{-1} and the amount of water used to produce this yield was 251 mm. However, in 2003 the lowest yield was 2662.34 kg ha^{-1} and the amount of water used was 552 mm, which is double of the water used in 2002. Highest seed yield was harvested from the non-stressed treatment in both years. The highest seed yield harvested in 2002 was 1850 kg ha^{-1} using 438 mm of water. However, in 2003 it was 3831 kg ha^{-1} using 709 mm of water.

In a general sense, seed yield was low during winter 2002 compared to 2003. It was also low compared to the studies conducted at USDA Central Great Plains Research Station (3416 kg ha^{-1}) (Nielson, 1997). The main reason was suspected to be water stress. Because in 2002 some replications of each treatment were showing stress signs two to three days after irrigation even for the unstressed treatment. However, irrigation was applied every five days based on the soil water deficit to field capacity. The second most likely reason for low yield in 2002 was the application of low nitrogen only once at planting. However, in 2003 nitrogen was applied to the plots twice in the season, once at planting and the other during the flowering stage. According to studies conducted by Dresser *et al.* (2002) canola needs about 50 kg ha^{-1} N during planting and the same amount as top dressing during the flowering stage depending on the fertility status of the soil.

According to studies carried out by Dreccer *et al.* (2000) on the amount and timing of fertilization, the plants which received higher nitrogen (110 kg ha^{-1}), produced the highest grain yield (3350 kg ha^{-1}) compared to those which received low nitrogen 50 kg ha^{-1} and 20 kg ha^{-1}, yielding 1650 and 1020 kg ha^{-1} respectively. With regard to timing, the addition of 50 kg ha^{-1} at the grain filling period for the plants, which already received 20 and 50 kg ha^{-1} at planting, resulted in an increase in grain yield of 510 kg ha^{-1} and 1210 kg ha^{-1} respectively. In other studies conducted by Wright, Smith and Woodroofe (1988) crops receiving 100 kg ha^{-1} N at different stages of growth produced lower yields (2400 kg ha^{-1}), compared to crops receiving 200 kg ha^{-1} N, which produced 3600 kg ha^{-1}.

Similarly Gabriel *et al.*, (1998b) elaborated on the effect of nitrogen fertilizer application timing and amount for Canola (*Brassica napus L.)* as follows: canola has a long growth cycle with large fertilizer requirements, compared to other winter crops such as winter wheat (*Triticum aestivum L.*). This long growth cycle exposes the available N in the soil profile to a greater risk of loss, if applied only at planting. In addition, according to Pechan and Morgan (1985) and Wright *et al.* (1988), pod growth and yield are frequently source limited during seed filling. This problem can be solved to some extent by commencing the seed filling period with a larger leaf area or by maintaining longer leaf area duration. In their conclusion, they mention the possibility of solving the source limitation partially by adding N during the seed filling period.

Statistical analysis was conducted to see if the effect of water stress on the yield of canola was statistically significant (Table 4.2).

Table 4.2 Statistical analysis of seed yield (Winters of 2002 and 2003)

Treatment	Yield (kg ha^{-1}) (2002)	Yield (kg ha^{-1}) (2003)
NNN	1850 a**	3831 a**
SNN	1659 a**	3218 b**
NSN	908 b	2662 c**
NNS	1588 a*	2987 d**
LSD (p=0.05)	520.26	
LSD (p=0.01)	689.71	30.95

* Statistically significant difference at p = 0.05

** Statistically significant difference at p = 0.01

ANOVA summary is displayed in Table A1 and A2 of the Appendix.

Statistical analysis of seed yield in 2002 showed that water stress during the flowering stage resulted in a statistically significant (p = 0.01) yield loss, compared to the treatments with no stress and stress during the vegetative stage. It also showed a statistically significant (p = 0.05) yield loss, compared to the treatment with stress during the grain filling stage. However, there was no statistically significant difference between the treatments with no stress, stress during the vegetative stage and stress during the grain filling stage. Statistical analysis shown in Appendix A1 also shows us that there was no significant difference between blocks.

Similarly statistical analysis of seed yield in 2003 showed that water stress during the flowering stage resulted in a statistically significant ($p = 0.01$) yield loss, compared to all the other treatments. It showed also water stress during the grain filling stage resulted in a statistically significant ($p = 0.01$) yield loss, compared to the non-stressed treatment and the treatment stressed during the vegetative stage. Stress during the vegetative stage also resulted in a statistically significant ($p = 0.01$) yield loss, compared to the non-stressed treatment.

4.5 Oil content

Canola oil content for the different water stress treatments ranged from 308 kg ha^{-1} (33.92%) for NSN to 675 kg ha^{-1} (36.47%) for NNN in 2002. However, the range was higher for 2003. It varied from 989.99 kg ha^{-1} (36.61%) for NSN to 1523.59 kg ha^{-1} (39.77%) for NNN (Figure 4.20).

The trend of decline in oil content for the different water stress treatments was similar to that of the yield in both years. The highest percentage oil was extracted from the treatment without water stress, followed by the treatment stressed during the vegetative, grain filling and flowering stages respectively in both years. This study showed that oil content increases with increase in the availability of soil water to the crop to satisfy the atmospheric demand. The effect of soil water deficit on canola seed oil content was explained very well by Manitoba Agriculture, Food and Rural initiatives (1999). According to them, greater soil water availability results in higher yields at comparable N supply levels. In addition they explained that in oil seed crops, oil content decreases with an increase in the protein content due to an increase in the level of nitrogen or as a result of low soil water supply.

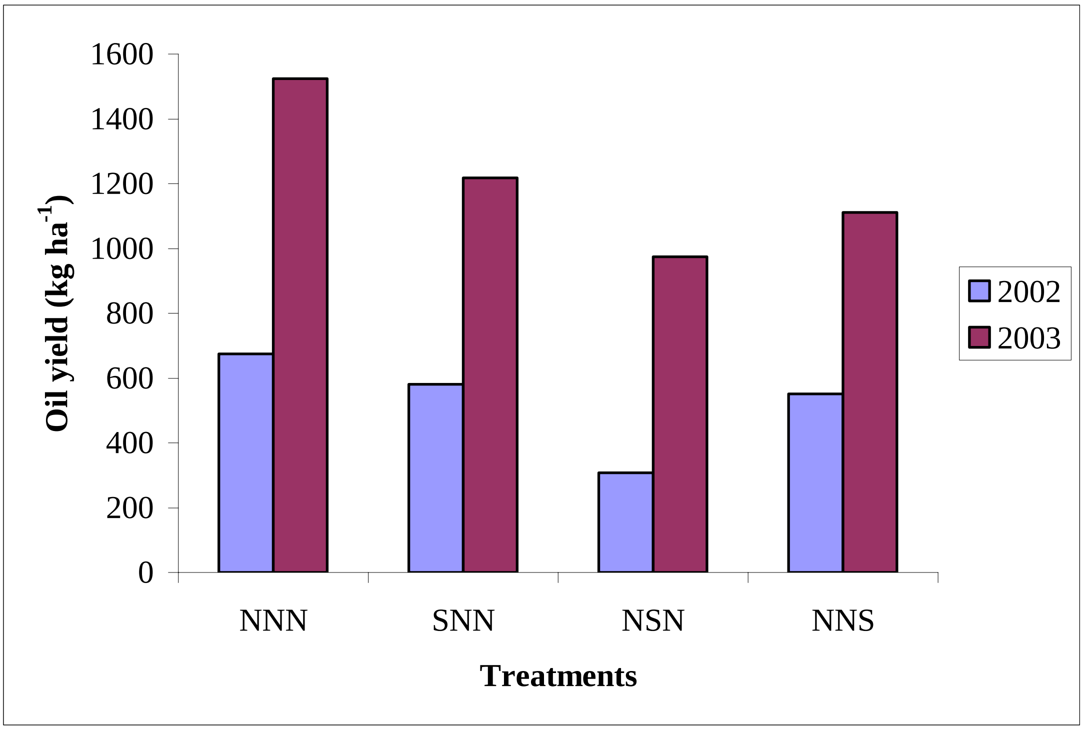

Figure 4.20 Average oil content of seed (Winters of 2002 and 2003)

The average percentage oil obtained in both years is lower than Nielsen (1997) found in his studies for different irrigation treatments ranging from 37% for lower irrigation to 44% for higher irrigation levels. However, the percentage oil for 2003 was similar to the values achieved by Francois (1994) for Westar (40%) and the yield for 2002 was similar to what was obtained by Al-jaloud, Hussian, Karimulla and Al-hamidi (1996) in Saudi Arabia. Their oil yield ranged from 30.9% to 36.1% under different irrigation treatments. According to them this result agrees well with the results of Krogman and Hobbs (1975) who obtained oil contents ranging from 35.8% to 37.2% under different fertiliser application treatments. Finally, they concluded the main reason for the decline in oil content to be the difference in the climatic conditions between the experimental sites, seed type, amount of irrigation applied and quantity of fertiliser applied. This was proved by studies conducted in the USA where similar cultivars with the same treatments grown at different places gave different oil contents (Shafii, Mahler, Price and Auld, 1992).

4.6 Water use and water use efficiency

The water use of canola ranged from as low as 238 mm (2002), and 552 mm (2003) for the treatment stressed during the flowering stage to as high as 438 mm (2002) and 709 mm (2003) for the unstressed treatment (Table 4.3). The main reason for the low water use during 2002 was because of the water use underestimation due to short neutron access usage.

Table 4.3 Water use and water use efficiency (winters of 2002 and 2003)

Treatment	**Water use (mm)**		**Water use efficiency (kg ha^{-1} mm^{-1})**	
	2002	**2003**	**2002**	**2003**
NNN	438	709	4.23	5.4
SNN	367	626	4.52	5.14
NSN	251	552	3.62	4.82
NNS	321	563	4.95	5.3

Highest water use was observed for the treatment without water stress in both years. The well-developed larger leaf area, which was maintained throughout the growing season, was the cause for this highest water use. In both years lowest water use was observed for the treatment with stress during the flowering stage. This was because of the senescence of the leaves due to water stress during the critical time. Stressing the crop during the vegetative stage saved 71 mm (710 m^3 ha^{-1} of land) during 2002 and 86 mm (860 m^3 ha^{-1} of land) of water during 2003 at the expense of 191 kg and 613 kg per hectare seed yield respectively.

On the other hand highest water use efficiency was observed for the treatment with stress during the grain filling stage during 2002 and for the unstressed treatment during 2003. The treatment stressed during the grain filling stage saved 117 and 46 mm of water compared to NNN and SNN at the expense of 262 kg and 71 kg seed yield respectively during 2002. However, the seed yield loss for that year was not statistically significant. Similarly during 2003 it saved 146 and 63 mm of water compared to NNN and SNN at the expense of 844 and 231 kg yield respectively. However, during this year the yield loss was statistically significant. Therefore in areas with water scarcity problems either this strategy of stressing the crop during the grain filling stage or stressing the crop during the vegetative stage could be followed to make best use of the available water. However, in areas with sufficient water supply it would be advisable to follow the strategy of irrigating the crop throughout the season to get the highest seed yield and percentage oil with better water use efficiencies.

4.7 Model calibration

Field data collected during the 2002 growing season was used to determine specific crop parameters of canola so as to calibrate the SWB model. Parameters like specific leaf area, leaf stem partitioning factor, thermal time requirements, maximum root depth, maximum crop height, top dry matter and harvestable dry matter were determined from field data. The remaining parameters were obtained from literature. These specific crop parameters are shown in Table 4.4.

The data was used to calibrate the model. Outputs of the SWB model simulation (lines) and measured data (symbols) are displayed in Figure 4.23 for irrigation treatment NNN, Figure 4.24 for SNN, Figure 4.25 for NSN and Figure 4.26 for NNS. Comparison of simulated to measured root depth values are shown on top left, and comparison of simulated to measured leaf area index (LAI) are shown on top right of each figure for each treatment. Comparison of simulated top and harvestable dry matter to measured values are shown on the bottom left and comparison of simulated water deficit from field capacity to measured values using a neutron water meter are shown on bottom right for each treatment in its corresponding figure.

The accuracy of SWB model simulations is assessed based on the five validation statistics proposed by De Jager (1994). These statistical parameters with their reliability criteria are displayed together in Table 4.5.

Table 4.4 Crop parameters of canola determined from 2002 field data and literature to calibrate the SWB model

Parameter		Values	Unit
Canopy extinction coefficient for solar radiation	*	0.6	-
VPD corrected Dry matter: water ratio		6.17	Pa
Radiation use efficiency	**	0.0024	kg MJ^{-1}
Base temperature	***	5	^oC
Optimum temperature	****	25	^oC
Maximum temperature	****	30	^oC
Thermal time: emergence (from planting)		77	d ^oC
Thermal time: reproductive phase (from planting)		997	d ^oC
Thermal time: maturity (from planting)		1742	d ^oC
Thermal time: transition		200	d ^oC
Thermal time: leaf senescence		900	d ^oC
Leaf water potential at maximum transpiration rate		-850	kPa
Maximum transpiration rate		7	mm day^{-1}
Specific leaf area		22.77	m^2 kg^{-1}
Leaf stem partitioning factor		1.8	m^2 kg^{-1}
Total dry matter at emergence		0.0005304	kg m^{-2}
Root fraction	*****	0.2	-
Stem translocation		0.05	-
Root growth rate	*****	3.8	m^2 $kg^{-0.5}$
Maximum canopy height		2.0	m
Stress index		0.8	

*	Gabriel *et al.* (1998b); Mendham *et al.* (1981)
**	Morison *et al.* (1995); Anderson *et al* (1996)
***	Thomas, 2001d; Gabrielle *et al.* (1997)
****	Virgil *et al*. 1997
*****	estimated

Table 4.5 Model evaluation parameters with their criteria (after De Jager, 1994)

Statistical parameter abbreviation	Extended meaning of abbreviation	Reliability criteria
N	Number of measured values	-
r^2	Coefficient of determination	> 0.8
D	Willmot (1982) index of agreement	> 0.8
RMSE	Root mean square error	-
MAE (%)	Mean absolute error expressed as a percentage of the mean of the measured values	< 20

Simulation generally agrees well with measured data for all treatments in 2002. Vertical bars are ±1 standard error of the measurement. Root growth was simulated to an acceptable level of accuracy for all the treatments until it reaches 1 m as all the parameters were within the accuracy limits listed in Table 4.5. Leaf area index was also simulated to an acceptable level of accuracy for all the treatments. However, it was underestimated for NSN during the flowering stage. Top dry matter was simulated to an acceptable level of accuracy for all treatments except NSN. Nevertheless, water deficit was overestimated for all treatments and this could be observed from statistical parameters, which showed a poor coefficient of determination for treatments NNN, SNN and NSN, poor Willmott's (1982) index of agreement for treatments NNN and NSN as well as a high mean absolute error (MAE) for all the treatments.

The model overestimated simulation of water deficit from the beginning of the flowering stage. According to neutron probe readings, roots grew to 1 m during the beginning of the flowering stage, which is 76 days after planting. Similarly the deficit increased over time in the lower 1 m layer (Figure 4.21), implying that the deficit extended below that layer through root extension, which coincides with the trial, conducted during winter 2003 (Figure 4.22) in the same place. Similarly studies conducted by Gabrielle, Justes and Denoroy [S.a][1] showed, roots extending to a 1m depth after around 80 days from planting and finally growing to a depth of 1.5 m at harvest.

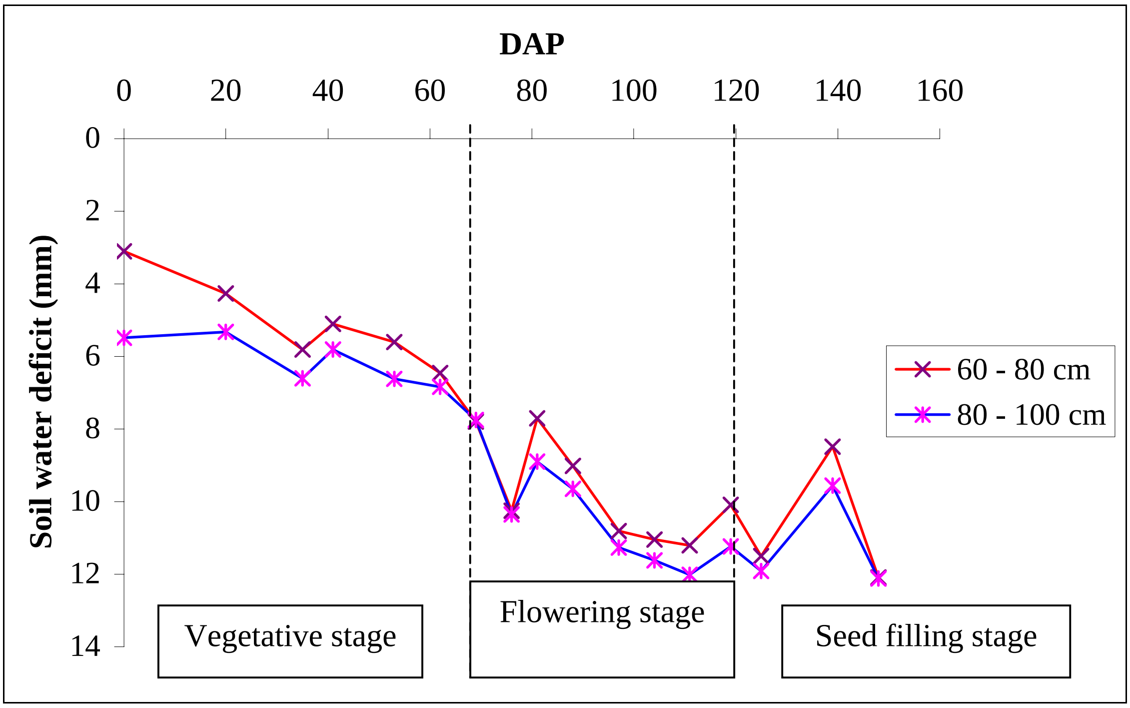

Figure 4. 21 Soil water deficit for the layers 60 – 100 cm (Winter 2002)

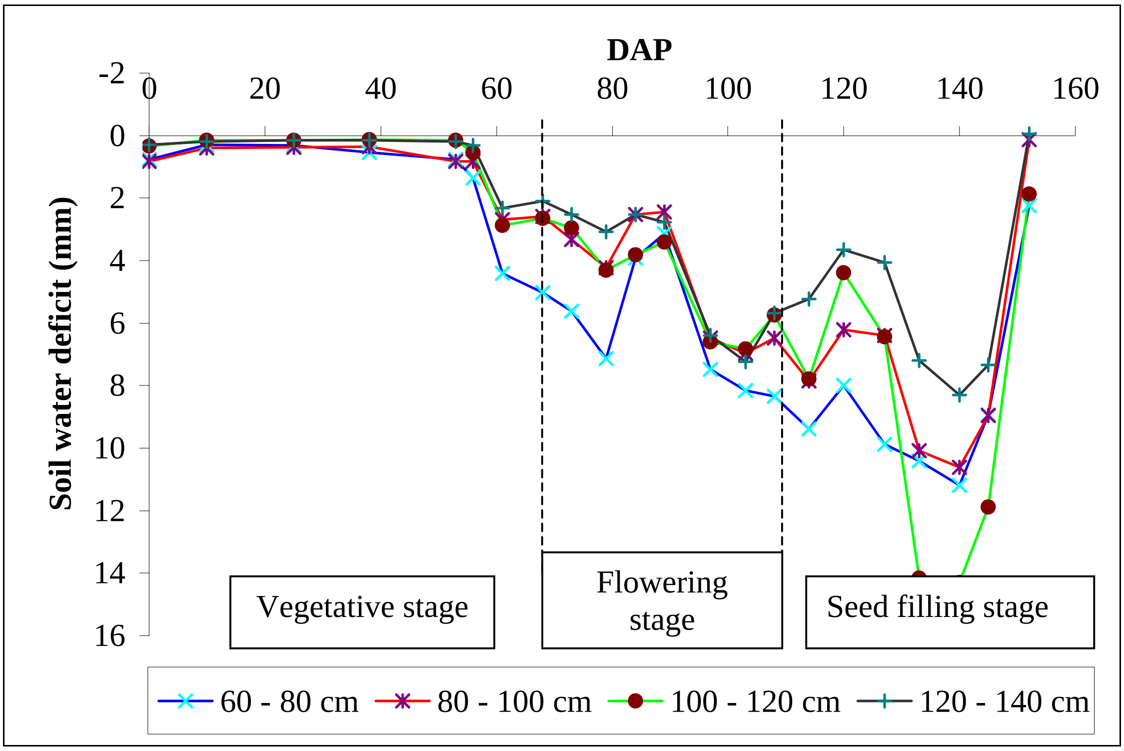

Figure 4. 22 Soil water deficit for the layers 60 – 140 cm (Winter 2003)

In this study 1 m depth access tubes were used to collect soil water content readings using a neutron water meter. As a result, the stress and at the same time the availability of soil water below 1 m depth was not taken into account. Consequently, the irrigation requirement of the unstressed treatment was probably underestimated due to an underestimation of field capacity for the whole root zone layer. This is because irrigation requirement is calculated as the difference between the field capacity of the root zone and the current water content. However, the model simulates water deficit based on the maximum root and soil profile depth entered.

Soil water deficit values were lower for measured than simulated. On the contrary, measured *LAI* and *TDM* was either equivalent to or slightly higher than that simulated for all treatments. This implies that the treatments were therefore probably receiving relatively more water than what they are able to get within the 1 m maximum root depth entered to the model. This enabled them to develop the measured leaf area index as well as top dry matter. Some replications of the treatments didn’t show any visual symptoms of water stress, whereas, some showed signs of stress during the flowering stages of the treatments NNN, SNN and NNS. It was therefore likely that roots grew below 1 m, starting from the beginning of the flowering stage, and as a result some water was extracted deeper than 1 m. This would be accompanied by the reduction of measured cumulative deficit within the top 1 m compared to that simulated, as the model considered soil water deficit within the top 1 m layer only. The growth of the roots deeper than 1m may be due to the reason given by Steyn (1997), who reports that the presence of water stress results in preferential assimilate partitioning to the roots at the expense of leaf growth. Therefore the actual water deficit in the root zone was supposed to be the sum of the deficit in the whole profile where there is active root growth and water extraction. As a result, the simulation was updated using measured values once during the flowering stage to improve the simulation from there on.

The wide error bars on each water deficit graph are an indication of very large spatial variation between replications. Each treatment used one main irrigation pipeline, so each replication of a treatment shared the same line. As a result, the amount of water applied was the average requirement of the replications. This resulted in the build up of a greater deficit in some of the replications, which had higher water requirements.

On the other hand, providing more water to those, which had lower demand, would have resulted in some percolation below 1 m. This water was most likely extracted by roots below 1 m, resulting in a higher than predicted *LAI* and *TDM.* Despite all this, the general trend of the measured deficit compares well to that simulated.

The underestimation of leaf area index during the flowering stage of the treatment NSN is primarily attributed to the over estimation of the soil water deficit. This could be explained as follows: according to Eq. 2.65, the lowering of soil matric potential (Ψ_m) due to soil water deficit overestimation, resulted in the reduction of the amount transpired. Consequently, the total dry matter production was reduced based on Eq. 2.24. This reduction of total dry matter was followed by the reduction of *LAI* based on Eq. 2.42 due to reduction in *LDM*. Low *LAI* means little radiation interception and less transpiration, which again contributed, to less total dry matter production. However, the measured value was higher than the simulated because as explained previously, the plant had most probably developed roots beyond 1 m. Consequently, the crop was most likely getting extra water to transpire more and produce a relatively higher *TDM* and therefore develop a larger *LAI* compared to that simulated.

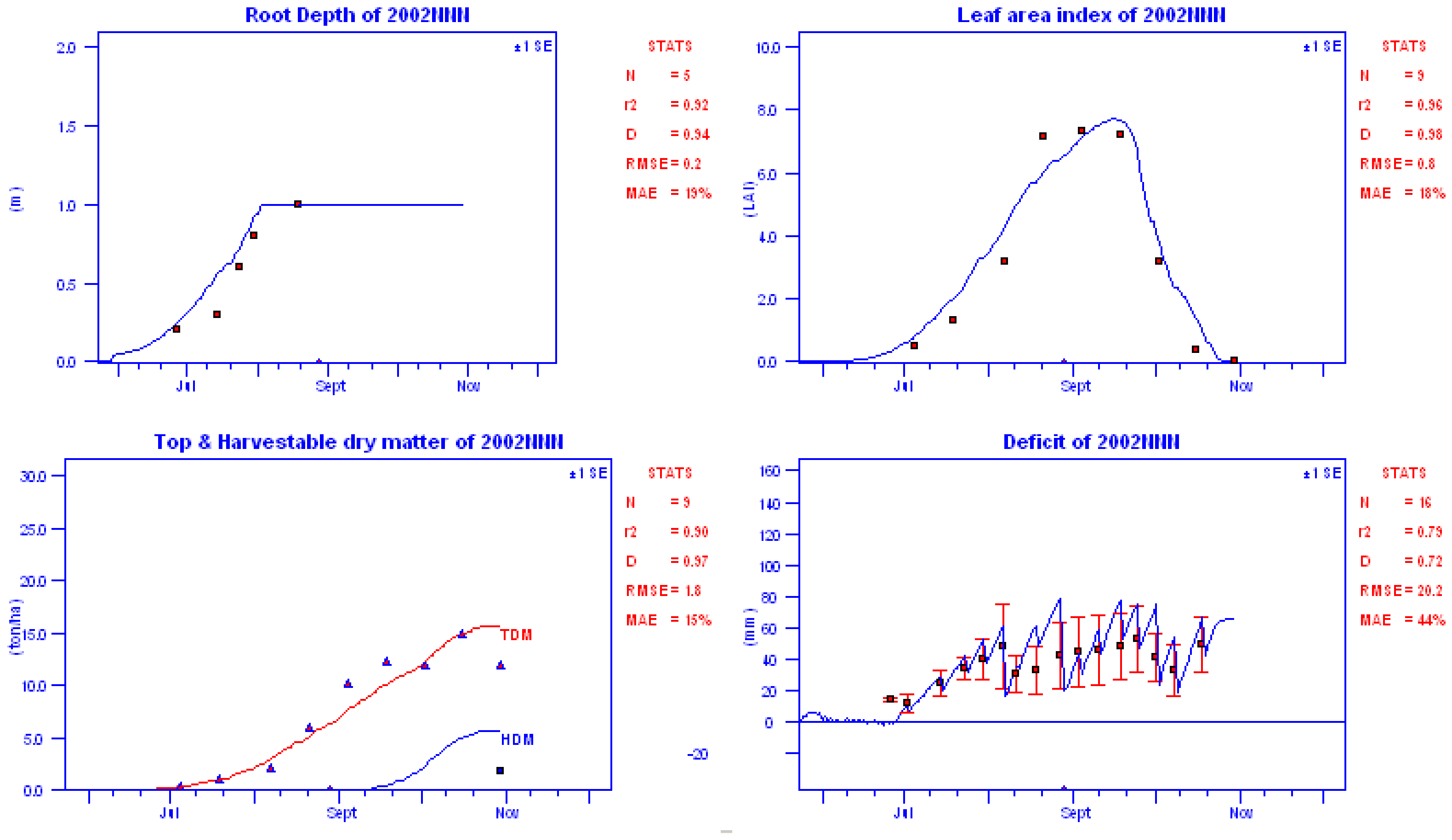

Figure 4.23 Simulated (solid lines) and measured values (points) of leaf area index (*LAI*), top dry matter (*TDM*) and harvestable dry matter (*HDM*), as well as deficit to field capacity (Winter 2002, treatment NNN).

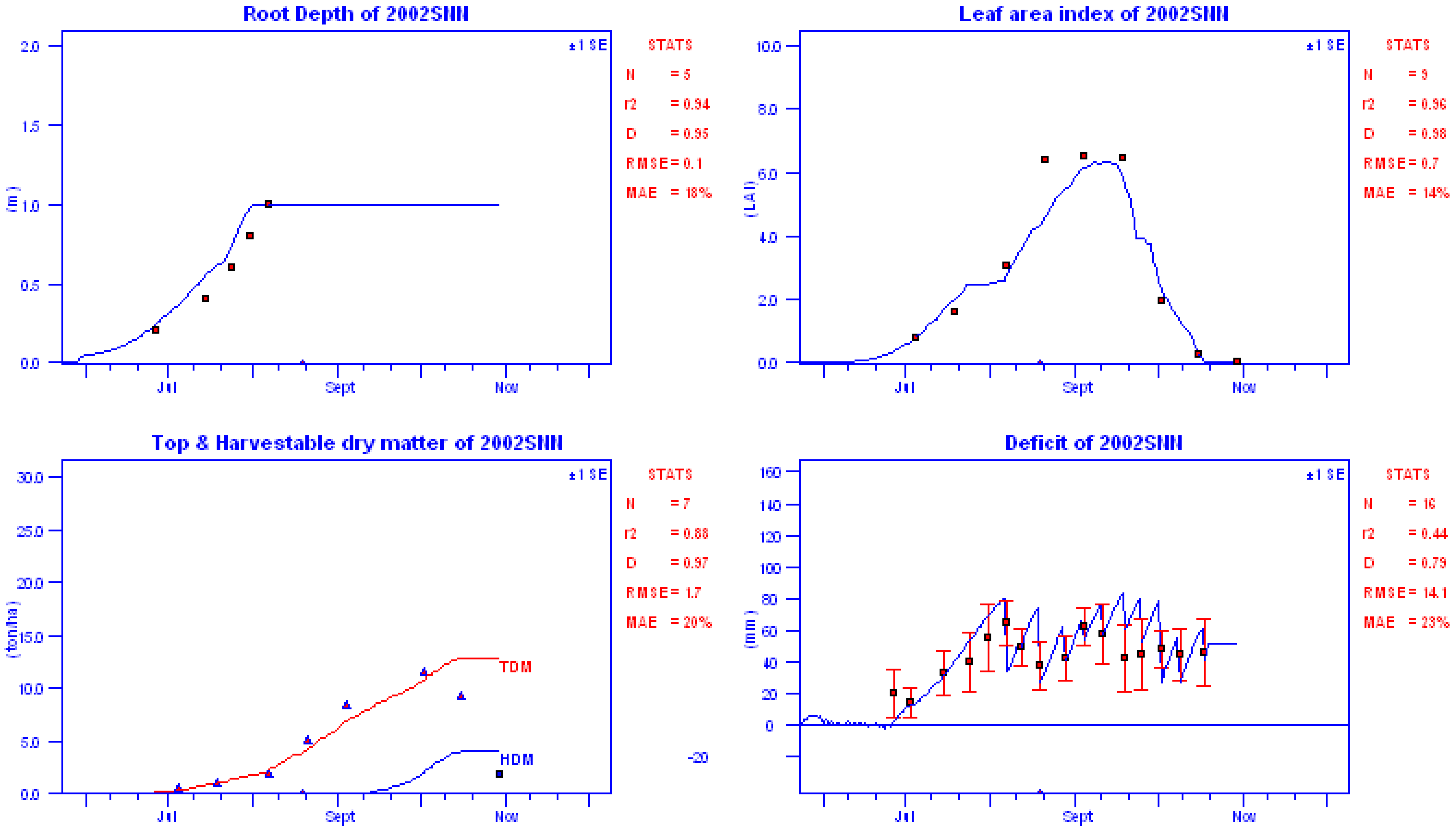

Figure 4.24 Simulated (solid lines) and measured values (points) of leaf area index (*LAI*), top dry matter (*TDM*) and harvestable dry matter (*HDM*), as well as deficit to field capacity (Winter 2002, treatment SNN).

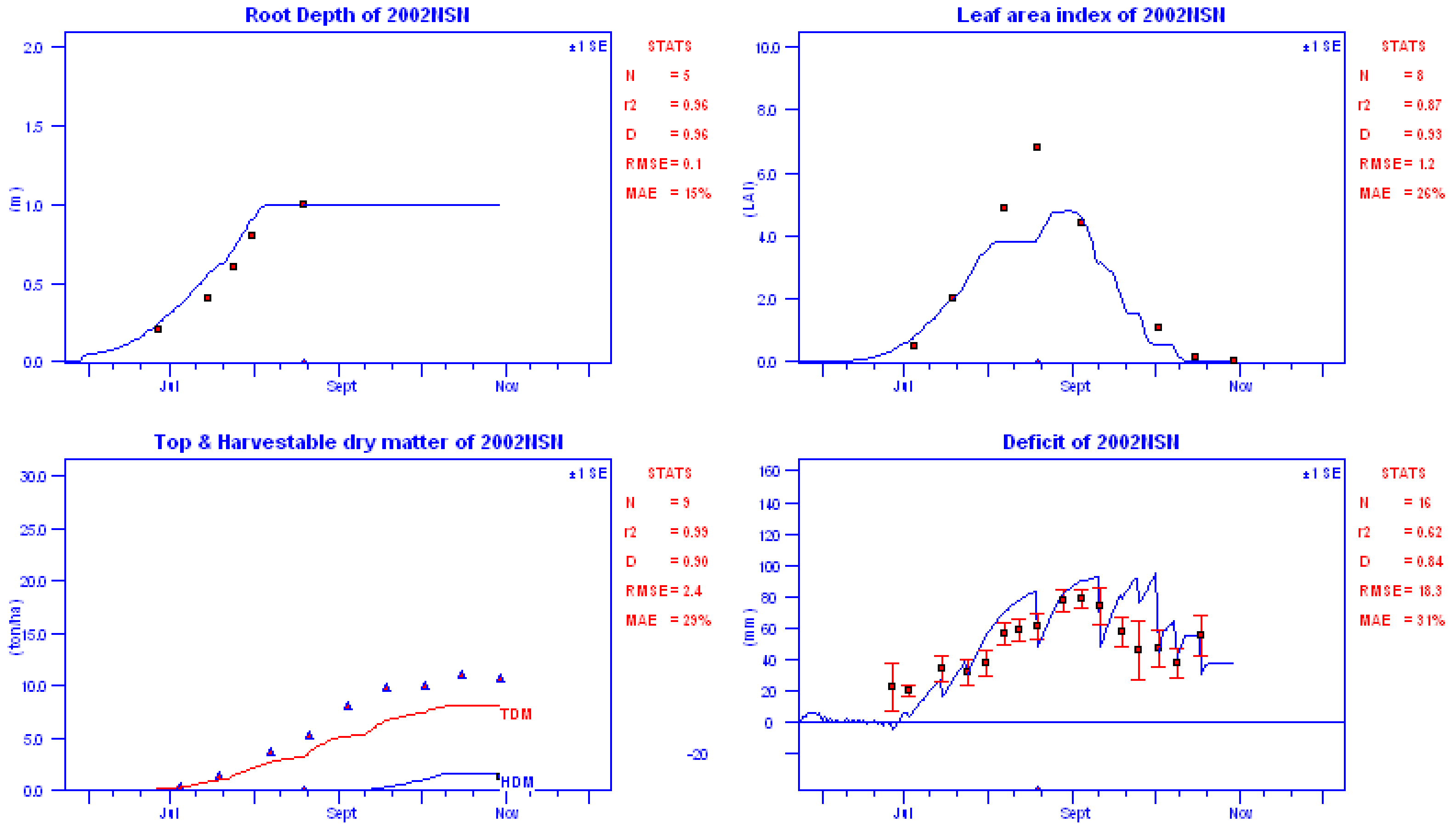

Figure 4.25 Simulated (solid lines) and measured values (points) of leaf area index (*LAI*), top dry matter (*TDM*) and harvestable dry matter (*HDM*), as well as deficit to field capacity (Winter 2002, treatment NSN).

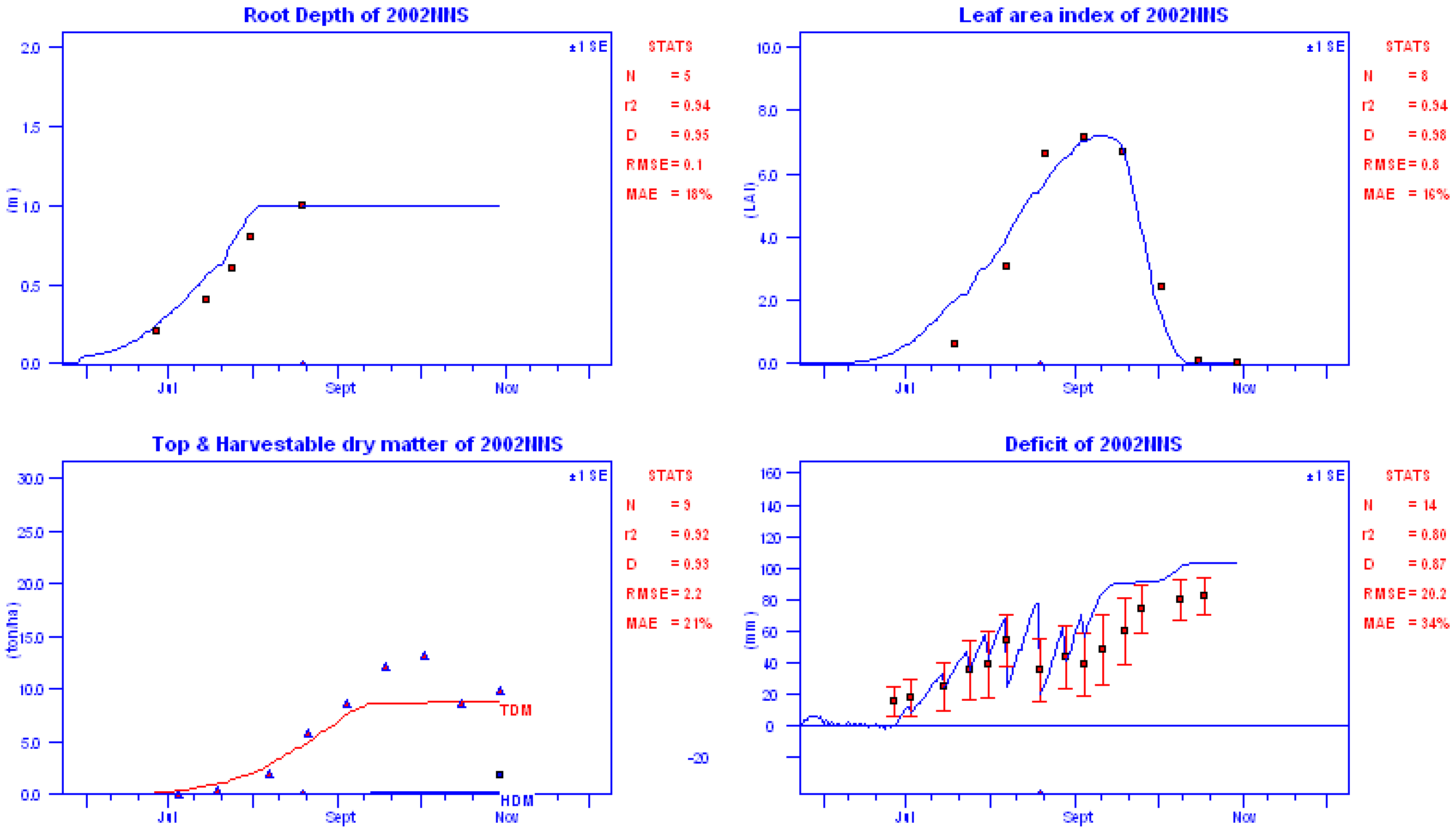

Figure 4.26 Simulated (solid lines) and measured values (points) of leaf area index (*LAI*), top dry matter (*TDM*) and harvestable dry matter (*HDM*), as well as deficit to field capacity (Winter 2002, treatment NNS).

4.8 Model validation

Model evaluation was conducted during winter 2003 on independent data sets of root growth, leaf area index, total dry matter, soil water deficit, crop height, grain yield and fractional interception. The evaluation was conducted on four irrigation treatments similar to 2002, namely a non stressed treatment (NNN), one stressed in the vegetative growth stage (SNN), another stressed in the flowering stage (NSN) and one stressed during the grain filling stage (NNS). Simulation output with corresponding measured values for winter 2003 are displayed in Figures 4.27 to 4.34.

Generally evaluation of the model against independent data sets proved to be very successful. Soil water deficit was simulated very well for all the treatments, as all the statistical parameters lie within the accuracy limits prescribed by De Jager (1994). Fractional interception of solar radiation was also simulated to a high degree of accuracy for all treatments. In addition, root growth and leaf area index were simulated to an acceptable degree of accuracy for all the treatments. Although leaf area index was overestimated for all treatments until the flowering stage, it tended to agree well later on in the season. Measured top dry matter for all treatments was lower than that simulated at the beginning of the vegetative stage, but recovered later towards the beginning of the flowering stage, and then came very close to simulated values.

The possible reason for the underestimation of leaf area index and top dry matter during the vegetative stage in 2003 was due to climatic change. This might probably be the relatively higher temperature observed during that year than 2002. The relatively small canola leaf and canopy size growth observed in 2003 was common in many parts of South Africa. The crop was observed in many places flowering while it is still short. The mean and median average daily temperatures were relatively higher for 2003 compared to 2002. Mean and median daily average temperatures during the vegetative growth stage of canola for 2002 was 11.99 and 11.78 ^{o}C respectively. However, it was 12.6 and 12.5 ^{o}C for 2003. In addition, comparison of thermal time and field observations showed that canola flowering initiation took place two days earlier in year 2003 compared to year 2002. The relatively higher temperatures observed during the vegetative stage of 2003 might have resulted in the reduction of leaf area index and top dry matter. This has been well explained by Thomas (2001d). According to him, canola is in favour of relatively cool temperatures for strong vegetative growth between emergence and flowering. Photoperiod might have also contributed to this insignificant variation between the measured and simulated *LAI* and *CDM* because the SWB model doesn't simulate the effect of photoperiod in the growth of plants. Top dry matter and leaf area index increased rapidly after the flowering stage during 2003.

Thermal time requirements computed during 2003 compared to 2002, and field observations do not show the necessity of developing other values to be used for different planting situations. Nevertheless, a general conclusion cannot be reached using two years of data only. As a result further investigation is required to come to a general conclusion.

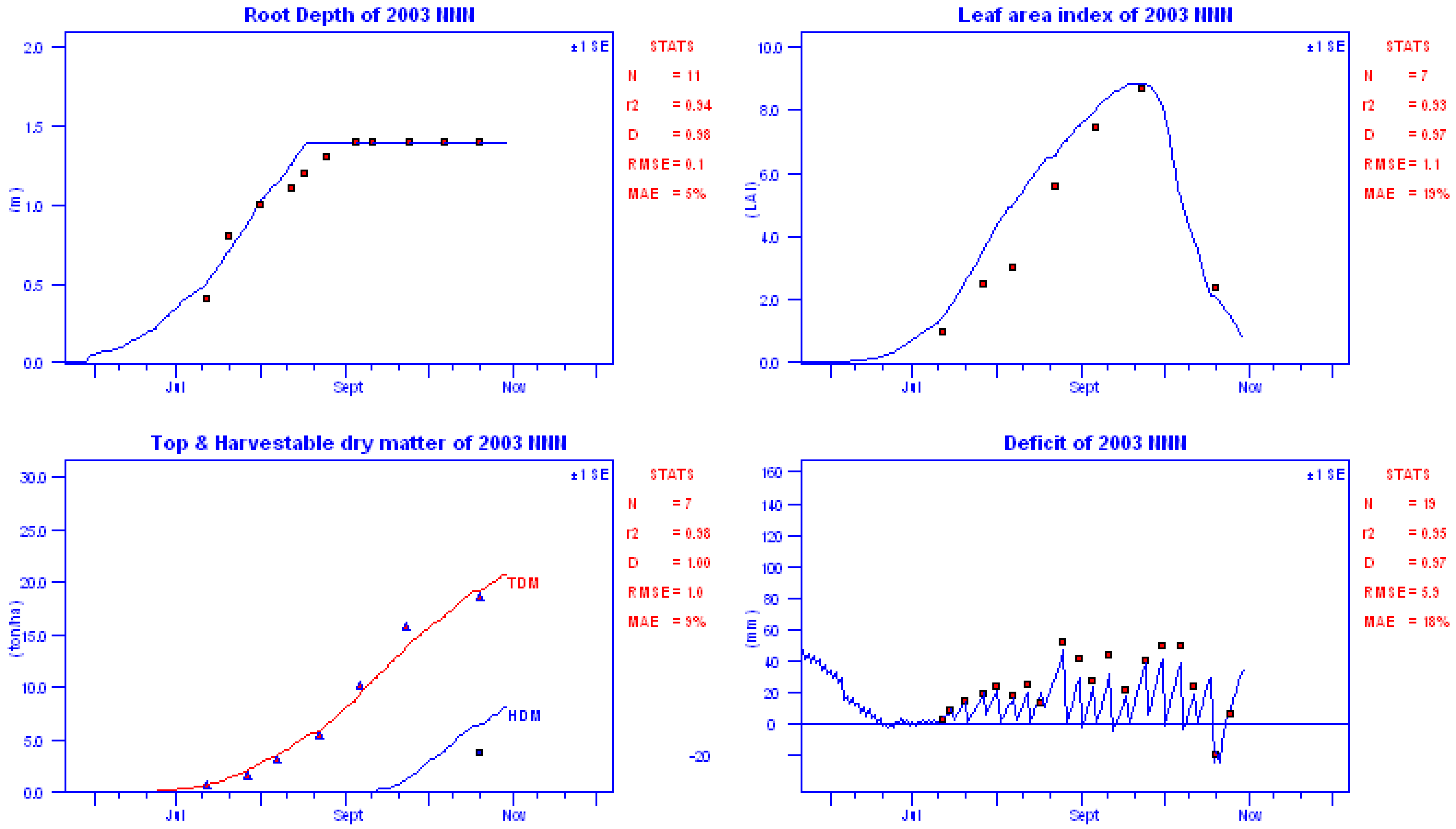

Figure 4.27 Simulated (solid lines) and measured values (points) of leaf area index (*LAI*), top dry matter (*TDM*) and harvestable dry matter (*HDM*), as well as deficit to field capacity (Winter 2003, treatment NNN).

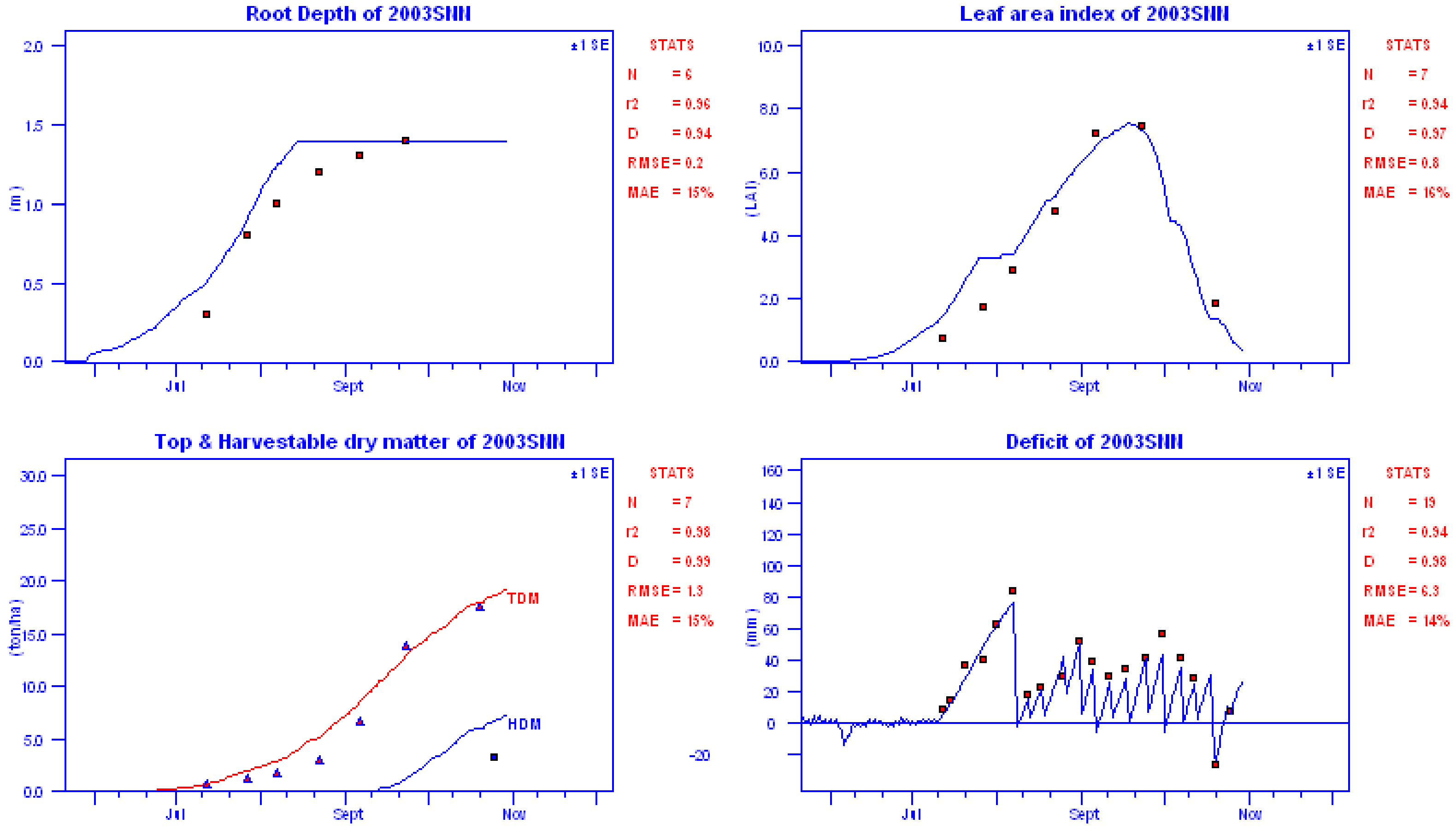

Figure 4.28 Simulated (solid lines) and measured values (points) of leaf area index (*LAI*), top dry matter (*TDM*) and harvestable dry matter (*HDM*), as well as deficit to field capacity (winter 2003, treatment SNN).

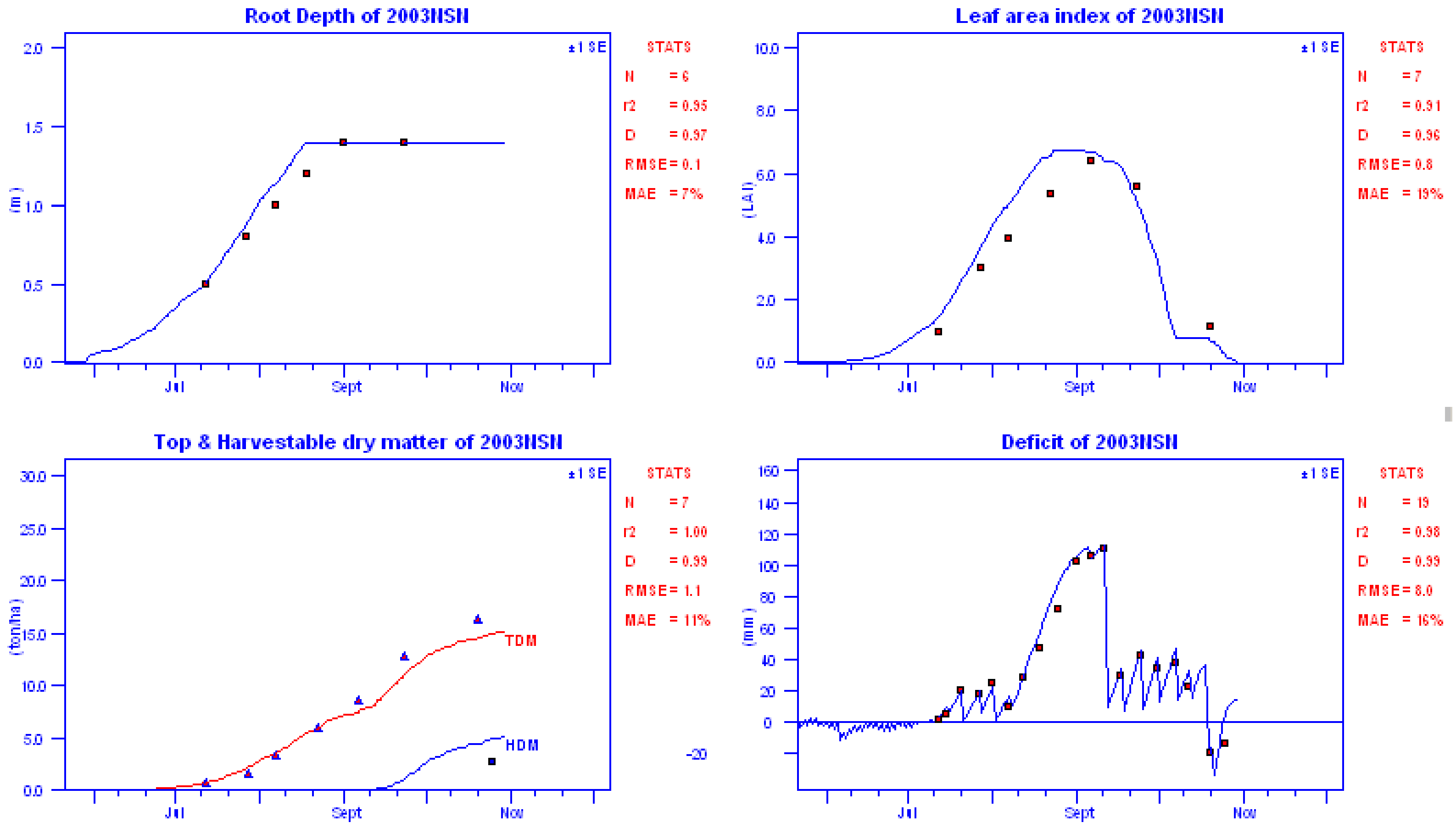

Figure 4.29 Simulated (solid lines) and measured values (points) of leaf area index (*LAI*), top dry matter (*TDM*) and harvestable dry matter (*HDM*), as well as deficit to field capacity (Winter 2003, treatment NSN).

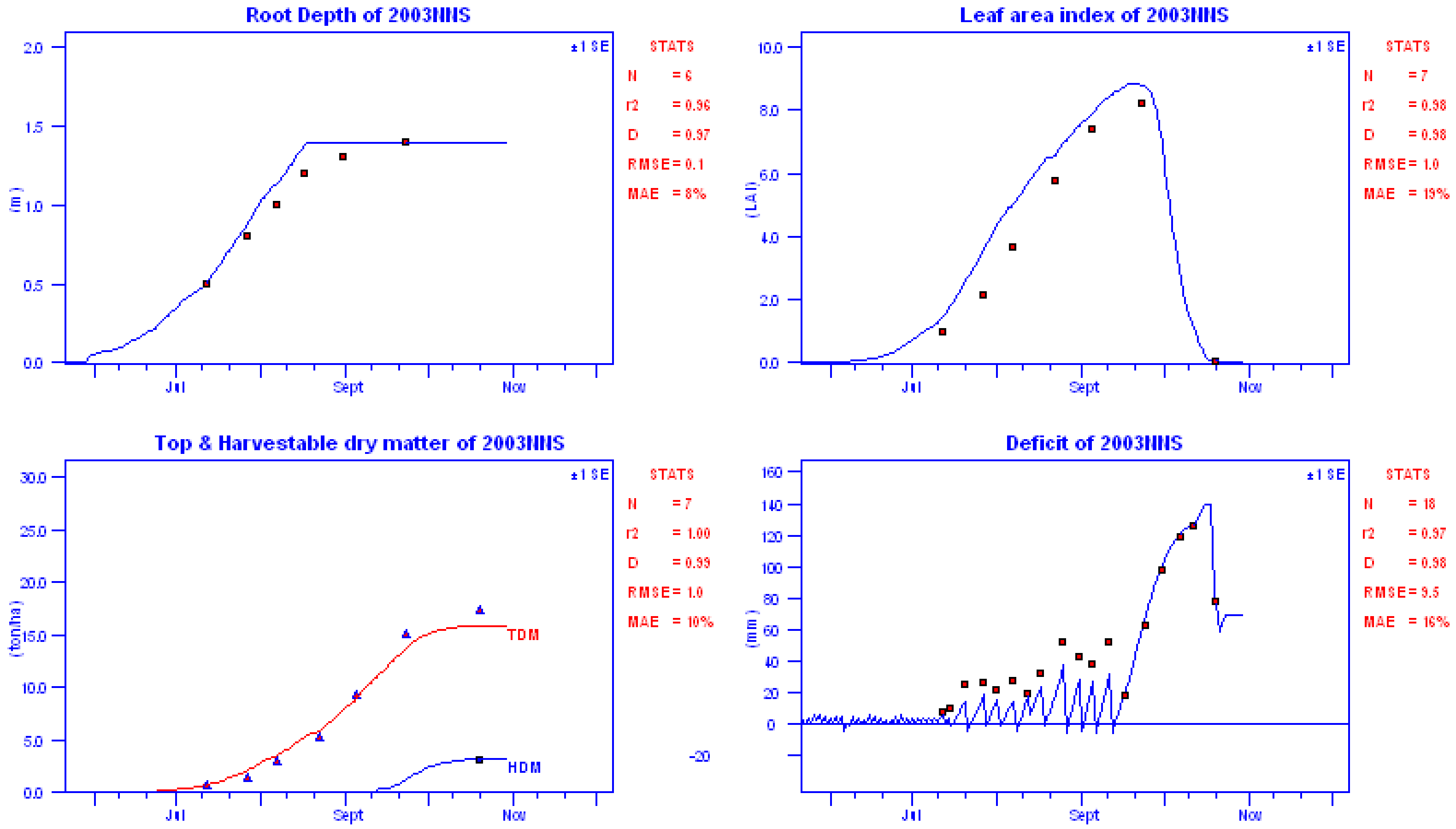

Figure 4.30 Simulated (solid lines) and measured values (points) of leaf area index (*LAI*), top dry matter (*TDM*) and harvestable dry matter (*HDM*), as well as deficit to field capacity (winter 2003, treatment NNS).

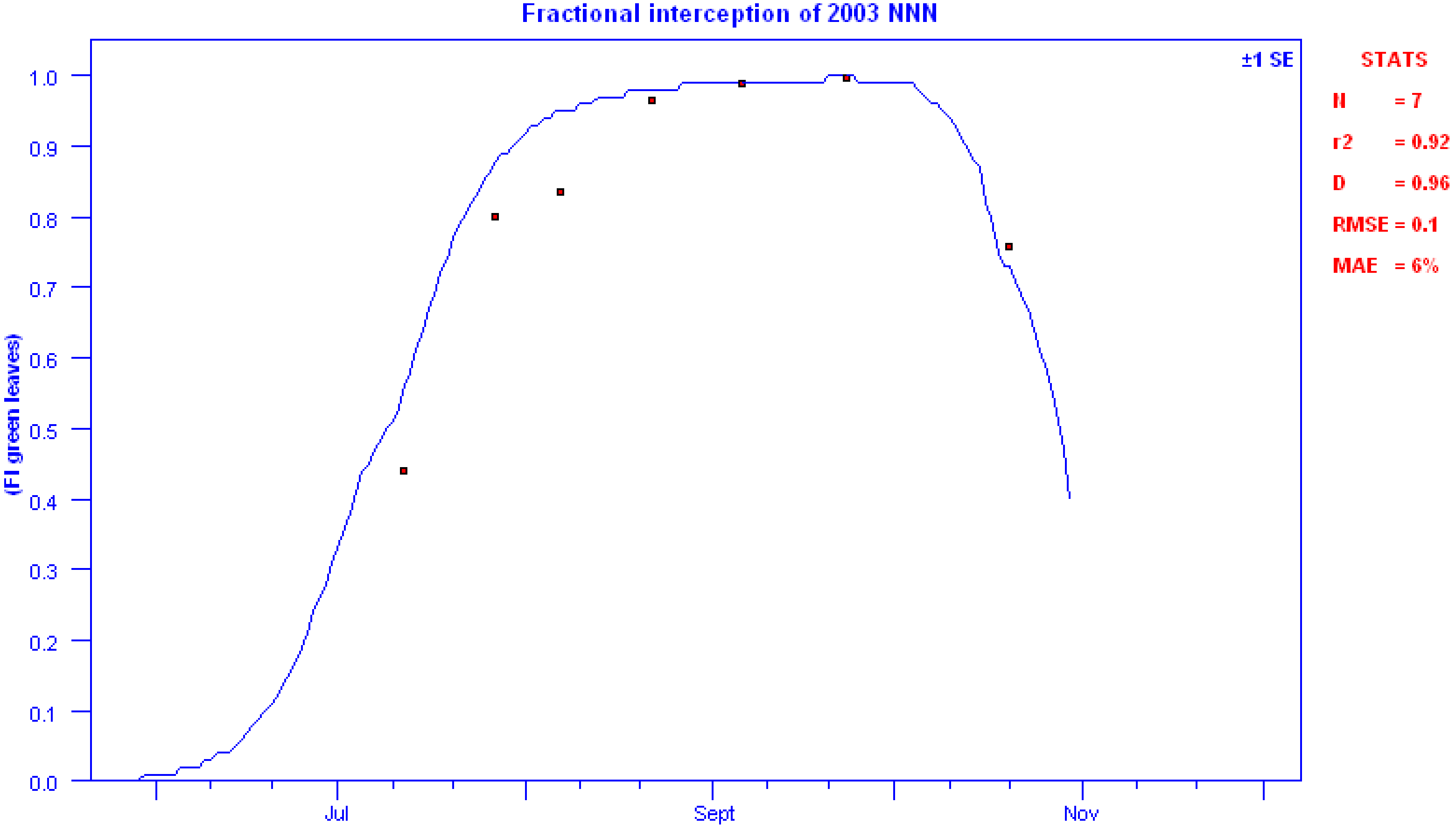

Figure 4.31 Simulated (solid lines) and measured values (points) of fractional interception for independent data set (Winter 2003, treatment NNN)

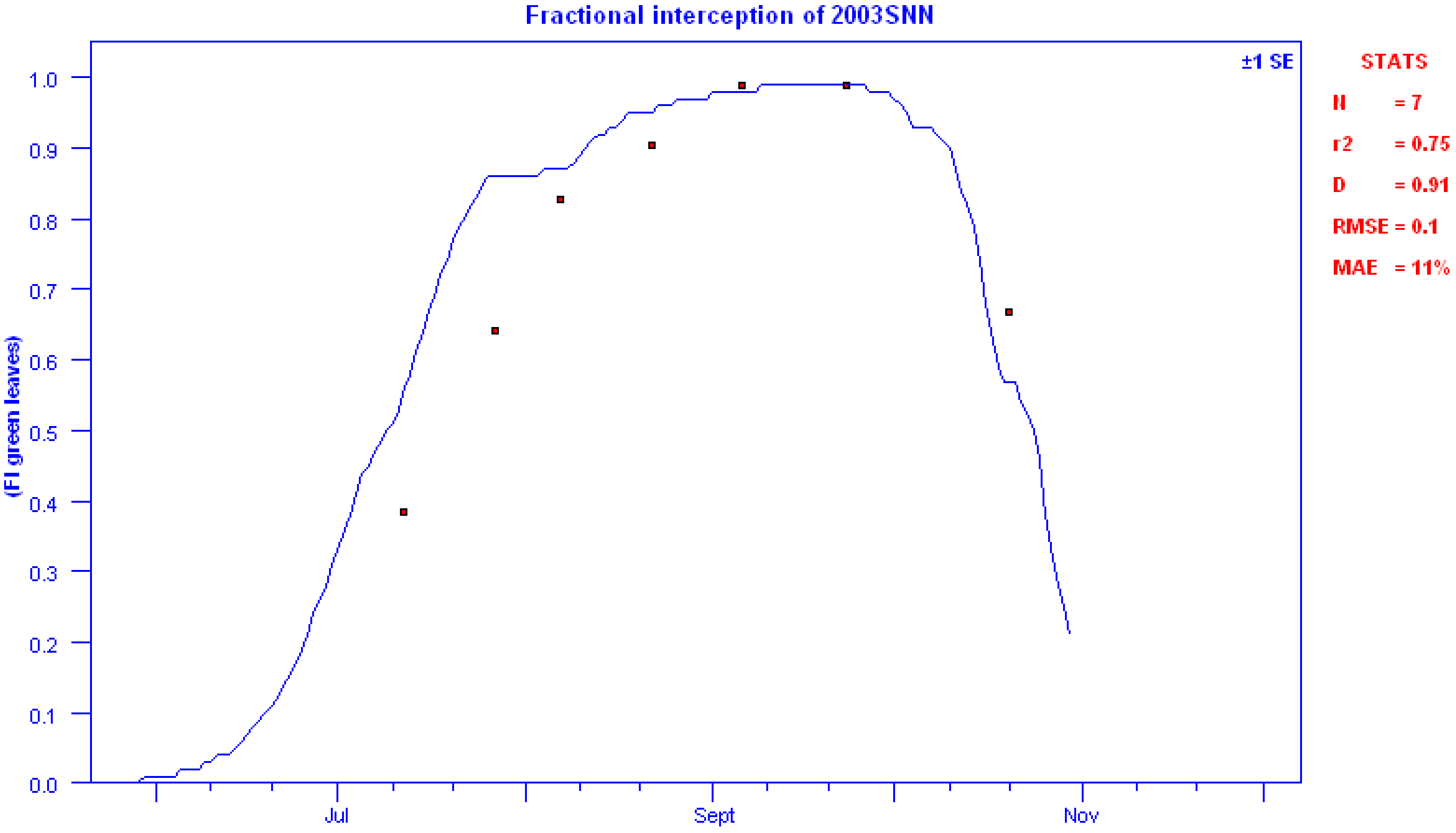

Figure 4.32 Simulated (solid lines) and measured values (points) of fractional interception for independent data set (Winter 2003, treatment SNN)

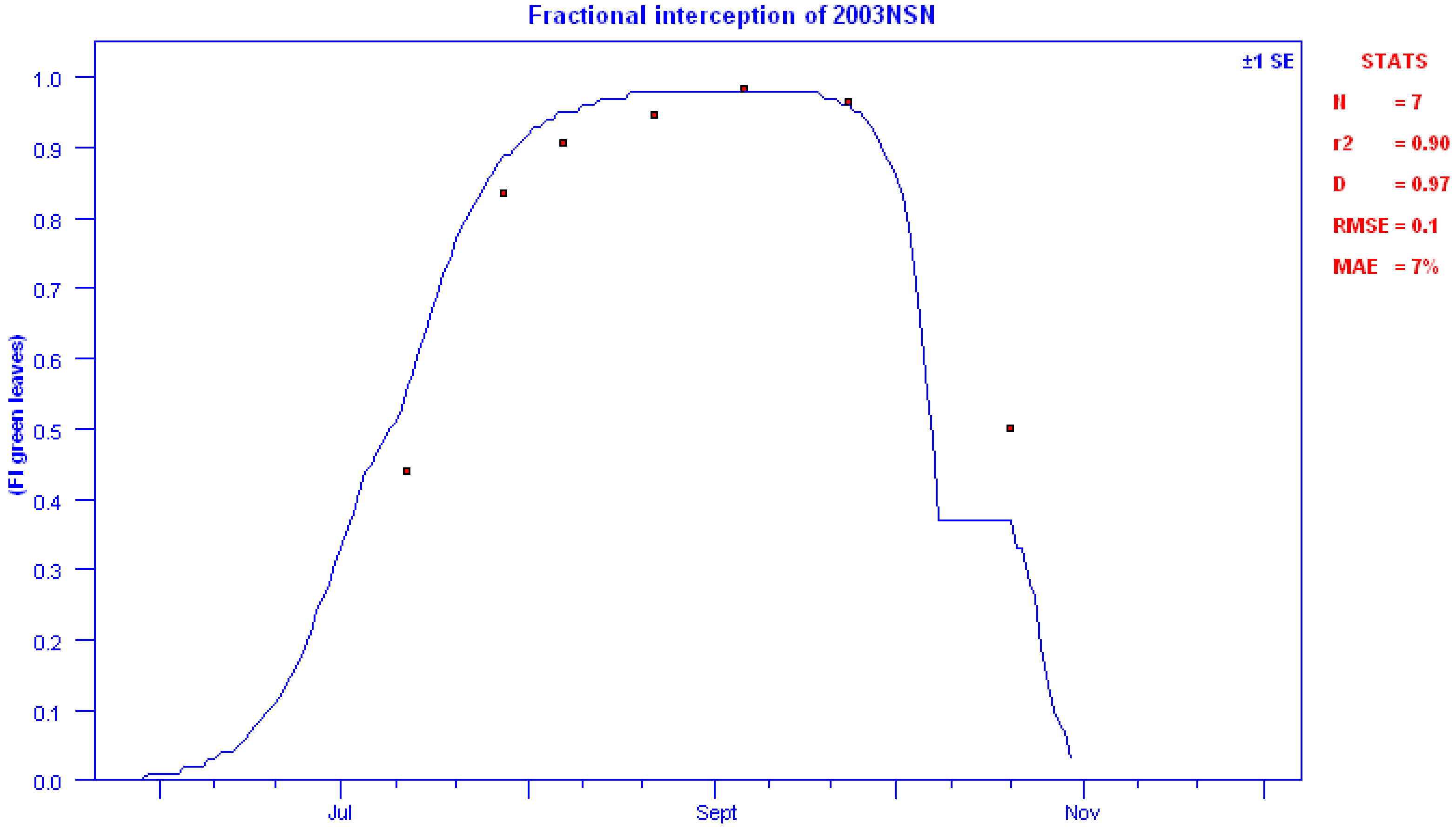

Figure 4.33 Simulated (solid lines) and measured values (points) of fractional interception for independent data set (Winter 2003, treatment NSN)

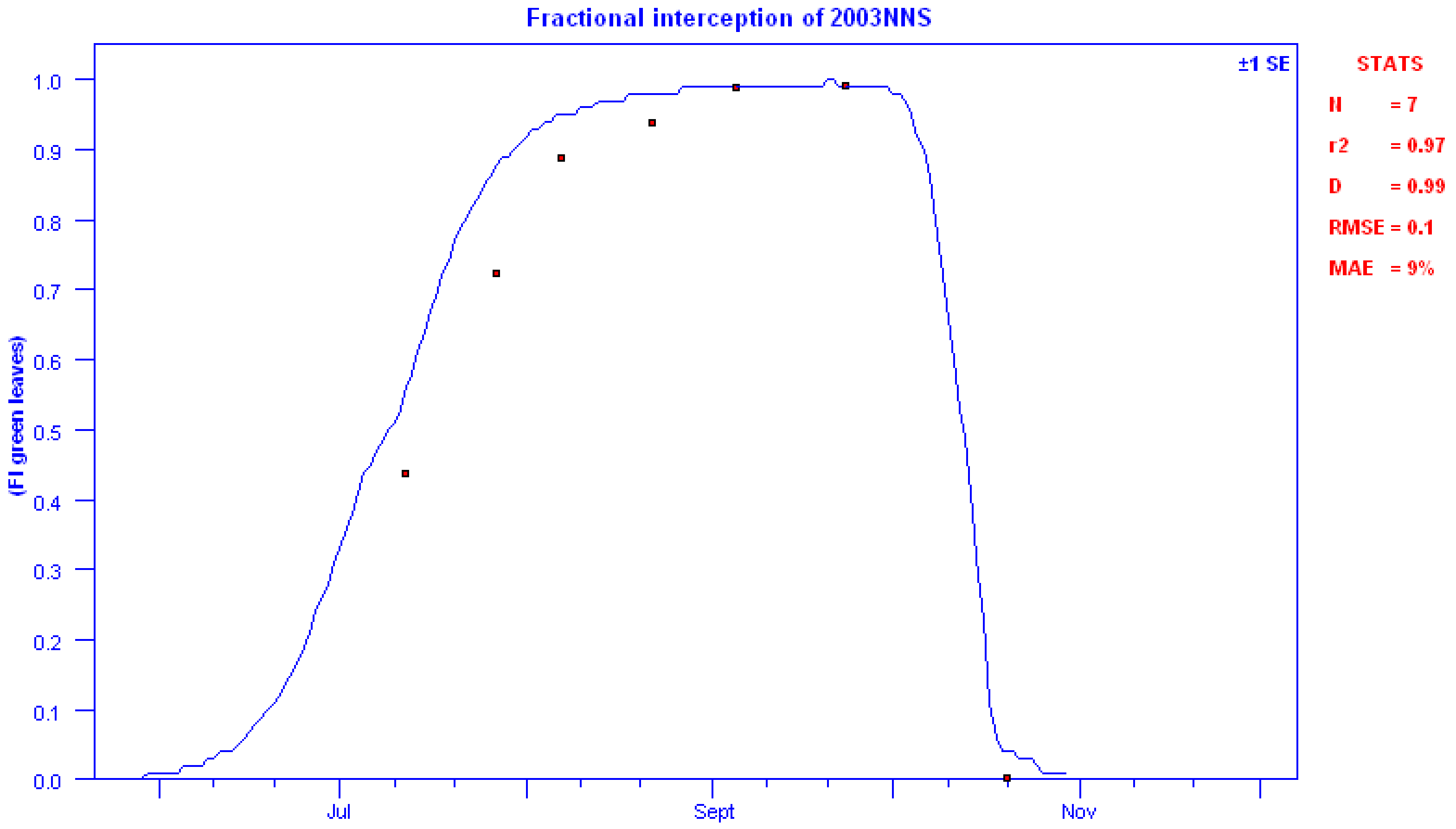

Figure 4.34 Simulated (solid lines) and measured values (points) of fractional interception for independent data set (Winter 2003, treatment NNS)

CHAPTER 5

CONCLUSION

Canola is an indeterminate crop whose leaf area recovers with the resumption of water supply after stress during the vegetative and flowering stages of growth. Water requirements of canola increase with vegetative and root growth until flowering, which is the peak water use period. Canola requires well-drained soils with sufficient available water for best seed and oil yields. However, best yield results, with greatest water use efficiency, could be achieved by improving fertility and available soil water throughout the season. Adequate soil water and well-fertilized soil improves canola seed and oil yield by increasing the number of branches per plant, number of flowers which bear seeds, number of seeds per pod and seed mass.

From the experiment conducted during winter 2002, the total growing day degrees till maturity for canola (Hyola 60) was determined to be 1742. Similarly, the study showed that the treatment without water stress consumed the most water, and this resulted in the production and maintenance of the largest leaf area index throughout the growing season. This contributed to the production of the greatest number of flowers and pods per plant, highest total dry matter as well as seed and oil yield. However, the treatment with stress during the flowering stage consumed the least water, resulting in the production and maintenance of the lowest leaf area index after flowering. This caused the abortion of flowers and pods, resulting in the production of the lowest total dry matter as well as seed and oil yield.

Canola is most sensitive to water deficit during the flowering stage and least sensitive during the vegetative stage. Water deficit during the flowering stage resulted in a statistically significant yield reduction, compared to the treatments with no stress, stress during the vegetative stage and stress during the grain filling stage.

Based on the data from this experiment and data obtained from studies conducted by Nielsen (1996) it is possible to conclude that in areas where the scarcity of water is a crucial issue, high water use efficiency at the expense of some seed and oil yield could be achieved by stressing the crop either during the seed filling or vegetative stage. On the other hand, in places where there is no shortage of water, the irrigator's choice could be to maximize transpiration so as to harvest the highest possible seed and oil yield. The water applied should not be excessive as this could leach out fertilizers and pesticides, which is accompanied by economic loss and at the same time groundwater pollution. Therefore choice of strategy of irrigation management should be made by the irrigator.

The main reason for low canola yield during 2002 was soil water stress. In addition to that low nitrogen supply during that year could have also partly contributed to lower yields. The problem with water stress is attributed to too short neutron probe access tube usage. This was proved by the experiment conducted on the same site in 2003 for model evaluation. The trial showed that canola used 709 mm of water for the non-stressed treatment. In addition 200 kg ha^{-1} of nitrogen (60 kg ha^{-1} at planting, 40 kg ha^{-1} in the vegetative stage and 100 kg ha^{-1} in the flowering stage) was added compared to 33.3 kg ha^{-1} (at planting only) in winter 2002. This doubled the yield (3831 kg ha^{-1}) in winter 2003 compared to winter 2002 (1850 kg ha^{-1}). Similar effects were observed in a study conducted by Dreccer *et al*. (2000) and Wright, Smith and Woodroofe (1988).

SWB is a mechanistic, generic crop growth and irrigation-scheduling model, which requires soil, crop and atmospheric inputs to simulate both crop growth and the soil water balance. Both the soil and atmospheric inputs are reasonably easily obtainable. To run the model, soil parameters, weather data and crop parameters need to be determined unless already determined. So, crop growth parameters of canola (*Brassica napus* L. cv. Hyola 60) were determined and SWB was successfully calibrated in winter 2002 despite the water stress problem experienced. Similarly, model evaluation done during 2003 showed that leaf area index, root growth rate, top dry matter and harvestable dry matter production, soil water deficit and fractional interception were simulated very well under different water regimes, despite problems experienced during the calibration year. The simulations also showed that SWB is able to simulate leaf recovery after stress.

The successful simulation of crop growth and crop water uptake under different soil water deficit treatments shows the potential of SWB as a useful tool for irrigation scheduling, not only at an extension level but also at the farmer level (depending on the literacy and financial status of the farmer), because of its user friendly windows interface. Recently the commercial production and wide distribution of personal computers have made it feasible to be used at farm level.

In conclusion, small irrigation amounts at short intervals, depending on the type of soil and climate, are required during the initial stage of canola growth so as to save both water and fertilizer. The provision of sufficient irrigation water improves yield. However, according to Andersen *et al*. (1996) optimal canola seed yield could be harvested if sufficient water is accompanied by proper nitrogen fertilization. The objective of nitrogen fertilization is to increase cumulative light absorption during the critical period of seed formation, and as mentioned by Dreccer *et al.* (2000), by enhancing leaf photosynthetic capacity during seed filling stage.

GENERAL RECOMMENDATIONS

i. The SWB model simulation can be refined using different specific leaf area and leaf stem partitioning parameters at different stages of growth because the pattern varies with stages of growth and type of crop.

ii. Including the availability of nitrogen in the soil, the effect of adding nitrogen fertilizer on the growth and yield of each crop and its interaction with water and weather factors.

iii. In the long-term inclusion of all other stress factors such as nutrients and pests for each crop in SWB.

iv. The influence of water stress on the thermal time requirements of the crop needs to be assessed.

v. Dry matter production during the seed filling stage of canola and all other oil crops needs to be refined.

SUMMARY

Canola is the third leading oil crop in the world after soybean and palm oil. It is a herbaceous plant and belongs to the *Cruciferae* family. The word canola is an acronym for Canada oil low acid. This name stands for the genetically selected and nutritionally superior rape seed with less than 2% erucic acid and less than 30 μmol g^{-1} glucosinulates in its oil. It grows in areas with rainfall more than 300 mm and a well-drained soil. Canola is expanding in the Western Cape province of South Africa, and it has the potential to grow on the highlands of Eritrea. However, water is becoming a scarce resource due to its high consumption rate for industrial, municipal, agricultural and domestic uses, in addition to its erratic nature in arid and semi arid regions.

In agricultural production it is possible to make best use of the available water efficiently through irrigation scheduling. Currently, accessibility of personal computers makes the use of models as irrigation scheduling tools possible. Optimum yield with the best water use efficiency could be achieved by scheduling irrigations with SWB. The Soil Water Balance model is a generic crop growth, irrigation-scheduling model. It needs specific parameters of each crop in order to simulate both crop growth and irrigation requirement. Specific parameters of several crops have already been determined. However, specific parameters of canola were not determined.

The objectives of this study were: a) To determine the specific model parameters so as to simulate canola growth and water use b) To determine the effect of water stress at different growth stages on the growth, seed yield and percentage oil content of canola.

Trials were conducted during the winters of 2002 and 2003 on the Hatfield experimental farm of the University of Pretoria. The first trail was conducted under an automated rain shelter to stop the interference of rain, and the 2003 trial was conducted in an open field. Each trial had four treatments, namely, NNN (unstressed), SNN (stressed during vegetative stage), NSN (stressed during flowering stage) and NNS (stressed during grain filling stage).

The trail showed the effect of water stress at different stages on the growth, on seed yield and percentage oil content of canola. The treatment with stress during the flowering stage maintained the lowest leaf area index after flowering, and as a result produced the lowest top dry matter, seed yield and percentage oil content. The unstressed treatment maintained the highest leaf area index throughout the growing season and produced the highest top dry matter, seed yield and percentage oil content. In Winter 2002 water stress during the flowering stage resulted in a highly statistically significant ($p = 0.01$) yield reduction compared to the unstressed treatment and that stressed during the vegetative growth stage. It also showed a statistically significant ($p = 0.05$) yield reduction compared to the treatment with stress during the seed filling stage. Similarly in Winter 2003 water stress during the flowering stage resulted in a highly statistically significant ($p = 0.01$) yield reduction compared to all the other stressed treatments. This shows that canola is most sensitive to stress during the flowering stage.

The Soil Water Balance model was calibrated using data collected during the winter of 2002. It was evaluated against independent data collected in winter 2003. It simulated soil water deficit and crop growth of all treatments very well. Therefore, SWB could in the future be used as an irrigation-scheduling tool both at a research and farm level by researchers, consultants and farmers.

APPENDIX A

SUMMARY OF ANOVA TABLE, SOIL CHEMICAL AND PHYSICAL ANALYSIS, WATER CHEMICAL ANALYSIS AND WEATHER DATA FOR WINTER 2002 AND 2003

1. Summaries of ANOVA table

Table A1 Summary of ANOVA table on the effect of water stress at different growth stages on canola yield (Winter 2002, Tukey's studentized range test).

Source	d.f.[1]	Mean sum of squares	F – value	Pr > F[2]
Treatment	3	675459.012	12.16	0.0016
Blocks	3	32925.992	0.59	0.6352
Error	9	55546.874		
Total	15			
CV (%)	15.70			
R^2	0.81			

d.f.[1] - degrees of freedom

Pr > F[2] - F-probability level

Table A2 Summary of ANOVA table on the effect of water stress at different growth stages on canola yield (Winter 2003, Tukey's studentized range test).

Source	**d.f.**[1]	**Mean sum of squares**	**F – value**	**Pr > F**[2]
Treatment	3	975576.229	4491.00	< 0.001
Error	12	217.229		
Total	15			
CV (%)	0.46			
R^2	0.99			

d.f.[1] - degrees of freedom

Pr > F[2] - F-probability level

2. Irrigation water as well as soil chemical and physical analyses for Winter 2002

Table A3 Irrigation water analysis data (Winter 2002)

pH	**EC**	**mg l^{-1}**															
	mS/m	**Ca**	**Mg**	**K**	**Na**	**Fe**	**Cu**	**Mn**	**Zn**	**P**	**SO_4**	**B**	**Cl**	**CO_3**	**HCO_3**	**NH_4**	**NO_3**
7.2	38.10	28	12	7.65	44	0.00	0.00	0.00	0.86	0.1	14.5	0.0	42.3	0	126	6.7	11.8

Table A4 Soil Chemical analyses of canola plots (Winter 2002)

Field	**pH**	**P (mg/kg)**	**Ca (mg/kg)**	**K (mg/kg)**	**Mg (mg/kg)**	**Na (mg/kg)**
North (plot)	6.2	59	940	192	319	53
South (plot)	6.7	47.5	883	171	277	47

Table A5 Textural analyses of the experimental plots (Winter 2002)

Field	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Total (%)**
North (plot)	56.2	8.2	37.3	101.7
South (plot)	64.2	11.4	26.6	101.2

3. Weather data for Winters of 2002 and 2003

Table A6 Weather data (Winter 2002, Hatfield Research Station, Pretoria, South Africa)

ddmmyy	Precip (mm)	T_{max} (^oC)	T_{min} (^oC)	Solar (MJ m^{-2} day^{-1})	U (m s^{-1})	RH_{min} (%)	RH_{max} (%)
23/05/02	0	20.8	11	16.8	2.1	34	100
24/05/02	0	21.6	10	12	1.7	31	74
25/05/02	0	24.6	6.8	17.1	1.8	29	92
26/05/02	0	25.3	7.6	16.8	2.2	26	88
27/05/02	0	22.2	8.9	16	2.4	48	96
28/05/02	0	22.4	8.8	16.3	1.9	47	100
29/05/02	0	25.1	8.1	16.2	1.6	28	100
30/05/02	0	24.4	11.5	15.3	2.3	38	71
31/05/02	0	19.2	9.2	4.6	3	69	100
01/06/02	0	15.1	9.1	6.3	1.9	79	100
02/06/02	0	17.1	6	12.7	3.1	65	100
03/06/02	0	16.5	6.6	12.5	1.5	53	100
04/06/02	0	18	5.2	13.3	1.6	36	100
05/06/02	0	17.6	4.6	16	1.8	48	99
06/06/02	0	16.6	5.6	12.9	1.5	49	100
07/06/02	0	18.4	3.2	15.7	1.2	43	100
08/06/02	0	18.4	6.5	16.1	1.7	42	100
09/06/02	0	21.2	5.8	16.4	2.5	21	94
10/06/02	0	21.6	5.5	16.4	1.8	27	73
11/06/02	0	21.2	4.9	16	1.9	36	100
12/06/02	0	18.4	8.2	11.2	2.4	56	100
13/06/02	0	21	10.3	12.2	2.6	49	100
14/06/02	0	14.8	5.5	16.4	2	44	100
15/06/02	0	18.8	4.6	16.1	2	37	100
16/06/02	0	20.4	3.8	16.2	1.5	27	100
17/06/02	0	19.3	8.8	16	1.9	41	83
18/06/02	0	21.6	5.7	15.9	1.4	27	100
19/06/02	0	22.6	5.9	15.6	1.7	24	88
20/06/02	0	19.6	7.4	15.2	2.6	50	100
21/06/02	0	17.4	8.5	12.1	2.9	56	98
22/06/02	0	17.5	7	14.6	1.4	50	100
23/06/02	0	18.9	7.1	15.5	1.7	40	100
24/06/02	0	15.7	6.2	15.1	2.6	23	100
25/06/02	0	17.9	4.9	16.4	3.5	30	93
26/06/02	0	17.3	4	15.9	1.8	42	100
27/06/02	0	18.9	4.3	15.8	1.2	34	100
28/06/02	0	19.5	3.6	15.8	1.6	33	96
29/06/02	0	20.2	4.6	15.9	2.1	28	95
30/06/02	0	19.7	5.5	17.5	2.2	11	85

01/07/02	0	17.2	4.8	16.4	2.1	43	100
02/07/02	0	17.2	2.3	15.9	1.2	45	100
03/07/02	0	19.7	2.8	15.8	1.2	20	100
04/07/02	0	17.3	3.9	16	1.9	31	95
05/07/02	0	19.1	2.6	16	1.1	25	92
06/07/02	0	18.6	2.7	15.3	1.1	29	78
07/07/02	0	19	2.8	15.9	2	27	88
08/07/02	0	20.8	4.1	15.3	1.4	27	75
09/07/02	0	21.8	6.2	15.9	3.3	26	74
10/07/02	0	16	3.8	18.5	2.9	19	81
11/07/02	0	16.6	0.5	18	1.6	30	90
12/07/02	0	17.2	1.1	17.4	1.5	31	86
13/07/02	0	19.3	3	16.8	1.1	32	95
14/07/02	0	20	4	17.2	1.3	33	83
15/07/02	0	21.3	5.2	14	1.7	31	91
16/07/02	0	16.4	5.5	17.8	2.2	25	81
17/07/02	0	14.8	3.4	15.6	2.6	18	53
18/07/02	0	15.3	1	16.9	2.5	28	97
19/07/02	0	15.6	2.8	17.3	4.1	29	100
20/07/02	0	14.4	4	16	4.7	56	94
21/07/02	0	15.4	3.5	14.6	2.3	42	100
22/07/02	0	19.3	3.3	18.2	2.1	33	85
23/07/02	0	22.2	2.4	18	1.5	15	97
24/07/02	0	23.9	3.5	18.3	2	15	66
25/07/02	0	21.3	5	18.8	2.2	17	57
26/07/02	0	21.8	3.5	19.5	2.2	12	65
27/07/02	0	24.3	5.1	18.1	1.6	25	90
28/07/02	0	25.8	6.2	17.9	1.6	18	75
29/07/02	0	26.8	7.5	17.6	1.8	17	75
30/07/02	0	25.9	9.1	19.3	3	13	54
31/07/02	0	20.3	7.1	13.7	4.1	53	97
01/08/02	0	16.6	7.4	11.5	1.9	65	100
02/08/02	0	22	5.2	18.8	1.7	34	100
03/08/02	0	24.8	7.3	18.1	2.5	12	93
04/08/02	0	18.8	10.5	8.1	3.5	61	97
05/08/02	0	20.6	7	18.3	2.3	46	100
06/08/02	0	24	7	17.9	1.5	27	100
07/08/02	0	24.1	9.8	18.1	2.1	32	90
08/08/02	0	22	9.7	18	1.8	47	100
09/08/02	0	23.5	7	18.9	1.6	26	100
10/08/02	0	24.5	6.4	19.5	2	13	97
11/08/02	0	19.8	7.3	20.6	2	36	92
12/08/02	0	20.8	5.5	20.8	1.9	26	100
13/08/02	0	24.3	6.7	20.5	1.9	22	77
14/08/02	0	27.4	10	19.5	2.6	18	79
15/08/02	0	24.5	14.4	14.2	2.7	46	100
16/08/02	0	26.2	9.7	16.6	2.4	41	76
17/08/02	0	20.7	14.4	5.7	3.5	54	91

18/08/02	0	14.7	12.2	1.3	2.5	79	100
19/08/02	0	20.4	10.7	11.4	1.7	65	100
20/08/02	0	23.8	10.1	20.3	2.2	38	100
21/08/02	0	23.4	12.5	16	1.9	42	100
22/08/02	0	24.8	9.9	18.2	1.7	40	97
23/08/02	0	24.6	13.4	18.4	2.1	41	83
24/08/02	0	24.6	10.4	20.3	1.9	34	86
25/08/02	0	25.9	12.6	20.4	2.3	26	81
26/08/02	0	26	13.2	18.6	2.3	42	100
27/08/02	0	22.6	12	6.9	3.3	50	100
28/08/02	0	22.8	11.2	17.7	3.2	62	100
29/08/02	0	18.9	12.8	8.4	2.2	70	97
30/08/02	0	20.6	12.2	13	2.2	63	100
31/08/02	0	23.9	10.1	21.9	2.4	37	100
01/09/02	0	22.2	10.2	16.1	2	47	100
02/09/02	0	23.2	10	19.9	1.8	41	100
03/09/02	0	24.3	10	21.8	2.2	36	100
04/09/02	0	26.6	11	21.8	2.1	26	91
05/09/02	0	24.4	11.4	17.1	4.4	34	95
06/09/02	0	21	10.7	15.7	3.6	58	97
07/09/02	0	20.7	11.9	11.8	1.9	56	99
08/09/02	0	22.5	10.3	14.1	2.2	54	100
09/09/02	0	26.3	11.4	19.1	3.7	31	98
10/09/02	0	14.7	5.2	22.2	3.7	43	83
11/09/02	0	16.8	4	26.1	2.5	22	84
12/09/02	0	22.3	4.1	25.5	2.4	25	82
13/09/02	0	22.9	8.8	25.2	3.7	28	79
14/09/02	0	21.5	7.2	26.1	2.6	31	98
15/09/02	0	23	7.7	26.7	1.8	26	94
16/09/02	0	25.6	8.5	26.2	1.9	20	86
17/09/02	0	27	8.3	25.3	2	19	88
18/09/02	0	27.1	11.5	24.6	2.1	25	74
19/09/02	0	27.1	12.3	25.8	2	23	82
20/09/02	0	26.9	11.2	26.7	2	18	79
21/09/02	0	26.7	10.5	27.3	1.8	21	88
22/09/02	0	28.1	10.8	26.8	2	20	79
23/09/02	0	27.9	13.3	26.9	2.3	19	88
24/09/02	0	30.1	12.3	26.6	1.9	16	74
25/09/02	0	32.3	16.4	24.7	2.4	15	48
26/09/02	0	30.3	17.1	21.1	2.1	15	41
27/09/02	0	24.1	15.3	8.7	2.5	26	82
28/09/02	0	28.8	11.5	26.6	2.2	24	100
29/09/02	0	30.2	14.8	25	3.3	16	96
30/09/02	0	25.3	13.7	12.7	3.3	55	97
01/10/02	0	27.6	12	28.2	2.8	10	100
02/10/02	0	29.1	11	33.3	3.2	31	93
03/10/02	0	26.4	11.6	19.6	3.6	16	100
04/10/02	0	27.8	7.8	29.9	3.2	13	92

05/10/02	0	24.2	11.5	15.3	2.2	55	100
06/10/02	0	27.2	13.1	22.6	2.4	41	100
07/10/02	0	22.5	13.7	12.5	2.4	64	100
08/10/02	0	23.4	12.7	15.4	3.2	59	100
09/10/02	0	22.8	9.7	27.9	1.5	48	100
10/10/02	0	25.6	11.8	28.9	1.7	24	100
11/10/02	0	30.8	10.4	26.6	1.6	25	86
12/10/02	0	29.9	13.4	29.4	1.9	27	94
13/10/02	0	27.5	12.6	31.5	2.1	14	83
14/10/02	0	27.6	13.6	29.3	1.8	14	74
15/10/02	0	30.6	12.4	38.4	1.8	14	70
16/10/02	0	33	15.7	33	2	19	82
17/10/02	0	34.5	15.6	28.8	2.3	18	84
18/10/02	0	33.6	17.2	30.9	2.2	15	57
19/10/02	0	34.6	16.1	31	2.6	14	71
20/10/02	0	27.7	14.9	24.8	3.6	46	97
21/10/02	0	28.8	12.6	30	2.4	41	100
22/10/02	0	30.6	17.5	28.5	3.9	32	78
23/10/02	0	30.2	16.6	29.7	2.7	34	86
24/10/02	0	31.3	14.5	31.9	2.5	15	96
25/10/02	0	30.8	12.9	31.7	3	14	89
26/10/02	0	30.7	16.2	29.2	2.7	31	100
27/10/02	0	28.3	15.7	14.5	2.4	38	100
28/10/02	0	29.6	17.4	19.3	2.8	31	85
29/10/02	0	25.8	15.4	18.7	2.2	50	100
30/10/02	0	18.3	12.3	6.1	4.6	89	100

Table A7 Weather data (Winter 2003, Hatfield Research Station, Pretoria, South Africa)

ddmmyy	Precip (mm)	T_{max} (^{o}C)	T_{min} (^{o}C)	Solar ($W\ m^{-2}$)	U ($m\ s^{-1}$)	RH_{min} (%)	RH_{max} (%)
21/05/03	0	18.6	6.4	13.1	1.8	50	100
22/05/03	0	20.7	7	12.4	1.1	45	100
23/05/03	0	21.2	6.3	15.7	1.3	42	100
24/05/03	0	23.7	6.5	16.2	1.4	34	100
25/05/03	0	24.6	10.4	16.8	2.4	19	74
26/05/03	0	25	8.4	16.4	2.8	26	71
27/05/03	0	18.3	3	17.5	2.4	24	78
28/05/03	0	20	5.3	17.1	2	21	71
29/05/03	0	21	2.6	16.7	1.3	25	88
30/05/03	0	21.6	4.3	16.3	1.3	35	87
31/05/03	0	22	6.3	15.8	1.1	44	100
01/06/03	0	22	6.8	15.6	1.3	35	100
02/06/03	0	21.4	5.9	15.3	1.3	39	100
03/06/03	0	22.1	7	13.6	1.8	35	98
04/06/03	2	21.9	9.1	14.6	2.5	48	100
05/06/03	0	20.9	8.4	16.1	2.6	34	89
06/06/03	6.5	16.1	9.8	3.6	1.9	88	100
07/06/03	0	18.8	8.8	11.1	1.7	65	100
08/06/03	0	22	5	15.3	1.7	35	100
09/06/03	0	20.6	9.8	15	3	21	92
10/06/03	0	16.7	6.9	12.3	3.6	62	100
11/06/03	0	17.3	3.8	15.4	1.4	44	100
12/06/03	0	18.7	4.4	14.5	1.4	51	100
13/06/03	0	19.4	5.5	15.3	1.4	41	100
14/06/03	0	20	4.3	15.5	1.5	32	95
15/06/03	0	22.5	4	16.2	2.9	17	89
16/06/03	0	19.3	5.5	15.3	1.8	42	100
17/06/03	0	20.8	4.5	15.1	1.8	31	99
18/06/03	0	19.6	6.6	15	2.2	42	100
19/06/03	0	18.8	6.5	15.1	1.7	46	100
20/06/03	0	19.2	5.3	13.9	1.3	47	100
21/06/03	0	19.7	4.9	14.4	1.2	39	100
22/06/03	0	19.9	4.9	14.9	1.4	42	100
23/06/03	0	19.9	6.9	10.8	2	34	100
24/06/03	0	18.6	7	14.9	3.6	32	100
25/06/03	0	17.9	7.1	15.2	4.3	46	91
26/06/03	0	19.5	6.1	15.6	3.3	43	93
27/06/03	0	18.3	3.7	16.6	3.9	21	100
28/06/03	0	17.6	6.8	15.2	4.5	44	100
29/06/03	0	18	8.4	12.9	3.7	46	100
30/06/03	0	18.1	4	15.9	2.4	31	100
01/07/03	0	19.5	4.1	15.7	1.9	27	72

02/07/03	0	19.4	3	16	2.1	18	61
03/07/03	0	18.3	2.9	16.1	1.9	25	67
04/07/03	0	18.9	4.1	16.1	1.8	41	97
05/07/03	0	15.5	4.7	9.4	2.8	46	100
06/07/03	0	15.2	5	14.8	2	51	98
07/07/03	0	14.9	1.5	16.6	1.6	40	100
08/07/03	0	16.3	0.2	16.5	1.1	35	94
09/07/03	0	15.4	1.8	16.6	1.7	39	89
10/07/03	0	16.6	1.5	16.7	1.7	42	97
11/07/03	0	20.2	3.6	15.5	1.8	29	98
12/07/03	0	18.1	7.4	12.8	3.9	41	98
13/07/03	0	18.9	4.7	15.5	1.9	36	100
14/07/03	0	22.1	4.8	16.4	1.5	16	89
15/07/03	0	20.7	5	16.8	1.4	22	79
16/07/03	0	21.9	2.7	16.1	1.3	21	78
17/07/03	0	22.6	4.9	16.3	1.4	17	73
18/07/03	0	20.5	3.9	17.5	1.8	25	75
19/07/03	0	22.3	5.5	17.3	1.9	22	76
20/07/03	0	21.6	4.6	17	1.5	23	80
21/07/03	0	17.6	8.5	13.5	2.3	57	100
22/07/03	0	20.5	4.5	17	1.2	36	100
23/07/03	0	21.1	6	17.4	1.9	23	87
24/07/03	0	19.4	5.9	17.9	2	36	99
25/07/03	0	21.6	5.4	17.3	1.7	35	92
26/07/03	0	23.1	4.9	17.8	1.7	16	84
27/07/03	0	25.1	6.5	18	1.6	11	64
28/07/03	0	26.1	6.4	18.2	1.6	9	55
29/07/03	0	25.5	6.8	18	1.7	10	52
30/07/03	0	22.5	9.5	18.1	1.8	26	98
31/07/03	0	23.8	6	17.3	1.6	27	94
01/08/03	0	21.1	8.6	19.4	2.2	26	75
02/08/03	0	21.8	5.4	17.9	1.7	36	88
03/08/03	0	18.8	8.8	12.3	2.3	55	100
04/08/03	0	20	6.7	18.6	2.1	42	100
05/08/03	0	21.6	6.9	17.9	2.5	32	94
06/08/03	0	15.6	9	6.2	3.2	65	96
07/08/03	0	18.8	5.1	18.7	2.2	46	100
08/08/03	0	20.2	5.7	18.3	2.1	32	100
09/08/03	0	19.5	9.9	17	2.3	40	88
10/08/03	0	21.6	8.4	18.9	2.5	39	97
11/08/03	0	25.1	12.4	15.1	3.3	26	73
12/08/03	0.5	20.6	6	20.9	2.3	19	76
13/08/03	0	16.6	11.2	23.4	3.7	19	39
14/08/03	0.5	17.2	5.7	32.6	3.1	24	70
15/08/03	0	12.8	7	30.4	0.9	22	45
16/08/03	0	15.3	9.7	26.4	0.9	30	49
17/08/03	0	17.3	10.8	25.8	1.3	29	47
18/08/03	0	22.8	19.1	21.7	2.5	31	39

19/08/03	0	14.8	10.4	23.5	2.9	19	45
20/08/03	0	6	0.7	8.5	2	29	43
21/08/03	0	15.3	-2.8	32.7	2.4	9	62
22/08/03	0	17.8	3	23.6	2.4	25	62
23/08/03	0	22.2	3.9	23.4	1.7	29	82
24/08/03	0	24.7	8.7	20.9	4	17	70
25/08/03	0	20.7	4	24.1	2.6	21	76
26/08/03	0	16.4	5.7	24.5	3	16	56
27/08/03	0	22.7	2.7	24.4	2.2	12	50
28/08/03	0	25	6	24.3	1.8	14	49
29/08/03	0	26.8	7.6	24.1	1.6	11	59
30/08/03	0	24.7	11.9	23.4	2.1	21	58
31/08/03	0	26.5	9.5	22.9	1.6	20	80
01/09/03	0	28.2	9.8	23.6	1.8	16	61
02/09/03	0	28.9	9.9	25.1	1.6	11	58
03/09/03	0	27.7	13.8	25.2	2.3	16	43
04/09/03	0	28.1	13.5	24.9	2.6	18	51
05/09/03	0	24.6	10.5	23.4	2.8	15	92
06/09/03	11.4	22	9.3	26.3	4.3	31	95
07/09/03	0	22.5	7.9	25.8	2.5	38	100
08/09/03	0	25.1	7.9	25.7	2.1	28	98
09/09/03	0	29.5	10.3	25.2	3.1	16	66
10/09/03	0	24.8	10.8	26.7	3	19	51
11/09/03	0	26.1	10.2	26	2.3	17	82
12/09/03	0	28.5	10.7	24.5	2.1	17	69
13/09/03	2.5	26.4	14.3	21.9	3.3	31	100
14/09/03	0	19.8	11.9	9.5	4.1	59	100
15/09/03	0	20.5	9.1	21.9	2.4	52	100
16/09/03	0	22.4	8.6	23	2.4	45	100
17/09/03	0	24.1	10.4	21.8	2.1	46	100
18/09/03	0.5	24.9	13	15.7	2.2	41	93
19/09/03	0	29.3	14.8	25.2	2.8	24	78
20/09/03	0	30.3	16.6	20.4	3.2	21	61
21/09/03	0	26.3	14.2	23.2	2.8	13	46
22/09/03	0	24.6	7.8	27.5	3.7	20	100
23/09/03	0	21.4	11.4	21.6	2.6	50	98
24/09/03	0	25.9	10.7	27.5	2.3	31	100
25/09/03	0	28.8	10.3	28.2	2.4	15	50
26/09/03	0	31	15.5	26.5	2.6	23	64
27/09/03	0	29.9	16.3	24.2	2.4	18	48
28/09/03	0	29.8	16.6	20.7	2.3	23	67
29/09/03	0	29	16.9	28.4	2.4	23	61
30/09/03	0	28.9	14.7	28.5	2.3	27	82
01/10/03	0	31.8	16.6	27.4	2.3	22	76
02/10/03	0	32.4	16.2	27.2	2.5	19	58
03/10/03	0	33.6	19.6	26.9	2.6	16	45
04/10/03	0	34	18.9	26	2.6	17	67
05/10/03	0	34.8	18.9	26.6	2.4	14	63

06/10/03	0	34	16.1	28.3	1.9	9	52
07/10/03	0	30.5	17.1	28.9	2.8	20	71
08/10/03	0	29.1	13.5	30.9	2.8	26	92
09/10/03	0	29.9	12.9	28.8	2.1	27	100
10/10/03	0	32.1	18.4	21.9	3.2	23	69
11/10/03	4	32	16.7	22.6	3.4	29	100
12/10/03	0	28.9	15.3	24.2	2.1	43	100
13/10/03	0	30.7	16.8	26.8	3	33	99
14/10/03	0	31.3	17.2	27.4	3.7	18	95
15/10/03	0	30.4	13.9	31.6	2.8	17	73
16/10/03	0	31.1	14.2	31.2	3.1	19	96
17/10/03	0	27.7	12.3	32.7	3.6	11	86
18/10/03	0.5	15.9	8.4	10.1	5.9	60	100
19/10/03	56.2	9.2	6	4.2	6.5	92	100
20/10/03	10.4	13.9	9.8	8.7	5.4	83	100
21/10/03	19.4	18.2	9.4	15.5	3	73	100
22/10/03	0	23.6	9.7	24.2	1.6	50	100
23/10/03	0	27	12.2	27.6	1.9	30	100
24/10/03	0	29.3	16.9	29.5	2.5	29	80
25/10/03	3	29.8	18.1	23.9	2.4	37	98
26/10/03	0	31.5	15.3	32.9	2.8	15	97
27/10/03	0	28.1	17.3	27.4	2.9	20	95
28/10/03	0	27.8	15.3	30.9	2.3	47	100
29/10/03	0	29.1	16.1	31.7	2.1	33	98
30/10/03	0	31.1	18.3	31	2.2	30	93

APPENDIX B

NEUTRON WATER METER CALIBRATION PROCEDURES AND EQUATION DETERMINATION FOR CANOLA TRIAL DURING WINTER 2002 AND 2003

1. Neutron water meter calibration procedure

Wet and dry site neutron probe readings need to be determined with their corresponding volumetric water contents so as to get the best-fit regression equation (Campbell and Mulla, 1990). This equation converts each neutron probe reading to its corresponding volumetric water content. The procedure for wet site calibration is as follows:

a. Select representative site.
b. Prepare a dam of at least 2m × 2m without disturbing the soil surface.
c. Install neutron access tube in the middle of the area to be ponded.
d. Fill the dam with water until you get a steady rate of infiltration.
e. Cover the dam with a plastic sheet to prevent evaporation and leave it at least for 48 hours for soil water redistribution.
f. Collect neutron water meter readings, and dig a profile hole close to the access tube.
g. Collect samples from each layer for gravimetric water content determination where the corresponding neutron water meter readings have been collected.
h. Place the samples in labeled brown paper bags with known mass, and put them inside plastic bags, or other airtight containers with known mass to prevent evaporative losses during transportation.
i. Weigh the samples while inside the airtight container, and then remove them and dry in an oven for 24 hours at 105 ^{o}C (Campbell and Mulla, 1990).
j. Take the samples out of the oven and weigh them to get the dry mass.
k. Calculate the gravimetric water content (w_w) in (g g^{-1} or kg kg^{-1}) using Eq. B1

$$w_w = \left(\frac{(Wet\,mass - Dry\,mass)}{Dry\,mass} \right) \quad \text{B1}$$

l. Calculate volumetric water content of the soil using Eq. B2

$$\theta_w = \left(\frac{(w_w \times \rho_b)}{\rho_w} \right) \quad \text{B2}$$

ρ_b - Bulk density of the soil (Mg m^{-3} or kg m^{-3}) calculated using Eq. B3

ρ_w - Density of water (1 Mg m^{-3} or 1000 kg m^{-3})

θ_w - Volumetric water content (m water per m soil depth)

$$\rho_b = \left(\frac{m}{v} \right) \quad \text{B3}$$

m - Mass of oven dry soil (Mg or kg)

v - Volume of sampler (m^3)

The procedure for dry site calibration is the same as the wet site calibration except that there is no need for ponding. Instead, the neutron access tube is installed in a dry representative site, and all the other procedures remain the same.

Finally best-fit regression equations are drawn from the neutron water meter reading ratios of both the wet and dry sites and their corresponding volumetric water contents.

2. Calibration equations determination for canola trial (Winter 2003)

2.1 Dry site calibration

Table B1 Volumetric water content determination of dry site

Soil layer	Total mass (g) (Pl + Pa + ws)	Plastic mass g	Paper mass g	Dry soil + Paper (g)	Dry paper mass (g)	w_w (g g^{-1})	ρ_b (kg m^{-3})	θ (m^3 m^{-3})
0 - 20 cm	588.00	17.80	9.46	515.40	9.00	0.11	1478.05	0.15
20 - 40 cm	551.65	17.30	9.46	464.10	9.00	0.15	1540.24	0.24
40 - 60 cm	533.60	15.90	9.46	435.05	9.00	0.19	1333.08	0.26
60 - 80 cm	608.35	16.35	9.46	516.85	9.00	0.15	1634.15	0.24
80 - 100 cm	624.10	16.40	9.46	545.00	9.00	0.12	1874.39	0.22
100 - 120 cm	546.35	18.20	9.46	442.30	9.00	0.20	1327.29	0.26
120 - 140 cm	498.70	17.25	9.46	398.30	9.00	0.21	1345.43	0.29

Table B2 Neutron water meter reading ratio calculation of dry site

Soil layer	Neutron probe readings from soil layers	Average standard reading in air	Ratio
0 - 20 cm	2247	8710.18	0.21
20 - 40 cm	14136	8710.18	1.30
40 - 60 cm	16096	8710.18	1.48
60 - 80 cm	15707	8710.18	1.44
80 - 100 cm	8700	8710.18	0.80
100 - 120 cm	15393	8710.18	1.41
120 - 140 cm	16311	8710.18	1.50

2.2 Wet site calibration

Table B3 Volumetric water content determination of wet site

Soil layer	Total mass (g) (Pl + Pa + ws)	Plastic mass g	Paper mass g	Dry soil + Paper (g)	Dry paper mass (g)	w_w (g g^{-1})	ρ_b (kg m^{-3})	θ (m^3 m^{-3})
0 - 20 cm	614.25	18.50	9.70	493.90	9.10	0.21	1478.05	0.31
20 - 40 cm	624.35	17.10	9.70	514.30	9.10	0.18	1540.24	0.28
40 - 60 cm	584.40	17.50	9.70	467.90	9.10	0.22	1398.78	0.30
60 - 80 cm	550.30	18.20	9.70	433.05	9.10	0.23	1292.53	0.30
80 - 100 cm	715.90	17.40	9.70	623.90	9.10	0.12	1874.39	0.23
100 - 120 cm	592.00	15.80	9.70	474.50	9.10	0.22	1418.90	0.31
120 - 140 cm	575.55	18.20	12.50	453.10	11.80	0.24	1345.43	0.32

Table B4 Neutron water meter reading ratio calculation of wet site

Soil layer	Neutron probe readings from soil layers	Average standard reading in air	Ratio
0 - 20 cm	17449	11203.50	1.56
20 - 40 cm	17175	11203.50	1.53
40 - 60 cm	17717	11203.50	1.58
60 - 80 cm	17480	11203.50	1.56
80 - 100 cm	9324	11203.50	0.83
100 - 120 cm	18680	11203.50	1.67
120 - 140 cm	17135	11203.50	1.53

2.3 Best-fit regression equation determination

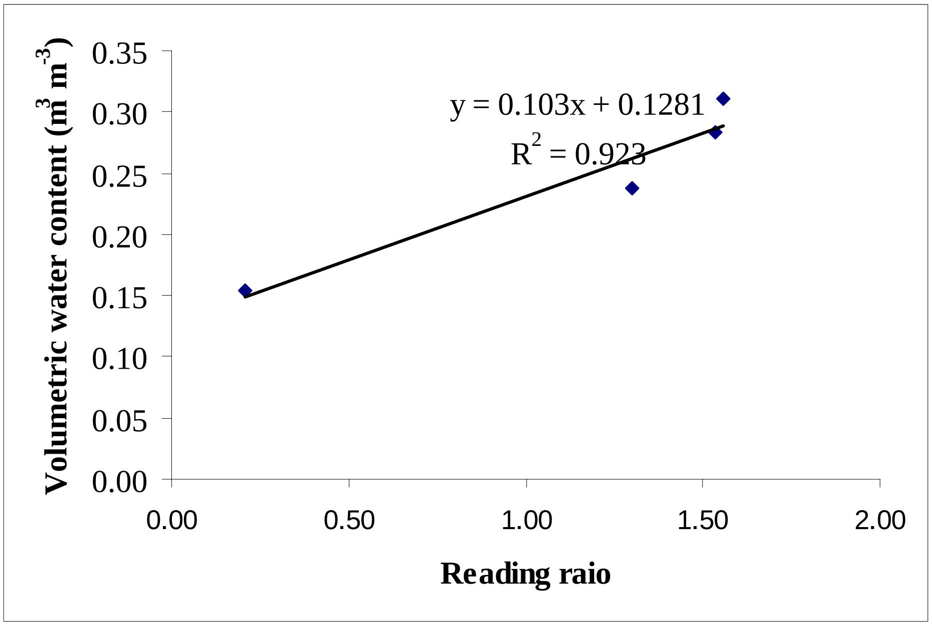

Figure B1 Best-fit regression equation (0 – 40 cm soil layer)

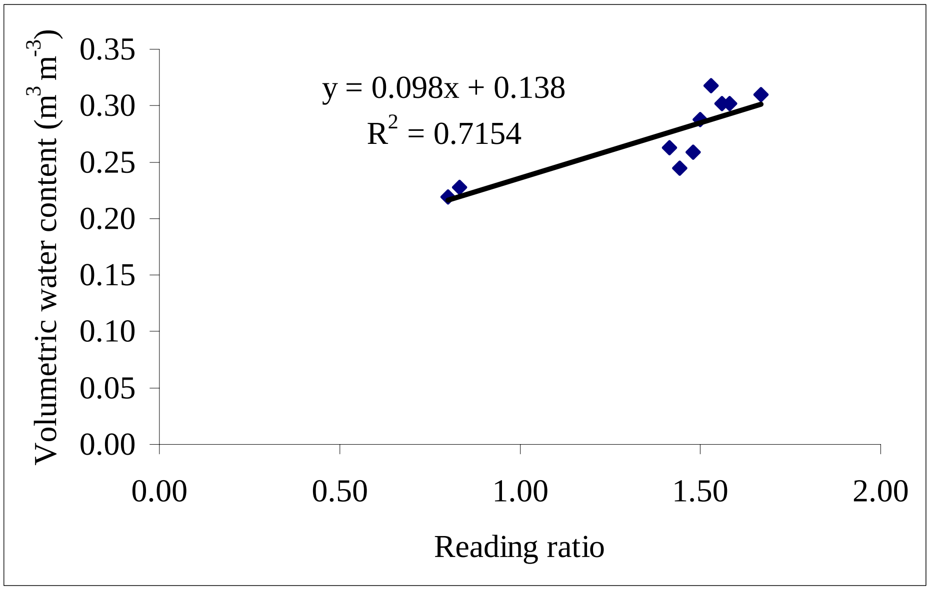

Figure B2 Best-fit regression equation (40 –140 cm soil layer)

APPENDIX C

Specific leaf area and leaf stem partitioning parameter determination for canola

Table C.1 Specific leaf area of canola determined in winter 2002

Average seasonal LAI (m^2 m^{-2})	4.1
Average seasonal LDM (kg m^{-2})	0.18
Average seasonal SLA (m^2 kg^{-1})	22.77

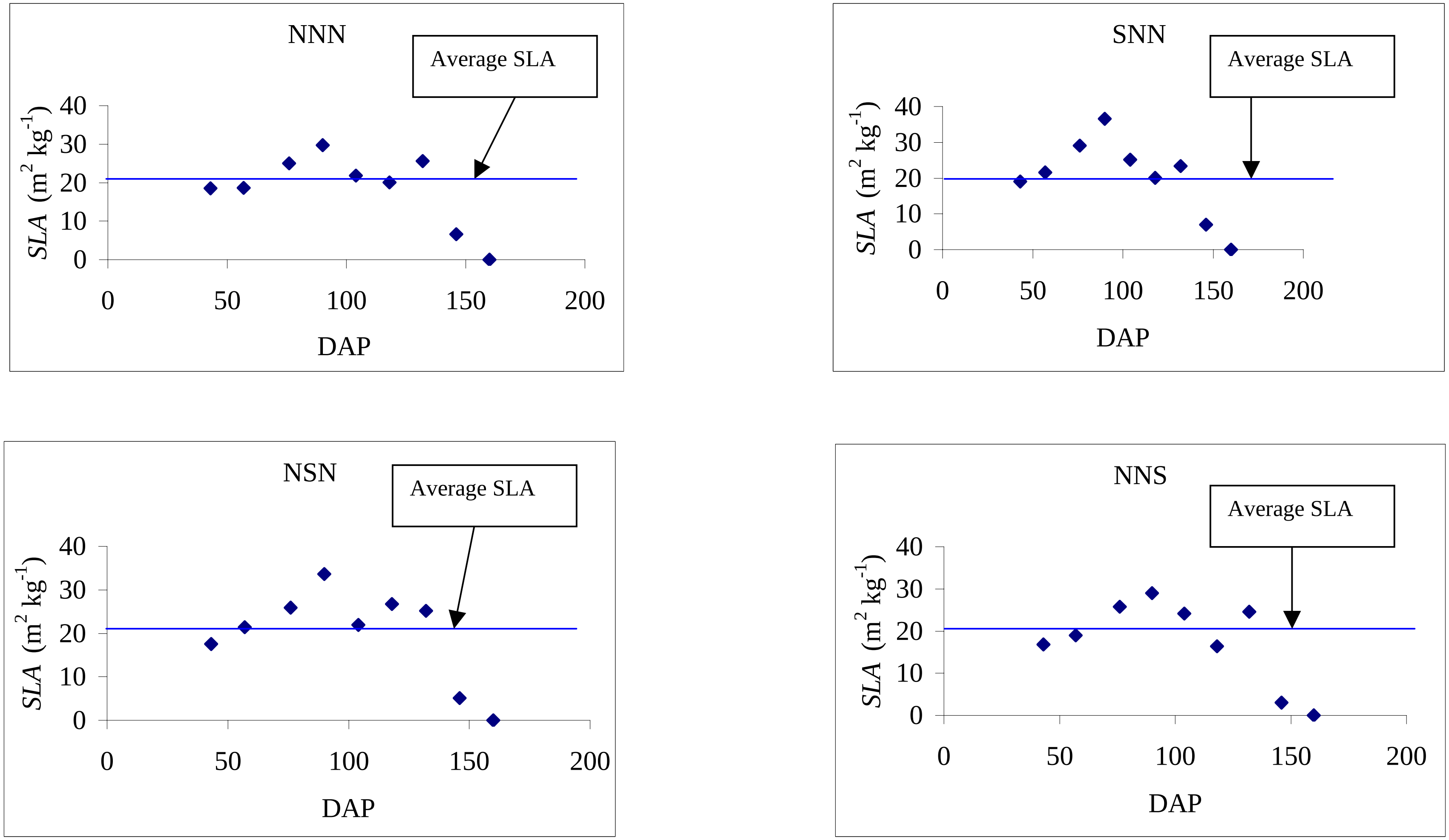

Figure C1 Specific leaf area for all treatments (Winter 2002)

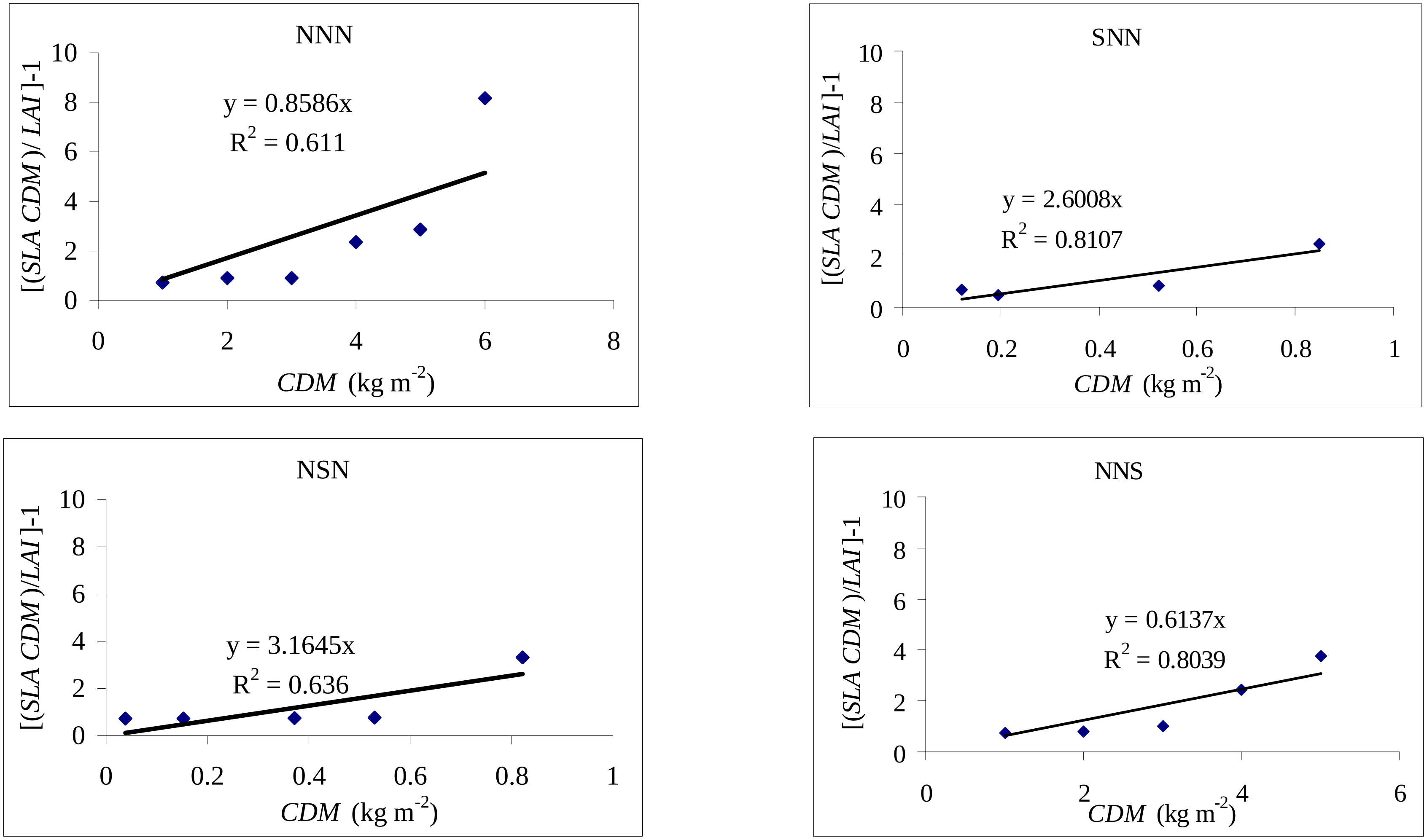

Figure C2 Leaf stem partitioning parameter of all treatments (Winter 2002)

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