OPTIMIZING RAINFALL USE EFFICIENCY FOR DEVELOPING FARMERS WITH LIMITED ACCESS TO IRRIGATION WATER

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Report to the Water Research Commission
by
ARC-Institute for Soil, Climate and Water

ARC-ISCW Report No:GW/A/1999/79
WRC Report N0. 878/1/00
ISBN No. 1 86845 542 4

January 2000

EXECUTIVE SUMMARY:

The project had three aims. One of these was technical, whereas the other two consisted of socio-economic benefits which it was hoped would flow from the investigation and solution of the technical problem.

The technical problem concerns the low crop production potential of the large area east of Bloemfontein earmarked by the State for developing farmers. The reason for the low crop production potential is marginal and erratic rainfall, exacerbated by high runoff and evaporation losses. The hypothesis was that a production technique combining the water conservation benefits of water harvesting, no-till, basin tillage, mulching and long-fallow would make sustainable crop production possible at a reasonable level for selected crops. Field experiments were conducted over three growing seasons on four ecotopes with maize, sunflower, sorghum and wheat to test the hypothesis. They consisted of statistically designed experiments on two ecotopes at Glen and semi-statistical demonstration trails on two ecotopes on developing farmer's lands near Thaba Nchu. Detailed soil water content measurements were made on all four ecotopes, and runoff measurements were also made with automatic runoff measuring devices on the Glen ecotopes. These measurements made it possible to quantify the water balance and determine precipitation use efficiency. Maize and sunflower were found to be the best crops. Simulation models of these two crops, calibrated against measured results, were used together with long-term climate data to test the long-term validity of the short-term results from the field experiments. The results of both sets of tests showed that the water harvesting and basin tillage (WHB) part of the hypothesis is correct. Indications are that in the long-term, average yield increases compared to conventional tillage, of around 50% can be expected from maize and sunflower using the technique on the ecotopes tested. Although long-fallow has proved its value for very dry seasons, long-term yield predictions indicate that this strategy will be uneconomical. Mulch in the basins has been shown to be beneficial under certain circumstances. Additional research is needed for clarification in this connection. The technical aim of the project can be considered to have been achieved.

The second aim was to develop the capacity of two previously disadvantaged young people, with the aim of their becoming effective technical assistants for this kind of work. Intimate involvement with the many measurements and procedures necessary during field experimentation over the years has resulted in their becoming useful technical assistants. Theoretical training has also been carried out. First they were assisted to pass Std. 10 Biology to qualify them for further study. Then they were registered during 1999 for the first year of study towards the Diploma in Agricultural Management at Technikon SA. It is considered that this aim has also been satisfactorily achieved.

The third aim was to transfer to the emergent farmers the technology which had been developed. A number of field demonstrations and information days were held. Attendance was reasonably good. It is difficult to evaluate the extent to which this aim has been achieved.

Regarding the technical aim, the critical end products of the work are the measured yields for the different treatments and the CPF graphs of predicted long-term yields of maize and sunflower. The latter embody the current understanding by the authors of the critical water balance processes, and their ability to express these quantitatively and model them in a simple empirical way. Because of its simplicity in focusing on the dominating factor, and ease of adaptation to the complex spatial non-homogeneity of the WHB technique (Figure 2.1.1), the empirical sunflower stress model has made a valuable contribution to this study. With the introduction of more advanced modelling procedures it may be possible to adapt the DSSAT V3 maize model to perform well even for very low yields. The world-wide use of this model and the large number of very capable research workers involved make it attractive. The overall result is confidence in the conclusion that the WHB technique is significantly better than conventional tillage on these ecotopes for maize and sunflower, and probably also for sorghum. Sunflower and the new short season maize cultivars have the advantage that they can be planted early in January, which ensures flowering in March which has the most favorable rainfall: evaporation ratio of the summer months, and also the highest and most reliable rainfall (Table 3.2.1.). Sorghum and wheat are not well suited to these ecotopes for a number of reasons; details are presented in the report. The main reason for the success of the WHB technique is its ability to reduce runoff to zero, and reduce Es significantly.

Because of the large amount of handwork involved, the WHB technique is well suited for use on small plots and even in townships. Many people in semi-arid areas could be usefully employed if this technique was widely adopted, and food insecurity could be reduced at the same time.

Because the WHB technique has been shown in these experiments to generally reduce the overall runoff from the land to zero, soil loss from the land as a whole will also be minimal. This is an important advantage over conventional tillage. Measurements of soil losses on the long-term experiments at Pretoria and Glen have shown that mean annual soil losses from conventionally tilled lands range from 8 to 22 tons ha^{-1}, compared to 0.3 to 0.7 tons ha^{-1} from veld. Use of the WHB technique will therefore make a contribution to sustainable productivity. It is intended in a follow-up experiment to measure the extent of soil movement from the runoff strip into the basins, and possibly suppress this movement by placing mulch or stones on the runoff strip.

Additional research is needed to study the following:

* the influence of stones and mulch in the basin and runoff strip on yields and sustainability;
* detailed studies on the influence of different amounts of mulch, and of stones, on Es;
* the introduction of a legume in a rotation to reduce fertilizer costs;
* socio-economic aspects of the WHB technique with the aim of providing the Department of Agriculture with information regarding the area of land on different ecotopes needed to provide the basic food requirements and/or income for a family;
* soil fertility aspects of the WHB technique;
* improvements to the sunflower stress model and DSSAT V3 maize model, and the development of a simple maize stress model;
* the possibility of employing micro-catchment runoff farming to further improve crop water supply (Figure 1.3.1.);
* detailed rainfall intensity – runoff studies, in cooperation with Prof. S. Walker in her WRC project titled "The application of rainfall intensity-runoff relations to water harvesting from micro-catchments to stabilize food production in rural and peri-urban settlements".

Acknowledgements:

The contributions of the following people and organizations towards the success of this project are gratefully acknowledged:

1) The Water Research Commission for funding the project.

2) The members of the Steering Committee:

Mr. D.S. van der Merwe	Water Research Commission (Chairman)
Dr. G.C. Green	Water Research Commission
Mr. F.P. Marais	Water Research Commission (Secretary)
Dr. D.J. Beukes	ARC – ISCW
Prof. S. Walker	University of the Free State
Dr. L.D. van Rensburg	University of the Free State

3) The Agricultural Research Council for funding, and the Management and Administration of the Institute for Soil Climate and Water for their continual support in many ways. The valuable and considerable input by Dr. Beukes is acknowledged in particular.

4) The Free State Department of Agriculture for providing office accommodation, experimental land, much support from the Farm, IT and Extension sections, and support in many other ways. Valuable assistance from the following people is acknowledged in particular: Jaen van der Walt, Benedict Modise, Johan van den Berg, Francois van Deventer, Cecil Manley, Maksie Baard, Koos Snyman, Dr. Matli, George Madiba and Stephanie Bekker.

5) Farmers, Mr. R. Thekisho and Mr. C. Ramagaga, for providing land for the on-farm demonstration plots.

6) The PANNAR and SENSAKO companies for supplying seed.

7) Mr. Mike Fair at UOVS for statistical analyses.

8) All the non-author members of the ARC – ISCW research team at Glen who worked diligently, loyally and consistently, sometimes under very adverse conditions in the field.

Mrs. Trix de Bruin
Mr. Daniel Thutani
Mr. Phillip Khumisi
Mr. Elias Sebolai
Mr. David Thamae
Also many other labourers

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LIST OF ABBREVIATIONS

α	=	slope of the relationship for phase 2 evaporation between ΣEs en $t^{1/2}$ (Ritchie, 1972)
AI	=	aridity index (rainfall/evaporation)
ARC	=	Agricultural Research Council
ARC-GCI	=	Agricultural Research Council - Grain Crops Institute
ARC-ISCW	=	Agricultural Research Council - Institute for Soil Climate and Water
BD	=	bulk density
Bo	=	Glen/Bonhein-Onrus ecotope
CEC	=	cation exchange capacity
CGIAR	=	Consultative Group for International Agricultural Research
cl	=	clay
CMUL	=	crop modified upper limit of plant available water
CPF	=	cumulative probability function
CR	=	neutron water meter count ratio
CR_{max}	=	maximum count ratio
CV	=	coefficient of variation
D	=	deep drainage
DAP	=	days after planting
Dg	=	deep drainage during the growing season
DkBr	=	dark brown
DSSAT-V3	=	Decision Support System of Agrotechnology Transfer - version 3
DUL	=	drained upper limit of available water (the value obtained with the soil surface covered with a plastic sheet, i.e. zero evaporation)
DUL_{ES}	=	drained upper limit of available water with the soil surface exposed to evaporation
Ei	=	evaporation from the soil surface during the first phase
Eo	=	atmospheric evaporative demand
Ep	=	potential evaporation
Es	=	evaporation from the soil surface
ET	=	evapotranspiration (the same as Es + Ev or Es + T)
ET_r	=	evaportranspiration rate
Ev	=	evaporation from the vegetation
fPo	=	fraction of porosity
fSat	=	field saturation
FSDA	=	Free State Department of Agriculture
FTESW	=	fraction of total extactable soil water
HC	=	hydraulic conductivity

IBSNAT	=	International Benchmark Sites Network for Agrotechnolgy Transfer
If	=	final infiltration rate
ISCW	=	Institute for Soil Climate and Water
ISF	=	integrated stress factor
Ks	=	Khumo/Swartland-Amandel ecotope
κ	=	transpiration efficiency coefficient (the product of transpiration efficiency and the mean saturation deficit, over the growing season, of the atmosphere during sunlight hours)
LL	=	lower limit of plant available water
LSD	=	least significant difference
λ	=	stress weighting factor in the sunflower model
M	=	measured
MACRF	=	macro-catchment runoff farming
MICRF	=	micro-catchment runoff farming
ml	=	melanic
MNCRF	=	mini-catchment runoff farming (equivalent in this project to in-field water harvesting)
mottl.	=	mottled
MSS	=	minimum surface storage
ND	=	not determined
NSD	=	no significant difference
NWM	=	neutron water meter
NY	=	zero yield
θ	=	soil water content
$\theta h_{(n)}$	=	soil water content (volumetric basis) of the root zone at harvest for the current growing season
$\theta h_{(n-1)}$	=	soil water content (volumetric basis) of the root zone at harvest for the previous growing season
θi	=	initial soil water content during Es measurements
θm	=	soil water content on a mass basis
θo	=	soil water content at which Es ceases
θp	=	soil water content (volumetric basis) of the root zone at planting
$\theta p_{(n)}$	=	soil water content (volumetric basis) of the root zone at planting for the current growing season
θr	=	soil water content (volumetric basis) of the root zone
θv	=	soil water content on a volumetric basis
ot	=	orthic diagnostic soil horizon
P	=	precipitation
P_f	=	precipitation during the fallow season
P_g	=	precipitation during the growing season
P_i	=	precipitation (or rainfall) intensity

PUE	=	precipitation use efficiency
PUE_g	=	precipitation use efficiency for the growing season
PUE_{gf}	=	precipitation use efficiency for the growing season plus fallow season
$PUE_{gf(R)}$	=	as PUE_{gf} but expressed in terms of gross earnings
Po	=	porosity
R	=	runoff
R_a	=	runoff measured from runoff plots with an automatic measuring device
RFWH	=	runoff farming water harvesting
R_g	=	runoff during the growing season
R_l	=	runoff measured in the land
RMSE	=	root mean square error
$RMSE_s$	=	systematic root mean square error
$RMSE_u$	=	unsystematic root mean square error
RSE	=	rainfall storage efficiency
R%	=	runoff expressed as a percentage of the rainfall
SD	=	saturation deficit
SD_o	=	a saturation deficit of 1 k Pa
SF	=	stress factor in the sunflower model
Si	=	silt
SIWH	=	supplemental irrigation water harvesting
so	=	saprolite
SS	=	serious stress
SST	=	surface storage
Sw	=	Glen/Swartland-Rouxville ecotope
ΔS	=	water stored in the root zone
t	=	time after wetting
T	=	transpiration (equivalent to Ev)
TA	=	technical assistant
TESW	=	total extractable soil water
ti	=	period of phase 1 evaporation from the soil surface
TST	=	total soil tillage (equivalent to conventional soil tillage)
TSTM	=	total soil tillage with mulch in the 1 m crop row
U	=	the upper limit of the amount of water evaporated during phase 1 of evaporation from the soil surface (Ritchie, 1972)
Va	=	Vlakspruit/Arcadia-Lonehill ecotope
ve	=	vertic diagnostic horizon
vp	=	pedocutanic diagnostic horizon
WH	=	water harvesting
WHB	=	the production technique employing a combination of water harvesting and basins
WHB(A)	=	WHB planted annually

WHB(B)	=	WHB planted biannually (long fallow)
WHBM	=	WHB with mulch in the basins
WHBM(A)	=	WHB with mulch in the basins and planted annually
WHBM(B)	=	WHB with mulch in the basins and planted biannually
WUE	=	water use efficiency
WUE_{ET}	=	water use efficiency in terms of water used for evapotranspiration
WUE_T	=	water use efficiency in terms of water used for transpiration
Y	=	crop yield, either as grain or biomass
Zi	=	thickness of the soil layer from which evaporation takes place

Figure 1 Locality map showing the position of the ecotopes on which the field trails were carried out: Glen/Bonheim-Onrus (Bo); Glen/Swartland-Rouxville (Sw); Khumo/Swartland-Amandel (Ks); Vlakspruit/Arcadia-Lonehill (Va)

1. INTRODUCTION

1.1 THE PROBLEM AND PROPOSED SOLUTION

A large area east of Bloemfontein, has been earmarked for developing farmers. There is a large population in the scattered villages and the two towns Thaba Nchu and Botshabelo. The area is marginal for crop production because of relatively low and erratic rainfall and dominantly clay soils on which the precipitation use efficiency (PUE) is low because of high losses due to runoff (R) and evaporation from the soil surface (Es). It is hypothesised that a production technique that combines the advantages of water harvesting, no-till, basin tillage, mulching and long-fallow, will make sustainable production possible at a reasonable level for selected crops. The specific advantages of each of these techniques are considered to be:

(a) basin tillage will minimize overall runoff from the land;

(b) water harvesting from the untilled, crusted soil, 2 m wide inter-crop row area will serve to concentrate runoff water in the basins and by so doing promote infiltration of as much water as possible past the Es sensitive surface zone, and so minimize the loss due to Es;

(c) mulch in the basins will minimize Es;

(d) long-fallow will serve to get the root zone water content (θr) as high as possible at planting, and by so doing increase the chance of attaining sustainability.

1.2 AIMS OF THE PROJECT

1.2.1 To identify for selected benchmark ecotopes, in a marginal cropping area, the crop production techniques that will result in optimum PUE and sustainable productivity being achieved.

1.2.2 To develop the capacity of two previously disadvantaged young people, with the aim of their becoming effective technical assistants.

1.2.3 To embark on an effective technology transfer programme to ensure optimum application of the results by the farmers, by including the farmers' committees as role players in the project.

1.3 TERMINOLOGY

Water harvesting

The term water harvesting is used to describe a number of different practices that have been used for centuries in dry areas to collect and use rainfall more efficiently. There is a certain amount of confusion with regard to terminology about this subject in the literature. It is therefore considered advisable to adhere to those terms and their definitions which currently have the best chance of being accepted world-wide. The terms that will be used in this report have been taken from a recent paper (Oweis, Hachum & Kijne, 1999) from the International Water Management Institute which is one of the CGIAR Centres. Water harvesting (WH) is the defined as "the process of concentrating rainfall as runoff from a larger area for use in a smaller target area". WH is further subdivided as shown in Figure 1.3.1.

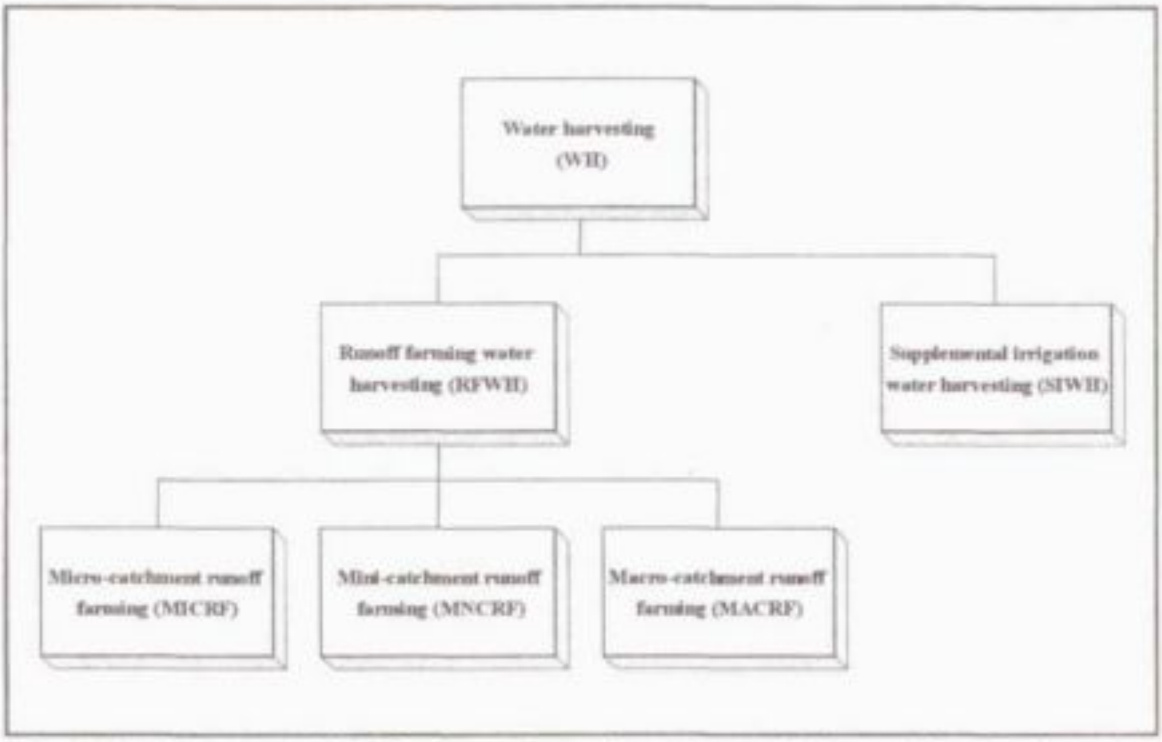

Figure 1.3.1 Proposed classification of water harvesting techniques (After Oweis, Hachum & Kijne, 1999)

The relevant term for the procedure used in the present study is "mini-catchment runoff farming" (MNCRF). This term will be considered as equivalent to the term "in-field water harvesting" used in earlier progress reports.

Precipitation use efficiency (PUE) and water use efficiency (WUE)

PUE is used in preference to rainfall use efficiency to avoid confusion since RUE is used in international agricultural literature for radiation use efficiency. Good understanding of the PUE concept is important for this project as it is a focal point in the title. It is a focal point because the project involves comparing the efficiency with which different **tillage practices** conserve water. This comparison cannot effectively be made using WUE as defined and widely used in agricultural literature. WUE is in fact a component of PUE, as will be shown in the discussion which follows.

The general water balance equation for dryland crop production can be written as follows:

$$\underset{\text{water for yield}}{T} = \underset{\text{water gains}}{(P + \Delta S)} - \underset{\text{water losses}}{(R + Es + D)} \quad \ldots\ldots (1.1)$$

where:

T = transpiration (or, evaporation from the crop Ev) (mm)
P = precipitation (mm)
ΔS = water extracted from the root zone (mm)
Es = evaporation from the soil surface (mm)
R = runoff (mm)
D = deep drainage (mm)

The comparable equation used by Gregory (1989) (his equation 3), is misleading since ΔS has been excluded.

Where the water balance refers to the growing season only the suffix g is needed for each of the components. In order to insure that ΔS gets the correct sign it is necessary to specify that:

$$\Delta S = \theta_{p\,(n)} - \theta_{h\,(n)} \quad \ldots\ldots (1.2)$$

where:

$\theta_{p\,(n)}$ = water content of the root zone at planting for the current season(mm)
$\theta_{h\,(n)}$ = water content of the root zone at harvest for the current season (mm)

Tillage practices such as WH, and specifically the MNCFR strategy being dealt with here, are concerned with water conservation during the fallow period as well as during the growing season. For the fallow period the rainfall storage efficiency (RSE) equation of Mathews & Army (1960) is relevant, viz.

$$RSE = \frac{(\theta_{p\,(n)} - \theta_{h\,(n-1)})}{P_f} \quad \ldots\ldots (1.3)$$

where:

$\theta_{p\,(n)}$ = as in eqn. 1.2
$\theta_{h\,(n-1)}$ = water content of the root zone at harvest for the previous season (mm)
P_f = precipitation during the fallow period (mm)

The following is a widely used definition of water use efficiency (Hillel, 1972; Passioura, 1983; Tanner & Sinclair, 1983).

$$WUE = \frac{Y}{T + Es} \ \ldots\ldots \ \text{kg mm}^{-1}\ \text{ha}^{-1} \ \ldots\ldots (1.4)$$

where: Y = crop yield (kg ha^{-1})

WUE therefore measures the efficiency with which a particular crop can convert the water available to it, during a particular growing season, into yield. It does not measure the efficiency with which the total amount of rainfall which fell during the growing season became available to the crop. WUE also ignores rainfall during the preceding fallow season.

If it is possible to separate T and Es, WUE can also be defined by equation 1.5, (Tanner & Sinclair, 1983).

$$\mathrm{WUE} = \frac{Y}{T} \quad \ldots\ldots\ldots\ldots \quad \mathrm{kg\ mm^{-1}\ ha^{-1}} \quad \ldots\ldots\ldots\ldots \quad (1.5)$$

Equation 1.5 is more meaningful than equation 1.4 since it quantifies more accurately the physiological ability of the crop to convert water into yield.

To study MNCFR strategies, a holistic parameter is needed that incorporates the following: water losses (R + Es + D) during the growing season; (RSE); and WUE. PUE for the growing season plus fallow season (PUE_{gf}) as defined by Hensley, Snyman and Potgieter (1990), meets these requirements. It is formulated by combining equations 1.1 and 1.3, and1.4.

$$\mathrm{PUE}_{gf} = \frac{Y}{(\theta_{h(n-1)} - \theta_{p(n)}) + R_g + D_g + (Y/\mathrm{WUE}) + [(\theta_{p(n)} - \theta_{h(n-1)})/\mathrm{RSE}]} \quad \ldots \ \mathrm{kg\ ha^{-1}\ mm^{-1}} \ \ldots \ (1.6)$$

To be able to use this equation to express PUE quantitatively, reliable measurements or estimates of R_g and D_g are needed. The equation shows that increases in R_g and D_g cause PUE to decrease, whereas increases in WUE and RSE cause PUE to increase. PUE_{gf} can also be expressed in the simplified form given in equation 1.7.

$$\mathrm{PUE}_{gf} = \frac{Y}{P_g + P_f + (\theta_{h(n-1)} - \theta_{h(n)})} \quad \ldots\ldots\ldots\ldots \quad \mathrm{kg\ ha^{-1}\ mm^{-1}} \quad \ldots\ldots\ldots\ldots \quad (1.7)$$

PUE for the growing season (PUE_g) is defined by equation (1.8).

$$\mathrm{PUE}_{g} = \frac{Y}{P_g + (\theta_{p(n)} - \theta_{h(n)})} \quad \ldots\ldots\ldots\ldots \quad \mathrm{kg\ ha^{-1}\ mm^{-1}} \quad \ldots\ldots\ldots\ldots \quad (1.8)$$

2. PROCEDURE

2.1 IDENTIFYING BENCHMARK ECOTOPES

An early preparatory step was to make a rapid reconnaissance soil survey of the target area to identify important ecotopes. Good use was made of valuable information from the Land Type Survey (Soil and Irrigation Research Institute, 1991). The target area is situated immediately east of Bloemfontein and approximately between Excelsior in the north and De Wetsdorp in the south.

This step was followed by a search for two similar ecotopes on the Glen Experiment Station where the climate, topography and geology is similar; and for two suitable ecotopes on the farms of developing farmers in the target area - to serve as demonstration plots. Two suitable ecotopes were found at Glen about 300 m apart in well-fenced camps (See Figure 1). Permission was obtained from the Free State Department of Agriculture to carry out agronomic experiments on these areas. For the demonstration plots permission was obtained from Mr. C. Ramagaga and Mr. R. Thekisho to establish these on their farms Vlakspruit and Khumo respectively, where suitable ecotopes had been identified (See Figure 1). These two farms are situated between Thaba Nchu and Excelsior. The climate is similar to that at Glen.

2.2 EXPERIMENTAL PLAN

To test the hypothesis on the two ecotopes at Glen ("on-station" experiment) a partially randomised statistical design with two tillage treatments and three replications was employed. The two tillage treatments were as follows:

- TST: annual cropping with conventional total soil tillage methods,
- WHB: annual cropping employing a combination of a no-till type of mini-catchment runoff farming (MNCFR or in-field water harvesting) and basin tillage.

An additional treatment was WHB planted bi-annually, i.e. long fallow. The annual and bi-annual treatments are differentiated by the symbols A or B in brackets after the treatment symbols. The experiment was repeated for each of the crops maize, sunflower, sorghum and wheat in four separate blocks. The size of each block was 39 m x 48 m and it contained 12 plots, each 12 m x 13 m in size.

Funding for the project was provided for the three calender years 1997, 1998 and 1999. As this period only covered two complete summer seasons it was decided to include a crop during the 1996/97 season on "temporary" plots outside the final experimental area, which had not yet been laid out at planting time for the 96/97 season. For that season the two treatments were TST and WHB as described above. While preparing for the 97/98 season, it was decided to introduce mulching as an additional treatment superimposed on the others in a split-plot design. The symbol M immediately after TST or WHB indicates mulching.

The whole land was ploughed initially and then disced to obtain a fairly level surface. All subsequent tillage actions were on the contour. On the WHB plots basins were initially constructed using a basin tillage plough. Final forming to produce the layout shown in Figure 2.2.1 was done by hand. The runoff area on the WHB plots was levelled by raking and then left undisturbed, weeds being controlled by spraying with weed-killer. The surface soon developed a crust which enhanced runoff into the basins. On the TST plots, the 2 m interrow area was cultivated at appropriate times in the conventional way. The surface therefore remained rough. On all the mulch treatments the organic material was placed between the 1 m rows at an application rate around 8 tons ha^{-1}. NWM (neutron water meter) access tubes were inserted to a depth of 1200 mm in the basins, in the crop rows, and in the runoff area as shown in Figure 2.2.1. All four access tubes were not always present in each replication, as this would have meant too large a number (768) to read regularly. Rationalization was necessary. The total number of access tubes inserted on the two Glen ecotopes was 526 and a total of 68 in the Thaba Nchu demonstration plots. It was considered that this would compensate for spatial variation to a reasonable extent and provide useful mean values.

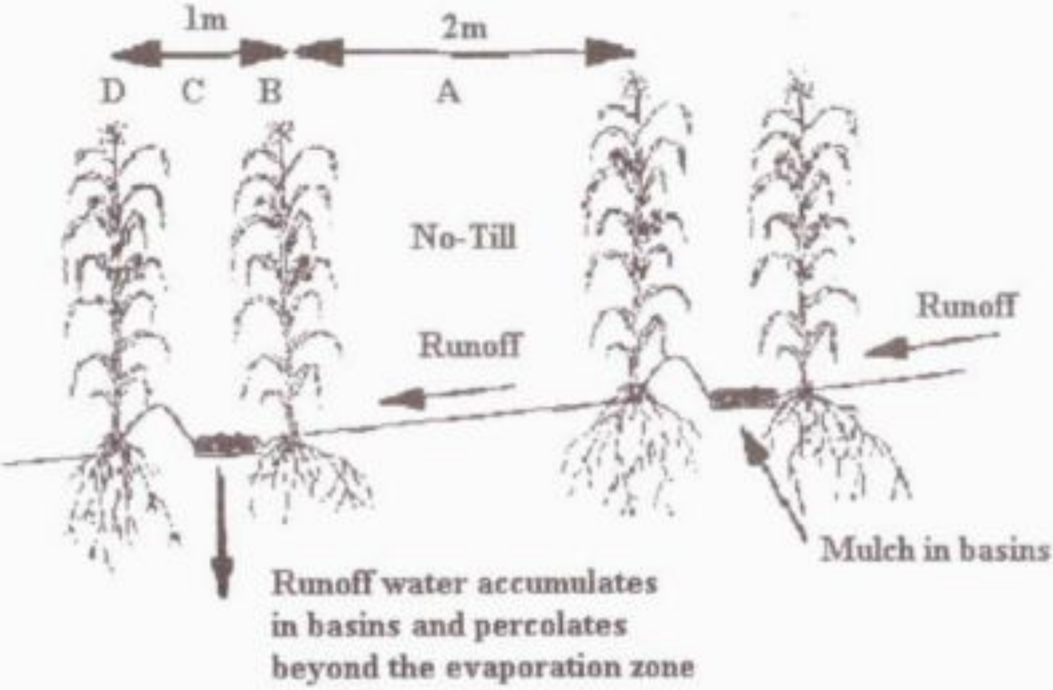

Figure 2.2.1 A diagrammatic description of the WHBM production technique, showing the distribution of access tubes (A, B, C, D). Row spacing and access tube distribution was similar in the other treatments

For the demonstration plots on Vlakspruit and Khumo (Thaba Nchu "on-farm" trials) a semi-statistical design was employed consisting of 2 treatments with 3 replications. The treatments were the same as those in the on-station trials, excepting that mulch was applied on a split plot basis only to the WHB treatments.

Crop details for the experiments are presented in Table 2.1. Soil samples were taken for fertility tests prior to each growing season. Since water is the main limiting factor on these ecotopes, fertilizer applications aimed at a moderate yield were applied. They are as follows for all crops on all ecotopes: 50 kg ha^{-1} of 3:1:0 (28%) + Zn.

Table 2.1 Crop details for the Glen and Thaba Nchu experiments

LOCALITY	CROP	CULTIVAR	ROW SPACING (m)	POPULATION (plants ha^{-1})	BONHEIM		SWARTLAND	
					Planting date	Harvest date	Planting date	Harvest date
Glen	Wheat	TUGELA DN	0.45 m	653 600	16-07-97	03-12-97	19-06-97	21-11-97
					17-07-98	29-11-98	17-07-98	29-11-98
	Sorghum	DC 75	tramlines at 1 m x 2m	51 500	17-12-96	13-05-97	17-12-96	13-05-97
				60 600	05-01-98	20-05-98	06-01-98	18-05-98
					01-12-98	22-04-99	02-12-98	21-04-99
	Maize	PAN 6043	tramlines at 1 m x 2m	15 300	17-12-96	05-05-97	17-12-96	05-05-97
				10 000	17-12-97	05-05-98	18-12-97	06-05-98
					7-12-98	09-04-99	7-12-98	10-04-99
	Sunflower	SNK 37	tramlines at 1 m x 2m	26 900	17-12-96	22-04-97	17-12-96	22-04-97
				33 300	13-01-98	12-05-98	14-01-98	06-05-98
					05-01-99	08-05-99	06-01-99	06-05-99
Thaba Nchu	Sunflower	SNK 37	tramlines at 1 m x 2m	33 300	08-01-98	21-05-98	07-01-98	21-05-98
					06-01-99	12-05-99	07-01-99	16-05-99

2.3 MEASUREMENTS MADE

Climate measurements were made by means of an automatic weather station at the experimental site on the Glen ecotopes. For times when this station failed for some reason, data from the nearby Glen meteorological station were used. For the Thaba Nchu plots rainfall was measured by means of rain gauges and also by tipping bucket rain gauges capable of measuring rainfall intensity.

In situ NWM calibrations were made for each of the soils. Details of the procedure adopted are presented in Appendix 2.3.1. NWM soil water content measurements were made frequently at all access tubes. Four readings were always made at each tube, one for each of the depths 0-300 mm, 300-600 mm, 600-900 and 900-1200 mm. Summation of the results gave the water content of the root zone (θr).

Runoff measurements were made on 3 m wide x 20 m long runoff plots on each of the two Glen ecotopes using automatic tipping bucket runoff meters. There were separate runoff plots to represent the tillage treatments used on the experiments, viz. no-till (with a flat, minimum surface storage surface), TST and WHB. During the 1998/99 rain season runoff was also measured on the Glen ecotopes from selected 2 m runoff strips in the experimental plots. Three of the long-fallow plots on each ecotope were used. A plastic lined sump at the base of the runoff strip was used to collect the water. The water was pumped out after each rainfall event into calibrated plastic drums and the volume recorded.

Plant measurements included flowering dates, biomass and grain yield.

3. ECOTOPE CHARACTERIZATION

3.1 INTRODUCTION

The biological system which produces all the land-grown food and fibre in the world is depicted in Figure 3.1

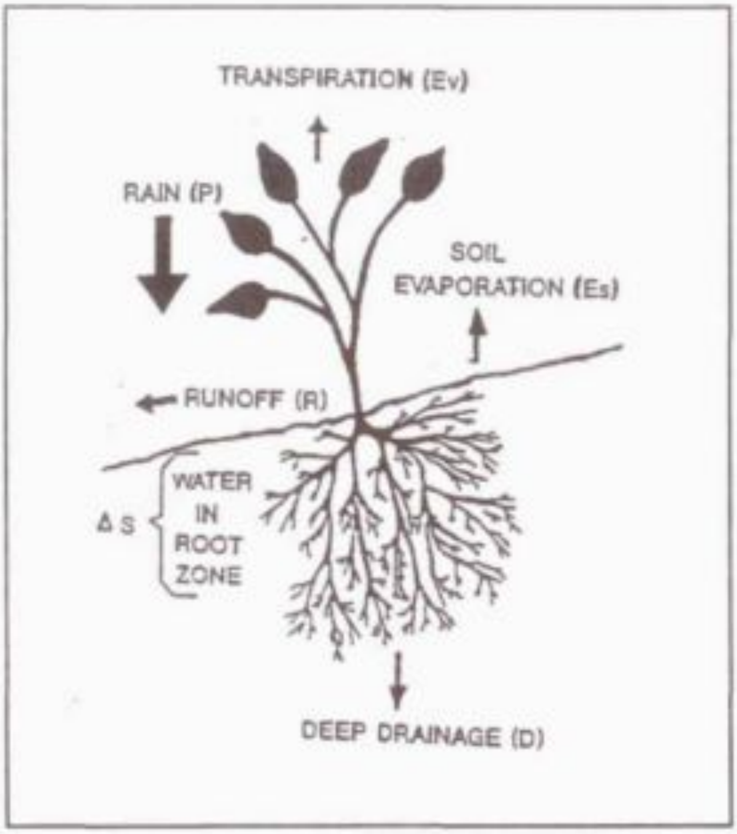

Figure 3.1 A diagrammatic representation of the atmosphere-plant-soil system showing the main water balance processes

There are three natural resource factors which influence the productivity of this system. They are climate, topography and soil. Each homogenous-piece of land has a unique combination of climate characteristics, topographic characteristics and soil characteristics. Such a piece of land is described as an ecotope (MacVicar, Scotney, Skinner, Niehaus, & Loubser, 1974). Wherever this unique combination is replicated anywhere in the world, the productivity of the system and the management practices needed to optimise this productivity at a sustainable level will be the same. An ecotope can also be defined conceptually by expanding the atmosphere-plant-soil system spatially to those points in the landscape where there is a significant change in any of these three factors. Because of the wide implications inherent in its definition, the ecotope is clearly the correct landscape unit in which to store and transfer all information about agricultural productivity. A vast improvement in the efficiency of agricultural research world-wide should be possible if this concept was used effectively.

It is not possible to do detailed research work on every ecotope used for crop production in a country. To maximize research efficiency it is therefore necessary that attention be focussed on carefully selected benchmark ecotopes. To ensure efficient extrapolation of the results obtained on these ecotopes to all the others (i.e. pedotransfer actions), it is desirable that the main ecotope characteristics that affect productivity be characterized in detail. It has been attempted to do this in the present study on four benchmark ecotopes chosen to represent the large marginal cropping area east of Bloemfontein.

Each of the three natural resources factors, i.e. climate, topography and soil, have characteristics which have a major influence on the productivity of the system as a whole. The main focus here will be placed on these characteristics, with soil as the central theme in the short literature review which follows. The water balance equation presented in equation 1.1 will be used as the framework. To optimize rainfall use efficiency it is necessary that water losses via Es, R and D be minimised. Because of what has already been said in Chapter 1, the two important losses here are Es and R.

Evaporation

Hoffman (1997) studied Es from different soils contained in microlysimeters. He concluded that the soil water content at which Es ceases (θ_0), and the thickness of the soil layer from which Es takes place (Zi), can be estimated from the silt (Si) plus clay (Cl) content of the soil using the following equations:

$$\theta_0 = 0.001\,(Si + Cl) + 0.00756 \qquad (3.1)$$

$$Zi = \exp\,[3.4244\,(Si + Cl)^{-2} + 5.7193] \qquad (3.2)$$

Equation 3.1 did not give reliable predictions of θ_0 for the soils in this study, possibly because the clay contents are generally far higher than those in the soils studied by Hoffman. Equation 3.2 predicts a Zi value of 305 mm for all the soils studied in this report. The equation predicts a significant increase in this depth to 315 mm only when the Si + Cl content decreases to 10%. This provides support for restricting the Es zone in this study to the 0-300 mm layer.

Hoffman (1997) compared four evaporation equations and found that the Ritchie (1972) model predicted cumulative Es (ΣEs) the best, and recommends the following slightly adapted version of the Ritchie model:

$$\Sigma Es = [\,47.0497\,(\theta_i - \theta_0) + 0.623]\,\sqrt{t} \qquad (3.3)$$

where t = time after starting (days)

θ_i = soil water content at the start of the measurement (v/v)

Where θ_i was taken as the field determined drained upper limit for the 0-300 mm layer ($DUL_{0\text{-}300}$) in this study, the equation predicted ΣEs well for the Bonheim soil, and less well where θ_i was taken as field saturation (fSat.). Using for most of his experiments soils which ranged in (Si + Cl) content from 5% to 16%, Hoffman (1997) reported that "the constant evaporation stage (stage

1) lasted only a few hours". There is however, evidence from two of his experiments for more prolonged phase 1 evaporation. In his investigation to determine "potential" Es, soils of four different textures were kept close to saturation by maintaining a water table at a depth of 100 mm. It was found that Es was on the average 1.56 Ep (where Ep = potential evaporation, i.e. atmospheric evaporative demand). Whatever the reason may be for Es being so high, this is evidence that the hydraulic conductivity of the soil played a negligible role in these very wet soils, and hence evidence for phase 1 evaporation. In the study of the influence of 20%, 40% and 80% of shading on Es it was found that all these reduced Es; that the reduction was in proportion to the degree of shading during of the first 30 days after wetting to "field capacity", and further that the influence of shading was more pronounced on a sandy clay loam soil than on a sand. It seems logical that if there was no phase 1 Es controlled by Ep, reducing the latter by shading should have no influence on Es. Conversely, the observation that shading did in fact reduce Es indicates that there is a phase controlled by Ep, which becomes extended by shading.

Ritchie proposed Equation 3.4 to describe Es from a bare soil.

$$\Sigma Es = \Sigma Ei + \alpha(t - t_i)^{1/2} \quad \text{for } t > t_i \qquad (3.4)$$

where

ΣE_i = cumulative evaporation during the first phase = ΣEp
ΣEp = cumulative potential evaporation (mm)
t = time after wetting (days)
t_i = period of phase 1 (days)
α = slope of the relationship for phase 2 between ΣEs and $t^{1/2}$

It will be assumed that equation 3.4 is a suitable description of evaporation from a bare soil. Effective characterization of the process on a particular ecotope therefore requires that an evaporation curve be determined over a suitable period of time and that Ep be measured simultaneously. The results will provide the information needed to determine the two characteristic values proposed by Ritchie (1972), namely the upper limit of stage 1 cumulative evaporation (U (mm)), and α as defined for equation 3.4.

3.2 GLEN/BONHEIM-ONRUS ECOTOPE (Bo)

3.2.1 Climate

Rainfall and temperature data for Glen are available for 74 years (1922-1996) and class A pan evaporation data for 38 years (1958-1996). Monthly averages are presented in Table 3.2.1

Table 3.2.1 Long-term monthly and annual climate data from the Glen meteorological station (ARC-ISCW data)

Item	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Long term mean
rain (mm)	8	12	19	48	67	67	82	79	84	51	19	9	545
evap.*1	96	143	219	248	264	301	313	216	186	129	118	84	2317
max T*2	17.8	20.6	24.5	26.8	28.4	30.3	30.9	29.4	27.2	23.8	20.6	17.6	24.8
min T	-1.6	0.9	5.2	9.2	11.7	13.9	15.2	14.6	12.3	7.7	2.6	-1.2	7.5
ave. T	8.1	10.7	14.9	18.0	20.2	22.1	23.0	22.0	19.7	15.7	11.6	8.2	16.2
AI*3	0.08	0.08	0.09	0.19	0.25	0.22	0.26	0.37	0.45	0.40	0.16	0.11	0.24

*1 Class A pan
*2 T = temperature in °C; mean values for the month
*3 Aridity index = rain/evap.

The high evaporative demand and relatively low rainfall, make this a semi-arid climate, with worst conditions for crop production generally occurring during December, January and February. Rainfall during these months is generally very erratic with much of it in the form of high intensity rainfall events. March rainfall is the highest and also the most reliable, with the additional advantage during this month of by far the lowest evaporative demand of the summer growing season months. This feature can be used to advantage by planting crops with a short growing season early in January. Examples are sunflower and the new quick-growing maize cultivars. Low temperatures are experienced during the winter, coupled with very little rain. In this sort of climate there is generally no shortage of radiation.

3.2.2 Topography

The experimental plots are located on an upper footslope terrain unit with a straight, 1% slope in a westerly direction.

3.2.3 Soil

Pedological characteristics

A detailed profile description together with analytical data is presented in Appendices 3.2.3.1 and 3.2.3.2. The soil is classified as belonging to the Onrus Family of the Bonheim Form. It is a dark brown clay soil overlying $CaCO_3$ enriched sandstone saprolite at a depth of 800 mm. The parent material of the solum is a mixture of dolerite and sandstone colluvium, with dolerite dominating. The underlying saprolite is sufficiently weathered to a depth of at least 1200 mm to offer no significant impedance to root development to that depth. The soil has a high CEC of 24-25/ $cmol^{+}$ kg^{-1} soil, a strong structure, and a high content of smectite clay minerals which cause large cracks that penetrate deep into the soil when it is very dry. The surface soil has a high plasticity index of between 21 and 33, and self-mulching properties which promote erosion when high intensity rain falls on the dry soil. In the surface soil the exchangeable Na content is fortunately low (0.7 $cmol^{+}$ kg^{-1} soil) and it cannot therefore be blamed for exacerbating the swell-shrink properties. However, the relatively high exchangeable Mg content (11-12 $cmol^{+}kg^{-1}$ soil), may be promoting the cracking.

Soil water extraction and drainage characteristics

Important features are summarised in Table 3.2.3.1. The high water holding capacity of the root zone is expressed by the high DUL value of 385 mm. The equivalent for a loamy sand soil would be of the order of 180 mm. In spite of the high clay content and strong structure of the B horizon, root water extraction to the lower limit is shown to be very similar from each 300 mm layer to the bottom of the root zone. However, a considerable fraction of total extractable soil water (TESW) for all the crops probably occurs between first serious stress (SS) and LL, and therefore presumably does not contribute a great deal to grain yield. This can therefore be described as "slowly available". In the case of maize the root zone value of SS-LL is 31 mm, comprised of 6 mm, 9 mm, 8 mm, and 8 mm, for each of the soil layers in order of increasing depth. These values reflect the decreasing density of root ramification with depth. A clearer picture of water extraction by the four crops is presented in Figure 3.2.3.1. The area of each rectangle, representing a soil depth of 300, mm is proportional to TESW for that layer.

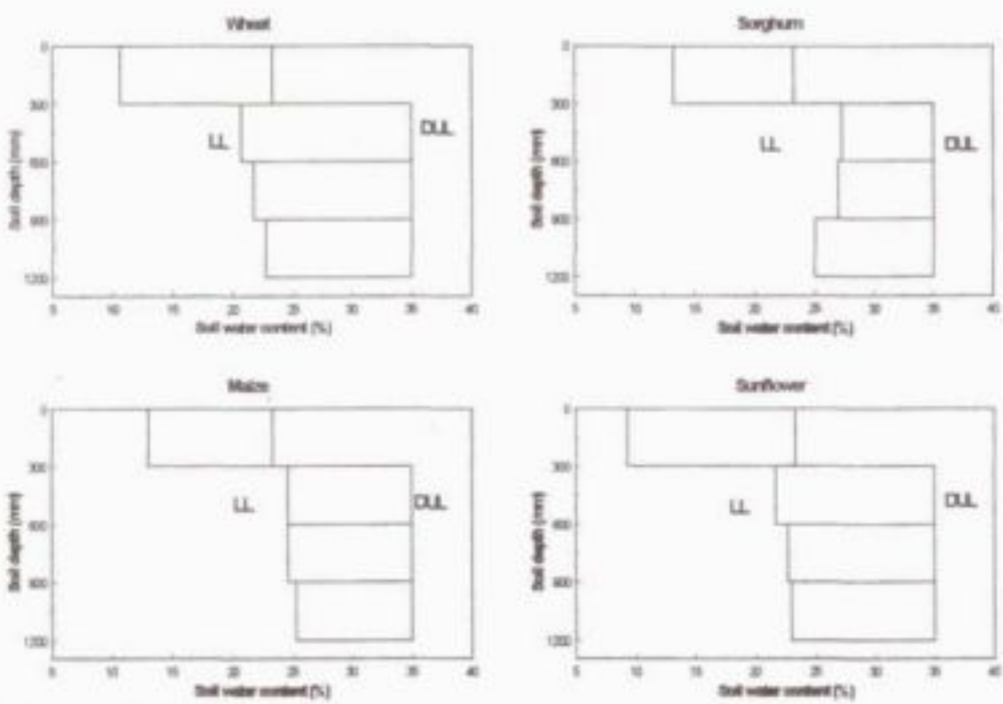

Figure 3.2.3.1 Soil water extraction diagrams for different crops on the Glen/Bonheim-Onrus ecotope : Rootzone1200 mm. Soil water content is vol.%

A drainage curve for the whole root zone, which provides the information for determining DUL, is presented in Figure 3.2.3.2. Equation 3.2.3.1 provides a mathematical description of the curve and enables the drainage rate at any time after field saturation (fSat) to be calculated.

$$Y \quad = \quad 507 - 17.64\,(\ln t) \ldots\ldots \text{mm} \ldots\ldots\ldots r^2 = 0.89 \ldots\ldots\ldots\ldots \quad (3.2.3.1)$$

where:

Y = water content of the root zone (mm)
t = time (hrs) after the drainage starts at a root zone water content of fSat.

Equation 3.2.3.1 makes it possible to make estimates of D after periods of heavy rain. This is necessary to quantify the water balance (equation 1.1). For these estimates to be reliable, another factor needs to be taken into account. When the water content of the root zone (θr) exceeds DUL, D does not necessarily start. The water above DUL, percolating slowly through the root zone, that is taken up by plant roots is catered for by the crop modified upper limit (CMUL) concept (Hattingh, 1993). Using that procedure the CMUL value for maize is 422 mm i.e. 37 mm above DUL. The CMUL concept as originally formulated is, however, inadequate as it assumes equal distribution of extraction in terms of Es + T from each of the soil layers. Since the intensity of root ramification is greater in the surface soil, and decreases with depth, the rate of soil water extraction is expected to follow the same pattern. Appropriate refinement of the CMUL concept is therefore necessary. Details in this connection are presented in appendix 3.2.3.4, but adherence to this degree of detail has not been observed in this project.

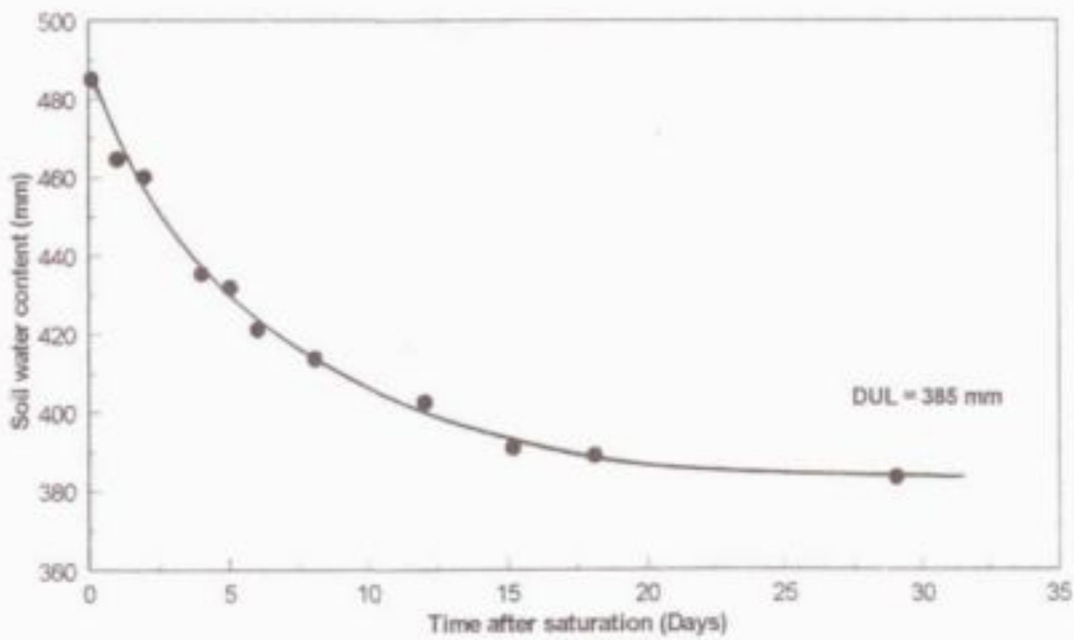

Figure 3.2.3.2 Drainage curve for the Glen/Bonheim-Onrus ecotope: Rootzone 1200 mm

Another factor that needs to be considered when estimating D is the water content of the deepest layer ($\theta_{900\text{-}1200}$). Only if this exceeds $DUL_{900\text{-}1200}$ can one be sure that D has occurred. This principle was observed in this study. For an example see paragraph (a) under 5.1.1.

The root zone drainage curve described in Figure 3.2.3.2 is determined with a plastic sheet on the surface to prevent Es. In a bare field soil saturated after heavy rain, there will be water losses by D and Es from the surface layer between fSat and DUL. Below DUL Es will be the only loss. Because of this, the field determination of an Es curve requires that losses by D be taken into account between fSat and DUL. A drainage curve for the 0-300 mm layer, obtained with a plastic cover, provides the necessary information. Equation 3.2.3.2 describes the curve for Bo. Symbols are the same as for equation 3.2.3.1.

$$Y = 145 - 11.65 (\ln t) \text{ ......mm.......... } r^2 = 0.92 \text{ .... } (3.2.3.2)$$

Table 3.2.3.1 The soil component of the Glen/Bonheim-Onrus ecotope. The effective root zone for the crops recorded is considered to be 0-1200 mm

PROFILE DETAIL						SOIL WATER EXTRACTION PROPERTIES											
						WHEAT			SORGHUM			MAIZE			SUNFLOWER		
Diag hor*1	Colour	Clay (%)	BD (g cm^{-3})	Depth	DUL (mm)	LL (mm)	TESW*2 (mm)	CMUL*3 (mm)	LL (mm)	TESW (mm)	CMUL (mm)	LL (mm)	TESW (mm)	CMUL (mm)	LL (mm)	TESW (mm)	CMUL (mm)
ml	DkBr	45	1.30	300	70	32	38		40	30		39	31		28	42	
vp	DkBr	43	1.45	600	105	62	43		82	23		74	30		65	40	
vp	DkBr	40	1.45	900	105	65	40		81	24		74	30		68	37	
so	Mottl.	38	1.45	1200	105	68	37		75	30		76	29		69	36	
				Total	385	227	158		278	107	422	263	122	422	230	155	422

*1 Abbreviations according to SIRI 1991

*2 Total extractable soil water

*3 Crop modified upper limit

Land type: Ea39c

Terrain morphological unit : Upper footslope

Slope % : 1

Soil classification : Form : Bonheim

Family : Onrus

Evaporation characteristics

All the measurements reported were made in the 0-300 mm layer by NWM. Values are in all cases means from at least 3 access tubes. Since most of Es probably occurs in the top 100 mm of soil, and the NWM is calibrated for the 0-300 mm layer, it is not a good instrument for these measurements. It was, however, the best that was available, and reasonable results were obtained.

Data for stage 1 Es are presented in Table 3.2.3.2. The theoretical field saturation (fsat) value for this 0-300mm soil layer is 137mm (0.9 Po-see the third paragraph in Appendix 2.3.1), and the DUL value is 70mm. A very wet range is therefore represented here.

Table 3.2.3.2 Comparing Es and Ep values during stage 1 evaporation on the Glen/Bonheim-Onrus ecotope. No rain occurred during the period over which these measurements were taken

Date	Time of reading	θ 0-300 (mm)	$\Delta\theta$ (mm)	D*[1] (mm)	Es*[2] (mm)	Ep (mm)
27/11/98	17h00	130.3	-	-	-	-
28/11/98	08h30	104.3	26.0	16.7	9.3	7.1
29/11/98	09h30	83.4	20.9	3.6	17.4	10.4
30/11/98	08h30	77.5	5.9	1.0	4.9	5.9
02/12/98	08h30	73.5	4.0	1.4	2.6	8.5
TOTAL					34.2	31.9

*[1] D = drainage out of the 0-300 mm layer determined using equation 3.2.3.2
*[2] Es = calculated as ($\Delta\theta$ - D).

Noticeable irregularities when comparing Es and Ep values are those for 29/11/98 and 02/12/98. These are probably due to NWM inaccuracy. That the inaccuracies tend to balance each other is shown by the close equivalence of ΣEs and ΣEp on 02/12/98. There would be imbalance if stage 1 had been considered to have ceased on 30/11/98. It is noticeable that stage 1 Es stops close to DUL_{0-300} mm. It may be that this is a characteristic of melanic A horizons. The upper limit of stage 1 ΣEs, Ritchie's "U" value, is therefore 34 mm.

Data for the stage 2 Es is presented in Appendix 3.2.3.3. The determinations was made during summer. The Ritchie (1972) α value is 2.75 mm $t^{-1/2}$. It is of the same order as the values which he presents for Adelanto clay loam (5.08), Yolo loam (4.04), Houston black clay (3.50) and Plainfield sand (3.34).

3.3 GLEN/SWARTLAND-ROUXVILLE ECOTOPE (Sw)

3.3.1 Climate

Since the ecotope is situated a few hundred meters downslope from Bo, the climate is as described under 3.2.1.

3.3.2 Topography

As for Bo.

3.3.3 Soil

Pedological characteristics

A detailed profile description together with analytical data is presented in Appendices 3.3.3.1 and 3.3.3.2. The soil is classified as belonging to the Rouxville Family of Swartland Form. Its characteristic morphological feature is that of a dark brown, poorly structured, fine sandy clay, orthic A horizon with a clear transition at about 250 mm to a strongly structured, dark brown, sandy clay, pedocutanic B horizon. The structure of the B horizon becomes moderately strong below 400 mm, and merges into calcareous, sandstone saprolite at 1000 mm. The saprolite is well weathered, offering no significant impedance to root development to at least 1200 mm. The soil has a high CEC (23-27 c mol^{+} kg^{-1} soil) throughout, low exchangeable Na content, and considerably more exchangeable Mg (7-11 mol^{+} kg^{-1} soil) than Ca (5-7 mol^{+} kg^{-1} soil) up to a depth of 800 mm. Wide cracks appear in the B horizon when the soil is dry. When extremely dry these cracks are transmitted to the A horizon as well. The plasticity index is relatively low (22) compared to Bo.

Soil water extraction and drainage characteristics

Important features are summarised in Table 3.3.3.1. The water holding capacity of the 0-1200 mm root zone is high giving a DUL value of 358 mm. The high value for the 0-300 mm layer (82 mm) compared to Bo (70 mm), in spite of a coarser texture, is probably due to the influence of the clear A horizon- B horizon transition which causes a semi-perched water table to form during drainage. This observation accentuates the importance of field determined DUL values wherever possible, in preference to values obtained from matric suction curves, or from regressions based on texture alone. The restrictive influence of the strongly structured B1 horizon (approx. 300-600 mm) on root water extraction, and therefore presumably on root ramification, is disclosed by the higher LL values for maize and sorghum in the 300-600 mm layer compared to the two deeper layers.

As in the case of Bo water extraction is effective to the bottom of the root zone. The remarks there regarding SS are also relevant here. A clearer picture of water extraction by the four crops is presented in Figure 3.3.3.1.

A drainage curve for the whole root zone is presented in Figure 3.3.3.2. Equation 3.3.3.1 describes the curve, and facilitates the calculation of the drainage rate at any stage, and therefore quantification of the water balance.

$$Y = 442 - 11.43\ (\ln t) \ldots \text{mm} \ldots r^2 = 0.90 \ldots \quad (3.3.3.1)$$

Equation 3.3.3.2 describes the drainage curve for the 0-300 layer

$$Y = 137 - 7.85\ (\ln t) \ldots \text{mm} \ldots r^2 = 0.93 \ldots \quad (3.3.3.2)$$

For the meaning of the symbols see equation 3.2.3.1.

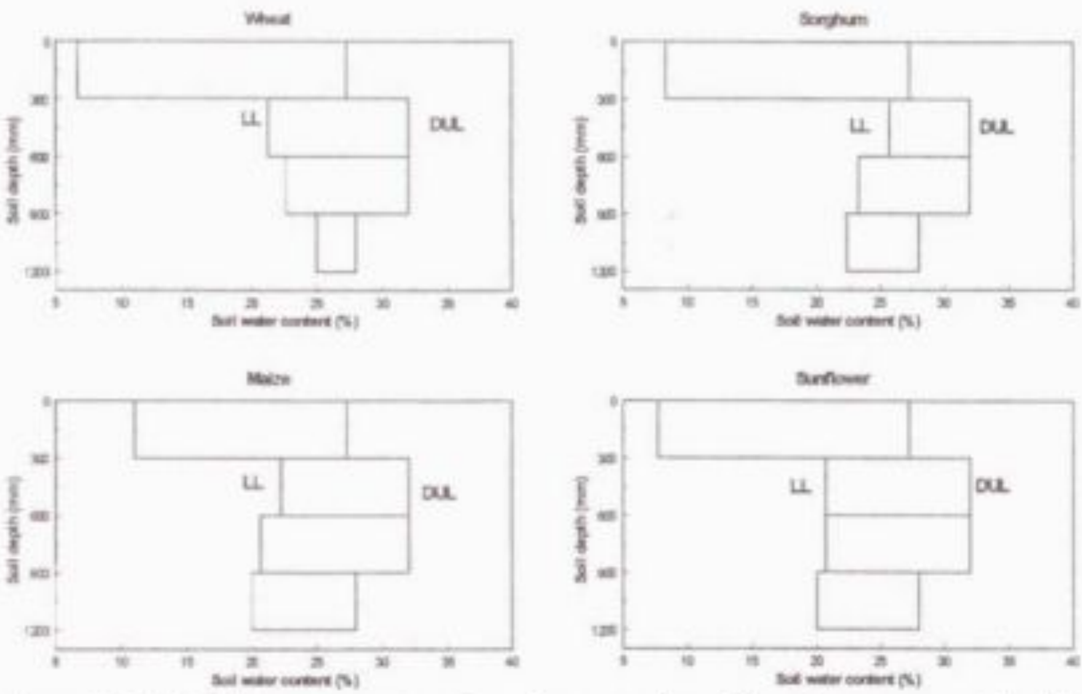

Figure 3.3.3.1 Soil water extraction diagrams for different crops on the Glen /Swartland-Rouxville ecotope : Rootzone 1200 mm. Soil water content is vol.%

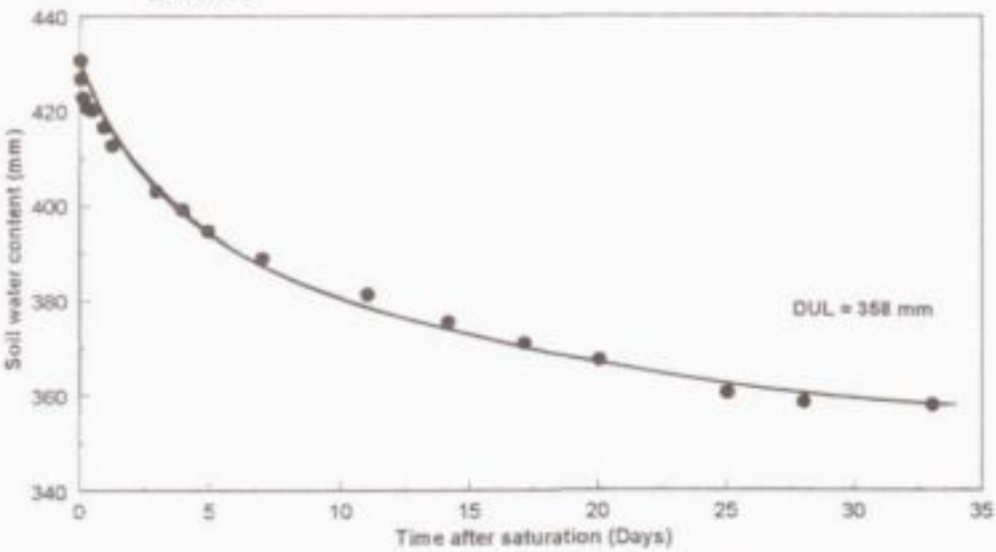

Figure 3.3.3.2 Drainage curve for the Glen/Swartland-Rouxville ecotope: Rootzone 1200 mm

Table 3.3.3.1 The soil component of the Glen/Swartland-Rouxville ecotope. The effective root zone for the crops recorded is considered to be 0- 1200 mm

PROFILE DETAIL						SOIL WATER EXTRACTION PROPERTIES											
						WHEAT			SORGHUM			MAIZE			SUNFLOWER		
Diag hor*1	Colour	Clay (%)	BD (g cm^{-3})	Depth	DUL (mm)	LL (mm)	TESW (mm)	CMUL*2 (mm)	LL (mm)	TESW (mm)	CMUL (mm)	LL (mm)	TESW (mm)	CMUL (mm)	LL (mm)	TESW (mm)	CMUL (mm)
ot	DkBr	38	1.50	300	82	20	62		25	57		33	49		23	59	
vp	DkBr	40	1.66	600	96	64	32		77	19		67	29		62	34	
vp	DkBr	44	1.51	900	96	68	28		70	26		62	34		62	34	
so	Mottl.	35	1.46	1200	84	75	9		62	17		60	24		60	24	
Total					358	227	131		239	119	393	222	136	393	207	151	393

*1 Abbreviations according to SIRI 1991

*2 Crop modified upper limit

Land type: Ea39c

Terrain morphological unit : Upper footslope

Slope % : 1

Soil classification : Form : Swartland

Family : Rouxville

Evaporation characteristics

Data for stage 1 Es are presented in Table 3.3.3.2. The 0.9 Po and DUL values for the 0-300 mm layer are 122 mm and 80 mm respectively. The soil water content range represented here is therefore between fSat and DUL.

Table 3.3.3.2 Comparing Es and Ep values during stage 1 evaporation on the Glen/Swartland-Rouxville ecotope (Sw). No rain occurred during the period over which these measurements were taken

Date	Time of reading	θ 0-300 (mm)	$\Delta\theta$ (mm)	D*1 (mm)	Es*2 (mm)	Ep (mm)
27/11/98	16h30	129.4	-	-	-	-
28/11/98	08h00	110.7	18.7	13.5	5.2	7.1
29/11/98	08h30	96.7	14.0	2.7	11.3	10.4
30/11/98	08h00	87.5	9.2	0.6	8.6	5.9
TOTAL					25.1	23.4

*1 D = Drainage out of the 0-300 mm layer determined by using equation 3.3.3.2
*2Es = calculated as ($\Delta\theta$ - D)

There is relatively good agreement between the Es and Ep values for each of the periods. The end of stage 1 has evidently been reached 2½ days after starting, giving a U value of 25 mm. This stage also ends close to DUL_{0-300} as in Bo.

Data for stage 2 Es is presented in Appendix 3.3.3.3. The α value of 6.57 mm $t^{-½}$ ($r^2 = 0.97$), is considerably higher than the Bo value. This is as expected since α is related to the hydraulic conductivity (HC) of the soil (Ritchie, 1972) and the coarser textured A horizon of Sw should have a higher HC than that of Bo.

3.4 KHUMO/SWARTLAND-AMANDEL ECOTOPE (Ks)

3.4.1 Climate

Daily rainfall for a nearby farm "North Bend" at latitude 29° 04' 30" and longitude 26° 5' is available from 1913 to 1984. It is situated about 2 km N of Vlakspruit and about 4 km W of Khumo. Long term monthly average rainfall from "North Bend" is presented in Table 3.4.1.

Table 3.4.1 Long term monthly rainfall for the Thaba Nchu ecotopes

Item	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Long term mean
rain (mm)	11	13	23	48	77	69	91	81	88	57	20	10	588

Ks is situated in a semi-arid region with low and erratic rainfall where conditions are marginal for crop production. The average total long-term rainfall may appear to be adequate for the production of a cash crop but the intensities and distribution are of such a pattern that the water available during the crop growth cycle is inadequate to support a good harvest.

3.4.2 Topography

The experimental plots are located on an upper footslope terrain unit with a straight, 2% slope in a northerly direction.

3.4.3 Soil

Pedological characteristics

A detailed profile description together with analytical data are presented in Appendices 3.4.3.1 and 3.4.3.2. The soil is classified as belonging to the Amandel Family of the Swartland Form. It is a dark brown soil with 17 % clay in the A-horizon, with a clear transition to the B-horizon which overlies $CaC0_3$ enriched sandstone saprolite at a depth of 700 mm. The soil has a strong structure in the B-horizon and a high content of smectite clay minerals which cause large cracks that penetrate deep into the soil when it is very dry.

Soil water extraction and drainage characteristics

Important features are summarised in Table 3.4.3.1. The high water holding capacity of the root zone is expressed by the high DUL value of 385 mm. The high value of the 0-300 mm layer (69 mm) compared to the Glen/Bonheim ecotope (70 mm) in spite of a coarser texture, is probably due to the influence of the clear A-horizon - B-horizon transition which causes a semi-perched water table, to form during drainage. The DUL value of 69 mm is high for an Orthic A-horizon with a Cl % of 17. This also accentuates the importance of a field determined DUL. The soil water extraction diagram for sunflower is presented in Figure 3.4.3.1. The area of each rectangle, representing a soil depth of 300 mm, is proportional to TESW for that layer. The restrictive influence of the strongly structured B horizon on root water extraction, and therefore presumably on root ramification, is disclosed by the higher LL value in the 300-600 mm layer compared to the deeper layers.

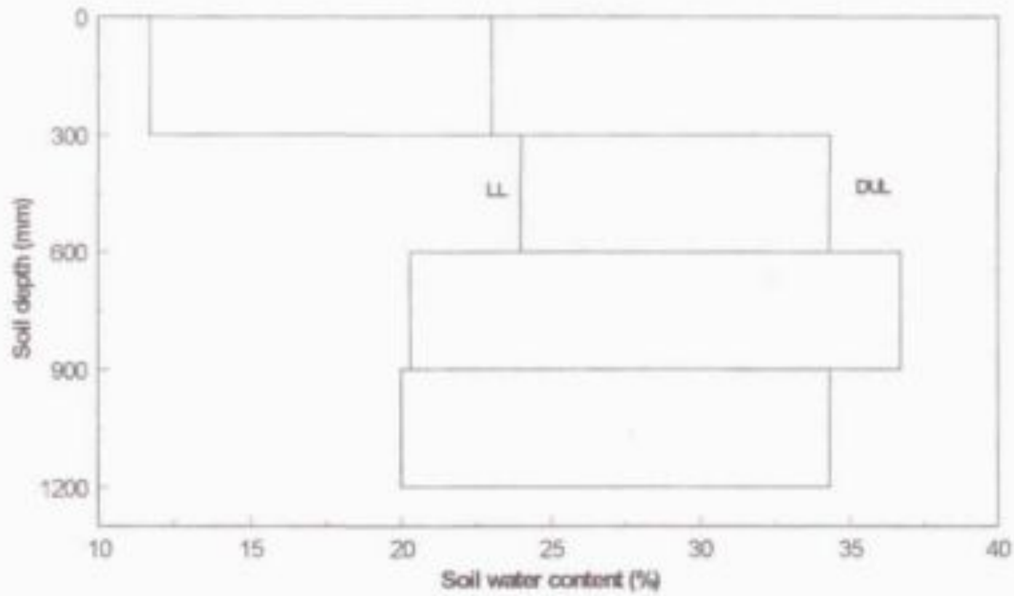

Figure 3.4.3.1 Soil water extraction diagram for sunflower on the Khumo/Swartland ecotope

A drainage curve for the whole root zone, which provides the information for determining DUL and CMUL is presented in Figure 3.4.3.2. Equation 3.4.3.1 provides a mathematical description of the curve and enables the drainage rate at any time after field saturation (fSat) to be calculated.

$$Y = 446.64 - 6.84\,(\ln t) \ldots \text{mm} \ldots r^2 = 0.95 \ldots \quad (3.4.3.1)$$

where:

Y = water content of the root zone (mm)

t = time (hrs) after drainage started, i.e. root zone water content at fSat.

Equation 3.4.3.1 can be used to calculate drainage out of the root zone after a heavy rainstorm has occurred. This is necessary to quantify the water balance (equation 1.1).

Equation 3.4.3.2 describes the drainage curve for the 0-300 mm layer. Symbols are the same as for equation 3.2.3.1.

$$Y = 102.06 - 3.70\,(\ln t) \ldots \text{mm} \ldots r^2 = 0.93 \ldots \quad (3.4.3.2)$$

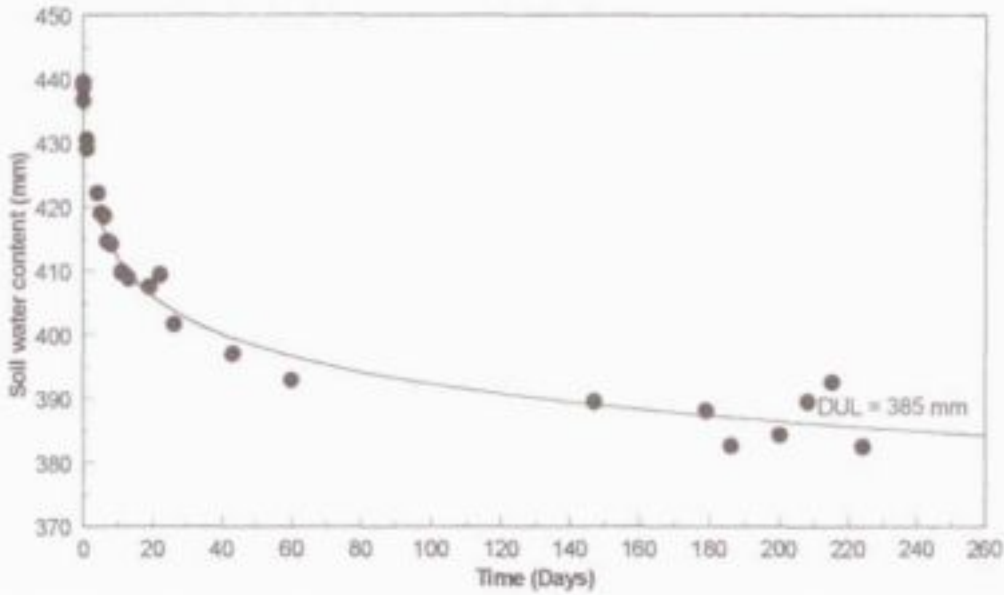

Figure 3.4.3.2. Drainage curve for the Khumo/Swartland ecotope

Table 3.4.3.1 The soil component of the Khumo/Swartland-Amandel ecotope. The effective root zone for sunflower is considered to be 0-1200 mm

PROFILE DETAIL						WATER PROPERTIES SUNFLOWER		
Diag hor*1	Colour	Clay (%)	BD (g cm⁻³)	Depth	DUL (mm)	LL (mm)	TESW*2 (mm)	CMUL*3 (mm)
ot	DkBr	17.5	1.50	300	69	35	34	
vp	DkBr	52.2	1.43	600	103	72	31	
vp	DkBr	45.2	1.42	900	110	61	49	
so	Mottl.	42.17	1.54	1200	103	60	43	
				Total	385	228	157	423

*1 Abbreviations according to SIRI 1991
*2 Total extractable soil water
*3 Crop modified upper limit
Land type: Db37b
Terrain morphological unit : Upper footslope
Slope % : 2
Soil classification : Form : Swartland
Family : Amandel

3.5 VLAKSPRUIT/ARCADIA-LONEHILL ECOTOPE (Va)

3.5.1 Climate

Since the ecotope is situated about five kilometres from Ks, the climate is as described under 3.4.1.

3.5.2 Topography

The plots are located on an upper foot slope terrain unit with a straight, 3% slope in a north-westerly direction.

3.5.3 Soil

Pedological characteristics

A detailed profile description together with analytical data is presented in Appendices 3.5.3.1 and 3.5.3.2. The soil is classified as belonging to the Lonehill Family of Arcadia Form. It is a vertic soil with 42 % clay in the A-horizon.

Soil water extraction and drainage characteristics

Important features are summarised in Table 3.5.3.1. The water holding capacity of the 0-1200 mm root zone is very high giving a DUL value of 456 mm. The high value for the 0-300 mm layer (113mm) compared to the Bo (70 mm) is a very good quality of this soil, which gives an enormous $TESW_{0\text{-}300\ mm}$ (76 mm) for sunflower.

As in the case of Ks water extraction is effective to the bottom of the root zone although most of the water for plant growth is extracted from the top soil layers. The soil water extraction diagram for sunflower on Va is presented in Figure 3.5.3.1.

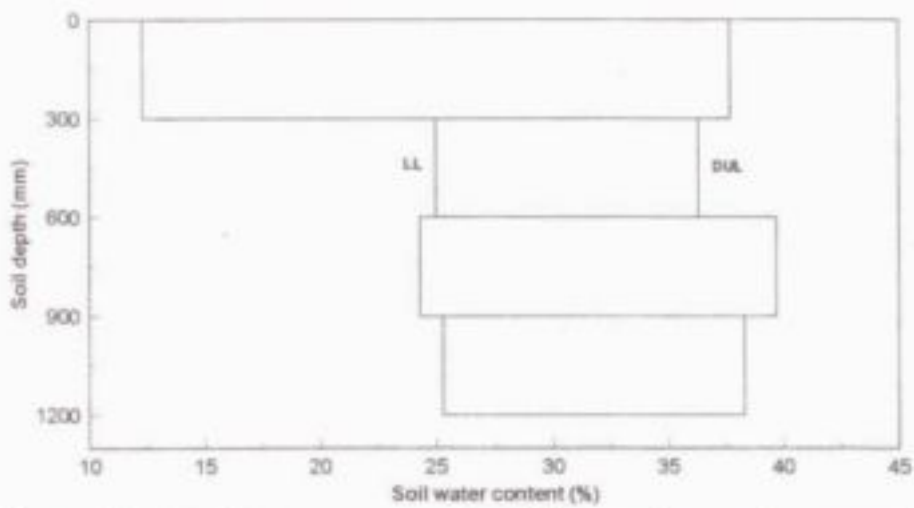

Figure 3.5.3.1 Soil water extraction diagram for sunflower on the Vlakspruit/Arcadia ecotope

A drainage curve for the whole root zone, which provides the information for determining DUL and CMUL is presented in Figure 3.5.3.2. Equation 3.5.3.1 provides a mathematical description of the curve and enables the drainage rate at any time after field saturation (fSat) to be calculated.

$$Y = 490.77 - 4.53 (\ln t) \ldots mm \ldots r^2 = 0.91 \ldots \quad (3.5.3.1)$$

where:

Y = water content of the root zone (mm)

t = time (hrs) after drainage started, i.e. root zone water content at fSat.

Equation 3.5.3.1 can be used to calculate drainage out of the root zone after a rainstorm. This is necessary to quantify the water balance (equation 1.1).

Equation 3.5.3.2 describes the drainage curve for the 0-300 mm layer. Symbols are the same as for equation 3.5.3.1.

$$Y = 136.08 - 3.04 (\ln t) \ldots mm \ldots r^2 = 0.96 \ldots \quad (3.5.3.2)$$

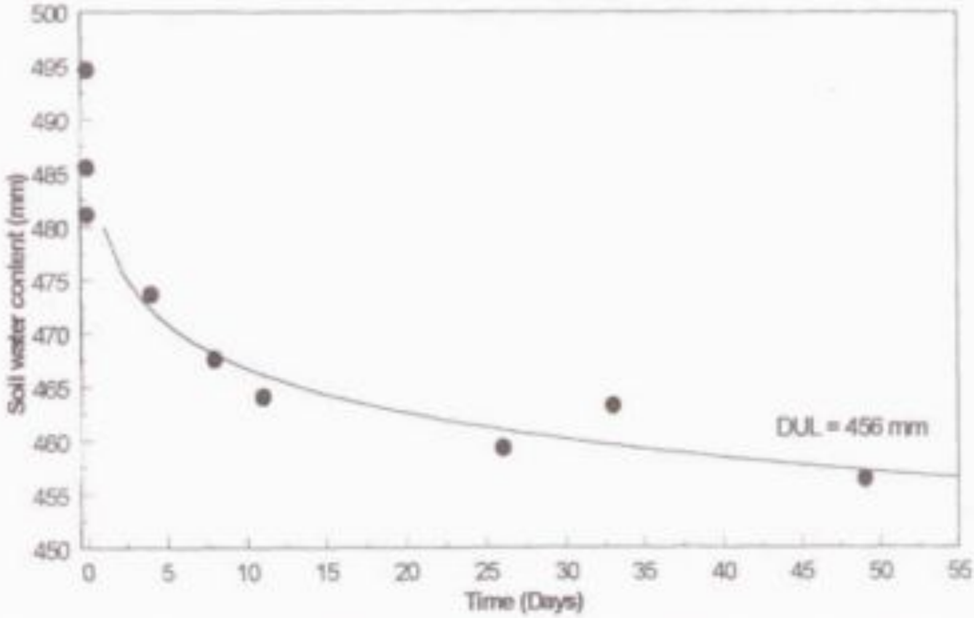

Figure 3.5.3.2. Drainage curve for the Vlakspruit/Arcadia ecotope

Table 3.5.3.1 The soil component of the Vlakspruit/Arcadia -Lonehill ecotope. The effective root zone for sunflower is considered to be 0-1200 mm

PROFILE DETAIL						WATER PROPERTIES SUNFLOWER		
Diag hor*1	Colour	Clay (%)	BD (g cm^{-3})	Depth	DUL (mm)	LL (mm)	TESW*2 (mm)	CMUL*3 (mm)
ve	DkBr	42.1	1.38	300	113	37	76	
ve	DkBr	53.5	1.43	600	109	75	34	
ve	DkBr	53.5	1.44	900	119	73	46	
ve	DkBr	53.5	1.49	1200	115	76	39	
				Total	456	261	195	477

*1 Abbreviations according to SIRI 1991
*2 Total extractable soil water
*3 Crop modified upper limit
Land type: Db37b
Terrain morphological unit : Upper footslope
Slope % : 3
Soil classification : Form : Arcadia
Family : Lonehill

4. RUNOFF: RESULTS AND DISCUSSION

Rainfall and runoff events during the three rain seasons 1996/97, 1997/98 and 1998/99 are presented in Appendices 4.1, 4.2 and 4.3 respectively. Results are summarised in Table 4.1. Runoff never occurred on the WHB runoff plots.

Table 4.1 Rainfall and runoff for the 1996/97, 1997/98 and 1998/99 seasons on the Bo and Sw runoff plots

Eco-tope	soil tillage treat-ment	1996/97			1997/98			1998/99			Mean
		P*1 (mm)	R (mm)	R*3 (%)	P (mm)	R (mm)	R (%)	P (mm)	R (mm)	R (%)	R (%)
Bo	MSS*2	452	88	19.5	589	80	13.7	462	60.7	13.1	15.4
	TST		ND*4	-		33	5.6		7.4	1.6	3.6
Sw	MSS	452	141	31.2	589	106	18.0	462	59.3	12.8	20.7
	TST		ND	-		43	7.3		2.4	0.005	3.9

*1 precipitation
*2 minimum surface storage, which simulates the no-till crusted surface on the WHB runoff strips - see Figure 2.1.1
*3 runoff as % of precipitation
*4 not determined

The difference in the soil water regime for crops on the WHB treatment compared to TST depends largely on the degree of runoff enhancement by no-till and crusting compared to conventional tillage on the 2 m interrow strip (Figure 2.2.1). The results in Table 4.1 show that there is a large difference. The difference is accentuated for 1998/99, the reason being that an unusually large fraction of the rain occurred as small events (less than about 10 mm), with no large events (> about 25 mm). The reason for this is the important role which surface storage plays in runoff. For example, where surface storage (SST) amounts to 10 mm, even on an impermeable surface on a slight slope R would be close to zero during a season like 1998/99. An SST value of 10 mm is easily achieved on a soil. The pattern was different during the 96/97 and 97/98 rain seasons with three and six large events respectively (see Appendices 4.1, 4.2 and 4.3). Considering the small slope on both ecotopes the R% is high. It provides evidence that the hypothesis for this study is valid.

It is useful to compare these results with long-term (17 yrs) runoff measurements made at Glen by Du Plessis & Mostert (1965), since the rainfall pattern is comparable. Their ecotope consisted of a Hutton Form soil with 15% clay in the topsoil situated on a 5% slope. Compared to Bo and Sw this slope would promote R, and the coarser textured, red coloured topsoil with a higher final infiltration rate (I_f) would suppress R to some extent. This soil is, however, known to form a strong crust making I_f somewhat lower than might be expected. Du Plessis & Mostert report R% values of 31.9 an 10.9 from treatments comparable to MSS and TST in this study respectively, providing further evidence that WHB treatments should be successful in improving yields.

In Figure 4.1 (a, b, c and d) cumulative rainfall and rainfall intensity are plotted against time for four selected rainfall events at the experimental site. The measured R values (mm) for the MSS runoff plots on the Bo and Sw ecotopes are also recorded on each figure. A study of these graphs and many other similar ones leads one to the conclusion that the final infiltration rate (I_f) of the crusted soil on both ecotopes is around 6 mm hr^{-1}. This means that whenever the surface soil has been satisfactorily wetted, all rain at intensity (Pi) greater than 6 mm hr^{-1} will run off. This can be demonstrated by reference to the figures. In the case of Figure 4.1 (a), the 72 mm rainfall event which occurred on 1 Jan. 1998 on a very dry soil, it can be seen that Pi was relatively low for the first 20 mm of rain (around 4.8 mm hr^{-1}). From about 300 minutes after the rain had started to about 450 minutes, approximately 40 mm of rain fell, i.e the steepest part of the curve. This gives an average Pi of 16 mm/hour over a period of approximately 150 minutes. Assuming that I_f is 6 mm hr^{-1}, R would occur at 10 mm hr^{-1} , and over a period of 150 minutes would therefore accumulate to a total value of 25 mm. This was approximately the runoff recorded on Sw. Conditions were suitable for high R % values. Results in this case were 36% for Sw and 28 % for Bo.

Figure 4.1 (b) depicts a case where the soil was fairly wet when the rainfall event started on 31/12/1998; there had been 25 mm of rain two days before. This was a short rainfall event (total of 12 mm) but high Pi (max. = 100 mm h^{-1}). The high Pi period only lasted about 5 minutes, with an average value of around 70 mm hr^{-1}. Again assuming that I_f is 6 mm hr^{-1} the predicted R is around 5 mm, which is close to the measured value. The result was a very high R % values, viz. 62 for Sw and 63 for Bo. Comparing Figures 4.1 (c) and 4.1 (d) is interesting. Both depict small rainfall events which occurred on consecutive days. On 17 Jan. 1997 (Figure 4.1 (c)) the soil was dry and although Pi > I_f for about 50 minutes, most of the 11 mm of rain was taken up by the process of wetting the surface soil, resulting in relatively little runoff. The R % values for Sw and Bo were 9 and 21 respectively. The rainfall event on the following day (Figure 4.1 (d)) was one of long duration (4.3 hours) and low Pi, which nevertheless exceeded I_f for a period of about 80 minutes. This results in the relatively high R % values of 32 and 21 for Sw and Bo respectively.

In most, but not all cases runoff was greater on Sw than on Bo. It seems that because of the lower clay content of the "orthic" A horizon of Sw a more permanent and impermeable crust forms, resulting in I_f being reached in a shorter time than on Bo. On the "melanic" A horizon on Bo, with its high smectite rich clay content and high plasticity index of between 21 and 33, a multiplicity of small cracks forms as the soil surface becomes dry. When the next rainfall event comes these cracks all have to be filled and the necessary expansion take place before surface sealing occurs and I_f is reached. By then the rain may be over. There is evidence that I_f on Bo may actually be slightly lower than on Sw. The extent of the difference in R on these two ecotopes is therefore a function of three factors viz. amount of rain, intensity of rain, and water content of the surface soil when the rainfall event occurs.

Runoff measurements (R_i) made in plastic lined basins on the experimental land during the 1998/99 season were successful and provide information more directly applicable to the field experiment since they reflect what actually happens from a 2 m wide runoff strip compared to measurements from the 20 m long runoff plots with automatic tipping bucket runoff meters (R_a). The problem with the latter is the possible confounding influence of overland flow on the results. R_i results are only available for the 1998/99 season. When comparing R_i and R_a for this season it was found that generally, per rainfall event, R_i was slightly greater than R_a. It is possible that in the process of forming the basins in the field that the slope of the 2 m runoff strip became slightly steeper than that of the land. This may account for $R_t > R_s$. A linear regression analysis on the two sets of data was performed using R_s as the independent variable - to enable extrapolation to the two previous seasons for which R_s values are available. The following results were obtained:

$$\text{for Bo } R_t = 1.28\, R_s + 0.70 \ldots\ldots\ r^2 = 0.87 \ldots\ldots \quad (4.1)$$

$$\text{for Sw } R_t = 1.1 R_s + 0.3 \ldots\ldots\ r^2 = 0.83 \ldots\ldots \quad (4.2)$$

Equations 4.1 and 4.2 were then used to convert the R_s data for 1996/97 and 1997/98 to R_t values.

The final agronomic aim of this study as a whole needs to be reiterated here in order to get these manoeuvres with the runoff data into perspective. Because we are dealing here with a marginal cropping area which is semi-arid and has a very erratic rainfall, long-term yields from the different production techniques being tested are desirable in order to make reliable decisions regarding which is best. If long-term rainfall data, including intensity were available, one could resort to using a runoff model, calibrated against measured values over a number of seasons, to predict runoff during each historical rainfall event. This would be ideal, and hence the value of results which will hopefully come from S. Walker's Water Research Commission project titled: "The application of rainfall intensity - runoff relations to water harvesting from micro-catchments to stabilize food production in rural and peri-urban settlements". In the meantime, however, it is necessary to resort to a simpler procedure since only long-term daily rainfall data are available for the Glen and Thaba Nchu ecotopes. The "simpler procedure" adopted here was developed as follows: The R_t values obtained from equations 4.1 and 4.2 for Bo and Sw were correlated with their relevant rainfall (P) events. A scatter diagram of the 68 points for the three seasons showed that it was beneficial to exclude very small runoff events i.e. when $P < 8$ mm. This left 52 points. A linear regression analysis, using P as the independent variable and R_t as dependant variable gave what is considered under the circumstances to be a reasonable r^2 value of 0.58 for Bo and 0.61 for Sw. Since the prediction equations for the two ecotopes were very similar, the data were pooled and yielded the following equation

$$R_t = (0.473 * P) - 2.168 \ldots\ldots \quad (4.3)$$

The long-term (18 years 1937/38 - 1954/55) runoff data obtained at Glen by Du Plessis & Mostert (1965) were then used to test the reliability of equation 4.3. In spite of an exhaustive search, which included advice from Dr. Du Plessis himself, it was not possible to locate runoff measurements for each rainfall event during the 18 year period. The only runoff data available from the Du Plessis & Mostert study were that in the published paper, which consisted of annual runoff. Equation 4.3 was applied to each rainfall event greater than 8 mm during the period 1937/38 - 1954/55 and the estimated runoff for each season was obtained by summation. The predicted values of annual runoff were then correlated with the measured values of Du Plessis & Mostert. Results are presented in Appendices 4.4 and 4.5. There is a reasonable correlation. Although the r^2 value is low, the D-index is high and the systematic error ($RMSE_S$) is less than 65% of RMSE - which is acceptable. It is therefore considered that equation 4.3 is sufficiently reliable to use for predicting R_t on Bo and Sw when using long-term daily rainfall data for Glen.

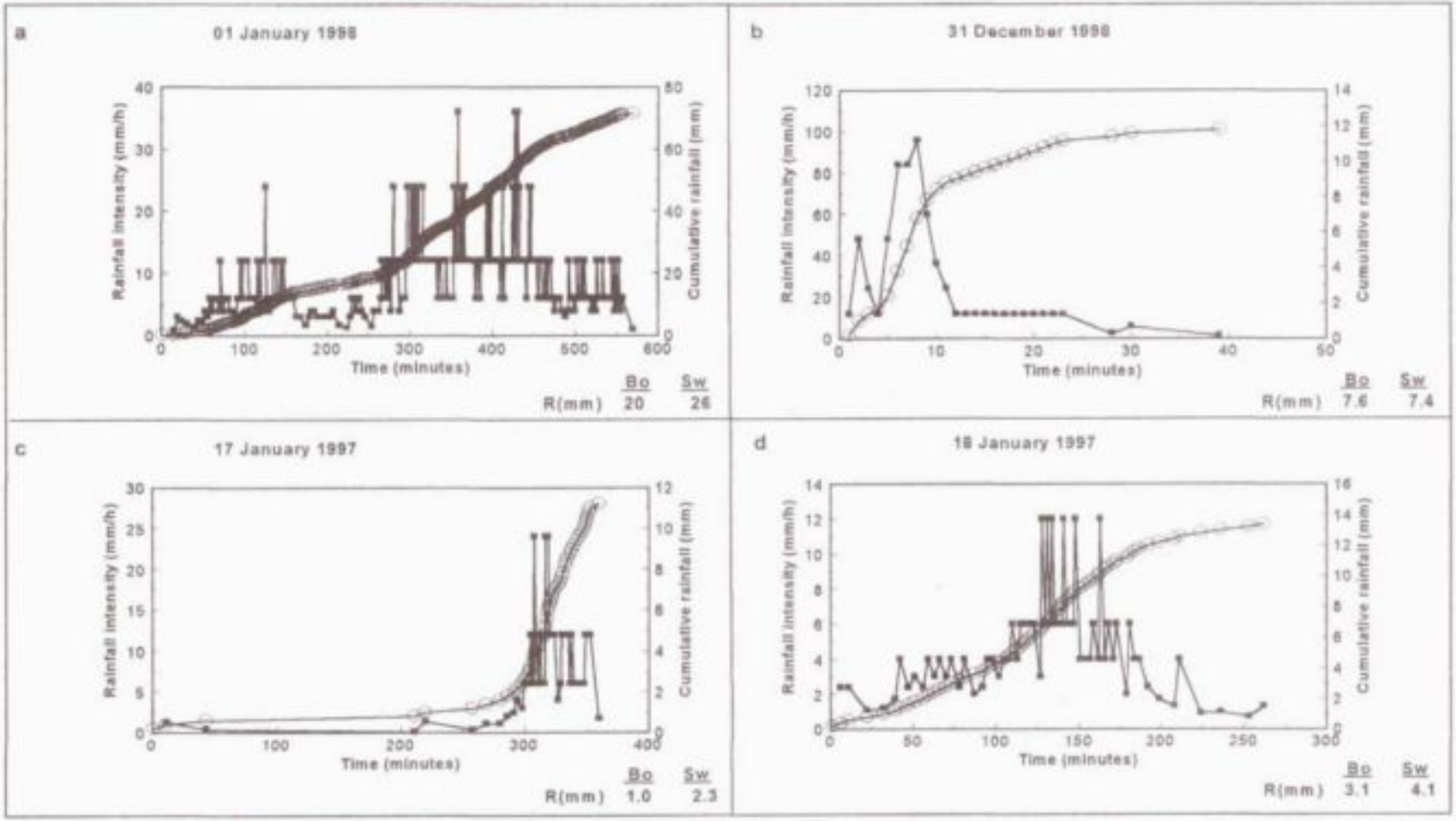

Figure 4.1 Rainfall intensity (Pi) and cumulative rainfall (Σ P) during four selected rainfall events on the Glen ecotopes. The values in the right hand corners are the runoff measured on the runoff plots on each of the ecotopes at the end of each rainfall event

5. MEASURED CROP YIELDS: RESULTS AND DISCUSSION

5.1 MAIZE

5.1.1 Glen/Bonheim-Onrus ecotope (Bo)

Grain and biomass yields for the three seasons are presented in Table 5.1.1.1 and results of the statistical analysis in Table 5.1.1.2

Table 5.1.1.1 Maize grain and biomass yields on Bo for the different treatments for the 1996/97, 1997/98 and 1998/99 seasons

Pg*1 (mm)	1996/97 303		1997/98 449		1998/99 205	
treatment*2	grain*3 (kg ha^{-1})	biomass*4 (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	2282	6020	3133	6907	0	935
TSTM (A)	-	-	4207	9397	14	1503
WHB (A)	2274	6828	4251	9798	35	1771
WHBM (A)	-	-	4678	10976	132	2309
WHB (B)	-	-	-	-	629	3280
WHBM (B)	-	-	-	-	789	4158

*1 Pg = precipitation during the growing season
*2 TST = conventional total soil tillage
*2 WHB = combination of mini-catchment runoff farming (in-field water harvesting) and basin tillage see Figure 2.2.1
*2 M = mulching
*2 (A) or (B) indicates annual, or bi-annual (long-fallow) planting respectively
*3 Grain at 12.5 % water content
*4 Total oven dry material, including oven dry grain.

Table 5.1.1.2 Results of statistical analyses of maize grain and biomass yields on Bo over three seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*1 (kg ha^{-1})	CV*2 (%)	(A)*3 vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*4 vs M
96/97	NSD	1 561	19.5	-	-	-	-	-	-	-
97/98	*	317	4.9	-	-	-	*	317	4.9	*
98/99	NSD	173	45.9	*	173	45.9	NSD	141	45.9	*
	BIOMASS									
96/97	*	728	5.3	-	-	-	-	-	-	-
97/98	*	61	0.8	-	-	-	*	61	0.8	*
98/99	NSD	478	14.9	NSD	479	14.9	*	391	14.9	*

NSD = no significant difference
* = significant at the 5% probability level
*1 = least significant difference
*2 = coefficient of variation
*3 = annual vs biannual cropping
*4 = interaction between tillage treatments and mulching

The diagrams in Appendix 5.1.1 describe the water regime during each growing season and help to explain the yields and water balance data. After a favourable start to the 96/97 season the crop suffered a severe setback during the period DAP 45 to DAP 73, which was characterized by very little rain and high temperatures. θr decreased to below the serious stress threshold value considered to be around 300 mm. As the plants were at the sensitive flowering period during this time, efficient fertilization could not take place making the achievement of a high yield impossible. These conditions probably contributed towards the high CV associated with grain yield (Table 5.1.1.2). Good rains, totalling 50 mm, between DAP 74 and DAP 80 prevented complete crop failure. The final yield of 2.3 t ha^{-1} is an acceptable one for this marginal area.

It was only possible to complete the tillage treatments just before planting on 17 December 1996. Preferential water storage by WHB(A) compared to TST(A) during the early season rains therefore did not occur. The runoff during this period, measured on the runoff plots which had been prepared early in November, amounted to 54 mm (Appendix 4.1). The absence of this legitimate benefit for WHB(A) probably contributed considerably towards the fact that there was no significant difference between the yields of the two treatments (Table 5.1.1.2). The greater amount of water available to WHB(A) is however expressed by the considerably larger biomass yield, which was significantly better than TST(A).

The 1997/98 season was characterised by high and well-distributed rainfall (Appendix 5.1.1.2) with θr only falling below the critical 300 mm level at the end of the season. The result was good yields on all the treatments, with WHB(A) significantly better than TST(A), mulching significantly better than no mulching and a significant interaction between mulching, and tillage (Table 5.1.1.2).

The 1998/99 season was extremely dry from DAP 40 until the end of the season (Appendix 5.1.1.3). The result was extremely low or zero yields on all treatments excepting long fallow (WHB(B) and (WHBM(B)). Complete crop failure on these treatments was avoided by the high θ_p values of around 400 mm compared to the other treatments which were around 350 mm for WHB(A) and 320 mm for TST(A). The grain yield from the biannual treatments (WHB(B) and WHBM(B)) were significantly better than the annual plantings (Table 5.1.1.2). In the case of the comparison mulch vs. no mulch there was no significant difference in grain yield, but for biomass the difference was significant.

Use of a transpiration efficiency coefficient (k) provides a simple and effective way of separating Es + T into its two components. The value of k is the product of transpiration efficiency (total biomass/T) and the mean saturation deficit over the growing season (SD) of the atmosphere during sunlight hours (Tanner & Sinclair, 1983; Chapman, Hammer & Meinke, 1993). The units of k are therefore grams of dry matter per kg water x k Pa. Gregory (1989) "normalises" the influence of SD by multiplying k by SD_n (1 k Pa). The confusing units of k are thereby eliminated and they become g dry matter per kg water, which is the same as the more convenient units g m^{-2} mm^{-1}. The adoption of this procedure will be assumed whenever k values are presented in this report.

Using data from 10 different experiments in the USA, and what they considered to be a "reasonable" ratio for maize of ((total dry matter) / (above ground dry matter)) of 1.2, Tanner & Sinclair (1983) reported a mean k value of 9.5 g m^{-2} mm^{-1}. Working in Canada over a wide range of soil water regimes, and using only above ground biomass, Walker (1986) reported a value of 7.4. Using results from field experiments in South Africa, and also using only above ground biomass Hattingh (1993) reported a value of 8.2. Using Tanner & Sinclair's factor of 1.2 to estimate total biomass for the last two mentioned estimates yields results of 8.9 and 9.8, and a mean value of 9.4, which is very close to Tanner & Sinclair's value of 9.5. The latter value was considered sufficiently reliable for this study.

Water balance and production efficiency data are presented in Table 5.1.1.3 The following are considered important features of the results:

(a) The complete suppression of R by all the WHB treatments and the resultant loss of water by D (15-18 mm) on these treatments during the very wet 97/98 season. A comparison of figures (a) and (b) around DAP 20 in Appendix 5.1.1.2, in relation to the relevant D values for the TSTM(A) and WHBM(A) treatments presented in Table 5.1.1.3 (zero and 18 mm respectively), give one the impression that faulty calculations have been made. The reason for this apparent anomaly is that in the case of TSTM(A) $\theta_{900\text{-}1200}$ did not actually exceed $DUL_{900\text{-}1200}$ after the heavy rains, whereas for WHBM(A) it did. This is an example of the principle described in the last paragraph under 3.2.3.

(b) The considerable amount of R on TST(A), but considerably less where mulch was present (TSTM(A)). As the latter was not measured it had to be estimated.

(c) The large benefit to T of mulch on all treatments. This is probably due to suppression of Es by the mulch immediately after each rain. This benefit is well expressed by the large biomass increases in all the valid comparisons mulch vs. no mulch. The mean biomass increment due to mulching is around 30% over all the comparisons and seasons.

(d) Because of the extreme drought conditions during 98/99 none of the production efficiency values for that season are meaningful.

(e) WUE_T is useful for comparing different crops. The high values for the first two seasons (mean of 25 kg ha^{-1} mm^{-1}) compared to the equivalent values for sunflower (mean of 15 kg ha^{-1} mm^{-1}) displays the ability of maize to produce staple food efficiently when sufficient water is available.

(f) When there are no water losses by D or R, PUE_g and WUE_{ET} have the same value. The difference between the values for this parameter reflects the extent of these losses - generally small here excepting for TST(A) during 97/98 due to a high R value.

(g) Since an important purpose of this investigation is quantify PUE for different tillage treatments, the most important parameter is PUE_{gf}. Since measurements are not available for the fallow periods preceding 96/97 and 97/98 it is not possible to determine meaningful values for these two seasons. In spite of the extremely low yields during 98/99, the steadily increasing PUE_{gf} values reflect the step by step improvement in the water conservation ability of the production techniques down the list. $PUE_{gf(T)}$ values follow the same trend. These values may be useful for comparing different ecotopes.

The general pattern of θr on the long fallow plots on the Bo and Sw soils is similar. Good rains early in 1998 quickly filled the root zones on all the plots. During the winter of 1998 there was a gradual decrease in θr on most of the plots due to drainage and evaporation, with no visible significant difference between the plots. The decline generally does not decrease significantly below the value of DUL minus the maximum value of Es 0-300, termed DUL_{ES}. On some of the plots, however, θr decreased in September 1998 to around 300 mm on Bo and around 280 on Sw, far below the DUL_{ES} values of 375 mm and 333 mm respectively. The cause is evidently large cracks which sometimes form around access tubes and elsewhere, causing drying to a considerable depth. Measured dimensions of some of these cracks near access tubes were as follows: width 5-25 mm, depth - up to 300 mm, length -up to 400 mm. This information illustrates the relative ineffectiveness of combining the WHB treatment with long fallow. Because of the efficiency of water storage with WHB these results suggest that long fallow will not prove economical in the long-term, although it will no doubt stabilize yields for extremely dry seasons as experienced in 98/99.

Table 5.1.1.3 Water balance and production efficiency data for maize over three seasons on Bo. All "efficiencies" are based on grain yield

Season	Treatment	Water balance components (mm)							Efficiencies				
									water ($kg\ ha^{-1}\ mm^{-1}$)				Income*1 ($R\ ha^{-1}\ mm^{-1}$)
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf}*2	$PUE_{gf(I)}$
1996/97	TST (A)	297	80	0	14	269	94	363	6.3	24.3	6.1	ND	ND
	WHB (A)	297	82	0	0	273	106	379	6.0	21.5	6.0	ND	ND
1997/98	TST (A)	451	28	0	33	326	120	446	7.4	26.1	6.5	ND	ND
	TSTM (A)	451	41	0	18	310	164	474	8.9	25.7	8.6	ND	ND
	WHB (A)	451	44	15	0	322	158	480	8.9	26.9	8.6	ND	ND
	WHBM (A)	451	35	18	0	280	188	468	10.0	24.9	9.6	ND	ND
1998/99	TST (A)	208	33	0	0	218	23	241	-*3	-	-	-	-
	TSTM (A)	208	41	0	0	212	37	249	0.06	0.37	0.06	0.03	0.03
	WHB (A)	208	66	0	0	230	44	274	0.13	0.80	0.13	0.08	0.06
	WHBM (A)	208	86	0	0	237	57	294	0.45	2.32	0.45	0.28	0.24
	WHB (B)	208	131	0	0	258	81	339	1.86	7.87	1.86	0.68	0.50
	WHBM (B)	208	160	0	0	260	103	363	2.17	7.66	2.17	0.87	0.65

*1 The maize price was taken as R740 ton^{-1}

*2 For the annual crops: ($P_g + P_f = 386$ mm) + relevant ΔS values (see equation 1.7)
For the biannual crops: ($P_g + P_f = 827$ mm) + relevant ΔS value

*3 Zero yield

ND = not determined as data not available

5.1.2 Glen/Swartland-Rouxville ecotope (Sw)

Grain and biomass yields are presented in Table 5.1.2.1, results of statistical analyses in Table 5.1.2.2, and water balance and production efficiency results in Table 5.1.2.3.

Table 5.1.2.1. Maize grain and biomass yields on Sw for the different treatments for the 1996/97, 1997/98 and 1998/99 seasons

Pg*1 (mm)	1996/97 303		1997/98 449		1998/99 205	
treatment*2	grain*3 (kg ha^{-1})	biomass*4 (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	1138	5342	3187	6714	41	1505
TSTM (A)	-	-	4988	10528	117	1965
WHB (A)	1917	6583	4575	9216	157	2455
WHBM (A)	-	-	5308	11199	234	2504
WHB (B)	-	-	-	-	845	3412
WHBM (B)	-	-	-	-	716	3485

For explanation of treatments and symbols see Table 5.1.1.1

Since rainfall is the same as on Bo, and the soil water characteristics of the two soils are similar, variations in the water regime of the root zone of the two ecotopes during the three growing seasons, generally follow a very similar pattern (Appendices 5.1.2.1 to 5.1.2.3). The relatively high R loss of 28 mm on TST(A) during 96/97 (Table 5.1.2.3) was presumably the reason for the significantly higher grain yields on WHB(A) where R was zero. For the high rainfall 97/98 season, presumably because of a high R potential, mulching had a very beneficial influence by decreasing R significantly as well as Es on the TSTM(A) treatment. TSTM(A) biomass and grain yields were unexpectedly higher than WHB(A), but the difference was not significant. The beneficial influence of mulching on growth is shown when the comparison mulch vs. no mulch is made over all the treatments. For 97/98 mulch is significantly better for both grain and biomass yields, and for 98/99 biomass only. In the comparison TST vs. WHB for grain yield the latter was significantly better for 96/97 and 97/98, but not for 98/99.

The water balance and production efficiency data are in general very similar to those on Bo. The following are notable differences:

(a) Considerably higher water losses due to R on the TST(A) treatments during 96/97 and 97/98. The severe crust on this soil is responsible.

(b) Less losses due to D on WHB(A) and WHBM(A) during the very wet season.

(c) The marked beneficial influence of mulching on T for the TST(M) treatment during 97/98.

Table 5.1.2.2 Results of statistical analyses of maize grain and biomass yields on Sw over three seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*[1] (kg ha^{-1})	CV*[2] (%)	(A)*[3] vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*[4] vs M
96/97	*	708.8	13.2	-	-	-	-			-
97/98	*	481.1	6.7	-	-	-	*	481.1	6.6	*
98/99	NSD	179.3	36.1	*	179.3	36.1	NSD	146.4	36.1	NSD
	BIOMASS									
96/97	NSD	612.8	4.2	-	-	-				
97/98	NSD	1495.2	19.9	-	-	-	*	1495.2	19.9	NSD
98/99	*	371.5	10.2	*	371.5	10.2	*	303.3	10.2	*

NSD = no significant difference
* = significant at the 5% probability level
*[1] = least significant difference
*[2] = coefficient of variation
*[3] = annual vs biannual cropping
*[4] = interaction between tillage treatments and mulching

Table 5.1.2.3 Water balance and production efficiency data for maize over three seasons on Sw. All "efficiencies" are based on grain yield

Season	Treatment	Water balance components (mm)							Efficiencies				
									water (kg ha^{-1} mm^{-1})				Income *1 (R ha^{-1} mm^{-1})
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf}*2	$PUE_{g(f)}$
1996/97	TST (A)	303	60	0	28	252	83	335	5.1	20.6	4.7	ND	ND
	WHB (A)	303	58	0	0	259	102	361	5.8	18.8	5.3	ND	ND
1997/98	TST (A)	451	35	1	41	327	117	444	7.2	27.2	6.6	ND	ND
	TSTM (A)	451	28	3	12	280	184	464	10.7	27.1	10.4	ND	ND
	WHB (A)	451	46	9	0	327	161	488	9.4	28.4	9.2	ND	ND
	WHBM (A)	451	60	11	0	304	196	500	10.6	27.1	10.4	ND	ND
1998/99	TST (A)	208	92	0	0	263	37	300	0.14	1.1	0.14	0.10	0.07
	TSTM (A)	208	79	0	0	238	49	287	0.41	2.4	0.41	0.29	0.21
	WHB (A)	208	68	0	0	215	61	276	0.57	2.8	0.57	0.38	0.28
	WHBM (A)	208	92	0	0	238	62	300	0.78	3.8	0.78	0.57	0.42
	WHB (B)	208	125	0	0	248	85	333	2.54	9.9	2.58	0.97	0.72
	WHBM (B)	208	104	0	0	226	86	312	2.29	8.3	2.29	0.80	0.59

*1 maize price taken as R740 ton^{-1}

*2 For the annual crops : ($P_g + P_f$ = 386 mm) + relevant ΔS value (see equation 1.7)
For the biannual crops : ($P_g + P_f$ =827 mm) + relevant ΔS value

ND = not determined as data not available

5.2 SUNFLOWER

5.2.1 Glen/Bonheim-Onrus ecotope (Bo)

Grain and biomass yields for three seasons are presented in Table 5.2.1.1, results of statistical analyses in Table 5.2.1.2 and water balance and production efficiency data in Table 5.2.1.3.

Table 5.2.1.1 Sunflower grain and biomass yields on Bo for the different treatments for the 1996/97, 1997/98 and 1998/99 seasons

Season Pg*1 (mm)	1996/97 296		1997/98 294		1998/99 139	
treatment*2	grain*3 (kg ha^{-1})	biomass*4 (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	1612	4133	2098	4695	594	1453
TSTM (A)	-	-	2476	5370	626	1700
WHB (A)	1853	4751	2773	5888	651	1730
WHBM (A)	-	-	2806	5948	804	1906
WHB (B)	-	-	-	-	1547	3670
WHBM (B)	-	-	-	-	1561	3703

Symbols have the same meaning as in Table 5.1.1.1, excepting that grain mass is at 13% water content.

A full set of diagrams showing changes in the water content of the root zone during each growing season are presented in Appendices 5.2.1.1 to 5.2.1.3. The following are important features of the diagrams which help to explain yield differences between treatments and seasons, presented in Table 5.2.1.1. The most critical factors are the amount and distribution of rainfall during the growing season, and θ_p. A high θ_p provides a buffer against low rainfall later in the season. This is clearly demonstrated by comparing the treatments WHB (A) and WHB (B) for the 1999 season - see Figure 5.2.1.3(b) and Figure 5.2.1.3(c). The θ_p values were 365 and 420 mm respectively. From DAP 48 to DAP 110 there was only 36 mm of rain with no event greater than 10 mm. The respective yields for these two treatments were 651 and 1547 kg ha^{-1} (Table 5.2.1.1).

It seems that when θr falls below about 260 mm serious stress sets in and yield becomes impaired, especially if this occurs during the drought sensitive growth stage, approximately between DAP 45 and 85. Figure 5.2.1.1. shows this. The critical water regime period is demarcated. The figure shows that the soil water regimes during the critical period become drier in the order WHB (A) 97/98, WHB (A) 96/97, WHB (B) 98/99, WHB (A) 98/99. Grain yields decrease in the same order, i.e 2.8, 1.8, 1.5, and 0.7 t ha^{-1}. It needs to be kept in mind that a good dryland yield of sunflower is around 3 t ha^{-1}. It seems that this would have been achieved had there been a good rain around DAP 65 during the 97/98 season.

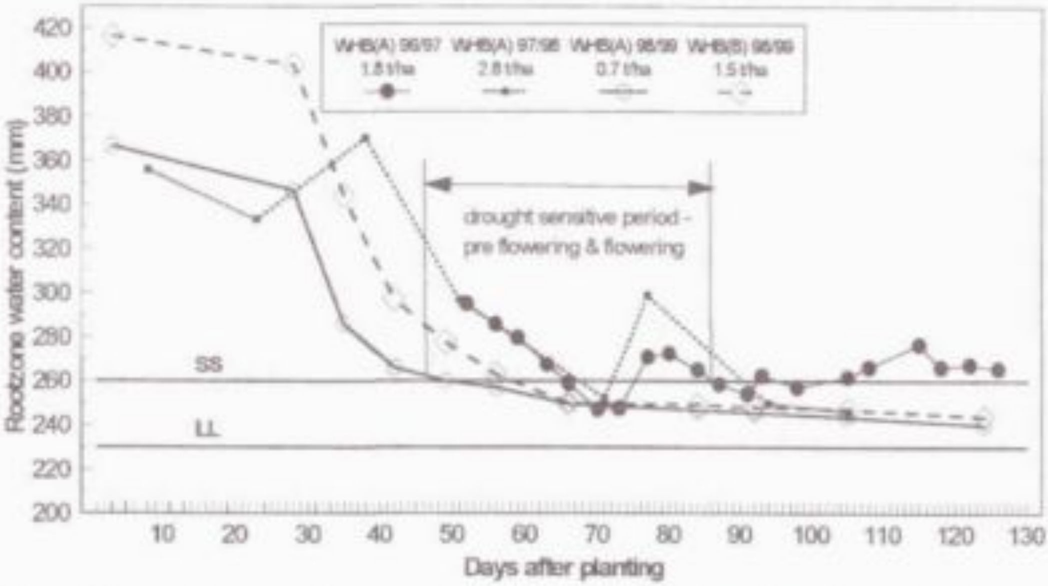

Figure 5.2.1.1 The growing season rootzone water regime of sunflower for four WHB treatments during three seasons on Bo

Results of statistical analyses are presented in Table 5.2.1.2. There were no significant differences for the 96/97 season - probably for the same reason as that given for maize. For the 97/98 season both grain and biomass yields are significantly better on the WHB treatments than on the TST treatments. The severe drought during 98/99 clouded any potential differences in yield between TST(A), TSTM(A), WHB(A) and WHBM(A) since all of these started with θr values below "full". Once their limited reserve had been depleted the plants became, and remained, severely stressed. There is a well defined significant difference in both grain and biomass yield between the biannual and annual cropping systems.

A suitable transpiration efficiency coefficient for above-ground biomass for sunflower of 4.5 g m^{-2} mm^{-1} k Pa was obtained from Chapman, Hammer & Meinke (1993). Using this value in the same way as already described for maize it was possible to calculate the T values shown in Table 5.2.1.3. The efficiency values were calculated as described for maize.

Significant features of the results in Table 5.2.1.3 are the following:

(a) Relatively high water losses due to R on the TST treatments - clearly the reason for the lower yields of these treatments (Table 5.2.1.1).

(b) The absence of D losses on all the treatments - due presumably to very efficient water extraction by the sunflower roots resulting in the soil becoming rapidly dried out to relatively low values before the next rain. The diagrams in Appendix 5.2.1.2 for the high rainfall 97/98 season show this well. θr values never exceed the CMUL value of 422 mm.

(c) The relatively low WUE_T values (the highest being 16.4 kg ha^{-1} mm^{-1} compared to maize (26.9 kg ha^{-1} mm^{-1}) is partly due to the fact that sunflower grain is much richer in oil than maize grain. The same amount of primary assimilate (1 g) converts to about 0.83 g of carbohydrate and only 0.33 g of lipid (Gregory, 1989). One would expect WUE_T to be fairly constant. The variations here, especially between the 97/98 and 98/99 seasons, are due to variations in harvest index brought about by the extreme drought conditions during 98/99 season.

(d) Because of the extreme drought experienced during 98/99 the PUE_{gI} and $PUE_{g(T)}$ values are not very meaningful for comparative purposes. They do, however, express the drought resistant quality of sunflower compared to maize and sorghum. The equivalent values were very much lower for these crops (Table 5.1.1.3 and Table 5.3.1.3).

(e) The similarity of Es values on WHB(A) and WHBM(A) during 97/98 is surprising. This may be due to losses from WHBM(A) by intercepted water from small rainfall events evaporating from the mulch before it reaches the soil.

Table 5.2.1.2 Results of statistical analyses of sunflower grain and biomass yields on Bo over three seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*1 (kg ha^{-1})	CV*2 (%)	(A)*3 vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*4 vs M
96/97	NSD	919.85	15.11	-	-	-	-	-	-	-
97/98	*	254.75	6.26	-	-	-	NSD	254.75	6.26	NSD
98/99	NSD	204.88	13.80	*	204.88	13.80	NSD	136.61	13.80	NSD
BIOMASS										
96/97	NSD	2299.10	15.11	-	-	-	-	-	-	-
97/98	*	494.02	5.31	-	-	-	NSD	494.02	5.31	NSD
98/99	NSD	589.83	16.22	*	589.83	16.22	NSD	393.29	16.22	NSD

NSD = no significant difference
* = significant at the 5% probability level
*1 = least significant difference
*2 = coefficient of variation
*3 = annual vs biannual cropping
*4 = interaction between tillage treatments and mulching

Table 5.2.1.3 Water balance and production efficiency data for sunflower over three seasons on Bo

Season	Treatment	Water balance components (mm)							Efficiencies				
									water (kg ha^{-1} mm^{-1})				Income *1 (R ha^{-1} mm^{-1})
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf} *2	$PUE_{g(I)}$
1996/97	TST (A)	296	64	0	13	231	116	347	4.6	13.9	4.5	ND	ND
	WHB (A)	296	78	0	0	241	133	374	5.0	13.9	5.0	ND	ND
1997/98	TST (A)	294	35	0	30	164	135	299	7.0	15.5	6.4	ND	ND
	TSTM (A)	294	37	0	17	160	154	314	7.9	16.1	7.5	ND	ND
	WHB (A)	294	29	0	0	154	169	323	8.6	16.4	8.6	ND	ND
	WHBM (A)	294	31	0	0	154	171	325	8.6	16.4	8.6	ND	ND
1998/99	TST (A)	139	43	0	0	125	57	182	3.3	10.4	3.3	1.5	1.65
	TSTM (A)	139	94	0	0	166	67	233	2.7	9.3	2.7	1.6	1.74
	WHB (A)	139	127	0	0	198	68	266	2.4	9.6	2.4	1.6	1.81
	WHBM (A)	139	146	0	0	210	75	285	2.8	10.7	2.8	2.0	2.23
	WHB (B)	139	141	0	0	135	145	280	5.5	10.7	5.5	1.8	1.84
	WHBM (B)	139	135	0	0	128	146	274	5.7	10.7	5.7	1.8	1.95

*1 Sunflower price taken as R1100 ton^{-1} as an average for the three years

*2 The precipitation included is that for the 97/98 growing season plus its preceding fallow period, plus the 98/99 growing season plus its preceding fallow period ; total= 819 mm plus the difference in the water content at the beginning and end of this period (see equation 1.7)

ND = not determined as data not available

5.2.2 Glen/Swartland-Rouxville ecotope (Sw)

Grain and biomass yields for the three seasons are presented in Table 5.2.2.1, results of statistical analyses in Table 5.2.2.2 and water balance and production efficiency data in Table 5.2.2.3.

Table 5.2.2.1 Sunflower grain and biomass yields on Sw for the different treatments for the 1996/97, 1997/98 and 1998/99 seasons

Season Pg (mm)	1996/97 296		1997/98 294		1998/99 139	
treatment	grain (kg ha^{-1})	biomass (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	1540	3949	2028	4552	506	1392
TSTM (A)	-	-	2281	5067	617	1823
WHB (A)	1751	4490	2462	5270	661	1627
WHBM (A)	-	-	2558	5522	815	1832
WHB (B)	-	-	-	-	1418	2808
WHBM (B)	-	-	-	-	1571	3245

Symbols have the same meaning as in Table 5.1.1.1.Grain yield is at a water content of 13%.

Diagrams describing the soil water regime during each growing season are presented in Appendices 5.2.2.1 to 5.2.2.3. Since the rainfall is the same as on Bo, and soil water characteristics are similar, the patterns on the two ecotopes are also similar. The importance of the threshold water content below which serious stress (SS) sets in is demonstrated in Figure 5.2.2.1. Yields are generally seen to increase approximately in proportion to the extent to which the θr value stays above this line.

Grain yields for the comparison TST(A) vs. WHB(A) are not significantly different for the 96/97 season, but are significantly different for the 97/98 and 98/99 seasons (Table 5.2.2.2). It seems that the efficient deep root system of sunflower counteracts its dependence on surface layer protection in the form of mulch from having a significant influence on yield. Although this proves to be correct for the wet 97/98 season, under the droughty 98/99 conditions mulch is shown to have had a significantly beneficial influence on the grain yield.

All the comments made for the water balance and production efficiency data for Bo are also relevant to Sw. The very large value of Es on TSTM(A) compared to WHB(A) during 97/98 is surprising. A possible explanation is that there was a large loss of water via interception and subsequent evaporation from the mulch.

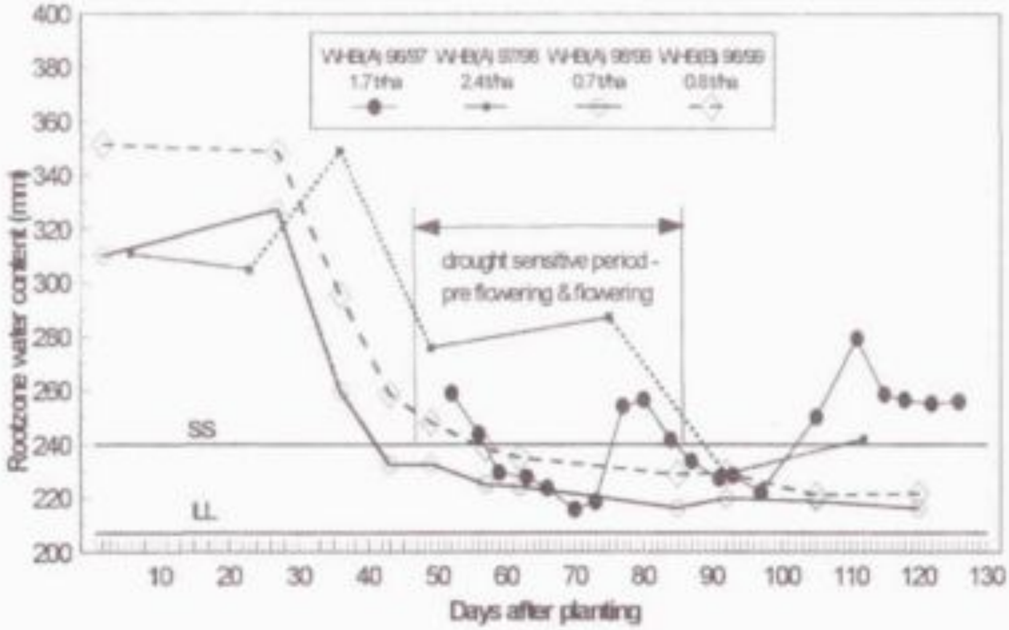

Figure 5.2.2.1 The growing season rootzone water regime of sunflower for four WHB treatments during three seasons on Sw

Table 5.2.2.2 Results of statistical analyses of sunflower grain and biomass yields on Sw over three seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*[1] (kg ha^{-1})	CV*[2] (%)	(A)*[3] vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*[4] vs M
96/97	NSD	1096.60	18.97	-	-	-	-	-	-	-
97/98	*	224.69	6.01	-	-	-	NSD	224.69	6.01	NSD
98/99	*	98.43	6.86	*	98.43	6.86	*	65.63	6.86	NSD
BIOMASS										
96/97	NSD	2741.1	18.96	-	-	-	-	-	-	-
97/98	*	406.87	4.69	-	-	-	NSD	406.87	4.69	NSD
98/99	NSD	551.91	16.89	*	551.91	16.89	NSD	368.00	16.89	NSD

NSD = no significant difference
* = significant at the 5% probability level
*[1] = least significant difference
*[2] = coefficient of variation
*[3] = annual vs biannual cropping
*[4] = interaction between tillage treatments and mulching

Table 5.2.2.3 Water balance and production efficiency data for sunflower over three seasons on Sw

Season	Treatment	Water balance components (mm)							Efficiencies				
									water (kg ha^{-1} mm^{-1})				Income (R ha^{-1} mm^{-1})*1
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf}*2	PUE_g $ND_{f(I)}$
1996/97	TST (A)	296	8	0	28	165	111	276	5.6	13.9	5.1	ND	ND
	WHB (A)	296	30	0	0	200	126	326	5.4	13.9	5.4	ND	ND
1997/98	TST (A)	294	47	0	40	168	133	301	6.7	15.5	5.9	ND	ND
	TSTM (A)	294	103	0	13	235	149	384	5.9	15.3	5.7	ND	ND
	WHB (A)	294	54	0	0	193	155	348	7.1	15.9	7.1	ND	ND
	WHBM (A)	294	64	0	0	196	162	358	7.1	15.8	7.1	ND	ND
1998/99	TST (A)	139	65	0	0	148	56	204	2.5	9.0	2.5	1.3	1.41
	TSTM (A)	139	87	0	0	153	73	226	2.7	8.5	2.7	1.6	1.71
	WHB (A)	139	94	0	0	168	65	233	2.8	10.2	2.8	1.7	1.84
	WHBM (A)	139	116	0	0	182	73	255	3.2	11.2	3.2	2.1	2.26
	WHB (B)	139	129	0	0	156	112	268	5.3	12.7	5.3	1.6	1.77
	WHBM (B)	139	143	0	0	152	130	282	5.6	12.1	5.6	1.8	2.00

*1 Sunflower price taken as R1100 ton^{-1} as an average for the three years

*2 For explanation of symbols see Table 5.2.1.3

ND = not determined as data not available

5.2.3 Khumo/Swartland-Amandel ecotope (Ks)

Grain and biomass data for the two seasons are presented in Table 5.2.3.1.

Table 5.2.3.1 Sunflower grain and biomass yields on Khumo/Swartland for the different treatments for the 1997/98 and 1998/99 seasons

Season Pg*1 (mm)	1997/98 290		1998/99 229	
treatment*2	grain*3 (kg ha^{-1})	biomass*4 (kg ha^{-1})	grain*3 (kg ha^{-1})	biomass*4 (kg ha^{-1})
TST (A)	1216	3188	1096	1730
WHB (A)	1734	4245	1260	2067
WHBM (A)	1876	4525	1628	2453
WHB (B)	-	-	1607	2578
WHBM (B)	-	-	1658	2890

For explanation of treatments and symbols see Table 5.1.1.1. Grain mass is at 13 % water content.

The diagrams in Appendices 5.2.3.1 and 5.2.3.2 describe the water regime during each growing season and help to explain the yields and water balance data.

The 1997/98 season was characterized by less than normal rainfall during the growing period. Nevertheless after a favourable start and well-distributed rainfall the crop never suffered from serious water stress. During the critical drought sensitive period between DAP 45 -80, θr for all the treatments were close to DUL or above DUL. During this period θr for the WHB(A) and WHBM(A) treatments was above DUL. This explains the higher yields compared to the TST(A) treatment. The result was good yields on all the treatments, with WHB(A) and WHBM(A) significantly better than TST(A), and WHBM(A)not significantly better than WHB(A).

The 1998/99 season's rainfall was also less than normal during the growing season. Although it was only 30 mm less than that for 1997/98, it was a very dry season. After a favourable start the crop suffered severe stress from DAP 50 until the end of the growing season. This period was characterized by well-distributed small rainfall events and high temperatures. Twenty six of the rainfall events were less than 10 mm, all of which would almost immediately have been lost by Es. There were six rainfall events between 10 and 20 mm, and only two between 20 and 30 mm both of which were in the first 15 DAP. If we compare these rainfall events with those in 1997/98 a totally different pattern emerges. In 1997/98 there were 12 rainfall events less than 10 mm, 4 events between 10-20 mm, 3 events between 20-30 mm and 2 well-distributed events between 40-52 mm. This explains why there were better yields in 1997/98.

Differences in θp were not the result of tillage differences only. Inadvertently the farmer ploughed the whole demonstration trial after the 1997/98 growing season. The treatments had to be remade, but the original plots locations were retained. The higher WHB(A), WHBM(A), WHB(B) and WHBM(B) yields might be the result of the ability of the sunflower to use not only the water in the basins better but also the water between the crop rows (2 m). This water might help the crop to survive if it can be utilized efficiently.

Results of statistical analyses are presented in Table 5.2.3.2. There were significant differences in yield and biomass between TST(A) and WHB(A) for the 97/98 season, but no significant difference between mulch and no-mulch. The statistical analyses data for the 98/99 season are more complicated because it is not a split plot design, and the fact that the farmer ploughed the trial contributes to the complexity. Although there was a difference in yield between WHB(A) and TST(A), it was not significant. Between the yields of WHBM(B), WHB(B) and WHBM(A) there are no significant differences, but all these treatments are significantly better than WHB(A) and TST(A). The reason could be that the mulch supressed Es during the fallow period (WHBM(A) and WHBM(B)) and that the accumulation of water during the long fallow (WHB(B) and WHBM(B)) gave the benefit of a higher θp than WHB(A). There is no significant difference in the biomass between TST(A) and WHB(A). The biomass of WHB(A) and WHBM(A) differs significantly. There is no significant difference in biomass between WHBM(A) and WHB(B), and no significant difference between WHB(B) and WHBM(B).

A suitable transpiration efficiency coefficient for above ground biomass for sunflower of 4.5 g m^{-2} mm^{-1} kPa was obtained from Chapman *et al.*, (1993). Using this value in the same way as already described for maize, it was possible to calculate the T values shown in Table 5.2.3.3. The efficiency values were calculated as described for maize.

Significant features of the results in Table 5.2.3.3 are the following:

(a) Relatively high water losses due to R on the TST treatments - definitely the reason for the lower yields of these treatments.

(b) Relatively low WUE_T values (the highest being 16.8 kg ha^{-1} mm^{-1}) as already explained for the Glen/Bonheim ecotope.

(c) No PUE_{gf} values due to the fact that the trial was ploughed out during the fallow period.

(d) The $PUE_{gf(l)}$ values are not very meaningful for comparative purposes due to the extreme drought experienced during the 1998/99 season. These values express the drought resistant quality of sunflower compared to maize and sorghum, where these values were very much lower.

Table 5.2.3.2 Results of statistical analyses of sunflower grain and biomass yields on Ks over three seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*1 (kg ha^{-1})	CV*2 (%)	(A)*3 vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*4 vs M
97/98	*	467,23	9.98	-	-	-	NSD	467.23	9.98	NSD
98/99	NSD	200.24	4.89	NSD	200.24	4.89	NSD	200.24	4.89	NSD
BIOMASS										
97/98	*	935.77	8.07	-	-	-	NSD	935.77	8.07	NSD
98/99	NSD	362.28	5.48	NSD	362.28	5.48	NSD	362.28	5.48	NSD

NSD = no significant difference

* = significant at the 5% probability level

*1 = least significant difference

*2 = coefficient of variation

*3 = annual vs biannual cropping

*4 = interaction between tillage treatments and mulching

Table 5.2.3.3 Water balance and production efficiency data for sunflower over two seasons on Ks. All "efficiencies" are based on grain yield

Season	Treatment	Water balance components (mm)							Efficiencies				
									water (kg ha^{-1} mm^{-1})				Income*[1] (R ha^{-1} mm^{-1})
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf}*[2]	$PUE_{gf(I)}$
1997/98	TST (A)	290	138	0	31	306	91	397	3.1	13.4	2.8	ND	ND
	WHB (A)	290	72	0	0	240	122	362	4.8	14.2	4.8	ND	ND
	WHBM (A)	290	73	0	0	233	130	363	5.2	14.4	5.2	ND	ND
1998/99	TST (A)	229	144	0	14	291	68	359	3.1	16.2	2.9	-	1.96
	WHB (A)	229	80	0	0	227	82	309	4.1	15.4	4.1	-	2.07
	WHBM (A)	229	82	0	0	214	97	311	5.2	16.8	5.2	-	2.59
	WHB (B)	229	83	0	0	210	102	312	5.2	15.8	5.2	-	1.97
	WHBM (B)	229	123	0	0	238	114	352	4.7	14.5	4.7	-	2.05

*[1] Sunflower price taken as R1100 ton^{-1} as an average for the three years
*[2] For explanation of symbols see Table 5.2.1.3
ND = not determined as data not available

5.2.4 Vlakspruit/Arcadia-Lonehill ecotope (Va)

Grain and biomass yields for the two seasons are presented in Table 5.2.4.1

Table 5.2.4.1 Sunflower grain and biomass yields on Va for the different treatments for the 1997/98 and 1998/99 seasons

Season Pg^{*1} (mm)	1997/98 268		1998/99 295	
treatment*2	grain*3 (kg ha^{-1})	biomass*4 (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	2134	5031	1045	1767
WHB (A)	2835	6360	1588	2976
WHBM (A)	2937	6549	1997	3994
WHB (B)	-	-	1994	3733
WHBM (B)	-	-	2581	5243

For explanation of treatments and symbols see Table 5.1.1.1. Grain mass is at 13% water content.

The diagrams in Appendices 5.2.4.1 and 5.2.4.2 show changes in the water content of the root zone during each growing season and help to explain the yield and water balance data. The most critical factors are the amount and distribution of rainfall during the growing season and θ_p. A high θ_p provides a buffer against a bad rainfall season especially later in the season.

After a favourable start to the 97/98 season the crop did not experience severe stress throughout the growing season. The rainfall during the season of 268 mm is less than the normal rainfall but the season was characterized by good rainfall events (4 rainfall events more than 30 mm) which were well distributed. The result was good yields on all the treatments with the WHB(A) and WHBM(A) significantly better than TST(A), and WHBM(A) not significantly better than WHB(A). During the critical drought sensitive period (DAP 45-80), θr of WHB(A) and WHBM(A) were constantly close to DUL, while TST(A) was far less than DUL but without any severe stress. This is the reason why TST(A) did not yield well. The only difference between TST(A) and WHB(A) was due to more R on the former.

The 1998/99 season was extremely dry from DAP 50. Although the total rainfall during the 98/99 growing season (295 mm) was considerable more than that in the 97/98 growing season (268 mm), the crop suffered far more stress during 98/99 due to the large number of small rainfall events. There were 22 rainfall events of less than 10 mm, which were almost immediately lost to Es; 6 events of between 10 and 20 mm, 1 between 20-30 mm, and 2 between 40 and 60 mm both in the first 60 DAP. The result was low yields, especially on the TST(A) treatment. During the 97/98 season the total rainfall during the growing season was less but much better yields were obtained. There were 15 rainfall events of less than 10 mm; 2 between 10-20 mm, 1 between 30-40 mm; 2 between 40-60 mm and 1 between 60-70 mm, with a very good distribution. This is one of the reasons why sunflower yielded better during the overall drier 97/98 growing season.

The importance of the other critical factor θ_p is clearly demonstrated by comparing treatments TST(A), WHBM(A) and WHBM(B) for the 98/99 season. The reasonable yield during the 98/99 season confirms the drought resistant quality of sunflower.

Results of statistical analyses are presented in Table 5.2.4.2. For the 97/98 season both grain and biomass yields are significantly better on the WHB(A) treatment than on the TST(A) treatment, but there is no significant difference between mulch and no-mulch. For the dry 98/99 season grain yield is significantly better on the WHB(A) treatment than on the TST(A) treatment. WHBM(B) grain yield is significantly better than all the treatments, but there is no overall significant difference between annual and biannual cropping. Grain yield of WHBM(B) is significantly better than WHB(A) and similarly between WHBM(A) and WHB(A). The biomass is not significantly better on the WHB(A) treatment than on the TST(A) treatment; mulch is not significantly better than no-mulch; and there is no significant difference between annual and biannual cropping. Biomass of WHBM(B) is significantly better than all the other treatments.

The same procedure as already explained for the Glen/Bonheim ecotope was used to calculate the water balance and production efficiency data for sunflower over two seasons. Results are presented in Table 5.2.4.3. The following are considered to be important features of the results:

(a) The complete suppression of R at all the WHB treatments and high water losses at the TST treatment due to R is clearly one of the reasons for the lower yield of this treatment.

(b) Because of the extreme drought experienced during 98/99 season the PUE_{gf} and $PUE_{gf(l)}$ values are not very meaningful for long-term comparisons. However, it is significant that whereas the PUE_{gf} value for TST is 1.5, the mean value for all the WHB treatments is 2.3. This is a big difference, especially during such a dry season. There is also a large difference in $PUE_{gf(l)}$ when TST and the average of all the WHB are compared; TST = 1.69, and mean for WHB = 2.47. Comparing these values with the other crops at Glen for the 98/99 season indicates the excellent drought resistant quality of sunflower.

Table 5.2.4.2 Results of statistical analyses of sunflower grain and biomass yields on Va over two seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*1 (kg ha^{-1})	CV*2 (%)	(A)*3 vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*4 vs M
97/98	*	128.96	1.68	-	-	-	NSD	128.96	1.68	NSD
98/99	*	163.72	3.15	NSD	163.72	3.15	*	163.72	3.15	NSD
BIOMASS										
97/98	*	238.53	1.37	-	-	-	NSD	238.53	1.37	NSD
98/99	NSD	1227.40	12.28	NSD	1227.40	12.28	NSD	1227.40	12.28	NSD

NSD = no significant difference

* = significant at the 5% probability level

*1 = least significant difference

*2 = coefficient of variation

*3 = annual vs biannual cropping

*4 = interaction between tillage treatments and mulching

Table 5.2.4.3 Water balance and production efficiency data for sunflower over two seasons on Va. All "efficiencies" are based on grain yield

Season	Treatment	Water balance components (mm)							Efficiencies				
									water (kg ha^{-1} mm^{-1})				Income (R ha^{-1} mm^{-1})
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf} *2	$PUE_{gf(I)}$
1997/98	TST (A)	268	142	0	38	228	144	372	5.7	14.8	5.2	ND	ND
	WHB (A)	268	96	0	0	182	182	364	7.8	15.6	7.8	ND	ND
	WHBM (A)	268	134	0	0	214	188	402	7.3	15.6	7.3	ND	ND
1998/99	TST (A)	295	86	0	48	263	70	333	3.1	14.9	2.7	1.5	1.69
	WHB (A)	295	-	0	0	-	118	-	-	13.5	-	2.1	2.34
	WHBM (A)	295	165	0	0	302	158	460	4.3	12.6	4.3	2.8	3.05
	WHB (B)	295	195	0	0	342	148	490	4.1	13.5	4.1	1.8	1.98
	WHBM (B)	295	244	0	0	332	207	539	4.8	12.5	4.8	2.3	2.5

*1 Sunflower price taken as R1100 ton^{-1} as an average for the three years

*2 For explanation of symbols see Table 5.2.1.3

ND = not determined as data not available

5.3 SORGHUM

5.3.1 Glen/Bonheim-Onrus ecotope (Bo)

Grain and biomass yields for the three seasons are presented in Table 5.3.1.1, statistical analyses in Table 5.3.1.2 and water balance production efficiency data in Table 5.3.1.3.

Table 5.3.1.1 Sorghum grain and biomass yields on Bo for the different treatments for the 1996/97, 1997/98 and 1998/99 seasons

Season Pg*1 (mm)	1996/97 303		1997/98 348		1998/99 231	
treatment	grain (kg ha^{-1})	biomass*1 (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	3321	11070	2005	10458	0	919
TSTM (A)	-	-	2892	11691	0	1029
WHB (A)	3521	11737	3240	13641	0	1356
WHBM (A)	-	-	3271	14074	5	1904
WHB (B)	-	-	-	-	197	2394
WHBM (B)	-	-	-	-	281	2943

For explanation of treatments and symbols see Table 5.1.1.1
*1 estimated values

Soil water regime diagrams for each season are presented in Appendices 5.3.1.1 to 5.3.1.3. In spite of periods of severe stress during 96/97 (DAP 70 to DAP 95) (Appendix 5.3.1.1) the crop grew reasonably well and produced a satisfactory grain yield of just above 3 t ha^{-1} on both treatments. There was no significant difference between TST(A) and WHB(A). In spite of a favourable water supply during 97/98, the yield was disappointing and lower than the previous season. The reason was a lack of heat units towards the end of the growing season. The cultivar used needs a warm growing season of about 145 days. It is therefore desirable to plant in November or December. Extremely dry conditions prevailed during November and December 1998; a total of only 75 mm of rain fell compared to the long-term average of 134 mm. Several unsuccessful attempts were made to plant in dry ground and providing water with watering cans. After very good rains early in January, planting was successfully carried out on 5/1/98. Cool weather came early that year resulting in the sorghum not having sufficient heat units to complete grain filling.

The statistical analyses (Table 5.3.1.2) show that using grain yields in the overall comparisons, for the 97/98 season for TST(A) vs. WHB(A), the latter was significantly better, and for mulch vs. no-mulch, the former was significantly better. The interaction between mulching and tillage treatments was also significant for grain yields for the 97/98 season. WHB(A) was also significantly better than TST(A) with regard to biomass yields for the 97/98 season. The crop failed completely (Table 5.3.1.1) during 98/99 except for the two long fallow treatments which gave a very low grain yield of less than 300 kg ha^{-1} which was obviously significantly better than the zero yields from the annual treatments. The biomass yields from the long fallow treatments were also significantly better than the annual treatments. Even this was only possible because of having had a very full profile at planting - around 430 mm compared to around 360 mm or less for the other treatments (Appendix 5.3.1.3).

Because of the temperature problem during 97/98 and severe drought in 98/99 the water balance and production efficiency data in Table 5.3.1.2 cannot provide much useful information. A reliable k value for sorghum has also not been found and consequently separating Es + T into its components was not possible.

Table 5.3.1.2 Results of statistical analyses of sorghum grain and biomass yields on Bo over three seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*[1] (kg ha^{-1})	CV*[2] (%)	(A)*[3] vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*[4] vs M
96/97	NSD	693.87	5.77	-	-	-	-	-	-	-
97/98	*	199.16	4.35	-	-	-	*	199.16	4.35	*
98/99	NSD	107.51	75.29	*	107.51	75.29	NSD	70.00	75.29	NSD
BIOMASS										
96/97	NSD	2312.1	5.77	-	-	-	-	-	-	-
97/98	*	2180.30	10.92	-	-	-	NSD	2180.30	10.92	NSD
98/99	NSD	795.83	25.56	*	795.83	25.56	NSD	518.18	25.56	NSD

NSD = no significant difference
* = significant at the 5% probability level
*[1] = least significant difference
*[2] = coefficient of variation
*[3] = annual vs biannual cropping
*[4] = interaction between tillage treatments and mulching

Table 5.3.1.3 Water balance and production efficiency data for sorghum over three seasons on Bo

Season	Treatment	Water balance components (mm)							efficiencies				
									water (kg ha^{-1} mm^{-1})				Income (R ha^{-1} mm^{-1})
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf}	$PUE_{gf(I)}$
1996/97	TST (A)	303	52	0	13	-	-	342	9.7	-	9.4	ND*[1]	
	WHB (A)	303	86	0	0	-	-	389	9.1	-	9.1	ND	
1997/98	TST (A)	348	-4	3	32	-	-	309	6.5	-	5.8	ND	
	TSTM (A)	348	25	19	23	-	-	331	8.7	-	7.8	ND	
	WHB (A)	348	49	5	0	-	-	392	9.3	-	8.2	ND	
	WHBM (A)	348	44	5	0	-	-	387	8.5	-	8.3	ND	
1998/99	TST (A)	231	63	0	0	-	-	294	NY*[2]	-	-	-	
	TSTM (A)	231	97	0	0	-	-	328	NY	-	-	-	
	WHB (A)	231	107	0	0	-	-	338	NY	-	-	-	
	WHBM (A)	231	101	0	0	-	-	332	0.02	-	0.02	0.01	
	WHB (B)	231	99	0	0	-	-	330	0.60	-	0.60	0.22	
	WHBM (B)	231	106	0	0	-	-	337	0.83	-	0.83	0.32	

*[1] Not determined as the necessary data is not available
*[2] Zero yield

5.3.2 Glen/Swartland-Rouxville ecotope (Sw)

Grain and biomass yields for the three seasons are presented in Table 5.3.2.1, statistical analyses in Table 5.3.2.2 and water balance and production efficiency data in Table 5.3.2.3.

Table 5.3.2.1 Sorghum grain and biomass yields on Sw for the different treatments for the 1996/97, 1997/98 and 1998/99 seasons

Season Pg (mm)	1996/97 303		1997/98 449		1998/99 205	
treatment	grain (kg ha^{-1})	biomass*[1] (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	3200	10668	1744	7963	0	848
TSTM (A)	-	-	2676	8554	15	1223
WHB (A)	3339	10357	2933	9098	10	1320
WHBM (A)	-	-	3025	9424	10	1330
WHB (B)	-	-	-	-	116	1971
WHBM (B)	-	-	-	-	149	1879

For explanation of treatments and symbols see Table 5.1.1.1.
*[1] estimated values

The soil water regime (Appendices 5.3.2.1 to 5.3.2.3) was very similar to that on Bo, and climatic conditions exactly the same. The result was very similar yields. There were no significant differences (Table 5.3.2.2) in 96/97; for 97/98 WHB was significantly better than TST, (grain and biomass), mulch significantly better than no-mulch (only grain), and a significant interaction between tillage practices and mulching (only grain). Because of the severe drought during the 98/99 season the only significant difference was between the biomass yields for the biannual and annual cropping. Because of the temperature problems during 97/98 and drought problems during 98/99, the "efficiencies" presented in Table 5.3.2.3 are not meaningful for these seasons. The PUE_g values for the 96/97 season compare favourably with equivalent values reported for experiments in Texas (Sow, Hossner, Unger & Stewart, 1996).

Table 5.3.2.2 Results of statistical analyses of sorghum grain and biomass yields on Sw over three seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*[1] (kg ha^{-1})	CV*[2] (%)	(A)*[3] vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*[4] vs M
96/97	NSD	1129.3	9.83	-	-	-	-	-	-	-
97/98	*	276.23	6.64	-	-	-	*	276.23	6.64	*
98/99	NSD	124.98	141.41	NSD	124.98	141.41	NSD	81.38	141.41	NSD
	BIOMASS									
96/97	NSD	3606.7	9.77	-	-	-	-	-	-	-
97/98	*	813.43	5.79	-	-	-	NSD	813.43	5.79	NSD
98/99	NSD	505.12	19.98	*	505.12	19.98	NSD	328.89	19.98	NSD

NSD = no significant difference
* = significant at the 5% probability level
*[1] = least significant difference
*[2] = coefficient of variation
*[3] = annual vs biannual cropping
*[4] = interaction between tillage treatments and mulching

Table 5.3.2.3 Water balance and production efficiency data for sorghum over three seasons on Sw

Season	Treatment	Water balance components (mm)							Efficiencies				
									water (kg ha^{-1} mm^{-1})				Income (Rha^{-1} mm^{-1})
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf}	$PUE_{gf(I)}$
1996/97	TST (A)	303	40	0	28	-	-	315	10.2	-	9.3	-	
	WHB (A)	303	48	0	0	-	-	351	9.5	-	9.5	-	
1997/98	TST (A)	348	12	1	40	-	-	319	5.5	-	4.8	ND*[1]	
	TSTM (A)	348	35	3	12	-	-	368	7.3	-	7.0	ND	
	WHB (A)	348	16	9	0	-	-	355	8.3	-	8.1	ND	
	WHBM (A)	348	28	11	0	-	-	365	8.3	-	8.0	ND	
1998/99	TST (A)	231	74	0	0	-	-	305	NY*[2]	-	-	-	
	TSTM (A)	231	76	0	0	-	-	307	0.05	-	0.05	0.04	
	WHB (A)	231	81	0	0	-	-	312	0.03	-	0.03	0.02	
	WHBM (A)	231	79	0	0	-	-	310	0.03	-	0.03	0.03	
	WHB (B)	231	88	0	0	-	-	319	0.36	-	0.36	0.16	
	WHBM (B)	231	103	0	0	-	-	334	0.45	-	0.45	0.21	

*[1] Not determined as the necessary data is not available

*[2] Zero yield

5.4 WHEAT

5.4.1 Glen/Bonheim-Onrus ecotope (Bo)

Grain and biomass yields for the 1997 and 1998 seasons are presented in Table 5.4.1.1. Rainfall was very low during both seasons and the crop grew very poorly with no yields exceeding 1 t ha^{-1} . There were no significant differences. Wheat is not a suitable crop for the WHB production technique. It would not have been included in these experiments if the information obtained during the past three years was available during planning. There are three reasons for wheat not being a suitable crop for use with the WHB tillage technique on the ecotopes studied during this project. The first reason relates to the dominating role which Es plays in the water balance on these ecotopes. Because of this, maximisation of PUE requires that the transformation process **rain water → transpiration water** be accomplished as quickly as possible - to minimise the period for which the water is subjected as Es to the evaporative demand of the atmosphere. Achieving this objective is not possible on local ecotopes since there is so little rain during the wheat growing season, leaving the crop to depend to a large extent on the previous summer season's rainfall which has been stored in the root zone. This storage process, quantified by the parameter RSE (Equation 1.3), is most efficient on soils which have the following characteristics:

- (a) sandy topsoils
- (b) rapid infiltration rate;
- (c) high TESW values;
- (d) occur on level areas where runoff is minimal.

Even on these soils RSE values are generally low (< 20 %). The soils being studied in this project have only one of these characteristics i.e. a high TESW value. Very low RSE values are therefore to be expected.

The second reason rests on the fact that this technique aims to concentrate water on a 1 m wide strip while using a 2 m wide strip as a runoff area. This uneven distribution of water suites row crops planted with alternate "tramline" row widths of 1 m and 2 m. Wheat, however, is planted in 0.45 m rows. This means that some rows will obtain benefit from the water stored during the summer in the basins, while other rows suffer on the runoff area!

The third reason revolves around costs. Once established, the WHB layout is intended to be a permanent, or at least semi-permanent, no-till strategy. To plant wheat in the normal way the basins have to be destroyed and remade each year. This is expensive.

Water balance and production efficiency data are presented in Table 5.4.1.3. as the growing seasons is mainly during a very dry period there are no water losses by D or R on any of the treatments, and WUE_{ET} is therefore the same as PUEg. Values for these parameters are low, approximately half of the equivalent values for maize and sorghum.

Table 5.4.1.1 Wheat grain and biomass yields (kg ha^{-1}) on Bo for the different treatments for the 1997 and 1998 seasons

Season Pg (mm)	1997		1998	
treatment	grain (kg ha^{-1})	biomass (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	457	1914	552	1724
WHB (A)	554	2317	618	1930
WHB (B)	653	2732	715	2236
WHBM (B)	-	-	986	3081

For explanation of treatments and symbols see Table 5.1.1

Table 5.4.1.2. Results of statistical analyses of wheat grain and biomass yields on Bo over two seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*1 (kg ha^{-1})	CV*2 (%)	(A)*3 vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*4 vs M
97	NSD	283.36	17.56	NSD	283.36	17.56	-	-	-	-
98	NSD	670.68	33.06	NSD	670.68	33.06	NSD	670.68	33.06	NSD
	BIOMASS									
97	NSD	1185.70	17.56	NSD	1185.70	17.56	-	-	-	-
98	NSD	2095.4	33.06	NSD	2095.4	33.06	NSD	2095.4	33.06	NSD

NSD = no significant difference
* = significant at the 5% probability level
*1 = least significant difference
*2 = coefficient of variation
*3 = annual vs biannual cropping
*4 = interaction between tillage treatments and mulching

Table 5.4.1.3 Water balance and production efficiency data for wheat over two seasons on Bo

Season	Treatment	Water balance components (mm)							Efficiencies				
									water (kg ha^{-1} mm^{-1})				Income (R ha^{-1} mm^{-1})
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf}	$PUE_{g(I)}$ *1
1997	TST (A)	118	52	0	0	-	-	170	2.7	-	2.7	ND	ND
	WHB (A)	118	64	0	0	-	-	182	3.0	-	3.0	ND	ND
	WHBM (A)	118	81	0	0	-	-	199	3.3	-	3.3	ND	ND
1998	TST (A)	99	54	0	0	-	-	153	3.6	-	3.6	0.9	0.8
	WHB (A)	99	32	0	0	-	-	131	4.7	-	4.7	1.0	0.93
	WHB (B)	99	41	0	0	-	-	140	5.1	-	5.1	ND	ND
	WHBM (B)	99	41	0	0	-	-	140	7.0	-	7.0	ND	ND

*1 Wheat price taken as R900 ton^{-1} as an average for the three years
ND = not determined as data not available

5.4.2 Glen/Swartland-Rouxville ecotope (Sw)

Grain and biomass yields for the 1997 and 1998 seasons are presented in Table 5.4.2.1.

Table 5.4.2.1 Wheat grain and biomass yields on Sw for the different treatments for the 1997 and 1998 seasons

Season Pg (mm)	1997		1998	
treatment*2	grain*3 (kg ha^{-1})	biomass*4 (kg ha^{-1})	grain (kg ha^{-1})	biomass (kg ha^{-1})
TST (A)	575	2408	557	1742
WHB (A)	778	3254	602	1882
WHB (B)	762	3185	815	2547
WHBM (B)	-	-	882	2755

For explanation of treatments and symbols see Table 5.1.1.1.

Grain and biomass yields are presented in Table 5.4.2.1 and statistical analyses in Table 5.4.2.2. Results were very similar to those on Bo and the comments made regarding the suitability of that ecotope for wheat are also relevant to Sw. The only comparison that showed a significant difference was that between annual and biannual cropping during the '98 season, for both biomass and grain yields. The yields were, however, very low. The small amount of extra water provided by the long fallow was beneficial.

Water balance and production efficiency data are presented in Table 5.4.2.3. Results are very similar to those on Bo in all respects.

Table 5.4.2.2 Results of statistical analyses of wheat grain and biomass yields on Sw over two seasons

Season	COMPARISONS									
	GRAIN									
	TST(A) vs WHB(A)	LSD*1 (kg ha^{-1})	CV*2 (%)	(A)*3 vs (B)	LSD (kg ha^{-1})	CV (%)	M vs no M	LSD (kg ha^{-1})	CV (%)	T*4 vs M
97	NSD	218.43	10.65	NSD	218.43	10.65	-	-	-	-
98	NSD	171.35	8.49	*	171.35	8.49	NSD	171.35	8.49	NSD
BIOMASS										
97	NSD	911.62	10.62	NSD	911.62	10.62	-	-	-	-
98	NSD	535.41	8.49	*	535.41	8.49	NSD	535.41	8.49	NSD

NSD = no significant difference
* = significant at the 5% probability level
*1 = least significant difference
*2 = coefficient of variation
*3 = annual vs biannual cropping
*4 = interaction between tillage treatments and mulching

Table 5.4.2.3 Water balance and production efficiency data for wheat over two seasons on Sw

Season	Treatment	Water balance components (mm)							Efficiencies				
									water (kg ha^{-1} mm^{-1})				Income (Rha^{-1} mm^{-1})
		P	ΔS	D	R	Es	T	Es+T	WUE_{ET}	WUE_T	PUE_g	PUE_{gf}	$PUE_{gf(I)}$ *[1]
1997	TST (A)	118	73	0	0	-	-	191	3.0	-	3.0	ND	ND
	WHB (A)	118	105	0	0	-	-	223	3.5	-	3.5	ND	ND
	WHBM (A)	118	105	0	0	-	-	223	3.4	-	3.4	ND	ND
1998	TST (A)	99	42	0	0	-	-	141	4.0	-	4.0	0.9	0.82
	WHB (A)	99	31	0	0	-	-	130	4.6	-	4.6	1.0	0.90
	WHB (B)	99	41	0	0	-	-	140	5.8	-	5.8	ND	ND
	WHBM (B)	99	38	0	0	-	-	137	6.4	-	6.4	ND	ND

*[1] Wheat price taken as R900 ton^{-1} as an average for the three years
ND = not determined as data not available

6. LONG-TERM SIMULATED YIELDS: RESULTS AND DISCUSSION

6.1 INTRODUCTION

To be able to make reliable recommendations concerning the best production techniques for a crop on a particular ecotope it is desirable to have long-term yields. The need for this is accentuated for ecotopes in semi-arid areas where rainfall is marginal, and also erratic with regard to amount, distribution and intensity. The use of crop models with long-term climate data to achieve this objective has been widely used in agriculture for more than a decade. The application of this strategy for the production techniques used in this study requires more than standard crop modelling procedures. The latter are satisfactory for the TST treatments. The difficulty with TSTM is that the mulch depresses both R and Es, although for small rainfall events Es may be enhanced. For WHB, to correctly simulate the soil water regime in the region of the basins requires that one is able to correctly predict R from the runoff strip for each rainfall event recorded in the long-term weather data set. For WHBM the suppression of Es by the mulch needs also to be taken into account. Predicting R would be simplified if the rainfall intensity (Pi) of each rainfall event in the long-term data set was available. A runoff model with Pi as an input could then be employed advantageously. This benefit is however not available at present and hence the value of the potential outputs from the Water Research Commission Project (No. K5/1049) being undertaken by Professor S. Walker at the University of the Free State.

Long-term yield prediction was only carried out for maize and sunflower. These two crops have proved to be the best out of the four crops tested over three years. For the reasons given in section 5.3 the sorghum yields were considered to be unrepresentative. To develop and/or calibrate a model using these results would not be a useful exercise and has therefore not been done. It was also thought not worth while to spend time on a wheat model for the reasons given in section 5.4.

The maize model used was DSSAT-V3 (Tsuji, Uehara & Balas, 1994). A brief description of the model is presented in Appendix 6.1. Model testing, calibration and the long-term runs were done at the ARC-Grain Crops Institute (ARC-GCI) by Dr.A. du Toit and co-workers. For sunflower J.J. Botha has developed a stress model based on selected measurements made on Bo and Sw (See 6.1.2.2). Since adaptations to cater for the WHB and mulch treatments were not always the same for both models, they will be discussed separately.

6.1.1 Maize

As a first step towards calibrating the DSSAT-V3 model for conditions at Glen the necessary input and output data for 17 maize yields from the research work of De Bruyn (1974) over 13 years on a red Swartland Form soil at Glen were given to the ARC-GCI team. Results of model reliability tests using the procedure of Wilmot (1981) are presented in Figure 6.1.1. The final model performance was very good. The systematic error ($RMSE_s$) was only 3 % of RMSE, and D-index and r^2 values were satisfactory at 0.91 and 0.70 respectively. It is noteworthy that only one of the 17 yields was slightly less than 1 t ha^{-1}, and that only one was more than 3 t ha^{-1}. The overall mean of these results of De Bruyn is 2054 kg ha^{-1}.

Adaptations to cater for WHB and mulch treatments were made via the rainfall file. The result was that seven different rainfall files, in the IBSNAT format (Ritchie, Godwin & Singh, 1989) needed by DSSAT-V3, were supplied to the ARC-GCI team. As this was a time-consuming task, it was only possible (in the time available) to complete it for the 18 year period 1980 to 1999. An example of a portion of the resultant data is presented in Table 6.1.1., together with the formulae used to calculate the "effective P" values for use by DSSAT-V3 to simulate long-term maize yields for different treatments on Bo and Sw.

Table 6.1.1 Data to demonstrate the calculation of "effective P" values for use by DSSAT-V3 to simulate long-term maize yields for different treatments on Bo and Sw

Date		DOY	P*1 (mm)	R_t*2 (mm)	"effective P" values for different treatments (mm)					
					TST *3	WHB *4	TSTM (Bo)*5	TSTM (Sw)*6	WHBM (Bo)*7	WHBM (Sw)*8
May 99	4	124	0.4	0.0	0.4	0.4	0.4	0.4	0.4	0.4
	8	128	6.6	0.0	6.6	6.6	6.6	6.6	6.6	6.6
	12	132	0.2	0.0	0.2	0.2	0.2	0.2	0.2	0.2
	14	134	9.0	2.1	8.2	13.2	8.2	8.2	13.2	13.2
	15	135	3.0	0.0	3.0	3.0	3.0	3.0	3.0	3.0
	16	136	0.2	0.0	0.2	0.2	0.2	0.2	0.2	0.2
	18	138	18.8	6.7	16.1	32.2	16.1	16.1	32.2	32.2
	19	139	20.0	7.3	17.1	34.6	19.5	20.7	38.0	38.4
	20	140	1.8	0.0	1.8	1.8	1.8	1.8	1.8	1.8
	22	142	0.6	0.0	0.6	0.6	0.6	0.6	0.6	0.6
	24	144	0.2	0.0	0.2	0.2	0.2	0.2	0.2	0.2
	27	147	0.6	0.0	0.6	0.6	0.6	0.6	0.6	0.6
Jun 99	5	156	5.2	0.0	5.2	5.2	5.2	5.2	5.2	5.2
	6	157	0.2	0.0	0.2	0.2	0.2	0.2	0.2	0.2

*1 actual rain

*2 estimating runoff from the 2 m runoff strip on WHB using equation 4.3

*3 $= P - (R_t \times 0.4)$. A study of the R data from the runoff plots on Bo and Sw showed that during a season with a reasonably normal rainfall R_{TST} approx. $= 0.4\ R_t$. Hence whenever equation 4.3 predicts that R_t occurred, it is reasonable to estimate that R on the TST plots would be around 40 % of it.

*4 $= P + (2\ R_t)$. Since the units of R_t are mm coming from a 2 m wide area, and the water is concentrated on a 1 m wide area, it is necessary to double the value of R_t to estimate the actual amount of additional water in mm made available to the crop. This value is then added to P for each day to obtain a total "effective P" value.

*5 for $P < 20$ mm $= P_{TST}$; for $P \geq 20$ mm $= P_{TST} + 14$ %. The formula was based on the results of a comparison of T values for TST(A) and TSTM(A) recorded in the water balance table for Bo (Table 5.1.1.3). It was found for the 97/98 and 98/99 seasons (there was no TSTM(A) treatment in 96/97) that $T_{TSTM} - T_{TST}$ was approximately equal to 14% of the sum of rainfall events greater than 20 mm. This seems to be a logical result for two reasons. Firstly, the depressive influence of mulch on R can be expected to be related to the amount of rain - especially since it has been shown that there is a correlation between R and rainfall amounts on these ecotopes. Secondly, the influence of mulch on Es needs to be considered. The mulch probably absorbs most of the rain of small events, the water then evaporating without any benefit to the crop. The larger the event, the greater the fraction which will enter the soil.

*6 for $P < 20$ mm = P_{TST}; for $P \geq 20$ mm = P_{TST} + 21 %. The explanation given above for Bo also applies here for Sw. Probably because of the slightly higher R potential and Es potential on Sw compared to Bo, the T benefit via TSTM(A) was found to be slightly higher than on Bo and approximately 21 % of $\Sigma P \geq 20$ mm.

*7 for $P < 20$ mm = P_{WHB}; for $P \geq 20$ mm = P_{WHB} + 10 %.

*8 for $P < 20$ mm = P_{WHB}; for $P \geq 20$ mm = P_{WHB} + 11 %.

The same procedure as described under *5 and *6 was followed to obtain the formulae for *7 and *8. The smaller benefit here of mulch is logical since runoff suppression is not involved.

Simulated and measured results are compared in Table 6.1.2 The model performs reasonably well for yields above about 1 t ha^{-1} but cannot adequately simulate the very low yields obtained in 98/99. This is not surprising for a mechanistic model. The physiological conditions in a plant at very high levels of water stress are very complicated and difficult to simulate. Results of model reliability tests using the procedure of Wilmot (1981) are presented in Figure 6.1.2. Although the r^2 and D-Index values are acceptable, the systematic error is high ($RMSE_s$ is 87 % of RMSE) due to poor prediction of the very low yields. Since such low yields are expected to constitute a small fraction of long-term yields, this weakness is not considered serious enough to disqualify the model at this stage.

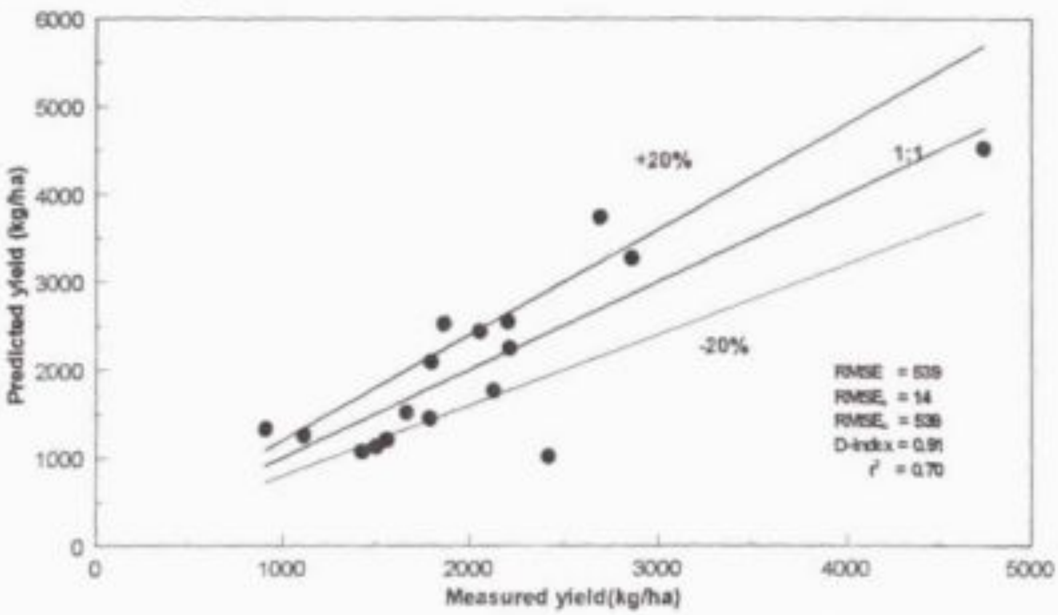

Figure 6.1.1 Measured versus predicted maize yields (kg ha^{-1}) by DSSAT-V3 for 17 data sets from De Bruyn (1974)

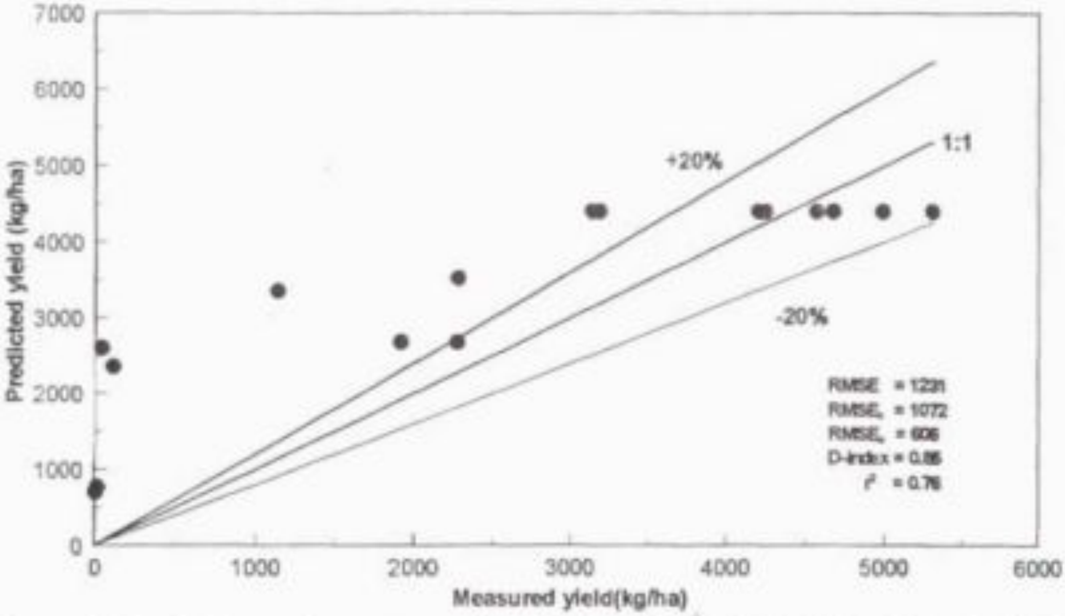

Figure 6.1.2 Measured versus predicted maize yields by DSSAT-V3(kg ha^{-1}) for all the treatments on Bo and Sw for the 96/97, 97/98 and 98/99 seasons

Table 6.1.2 A comparison between maize grain yields (kg ha^{-1}) measured (M) and simulated grain yields (S) by DSSAT-V3 over three seasons on Bo and Sw

Ecotope	Season	Treatments							
		TST(A)		TSTM(A)		WHB(A)		WHBM(A)	
		S	M	S	M	S	M	S	M
Bo	96/97	3523	2282	-	-	2681	2274	-	-
	97/98	4394	3133	4394	4207	4396	4251	4396	4678
	98/99	696	0	766	14	-	35	-	132
Sw	96/97	3353	1138	-	-	2681	1917	-	-
	97/98	4396	3187	4396	4988	4396	4575	4396	5308
	98/99	2606	41	2360	117	-	157	-	234

6.1.2 Sunflower

6.1.2.1 Summarised description of the Sunflower stress model developed by J.J. Botha.

The model is based on a similar principle to that used by Rasmussen & Hanks (1978). Details are presented in the following section and an example of one "run" in Appendix 6.2.

A reliable field measured value of total extractable soil water (TESW = DUL - LL) is of fundamental importance. The level of stress being experienced by the crop is defined as the fraction of TESW (FTESW) present at any particular time. Although FTESW is a satisfactory parameter to describe stress while the soil is drying, it is not satisfactory after a rainfall event, which may for example just wet the top 0-300 mm soil layer. In that situation the crop will suffer relatively little stress while it depletes the water in the surface soil, even if the rest of the root zone is relatively dry. An adaptation to cater for this situation has been introduced. It is based on field measurements of ET/Eo on relatively dry soils after rainfall events. The adapted FTESW value is designated as $FTESW_{aa}$. Allowance is also made in the model for D to occur when θr exceeds CMUL.

An $FTESW_{aa}$ value is calculated for each day and an average taken for periods of 15 days to give a stress factor (SF) for that period. The growing season is subdivided into eight 15 day periods and a stress weighting factor (λ) allocated to each period in accordance with its importance in relation to yield determination. An integrated stress index, or factor, termed ISF is obtained as a multiplicative summation of the SF values for the individual periods each raised to the power of λ.

6.1.2.2 Detailed description of the model

The inputs required by the model are DUL, LL, P, Eo and θp. Details are presented below concerning the various processes and parameters. An example of the calculation of the integrated stress factor (ISF) for a particular treatment for one season on an ecotope is presented in Appendix 6.2.

Catering for runoff(R) by adjusting rainfall(P) for different treatments. (P-R)

TST(A): IF (P <8): P = (P - O)
IF (P >8): P = P- ((0.473 x P) -2.168) x 0.4)
TSTM(A): IF (P <8): P = (P - O)
IF (P >8): P = P- ((0.473 x P) -2.168) x 0.2)
WHB(A) or (B): IF (P <8): P = (P + O)
IF (P >8): P = P+ ((0.473 x P) - 2.168) x 2)
(see in equation 4.3)

CF: crop factor

$CF = 0.0119 \times DAP^{1.5582} \times EXP.\ (-0.327 \times DAP)$ .... $r^2 = 0.98$

This is an adaptation of the equation of Bennie, Strydom & Vrey (1998) to give one which only has one input i.e. DAP. The cultivar (SNK37) used has a growth period of approximately 120 days. The adapted equation is specific for SNK 37.

EoCF: Crop water requirement

In order to get the crop water requirement per day, Eo must be multiplied by CF.

Treatments without mulch: TST(A); WHB(A or B): $EoCF = Eo \times Cf$

Treatments with mulch TSTM(A); WHBM(A or B): $EoCF = (Eo \times CF) \times 0.98$

Since the mulch reduces Es from the soil, measured yield averages show that the average difference in yield between WHB (A or B) and WHBM (A or B) is approximately 2 %, presumably because the mulch reduces Es. That is the reason the factor of 0.98 for treatments with mulch.

ESW_b: Extractable soil water at the beginning of a day

$ESW_b = \theta r - LL$

FTESW: Fraction of total extractable soil water

$FTESW = (ESW_b/TESW)$

$FTESW_{aa}$: Adapted Fraction of total extractable soil water

Bonheim: IF $(P/Eo) < 0.2$: $FTESW_{aa} = (FTESW + 0)$

IF $(P/Eo) > 0.2$: $FTESW_{aa} = (FTESW + (P/Eo) \times 0.4052 - 0.0729)$ up to a maximum of 1

Swartland: IF $(P/Eo) < 0.2$: $FTESW_{aa} = (FTESW + 0)$

IF $(P/Eo) > 0.2$: $FTESW_{aa} = (FTESW + (P/Eo) \times 0.4353 + 0.0518)>$ up to a maximum of 1

During a period where ESW_b is low and it rains during that day, the model did not take the rain in consideration, and penalised the extraction too much. That is why there is a adapted $FTESW_{aa}$ which takes the rain during a day into consideration. These two equations were developed on the Bo and Sw ecotopes respectively. The Bo equation was also used on the Va ecotope and the Sw equation on the Ks ecotope.

SWE: Soil water Extraction

$SWE = (-(EoCF \times FTESW_{aa})) + P$

θr_a: Water content of rootzone, not adapted to cater for values above CMUL

$\theta r_a = (ESW_b + Extraction + LL)$

θr_b: Adapted water content of rootzone, to cater for values not to exceed CMUL

IF $\theta r_a < CMUL$: $\theta r_b = (\theta r_a + 0)$

IF $\theta r_a > CMUL$: $\theta r_b = (\theta r_a \times 0) + CMUL$

This equation is to make sure that θr_b does not exceed CMUL, because when $\theta r > CMUL$ D occurs, and therefor everything above CMUL is wasted as D.

ESW_e: Extractable soil water at the end of a day
$ESW_e = (\theta r_b - LL)$
ESW_e is used to start the following day (ESW_b)

SF: Stress factor
SF_{0-15} = sum of $FTESW_{aa}$ for a period of 15 days
Each period is calculated separately. SF is the average FTESWaa for a set of 15 day periods up to a maximum of 8 periods.
Period 1 (SF_1): $SF_{0\text{-}15\ DAP}$
Period 2 (SF_2): $SF_{16\text{-}30\ DAP}$
Period 3 (SF_3): $SF_{31\text{-}45\ DAP}$
Period 4 (SF_4): $SF_{46\text{-}60\ DAP}$
Period 5 (SF_5): $SF_{61\text{-}75\ DAP}$
Period 6 (SF_6): $SF_{76\text{-}90\ DAP}$
Period 7 (SF_7): $SF_{91\text{-}105\ DAP}$
Period 8 (SF_8): $SF_{106\text{-}120\ DAP}$
If the last period has more than 15 days or less than 15days it is the average of the remaining days.
Example: $SF_{0\text{-}15}$; $SF_{16\text{-}30}$; $SF_{31\text{-}45}$; $SF_{46\text{-}60}$; $SF_{61\text{-}75}$; $SF_{76\text{-}90}$; $SF_{91\text{-}105}$; $SF_{106\text{-}126}$ or
$SF_{0\text{-}15}$; $SF_{16\text{-}30}$; $SF_{31\text{-}45}$; $SF_{46\text{-}60}$; $SF_{61\text{-}75}$; $SF_{76\text{-}90}$; $SF_{91\text{-}105}$; $SF_{106\text{-}112}$

ISF: Integrated stress factor and the stress weighting factor (λ)
For every SF period a stress weigh factor (λ) is allocated according to the critical importance of the period with regard to yield determination. The λ values range between 0 and 1 and their sum equals 1. The ISF value is obtained by a multiplicative summation of the individual SF values. The period DAP 46-60 is the critical period just before flowering; DAP 61-75 is the critical flowering period. Any water deficiency during these two periods has an important influence on yield. That is why these two periods have high λ values. The periods 0-15 DAP; 91-105 DAP and 106-end DAP were considered to be of very low importance regarding yield, especially the last two periods. The λ values allocated to each SF period are presented below:

$$ISF = (SF_1^{0.03} \times SF_2^{0.07} \times SF_3^{0.15} \times SF_4^{0.27} \times SF_5^{0.30} \times SF_6^{0.10} \times SF_7^{0.03} \times SF_8^{0.01})$$

Yield:
Yield = (ISF x 6188.56) - 1607.37.. $r^2 = 0.81$

This linear equation was obtained by using the 97/98 and 98/99 season's sunflower yields on the Glen/Bonheim and Glen/Swartland ecotopes with all the treatments.

6.1.2.3 Calibration and validation of the model

Sunflower yields on Bo and Sw from all treatments for the 97/98 and 98/99 seasons were used to calibrate the model. ISF values were calculated for each data set and a regression analysis performed of measured yields (Y) against the ISF values. The result was equation 6.1 with a reasonable r^2 value.

$$Y = (\text{ISF} \times 6188.56) - 1607.37 \quad r^2 = 0.81 \qquad (6.1)$$

Equation 6.1 was then used to make long-term simulations on all ecotopes. The input requirements for the model are DUL, LL, P, Eo and θp. These were available for all the ecotopes. For the determination of θp for the long-term simulations a different RSE was used for each treatment during the fallow and long-fallow periods. It was based on measured RSE values from Bo and Sw. The RSE value from Bo was used on Va, and Sw values on Ks. Results of simulated and measured yields for the Glen ecotopes are presented in Appendix 6.3.

The next step was validation of the model on the Ks and Va ecotopes. Results of model reliability tests using the procedure of Wilmot (1981) are presented in Figure 6.1.3. The model performed reasonably well. The r^2 value is very low but the D-Index value is acceptable. The systematic error is not too high ($RMSE_s$ is 62.7 % of RMSE); it is lower than the threshold value of 65 % used by modellers. The model simulates the yields reasonably accurately. It seems that the model under-predicts the higher yields and over- predicts the lower yields on the Ks and Va ecotopes.

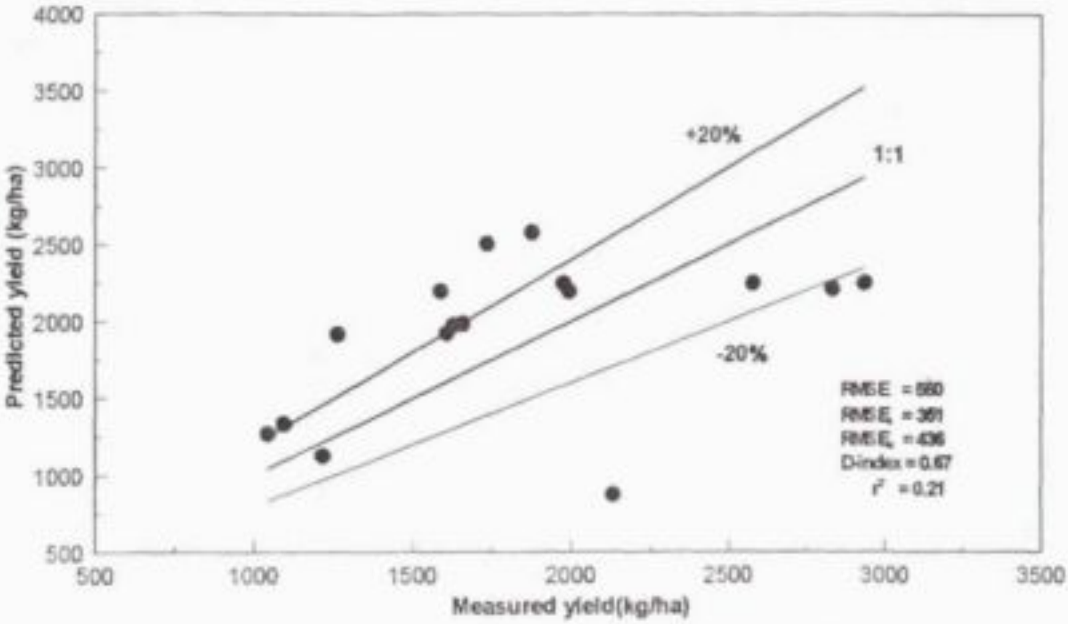

Figure 6.1.3 Measured versus predicted sunflower yields (kg ha^{-1}) for all the treatments on Ks and Va

6.2 Results and discussion

6.2.1 Maize

CPF graphs of simulated long-term maize yields on Bo and Sw are presented in Figures 6.2.1.1 and 6.2.1.3 respectively. For both ecotopes the WHB treatments are shown to exhibit well defined first-order stochastic dominance (Boehlje & Eidman, 1984) over the TST treatments. In both cases these simulated results indicate little benefit to yield by mulching. This result may however be partly due to the difficulty in modelling this benefit, and partly due to the short term of the measured results. There were only two seasons with mulch treatments, one of which was so dry that most yields were close to zero on the annually planted plots.

The graphs predict that the mean long-term yield (50 % probability) from the TST(A) and WHB(A) treatments on Bo and Sw are 3085 and 3382, and 3140 and 3382 kg ha^{-1} respectively. At this probability level it is predicted that the performance of the two ecotopes is approximately equal, with a relatively narrow yield margin between TST(A) and WHB(A). The predicted long-term mean value for TST(A) on Sw can be compared to that obtained by De Bruyn (1974) on a red Swartland soil at Glen over 13 seasons (1961/62 to 1973/74) using conventional tillage techniques. De Bruyn's mean value is 2054 kg ha^{-1} approximately 1 t ha^{-1} less than the long-term predicted yield from this study.. It is therefore almost certain that the latter are too high- probably because of the model's inability to predict very low yield.

The margin between TST(A) and WHB(A) is predicted to become narrower as the probability of non-exceedance (i.e smaller and smaller chance of achieving these higher yields), increases.

For Bo at 25 % probability of non-exceedance (i.e 75 % chance of achievement) the predicted yields for TST(A) and WHB(A) are 1738 and 2911 kg ha^{-1} respectively. The equivalent predictions for Sw are 2693 and 2912 kg ha^{-1} respectively, a much smaller difference between the two treatments than on Bo, but a far better performance by TST(A) on Sw than on Bo.

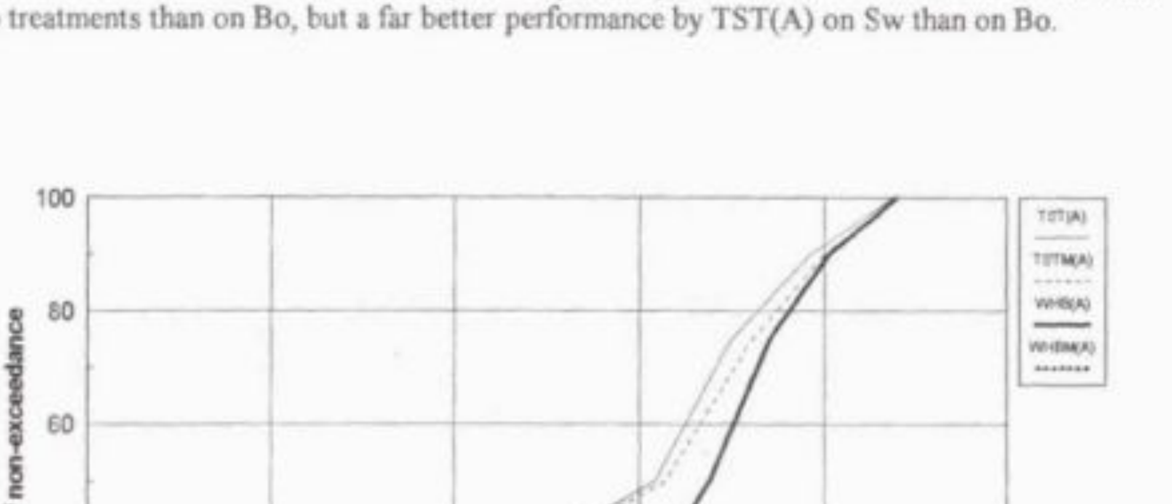

Figure 6.2.1.1 CPF graphs of long-term maize yields on the Glen/Bonheim-Onrus ecotope planted in middle December. The climate data used are for the 18 year period, 1980 - 1999

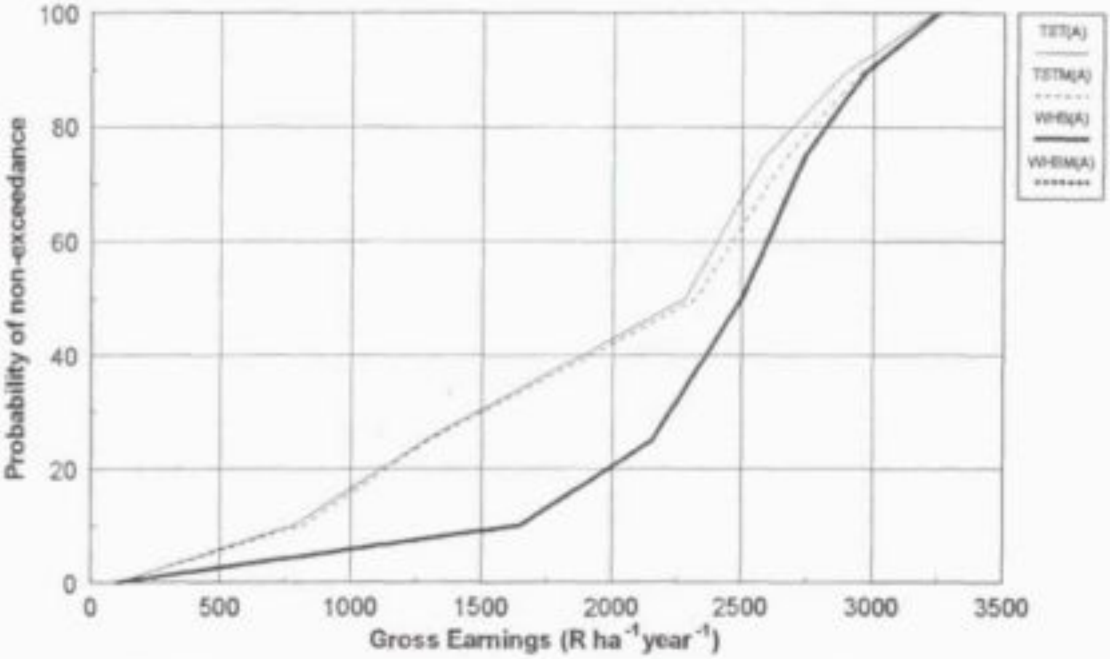

Figure 6.2.1.2 CPF graphs of long-term gross earnings from maize on the Glen/Bonheim-Onrus ecotope planted in middle December, and taking R740/ton as crop value. The climate data used are for the 18 year period, 1980 - 1999

In Figures 6.2.1.2 and 6.2.1.4 results for Bo and Sw respectively are expressed as gross earnings assuming a maize price of R740 ton^{-1}. For Bo a 75 % chance of achieving gross earnings (R ha^{-1} year^{-1}) of 1286 and 2154 for TST(A) and WHB(A), are predicted. The equivalent results for Sw are 1993 and 2155 R ha^{-1} year^{-1} respectively.

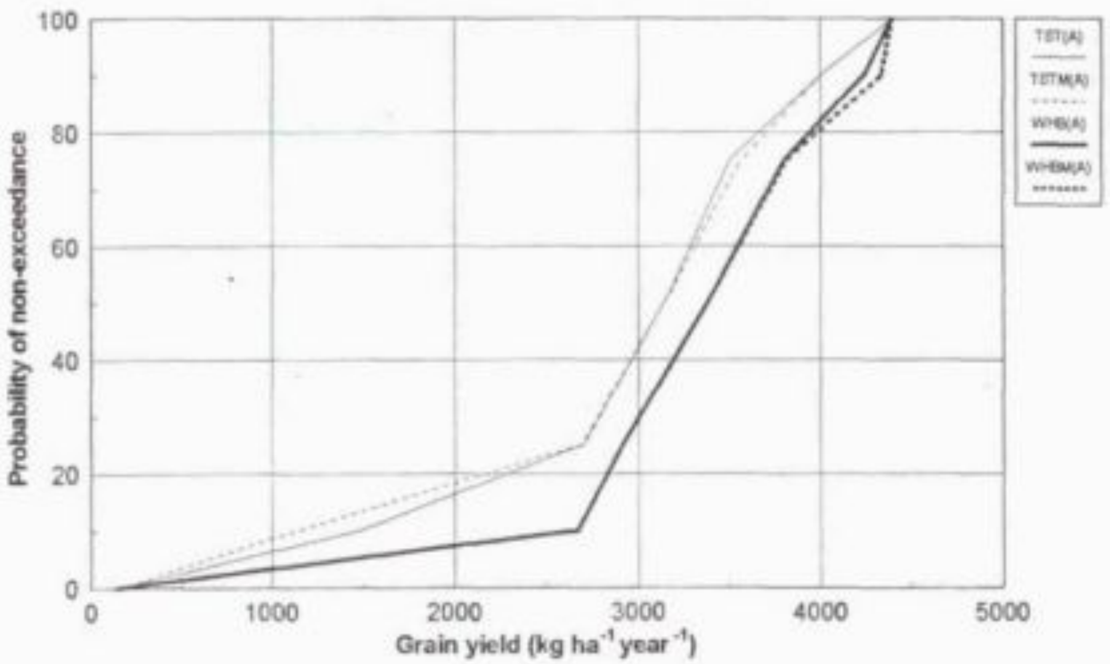

Figure 6.2.1.3 CPF graphs of long-term maize yields on the Glen/Swartland-Rouxville ecotope planted in middle December. The climate data used are for the 18 year period, 1980 - 1999

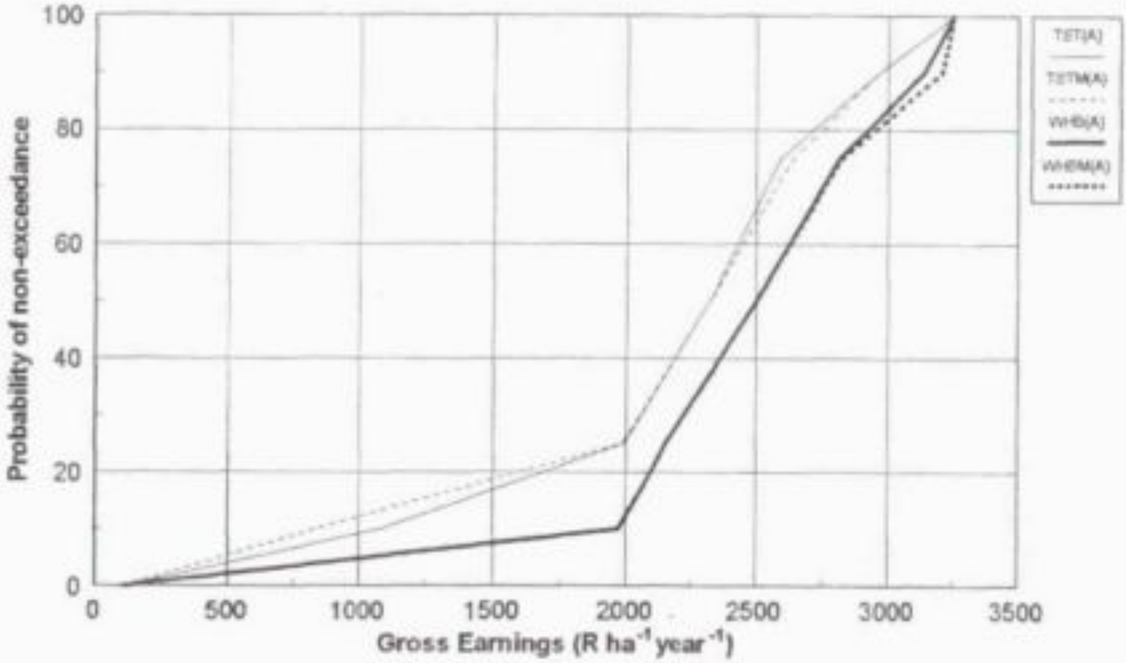

Figure 6.2.1.4 CPF graphs of long-term gross earnings from maize on the Glen/Swartland-Rouxville ecotope planted in middle December, and taking R740/ton as crop value. The climate data used are for the 18 year period, 1980 - 1999

Since a reasonable degree of model reliability is indicated by the results in Table 6.1.2 , these long-term predictions support the conclusion drawn from the field experiments on Bo and Sw that the WHB(A) treatment produces significantly higher yields than TST(A). It is, however, expected that the predicted long-term mean values for both treatments are too high.

6.2.2 Sunflower

6.2.2.1 Glen/Bonheim-Onrus ecotope

CPF graphs for sunflower with different treatments are presented in Figures 6.2.2.1, 6.2.2.2 and 6.2.2.3. The predicted mean long-term yields (50 % probability) for TST(A) and TSTM(A) are 1160 and 1408 kg ha^{-1} respectively, with the latter (mulch treatment) displaying first degree stochastic dominance (Boehlje & Eidman, 1984) over the former (no mulch). The graphs indicate that there is a 75 % probability that TST(A) and TSTM(A) will yield more than 560 and 808 kg ha^{-1} yr^{-1} respectively. It is therefore predicted that the TST(A) and TSTM(A) have a 75% probability of earning gross margins of R616 ha^{-1} yr^{-1} and R889 ha^{-1} yr^{-1} respectively (Figure 6.2.2.3).

It is predicted that WHB(A) and WHBM(A) have mean long-term yields of 2580 and 2640 kg ha^{-1} yr^{-1} respectively. The model also predicts that WHB(A) and WHBM(A) have a 75 % probability of yielding 1852 and 1920 kg ha^{-1} yr^{-1} respectively, and therefore the same probability of earning gross margins of R2037 $ha^{-1} yr^{-1}$ and R2112 $ha^{-1} yr^{-1}$. WHBM(A) exhibits first degree stochastic dominance over WHB(A), TSTM(A) and TST(A). The model predicts that a farmer has the best chance of producing a yield of 2000 kg $ha^{-1} yr^{-1}$ with sunflower on Bo using the WHBM(A) technique rather than the TST(A); TSTM(A) or WHB(A) techniques.

The simulated results indicate considerably less benefit from mulch with WHB than when combined with TST. This is presumably due to mulch producing a greater water conservation benefit in the case of TST via its depression of R than its depression of Es.

In Figure 6.2.2.2 it is shown that WHBM(B) gave the best yields expressed as kg ha^{-1} for the growing season, but not much better than WHBM(A). WHBM(A) has a 75 % probability of exceeding 1892 kg $ha^{-1} yr^{-1}$ while the equivalent yield for WHBM(B) is 2080 kg ha^{-1} every second year. This gives a 75 % probability of exceeding 1040 kg $ha^{-1} yr^{-1}$, since to produce the former yield one ha it has to lie fallow for a year. The model therefore predicts that a farmer would benefit more in the long-term by using WHBM(A) rather than WHBM(B). The long-term predictions support the conclusion drawn from the field experiments on Bo that WHB(A) and WHBM(A) produce significantly higher yields than TST(A) and TSTM(A).

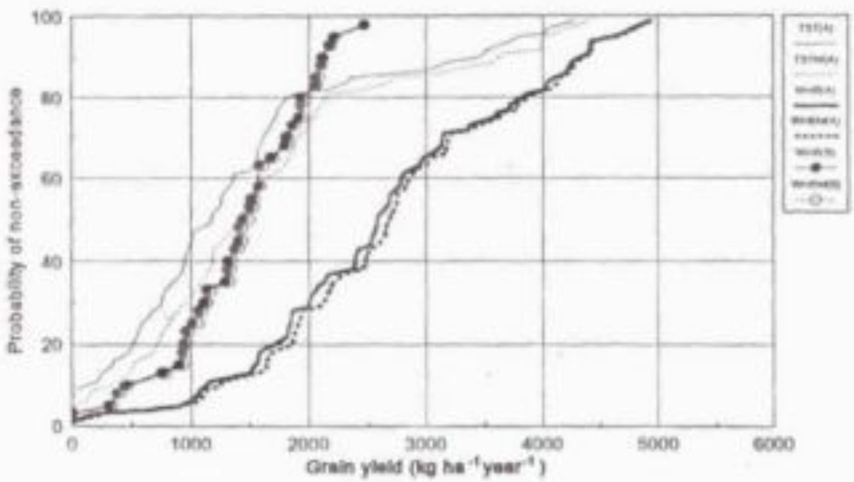

Figure 6.2.2.1 CPF graphs of long-term sunflower yields on the Glen/Bonheim-Onrus ecotope planted early in January (all treatments). The climate data used are for the 77 year period, 1922 - 1999

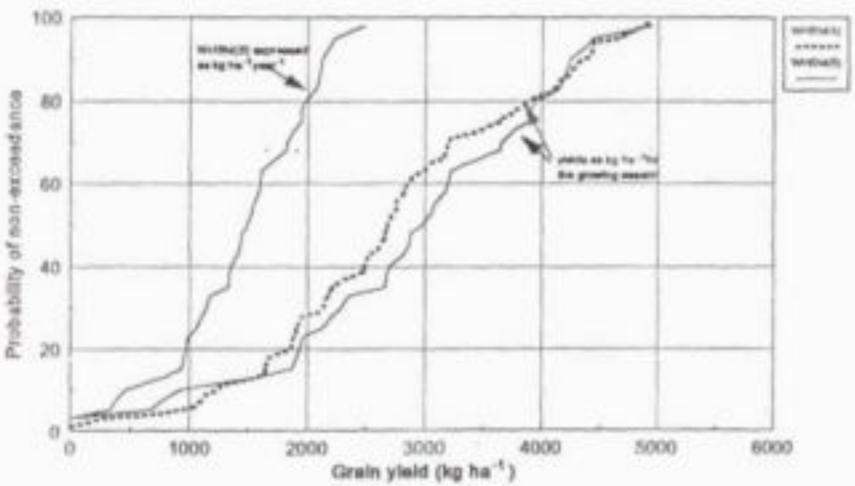

Figure 6.2.2.2 CPF graphs of long-term sunflower yields on the Glen/Bonheim-Onrus ecotope planted early in January (only treatments WHBM(A) and WHBM(B)). The climate data used are for the 77 year period, 1922 - 1999

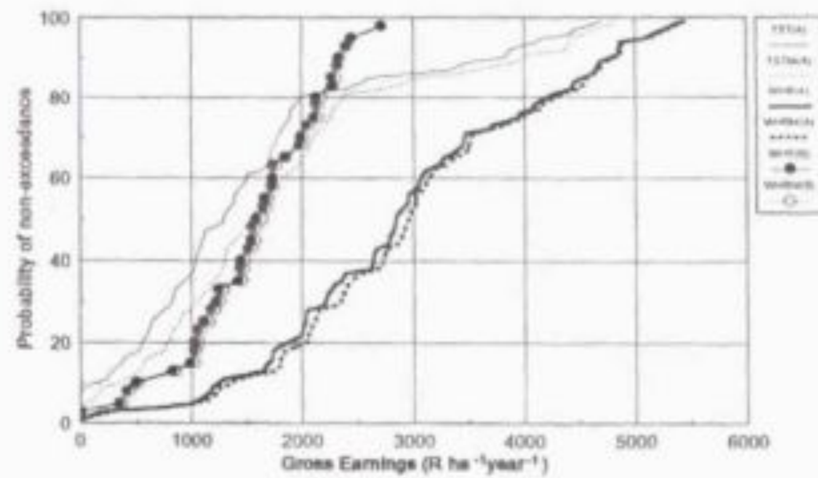

Figure 6.2.2.3 CPF graphs of long-term gross earnings from sunflower on the Glen/Bonheim-Onrus ecotope planted early in January, and taking R1100 ton^{-1} as the crop value. The climate data used are for the 77 year period, 1922 - 1999

6.2.2.2 Glen/Swarland-Rouxville ecotope

CPF graphs of simulated long-term sunflower yields on Sw are presented in Figures 6.2.2.4 and 6.2.2.5, and gross earnings in Figure 6.2.2.6.

Exactly the same trends as on the Bo can be seen here. The only difference is that the WHB(A) and WHBM(A) gave slightly higher yields on Sw than on Bo. In general, however, sunflower yielded better on Bo than Sw with the other treatments. The difference between WHB(A) and WHBM(A), and the other treatments, is slightly smaller on Sw than on Bo.

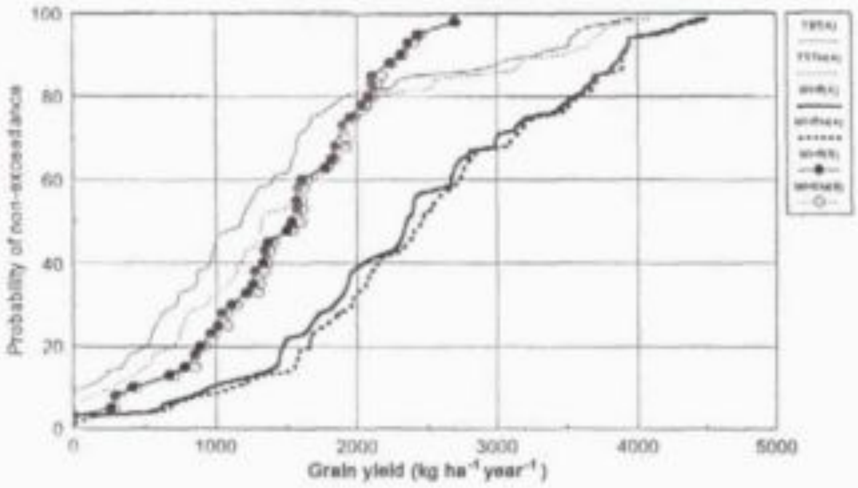

Figure 6.2.2.4 CPF graphs of long-term sunflower yields on the Glen/Swartland-Rouxville ecotope planted early in January (all treatments). The climate data used are for the 77 year period, 1922 - 1999

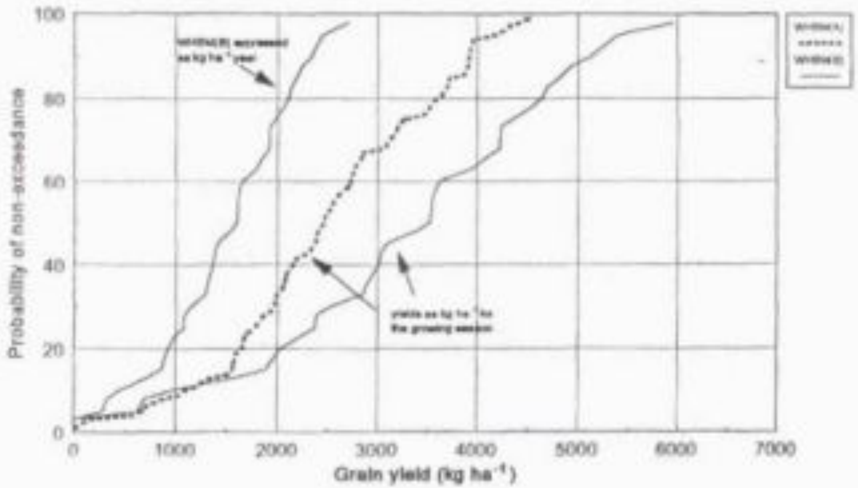

Figure 6.2.2.5 CPF graphs of long-term sunflower yields on the Glen/Swartland-Rouxville ecotope planted early in January (only treatments WHBM(A) and WHBM(B)). The climate data used are for the 77 year period, 1922 - 1999

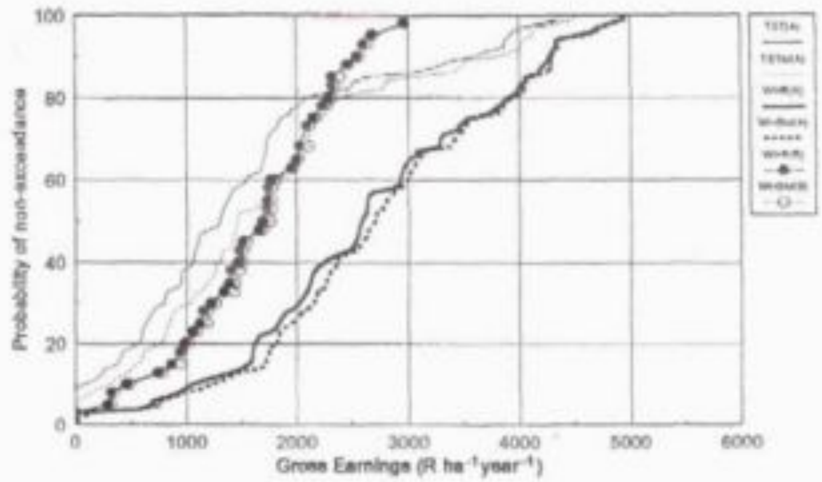

Figure 6.2.2.6 CPF graphs of long-term gross earnings from sunflower on the Glen/Swartland-Rouxville ecotope planted early in January, and taking R1100 ton^{-1} as crop value. The climate data used are for the 77 year period, 1922 - 1999

6.2.2.3 Khumo/Swarland-Amandel and Vlakspruit/Arcadia-Lonehill ecotopes

CPF graphs of simulated long-term sunflower yields on Ks and Va are presented in Figures 6.2.2.7; 6.2.2.8; 6.2.2.10 and 6.2.2.11 respectively, and of gross earnings in Figures 6.2.2.9 and 6.2.2.12 respectively.

For both ecotopes both the WHB treatments are shown to exhibit well-defined first-order stochastic dominance over the TST treatments (Figure 6.2.2.7 and 6.2.2.10). Comparing the CPF graphs of TST(A) with WHB(A) on both ecotopes reveals the large benefit of WHB(A) by eliminating runoff and increasing run-on into the basins. Comparing the WHB(A) and WHBM(A) treatments on both ecotopes suggests that mulch may not provide much benefit.

Figures 6.2.2.8 and 6.2.2.12 predict that WHBM(A) is superior to WHBM(B) in the long-term.

CPF graphs of simulated long-term yields with the TST(A) and WHBM(A) treatments on all the ecotopes are presented in Fig. 6.2.2.13 and 6.2.2.14 respectively. If a farmer wishes to harvest 2000 kg ha^{-1} yr^{-1} the model predicts that he has only 22 % chance of success using TST(A) on these ecotopes but 72 % chance of success using the WHBM(A) technique.

The difference between the ecotopes is small. Climate and the TESW values of the soils are important. The overall conclusion is that long-term predictions show that WHB(A) and WHBM(A) produce significantly higher yields than TST(A) and TSTM(A), and that it would pay better to plant annually than biannually.

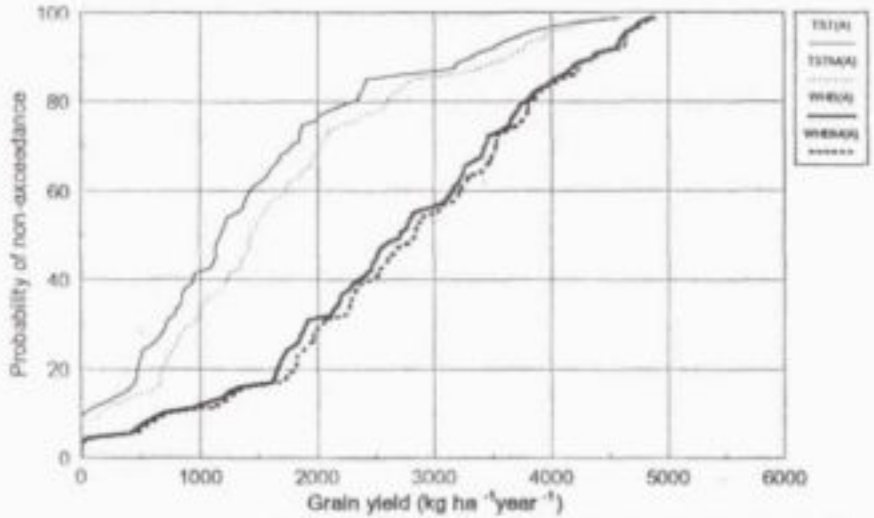

Figure 6.2.2.7 CPF graphs of long-term sunflower yields on the Khumo /Swartland-Amandel ecotope planted early in January (all treatments). The climate data used are for the 86 year period, 1913 - 1999

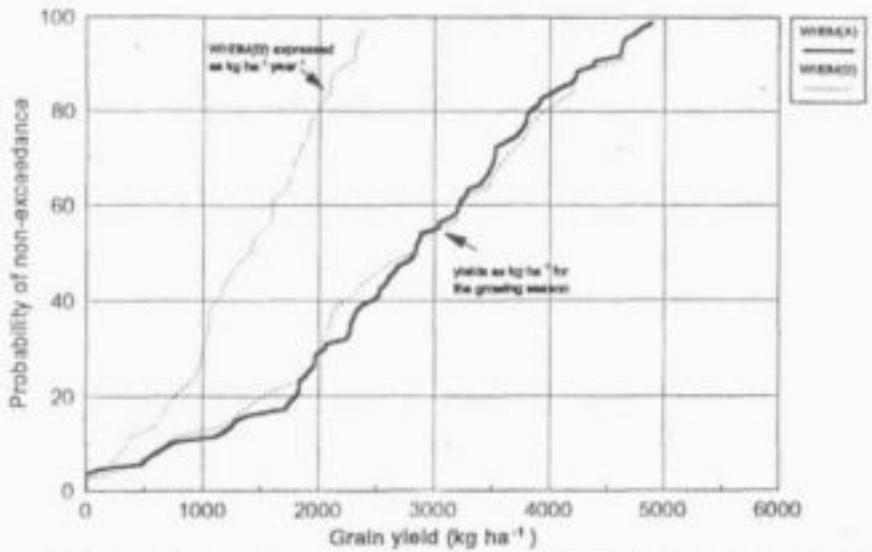

Figure 6.2.2.8 CPF graphs of long-term sunflower yields on the Khumo /Swartland-Amandel ecotope planted early in January (only treatments WHBM(A) and WHBM(B)). The climate data used are for the 86 year period, 1913 - 1999

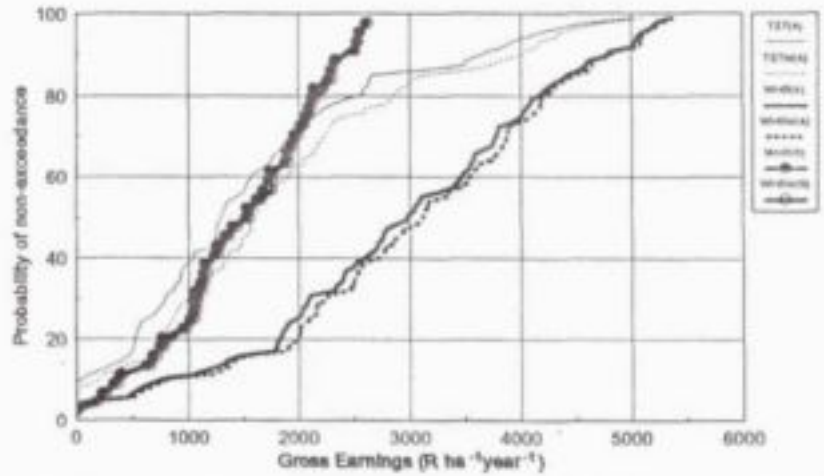

Figure 6.2.2.9 CPF graphs of long-term gross earnings from sunflower on the Khumo/Swartland-Amandel ecotope planted early in January, and taking R1100 ton $^{-1}$ as crop value. The climate data used are for the 86 year period, 1913 - 1999

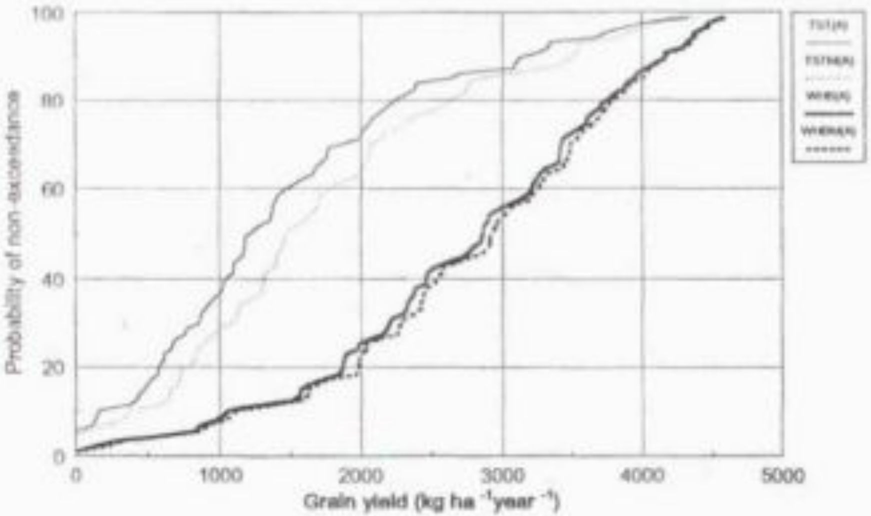

Figure 6.2.2.10 CPF graphs of long-term sunflower yields on the Vlakspruit /Arcadia-Lonehill ecotope planted in January (all treatments). The climate data used are for the 87 year period, 1913 - 1999

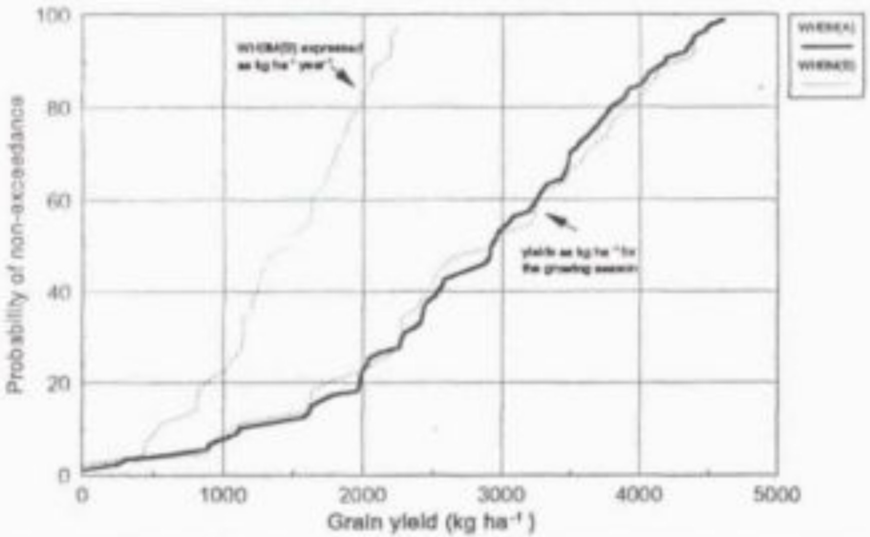

Figure 6.2.2.11 CPF graphs of long-term sunflower yields on the Vlakspruit /Arcadia-Lonehill ecotope planted in January (only treatments WHBM(A) and WHBM(B)). The climate data used are for the 87 year period, 1913 - 1999

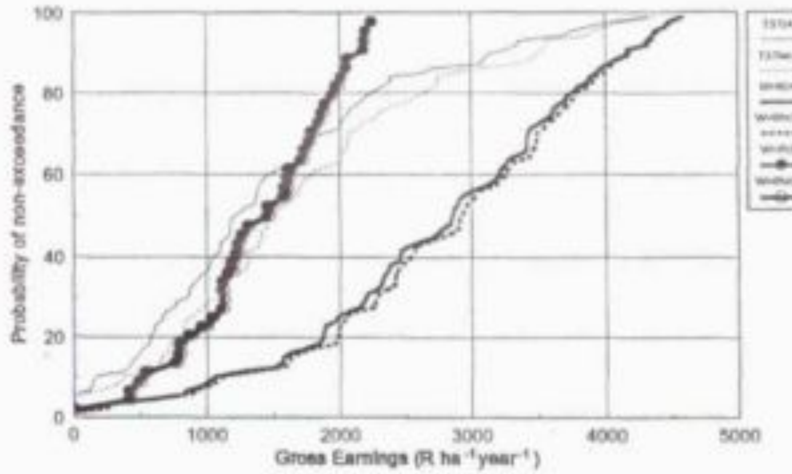

Figure 6.2.2.12 CPF graphs of long-term gross earnings from sunflower on the Vlakspruit/Arcadia-Lonehill ecotope planted early in January, and taking R1100 ton^{-1} as crop value. The climate data used are for the 86 year period, 1913 - 1999

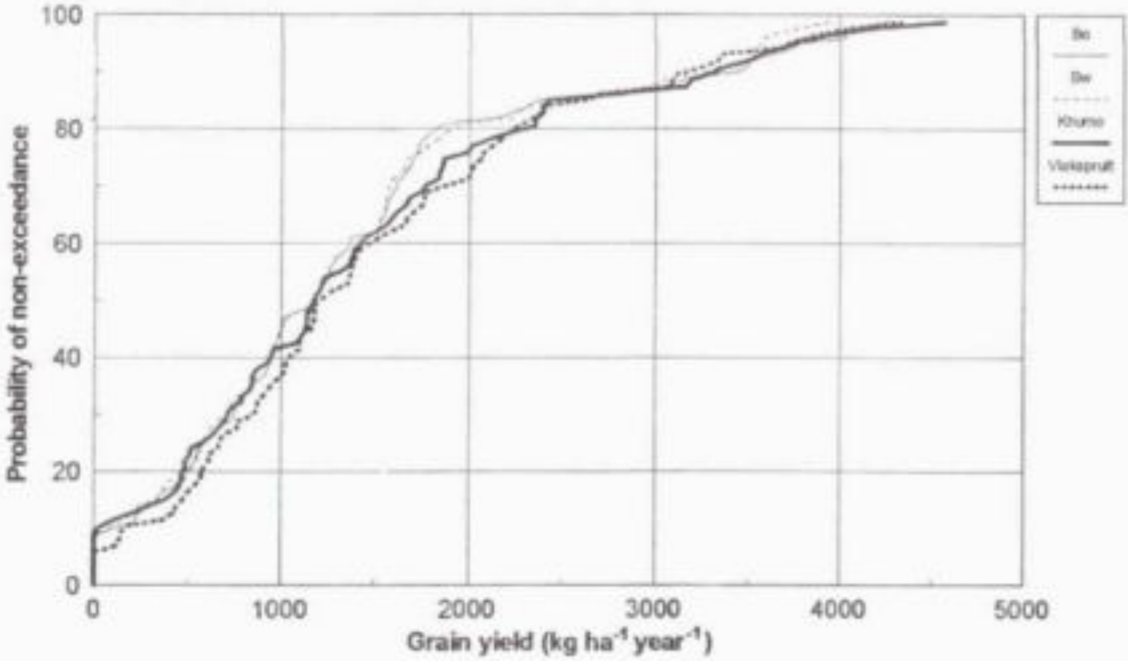

Figure 6.2.2.13 CPF graphs of long-term sunflower yields for the TST(A) treatment on four ecotopes planted early in January. The climate data used for the Glen ecotopes are for the 77 year period, 1922 - 1999. The climate data used for the Thaba Nchu ecotopes are for the 86 year period, 1913 - 1999

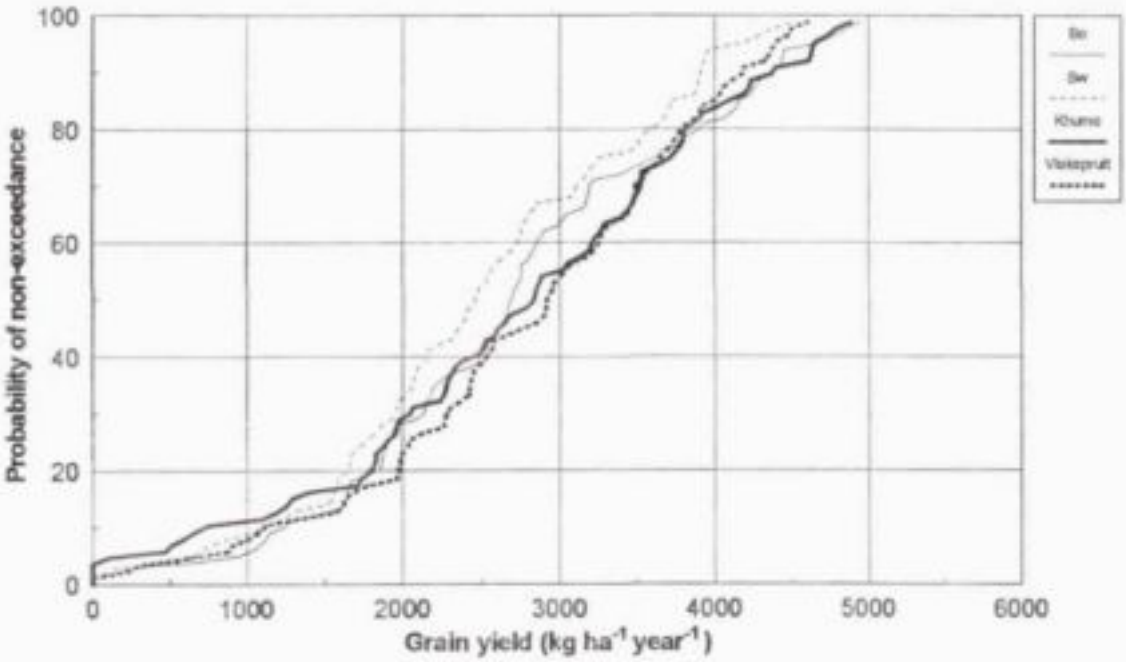

Figure 6.2.2.14 CPF graphs of long-term sunflower yields for the WHBM(A) treatment on four ecotopes planted early in January. The climate data used for the Glen ecotopes are for the 77 year period, 1922 - 1999. The climate data used for the Thaba Nchu ecotopes are for the 86 year period, 1913 - 1999

7. GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This project had three aims. The extent to which each of these have been achieved will be described separately.

Technical assistant capacity building

Early in the project two previously disadvantaged young men were selected for training as technical assistants (TA's). It was considered that two aspects of their training should receive attention. Firstly, in-service training to carry out the many necessary tasks associated with field experimentation, and secondly, some sort of academic training which would eventually provide them with a qualification. The in-service training process has proceeded well and the TA's are now able to carry out the following tasks effectively: prepare water harvesting/basin tillage plots; plant maize, sunflower, sorghum and wheat by hand on experimental plots, maintaining correct row spacing, seeding rate, and fertilizer application; thin the crops after germination to get the correct plant density; spray the crops with insecticides and apply chemical weed control procedures; take soil samples for NWM calibration and determine gravimetric water content on these samples; insert NWM access tubes; make soil water content readings with a NWM; measure leaf area indices; reap crops and record yields; obtain oven dry values for biomass yields; take samples for bulk density determinations and carry out the necessary calculations; assist with a variety of calculations using a hand calculator; simple tasks on the computer are being started.

To enable the TA's to be accepted as registered students at Technikon SA it was necessary to improve their school leaving results. They both needed a pass mark in Std. 10 Biology. They were registered with Damelin Correspondence College for this purpose during 1998, and were also given additional tuition. Although their marks for the end of the year examination were not good, they were accepted as students for a Diploma in Agricultural Management at Technikon SA on the basis of these marks, their previous Std 10 records, and their mature age. They elected to start off during 1999 with three of the 16 courses needed for the Diploma. During the year they also attended a one week's practical training course at Cedara.

It is considered that the capacity building aim has been achieved to a satisfactory extent.

Technology transfer to developing farmers

Two procedures were adopted to achieve this aim. The one consisted of maintaining demonstration plots at two sites on the land of developing farmers. There the production techniques being tested and the results were visible over two growing seasons for all to see. The water harvesting/basin tillage treatments produced impressive yield increases compared to conventional tillage, especially during the 97/98 season. The second procedure employed was to hold information days. These consisted of gathering as many small farmers/plot owners together and taking them to the field experiments at Glen and the demonstration plots near Thaba Nchu and showing them the crops approximately at their peak growth stage. Two of these meetings were held, with an attendance each time of 20 - 30 people. When the crops had been reaped and results were known these were presented at gatherings organised at Thaba Nchu and Botshabelo (one at each venue) by extension officers of the Free State Department of Agriculture (FSDA). Close cooperation was maintained throughout with the Farming Systems Research and Extension section at Glen and the relevant branch of the FSDA Extension Service in connection with these technology transfer actions.

It is difficult to assess the extent to which this aim has been achieved.

Identification of a production technique to optimise precipitation use efficiency (PUE)

The hypothesis is stated in detail in Section 1.1 . To test its validity field experiments were conducted on four ecotopes, using six different water conservation production techniques, and four crops viz. maize, sunflower, sorghum and wheat.

During the course of the study the requirements for success in achieving the technical objectives have become accentuated. The extreme climatic conditions experienced during the three seasons added to this. Because of the extremely adverse ratio of rainfall to evaporative demand during the growing season (e.g. 0.26 in January; Table 3.2.1), exacerbated by the erratic rainfall pattern, plant water stress dominatingly controls yield on these ecotopes. In order to make recommendations which are reliable for the long-term regarding appropriate production techniques, good understanding and reliable measurements of runoff (R) and evaporation (Es) are of cardinal importance, since these are the main causes of water wastage. The erratic nature of the rainfall pattern accentuates the need for long-term results, and therefore **the need to be able to model R and Es in a reliable way.** The spatial non-homogeneity of the WHBM production technique (Figure 2.2.1) complicates the task. The distilled products of the measurements made, the still very incomplete understanding of the water balance processes in the different treatments, and the very simple empirical way in which these were modelled, are expressed in the long-term predictions presented in Chapter 6 in the form of CPF graphs. The procedures followed require much improvement. Important needs to improve yield predictions include better understanding of the Es process, especially where mulch is present, and a more reliable way of predicting runoff from the no-till strip.

The overall main conclusions are that the water harvesting and basin tillage part of the hypothesis is correct; that although long fallow will definitely stabilize yield it will probably not be economical in the long-term; and that further research is necessary to clarify the influence of mulching.

The following are important details concerning the findings, conclusions, and recommendations:

(a) Success of the WHB technique depends on suppressing water losses by R and Es. Measurements show that R has been reduced to zero and that Es has been reduced considerably but still remains a serious avenue for water loss. Future experimentation needs to focus on suppressing Es by any possible means. A new experiment to achieve this has already been planned.

(b) The annually planted WHB treatment with mulch in the basins (WHBM(A)) generally gave the best results which were considerably better than TST(A). The data available show that WHBM(A) is, however, generally only marginally better than WHB(A). Results from more seasons are needed to quantify the extent of this difference in a reliable way.

(c) Choice of crop is important on these ecotopes. Best results can be expected from crops with a relatively short growing season (around 120 days) so that it can be planted early in

January and reach the sensitive flowering period during March which has the most favourable P/Eo value, i.e. 0.45 (Table 3.2.1), and also the most reliable rainfall. Sunflower fits these requirements and also has excellent drought resistant qualities. New short season maize cultivars are also available. These two crops are recommended for future studies. Wheat and sorghum are less satisfactory for the reasons presented in detail in Sections 5.3 and 5.4 respectively.

(d) Some degree of soil erosion occurs on most cultivated lands in South Africa. Relevant measured data is available from two long-term trials, one at Pretoria (mean annual rainfall (MAR) = 721 mm) and one at Glen (MAR = 507 mm). The Pretoria experiment was conducted on a Hutton Form soil on a 3.75 % slope over a period of 27 years (Haylett, 1960). The mean annual soil loss from continual maize with conventional tillage was 22.6 t ha^{-1}, compared to 0.7 t ha^{-1} for veld grazed in a normal way; equivalent figures for the Glen experiment conducted over 17 years (Du Plessis & Mostert, 1965) were 8.6 t ha^{-1} and 0.3 t ha^{-1} respectively. The latter trial was also on a Hutton soil, on a 5 % slope. The soil losses from the cultivation treatments represent soil thicknesses of about 1.5 mm and 0.3 mm per annum at the two sites respectively. On the ecotopes in the present study it has been shown clearly that no runoff occurs from the land as a whole when the WHB production technique is used. Soil loss from the land as a whole will therefore also be zero. This is an important advantage over the conventional TST treatment in terms of sustainability. There is, however, some soil movement from the runoff area (Figure 2.2.1) into the basins. It is intended to measure this in a follow-up experiment. Depression of this movement by placing mulch or stones on the runoff strip will also be studied.

(e) Initial investigations have shown that during very dry conditions large amounts of water for T (i.e. from 300-1200 mm depths) are withdrawn by sunflower from the region around the centre of the runoff strip, i.e. in the vicinity of access tube A in Figure 2.2.1. This may also be true for maize. How much of this water contributes to yield, and how much is slowly available and therefore only serves to keep the crop alive is not yet known. An answer is needed to this question. Mulch or stones placed on the runoff strip could prevent local soil movement but may reduce runoff into the basins. However, if the water in the vicinity of access tube A can serve a useful reserve for the mature crop, then retaining it there will not be a disadvantage.

(f) Results show that R is high on these ecotopes, especially where the surface storage is small. In view of the possibility of being able to obtain long-term rainfall data in the future which includes intensities, rainfall-runoff relationships on different ecotopes using models, needs further study.

(g) The WHB technique is well suited for use on very small plots, and even in townships. Extension work in this connection by the FSDA needs to be encouraged. Many people in semi-arid areas could be usefully employed if this technique was widely adopted, and food security could be increased at the same time.

(h) To reduce fertilizer costs the introduction of a legume into a crop rotation with maize and/or sunflower needs to be investigated.

(i) Economic aspects of the WHB technique need to be studied. Of particular importance is the determination of the area of land of the quality investigated here that could provide an average size of rural family with sufficient staple food and/or a reasonable income.

(j) The empirical sunflower stress model has made a valuable contribution to this study. It has been relatively easy to adapt for the influence of the unusual treatments and has made satisfactory yield predictions. These treatments will become more difficult to model in the future as efforts to depress Es are intensified. It could be that simple empirical models of this kind may be the most appropriate in the short term for the task of obtaining long-term yield predictions. Development of a simple maize model along these lines is therefore recommended.

(k) Reliable evidence is available to indicate that the maize model predictions are too high, probably because of the model's inability to predict very low yields. Without a very large and sophisticated input, which is beyond our capacity, mechanistic models such as DSSAT V3 cannot be expected to be completely effective under the unusual and extreme conditions of these experiments. Drawbacks are, incomplete understanding and quantification of the complex processes involved, and therefore an inability to express them quantitatively in a way that is appropriate for a mechanistic model striving to be process based. As understanding and quantification improves, it is hoped that it will be possible to adapt the DSSAT V3 maize model to perform effectively even under these conditions. Its world-wide use by a large number of capable research workers makes it attractive.

(l) At suitable sites in semi-arid areas it should be possible to improve crop water supply by employing micro-catchment runoff farming (Figure 1.3.1) in combination with WHB. Investigations in this connection are recommended.

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Appendices

PROCEDURE USED FOR NWM CALIBRATION:

7) NORMAL "DRY END" CALIBRATION LINE

A separate calibration line was constructed for each 300 mm layer that was significantly different in texture and / or structure to other layers in the particular soil profile. Working in a semi – arid area most readings in practice are generally below DUL. The "dry end" calibration line is therefore the main one under these conditions. A reliable BD value is essential. As many as possible samples for gravimetric water content (θm) determinations, over the whole range from very dry to near DUL, were taken at the same time as NWM readings. BD values were used for the conversion of θm to θv. The linear regression of θv against the relevant NWM count ratio (CR) values provides the calibration line.

8) "WET END" CALIBRATION LINE

The relationship between volumetric soil water content (θv) and NWM count ratio (CR) is linear up to a certain point only. Thereafter the line curves upwards towards a point defined by the maximum CR (CR_{max}) for the particular instrument, and θv at field saturation (fSat) for the particular soil layer. Details in this connection are explained in the Campbell Pacific 503 operating instructions provided with the NWM. It is stated there that the inflexion point is at a θv value of about 33%. Experience indicates that θv at this point is a variable, with a higher value in clay soils than in sandy soils. It is necessary to determine or estimate the inflexion point for each soil layer for which a calibration line is being constructed. Field experience has shown that the inflexion point is often in the vicinity of DUL.

The need for a "wet end" calibration can be clearly identified by the following experiment.

> A bulk density value (BD) for the particular soil layer will have been determined during the course of the construction of the normal "dry end" calibration line. Say for example, that this is a clay soil with a BD value of 1,40 g cm^{-3}. Porosity (Po), expressed as θv% is therefore 47.2. It is well known that field saturation (fSat) for a clay soil is around 0.9Po, which in this case will be 42,5%. (Experience has shown that for a sandy soil fSat is around 0,8Po). Continue to saturate the soil around triplicate access tubes, in the particular soil layer studied, until CR_{max} is achieved. Plot, on the normal "dry end" graph, the point defined by CR_{max} and 42,5% . If the "dry end" calibration line misses this point by a significant amount a "wet end" line is needed.

The following procedure can be used to determine the "wet end" line. It will be assumed that a "dry end" line has been constructed and therefore that BD and fSat values are available. Employ from 3 to 5 access tubes to counteract spatial variation. Saturate the soil until CR_{max} is achieved. Allow the soil to dry and as soon as possible after fSat take samples for water content determinations by the gravimetric method (θm), taking CR readings at each sampling. Continue at regular intervals until the soil is approximately at DUL. Plot θm against CR and obtain the regression line. Extrapolation of the line to CR_{max} and interpolation to the θm axis, provide an estimate of fSat. Because of the known approximate relationship between fSat and BD, it is now possible to make an independent estimate of BD with which to convert the θm vs. CR calibration line into the required θv vs. CR calibration line. To ensure the reliability of the "wet end" line it

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: Glen/Bonheim-Onrus

Site no. 1						
Horizon/Horison	A (veld)	A (profiel)	B1	B2	C	
Depth Diepte (mm)	0 - 300	0 - 400	400 - 550	550 - 800	800 - 1300	
Bag no /Sak nr						
Lab No/ nr	D1416	D1417	D1418	D1419	D1420	
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%						
>2 mm						
c-g sand 2-0.5 mm	0.5	0.1	0.6	0.3	1.3	
m 0.5-0.25 mm	2.7	1.7	1.8	1.9	2.1	
f sand 0.25-0.106 mm	23.7	23.1	21.9	22.6	20.4	
v/b f sand 0.106-0.05 mm	16.6	19.5	20.0	19.4	17.1	
c-g silt/slik 0.05-0.02 mm	4.9	5.1	7.3	6.8	5.7	
f silt/slik 0.02-0.002 mm	4.8	4.4	4.5	7.1	14.3	
clay/klei 0.002 mm	45.1	43.5	43.0	39.6	37.7	
Texture Tekstuur	Cl	Cl	Cl	ClLm	ClLm	
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS						
C %	0.85	0.57				
Plastisiteits indeks Plasticity index	33	21	33	29	28	
Al (me %) cmol(+)/kg						
Resistance Weerstand (ohm)	340	340	320	240	240	
pH H20	7.78	7.56	8.23	8.27	8.49	
pH KCl	6.50	6.11	7.06	7.36	7.60	
EXCHANGEABLE/EXTRACTABLE CATIONS c mol+ kg soil1 UITRUILBARE/EKSTRAHEERBARE KATIONE c mol+ kg grond						
Na	0.71	0.56	0.85	1.24	1.19	
K	0.80	0.65	0.55	0.62	0.58	
Ca	10.78	8.33	7.98	7.98	13.77	
Mg	11.24	12.22	11.53	11.94	8.86	
S value S waarde	23.53	21.76	20.91	21.78	24.40	
T value (CEC T waarde (KUK)	25.77	24.30	23.12	24.04	26.21	
SATURATION EXTRACT SOL. CATIONS c mol+/kg soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE c mol+ kg grond						
Na						
K						
Ca						
Mg						
Cond Geleid mS m						
Saturation Versadiging						

Data for stage 2 Es for Glen/Bonheim-Onrus ecotope

P (mm)	θ_{0-300} (mm)	$\Delta\theta$ (mm)	D (mm)	Es (mm)	ΣEs (mm)	t days	Σt (days)	$\sqrt{\Sigma t}$ $d^{½}$
	69.0	0	0	0	0	0	0	0
2.4	64.1	4.9	0	4.9	4.9	6	6	2.45
0	62.2	1.9	0	4.3	9.2	4	10	3.16
	61.6	0.6	0	0.6	9.8	4	14	3.74

Since the line should pass though the axis, hypothetical points at $\Sigma Es = 0.1$ and $\sqrt{\Sigma t} = 0.1$ were included in the linear regression analysis. The following was the result.

Σs = $2.75 \sqrt{\Sigma t} - 0.49$ (mm)......................$r^2 = 0.96$
Ritchie α value = 2.75 mm $t^{-½}$

is important that the BD value used for this conversion is appropriate for the water content vs. NWM readings which have been taken. Blind acceptance of the previously determined BD value is unacceptable as it might give an unsatisfactory fSat value – which would contradict the validity of the calibration procedure followed up to this point. The procedure is demonstrated by an example presented in Table A2.3.1.

Table A2.3.1. An example showing how an appropriate BD is chosen for converting the "wet end" θm vs. CR calibration line to a θv vs. CR calibration line. The θm value at CR_{max} is assumed to be 27,9%, and that the previously determined BD value is 1,40g cm^{-3}

*1 BD range (g cm^{-3})	1.25	1.3	1.35	1.40	1.45	1.50	1.55
*2 θv %	34.9	36.3	37.7	39.1	40.5	41.9	43.2
*3 Po (vol%)	52.8	50.9	49.1	47.2	45.3	43.4	41.5
*4 fPo	0.66	0.71	0.77	0.83	0.89	0.97	1.04

*1 With values above and below the original value

*2 The predicted value of θv assuming θm at fSat was 27,9%

*3 Po for the selected BD value

*4 The fraction which the predicted θv% would be of Po

From the calculated fPo values it is clear that all excepting 0.83, 0.89 and 0.97 are inappropriate, and that of these three 0.89 is the most appropriate. This indicates 1.45 as the "best fit" BD value. The BD value selected in this way is then used to convert the θm vs. CR line into a θv vs CR line. The inflexion point in the calibration is defined by the point at which the "wet end" line crosses the "dry end" line.

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2826CD Glen
*Latitude & Longitude:*28°55'13''/26°21'12''
*Land type No:*Ea39c
*Climate zone:*455
*Altitude:*1330m
*Terrain unit:*Upper Footslope
*Slope:*1%
*Slope shape:*Straight
*Aspect:*West
*Microrelief:*None
*Parent material solum:*Origin binary, local colluvium, solid rock
*Underlying material:*Sandstone (feldspathic)

*Soil form:*Bonheim
*Soil family:*Onrus
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*Sheet slight, partially stabilized
*Vegetation/Land use:*Agronomic cash crops
*Water table:*0mm
Described by: M. Hensley & P.P. van Staden
*Date described:*1998-02
*Weathering of underlying material:*Moderate physical, moderate chemical
*Alteration of underlying material:*Calcified

Horizon	Depth(mm)	Description	Diagnostic horizons
A	0 - 400	Dry; dry dark brown 7.5YR3/2, moist dark brown 7.5YR3/2; disturbed; clay; apedal coarse angular blocky; very hard; few normal fine pores; fine cracks; many clay cutans; very few fine pedotubules; water absorption: 1 second(s); few roots; gradual smooth transition.	Melanic
B1	400 - 550	Dry; dry dark brown 7.5YR3/4, moist dark brown 7.5YR3/4; undisturbed; clay; strong coarse angular blocky; very hard; few normal fine pores; fine cracks; many slickensides; many clay cutans; very few fine pedotubules; water absorption: 10 second(s); few roots; gradual smooth transition.	Pedocutanic
B2	550 - 800	Moist; dry brown to dark brown 7.5YR4/4, moist dark brown 7.5YR3/4; undisturbed; clay loam; common medium distinct black illuvial humus mottles; common medium distinct white oxidized iron oxide mottles; moderate medium subangular blocky; friable; few normal fine pores; non-hardened free lime, slight effervescence; few clay cutans; very few fine biocasts; water absorption: 8 second(s); few roots; gradual smooth transition.	Pedocutanic
C	800 - 1300	Moist; undisturbed; clay loam; many coarse distinct white lime mottles; many medium distinct many coloured geogenic mottles; non-hardened free lime, strong effervescence; few roots; not observed transition.	Saprolite

Remarks: The saprolite is favourable for roots.
*Survey name:*BEP - B01220
*NATIONAL SOIL PROFILE NO:*6222

Appendix 3.2.3.1

APPENDIX 3.2.3.4

REFINING THE CROP MODIFIED UPPER LIMIT OF AVAILABLE WATER (CMUL) CONCEPT

The CMUL concept as described by Hattingh (1993) consists of equating the drainage rate of the root zone as a whole with the evapotranspiration rate (ET_r) of the growing crop. The former is expressed quantitatively by differentiating the equation which describes the drainage curve, e.g. for equation 3.2.3.1 the drainage rate dy/dt = 17.64/t mm hr^{-1}. The CMUL concept is based on the assumption that while ET_r < dy/dt, deep drainage (D) occurs, and that D ceases when $ET_r \geq$ dy/dt. The concept assumes that water extraction from the root zone is equally distributed with depth. This is, strictly speaking, not correct since root density generally decreases with depth. It is therefore reasonable to expect that the water extraction rate will also decrease with depth. The decreasing rate of extraction with depth will probably be exaggerated by the fact that since the water is moving from the top downwards, the top layers will initially be the wettest. This factor will be accentuated in a slowly permeable soil.

The concept can be refined by calculating a CMUL value for each layer separately, and only allowing drainage to the next layer to occur when the CMUL value for the layer above it has been exceeded. Soil water extraction rates from each layer were obtained from measurements made on Bo after heavy rain which filled the root zone and when there was little rain during the measuring period. Such a situation occurred between DAP 65 and DAP 79 during the 97/98 season (Appendix 5.1.1.1). The water extraction rates from each layer in order downwards were found to be 2.3, 2.4, 1.1 and 0 mm day^{-1}. The CMUL value based on the whole root zone was 37 mm above DUL. Subdividing this value between the layers from the top downwards, in proportion to the extraction rates presented above, gives the following CMUL values per layer: 0-300 = 85 mm; 300-600 = 120 mm; 600-900 = 112 mm; 900-1200 = 105 mm. Using these values should make it possible to make more reliable estimates of D.

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2826CD Glen
*Latitude & Longitude:*28°55'13''/26°14'57''
*Land type No:*Ea39c
*Climate zone:*45S
*Altitude:*1325m
*Terrain unit:*Upper Footslope
*Slope:*1%
*Slope shape:*Straight
*Aspect:*West
*Microrelief:*None
*Parent material solum:*Origin binary, local colluvium
*Underlying material:*Sandstone (feldspathic)

*Soil form:*Swartland
*Soil family:*Rouxville
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*Sheet slight, partially stabilized
*Vegetation/Land use:*Agronomic cash crops
*Water table:*None
Described by: M. Hensley & P.P. van Staden
*Date described:*1998-02
*Weathering of underlying material:*Moderate physical, moderate chemical
*Alteration of underlying material:*Calcified

Horizon	Depth(mm)	Description	Diagnostic horizons
A	0 - 250	Moist; dry dark brown 7.5YR3/4, moist dark reddish brown 5YR3/3; disturbed; fine sandy clay; apedal massive; friable; few normal fine pores; water absorption: 1 second(s); few roots; clear smooth transition.	Orthic
B1	250 - 400	Moist; dry dark reddish brown 5YR3/4, moist dark reddish brown 5YR3/3; undisturbed; fine sandy clay; strong medium angular blocky; slightly firm; few normal fine pores; many clay cutans; water absorption: 2 second(s); few roots; gradual smooth transition.	Pedocutanic
B2	400 - 600	Moist; dry dark reddish brown 5YR3/4, moist dark reddish brown 5YR3/3; undisturbed; fine sandy clay; common fine distinct black illuvial humus mottles; moderate medium angular blocky; slightly firm; few normal fine pores; few slickensides; many clay cutans; very few fine sesquioxide concretions; water absorption: 4 second(s); few roots; gradual smooth transition.	Pedocutanic
B3	600 - 830	Moist; dry strong brown 7.5YR4/6, moist dark brown 7.5YR3/4; undisturbed; clay; many fine distinct black illuvial humus mottles; moderate coarse subangular blocky; friable; few normal fine pores; non-hardened free lime, slight effervescence; common clay cutans; very few fine sesquioxide concretions; water absorption: 1 second(s); few roots; gradual smooth transition.	Pedocutanic
B4	830 - 1000	Moist; dry strong brown 7.5YR4/6, moist dark brown 7.5YR3/4; undisturbed; fine sandy clay; many fine distinct yellow, olive and brown geogenic mottles; many fine distinct reddish brown oxidized iron oxide mottles; moderate medium subangular blocky; friable; few normal fine pores; non-hardened free lime, slight effervescence; few clay cutans; very few fine sesquioxide concretions; water absorption: 1 second(s); common roots; gradual smooth transition.	Pedocutanic
C	1000 - 1300	Moist; undisturbed; many medium distinct white lime mottles; many medium distinct many coloured geogenic mottles; non-hardened free lime, strong effervescence; very few fine sesquioxide concretions; few roots; not observed transition.	Saprolite

*Survey name:*BEP - SW1222
*NATIONAL SOIL PROFILE NO:*6223

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: Glen/Swartland-Rouxville

Site no. 1						
Horizon/Horison	A	B1	B2	B3	B4	C
Depth/Diepte (mm)	0 - 250	250 - 400	400 - 600	600 - 830	830 - 1000	1000-1300
Bag no/Sak nr						
Lab No/ nr	D1410	D1411	D1412	D1413	D1414	D1415
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%						
2 mm						
c g sand 2-0.5 mm	0.2	0.2	0.1	0.3	0.2	1.1
m 0.5-0.25 mm	2.2	2.0	2.0	1.9	1.7	2.6
f sand 0.25-0.106 mm	27.3	25.4	26.3	24.1	22.8	29.6
v/b f sand 0.106-0.05 mm	22.4	21.1	20.7	20.3	17.3	20.2
c g silt/slik 0.05-0.02 mm	4.7	3.1	5.4	2.8	4.1	4.9
f silt/slik 0.02-0.002 mm	2.8	3.2	3.5	4.6	8.8	8.3
clay/klei 0.002 mm	38.2	42.7	39.2	44.0	42.6	31.2
Texture/Tekstuur	FiSaCl	FiSaCl	FiSaCl	FiSaCl	Cl	FiSaClLm
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS						
C %	0.53					
Plastisiteits indeks/Plasticity index	22	27	28	33	34	22
Al (me %) cmol(+)/kg						
Resistance/Weerstand (ohm)	1400	1400	1600	1400	1400	420
pH H20	6.46	7.44	8.14	8.94	9.14	8.92
pH KCl	4.97	6.08	6.52	7.26	7.54	7.57
EXCHANGEABLE/EXTRACTABLE CATIONS c mol+/kg soil UITRUILBARE/EKSTRAHEERBARE KATIONE c mol+/kg grond						
Na	0.19	0.33	0.54	0.51	0.96	0.94
K	0.78	0.55	0.49	0.39	0.76	0.77
Ca	5.89	6.04	6.59	4.86	14.82	15.72
Mg	7.61	8.41	11.20	6.80	13.69	11.03
S value/ S waarde	14.47	15.33	18.82	12.56	30.23	28.46
T value (CEC)/ T waarde (KUK)	23.15	23.57	27.02	26.12	26.45	21.53
SATURATION EXTRACT SOL. CATIONS c mol+/kg soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE c mol+/kg grond						
Na						
K						
Ca						
Mg						
Cond/Geleid mS/m						
Saturation/Versadiging						

Appendix 3.3.3.3

Data for stage 2 Es for Glen/Swartland-Rouxville ecotope

P (mm)	θ_{0-300} (mm)	$\Delta\theta$ (mm)	D (mm)	Es (mm)	ΣEs (mm)	t days	Σt (days)	$\sqrt{\Sigma t}$ ($d^{½}$)
0	80.7	0	0	0	0	0	0	0
0.2	74.5	6.2	0	6.4	6.4	2	2	1.41
0.2	64.8	9.7	0	9.9	16.3	5	7	2.65
0.2	61.7	3.1	0	5.3	21.6	2	9	3.00
0.0	58.6	3.1	0	3.1	24.7	2	11	3.31
2.2	57.7	0.9	0	0.9	25.6	4	15	3.87
0	55.2	2.5	0	2.5	28.1	3	18	4.24
0	53.4	1.8	0	1.8	29.9	3	21	4.58
0	51.2	2.2	0	2.2	32.1	4	25	5.00
0	49.5	1.7	0	1.7	33.8	6	31	5.57

For the reason explained in appendix 3.2.3.3, hypothetic points at $\Sigma Es = 0.1$ and $\sqrt{\Sigma t} = 0.1$ were included in the linear regression analysis. The following was the result:

$$\Sigma Es \quad = \quad 6.57\sqrt{\Sigma t} - 0.31 \ldots\ldots\ldots\ldots r^2 = 0.97$$

Ritchie α value $\quad = \quad$ 6.57 mm $t^{-½}$

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*292688 Thaba Nchu
*Latitude & Longitude:*29°04'00''/26°56'39''
*Land type No:*Db37b
*Climate zone:*465
*Altitude:*1520m
*Terrain unit:*Upper Footslope
*Slope:*2%
*Slope shape:*Straight
*Aspect:*North
*Microrelief:*None
*Parent material solum:*Origin binary, local colluvium, solid rock
*Underlying material:*Sandstone (feldspathic)

*Soil form:*Swartland
*Soil family:*Amandel
*Surface rockiness:*None
Surface stoniness:<2% exposed surface, angular, stones
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*Sheet slight, stabilized
*Vegetation/Land use:*Agronomic cash crops
*Water table:*0mm
Described by: M. Hensley, P.A.L. le Roux, L.D. van Rensburg & J.J. Botha
*Date described:*1999-05
*Weathering of underlying material:*Moderate physical, moderate chemical
*Alteration of underlying material:*Ferruginised

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
A	0 - 300	Moist; dry brown 7.5YR5/4, moist reddish brown 5YR4/3; disturbed; fine sandy loam; apedal massive; friable; few normal fine pores; few coarse pores; water absorption: 1 second(s); common roots; gradual smooth transition.	Orthic
AB	300 - 400	Moist; moist dark reddish brown 5YR3/4; undisturbed; clay; strong fine angular blocky; slightly firm; common normal fine pores; few coarse pores; common clay cutans; very few fine sesquioxide concretions; water absorption: 3 second(s); common roots; clear smooth transition.	Pedocutanic
B1	400 - 550	Moist; moist brown to dark brown 7.5YR4/4; undisturbed; clay; many coarse distinct grey and yellow illuvial humus mottles; few fine distinct black oxidized iron oxide mottles; strong coarse angular blocky; firm; few normal fine pores; many clay cutans; very few fine sesquioxide concretions; water absorption: 3 second(s); few roots; gradual smooth transition.	Pedocutanic
B2	550 - 700	Moist; moist brown to dark brown 10YR4/3; undisturbed; clay; many coarse distinct grey and yellow illuvial humus mottles; few fine distinct black oxidized iron oxide mottles; strong coarse angular blocky; firm; few normal fine pores; many slickensides; many clay cutans; very few fine sesquioxide concretions; water absorption: 5 second(s); few roots; gradual smooth transition.	Pedocutanic
C1	700 - 1200	Moist; moist dark yellowish brown 10YR4/4; undisturbed; clay; common fine distinct black oxidized iron oxide mottles; common medium faint grey, yellow and olive illuvial humus mottles; strong coarse angular blocky; very firm; few normal fine pores; many slickensides; very few fine sesquioxide concretions; very few fine lime concretions; water absorption: 5 second(s); few roots; gradual transition.	Saprolite

*Survey name:*BEP-SW1122
NATIONAL SOIL PROFILE NO:6224

APPENDIX 3.4.3.2

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

ECOTOPE: KHUMO/SWARTLAND-AMANDEL

Site no. 1					
Horizon/Horison	A1	AB	B1	B2	C1
Depth/Diepte (mm)	0-300	300-400	400-550	550-700	700-1200
Bag no /Sak nr					
Lab No/ nr	M3552	M3553	M3554	M3555	M3556
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%					
>2 mm					
c/g sand 2-0.5 mm	2.1	0.7	0.6	0.5	0.5
m 0.5-0.25 mm	3.0	1.5	0.9	0.7	0.7
f sand 0.25-0.106 mm	27.1	15.1	10.4	11.3	10.9
v/b f sand 0.106-0.05 mm	29.4	18.1	14.5	17.4	19.8
c/g silt/slik 0.05-0.02 mm	11.9	8.3	8.1	10.8	12.4
f silt/slik 0.02-0.002 mm	6.8	4.9	4.8	6.8	10.1
clay/klei 0.002 mm	17.5	18.7	58.5	50.1	42.8
Texture/Tekstuur	FiSaLm	Cl	Cl	Cl	Cl
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS					
C %	0.37				
Titr. Acidity cmol(+)/kg					
Al (me %) cmol(+)/kg					
Resistance/Weerstand (ohm)	2800	1800	1600	1400	1400
pH H20	6.03	6.10	6.90	7.84	8.83
pH KCl	4.50	4.61	5.17	6.06	7.26
EXCHANGEABLE/EXTRACTABLE CATIONS c mol+/kg soil UITRUILBARE/EKSTRAHEERBARE KATIONEc mol+/kg grond					
Na	0.07	0.50	0.72	0.90	1.50
K	0.56	0.73	0.98	0.87	0.96
Ca	2.30	5.32	7.24	6.84	10.63
Mg	1.21	4.34	6.94	7.29	9.35
S value/ S waarde	4.14	10.89	15.88	15.90	22.44
T value (CEC/ T waarde (KUK)	8.01	14.66	16.92	16.48	19.00
P mg/kg					

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2926BB Thaba Nchu
*Latitude & Longitude:*29°05'37''/26°54'33''
*Land type No:*Db37b
*Climate zone:*46S
*Altitude:*1500m
*Terrain unit:*Upper Footslope
*Slope:*3%
*Slope shape:*Straight
*Aspect:*North-west
*Microrelief:*None
*Parent material solum:*Origin single
*Underlying material:*Basic extrusive rocks

*Soil form:*Arcadia
*Soil family:*Lonehill
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*None
*Vegetation/Land use:*Agronomic cash crops
*Water table:*0mm
Described by: M. Hensley, P.A.L. le Roux, L.D. van Rensburg & J.J. Botha
*Date described:*1999-05
*Weathering of underlying material:*Moderate physical, moderate chemical
*Alteration of underlying material:*Calcified

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
AP	0 - 150	Wet; disturbed; clay loam; strong fine angular blocky; friable, slightly sticky, plastic; few normal fine pores; few clay cutans; few roots; gradual smooth transition.	Vertic
A	150 - 540	Wet; undisturbed; clay; strong fine angular blocky; sticky, very plastic; few normal fine pores; many clay cutans; very few mixed-shape gravel; very few fine sesquioxide concretions; few roots.	Vertic
B1	540 - 1000	Wet; undisturbed; clay; common medium faint white lime mottles; strong coarse angular blocky; sticky, very plastic; few normal fine pores; non-hardened free lime, moderate effervescence; many slickensides; many clay cutans; few fine sesquioxide concretions; few roots.	Pedocutanic

*Survey name:*BEP- VLAKSPRUIT/ARCADIA
*NATIONAL SOIL PROFILE NO:*6225

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

ECOTOPE: VLAKSPRUIT/ARCADIA-LONEHILL

Site no. 1					
Horizon/Horison	Ap	A1	B1		
Depth/Diepte (mm)	0-150	150-540	540-1000		
Bag no /Sak nr	VL12	VL13	VL14		
Lab No/ nr	D1421	D1422	D1423		
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%					
>2 mm					
c/g sand 2-0.5 mm	1.1	0.6	0.3		
m 0.5-0.25 mm	1.5	0.9	0.7		
f sand 0.25-0.106 mm	20.4	14.7	12.1		
v/b f sand 0.106-0.05 mm	21.1	14.6	14.4		
c/g silt/slik 0.05-0.02 mm	9.6	8.0	8.3		
f silt/slik 0.02-0.002 mm	7.3	7.1	7.9		
clay/klei 0.002 mm	37.0	52.4	54.1		
Texture/Tekstuur	ClLm	Cl	Cl		
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS					
C %	0.82	0.69			
Titr. Acidity cmol(+)/kg					
Al (me %) cmol(+)/kg					
Resistance/Weerstand (ohm)	1600	1400	460		
pH H20	8.07	8.83	9.03		
pH KCl	6.41	6.71	7.36		
EXCHANGEABLE/EXTRACTABLE CATIONS c mol+/kg soil UITRUILBARE/EKSTRAHEERBARE KATIONEc mol+/kg grond					
Na	0.31	1.02	1.70		
K	0.50	0.63	0.43		
Ca	9.38	10.13	17.71		
Mg	7.11	10.00	14.82		
S value/ S waarde	17.30	21.78	34.66		
T value (CEC/ T waarde (KUK)	21.77	27.50	34.77		
P mg/kg					

Appendix 4.1

Rainfall for the Glen / Bonheim and Glen / Swartland ecotopes 1996/97 season, and measured runoff from the minimum surface storage (MSS) runoff plots.

Year	DOY	DAP	Rain (mm)	Runoff (mm)	
				Bonheim	Swartland
96	322		85.0	51.4	60.3
96	323		4.8	0.1	2.5
96	325		0.2	0.0	0.0
96	330		13.0	0.9	2.0
96	331		0.6	0.1	0.0
96	333		9.4	0.4	4.9
96	334		4.4	0.1	0.0
96	341		12.6	0.2	0.0
96	342		2.2	0.0	0.0
96	343		0.8	0.0	0.0
96	346		1.8	0.0	0.0
96	352	2	0.2	0.0	0.0
96	356	6	11.8	0.0	0.7
96	357	7	9.2	0.0	0.1
96	360	10	1.2	0.0	0.0
96	363	13	13.6	0.0	4.5
96	364	14	11.2	0.8	0.7
96	365	15	3.2	0.0	0.0
97	3	19	0.2	0.0	0.0
97	4	20	0.6	0.0	0.0
97	6	22	2.6	0.0	0.0
97	16	32	4.8	0.0	1.0
97	17	33	11.2	1.0	2.3
97	18	34	13.4	3.1	4.1
97	20	36	3.2	0.0	0.0
97	21	37	0.2	0.0	0.0
97	22	38	2.4	0.1	0.0
97	24	40	0.6	0.0	0.0
97	25	41	6.2	0.0	0.0
97	26	42	2.0	0.0	0.0
97	27	43	34.8	13.7	23.5
97	28	44	1.0	0.1	0.1
97	36	52	6.0	0.0	0.9
97	40	56	0.8	0.0	0.0
97	43	59	7.8	2.0	1.3
97	44	60	0.4	0.0	0.0
97	56	68	11.2	1.2	2.6
97	58	70	0.2	0.0	0.1
97	60	72	11.4	3.7	4.4
97	61	73	26.0	6.6	15.3
97	62	74	1.8	0.1	0.5
97	65	77	11.0	0.1	0.6
97	69	81	0.8	0.0	0.0
97	70	82	0.4	0.0	0.1
97	72	84	0.8	0.0	0.1
97	78	90	11.8	0.0	0.2
97	79	91	2.2	0.0	0.0
97	85	97	0.2	0.0	0.0
97	86	98	11.2	0.0	0.0
97	87	99	5.8	0.0	0.0
97	88	100	10.4	0.3	0.8
97	89	101	2.4	0.0	0.0
97	90	102	0.2	0.0	0.0
97	91	103	16.4	1.7	5.4
97	92	104	1.0	0.2	0.0
97	93	105	0.2	0.0	0.0
97	95	107	7.8	0.0	0.2
97	96	108	0.4	0.0	0.0
97	99	111	0.2	0.0	0.0
97	105	117	2.0	0.0	0.0
97	107	119	0.2	0.0	0.0
97	112	124	9.0	0.1	0.3
97	113	125	2.8	0.0	0.0
97	114	126	0.2	0.0	0.0
97	122	134	0.6	0.0	0.0
97	126	138	3.6	0.0	0.0
97	127	139	2.2	0.0	0.0
97	128	140	0.2	0.0	0.0
97	143	155	2.8	0.0	0.0
97	145	157	11.4	0.0	1.2
		Total	452.0	87.9	140.6
Runoff as % of rainfall				19.4	31.1

Rainfall and runoff on the minimum surface storage (MSS) and total soil tillage (TST) runoff plots on the Glen ecotopes during 1997/98

Year	DOY	Rain (mm)	Runoff (mm)			
			Bonheim		Swartland	
			MSS	TST	MSS	TST
97	151	0.2				
97	161	1.4				
97	162	3				
97	163	0.4				
97	165	0.2				
97	180	1.2				
97	208	21.5	2	0	3	0
97	210	0.2				
97	212	0.2				
97	216	1.2				
97	242	5				
97	251	12	0.8	0	1.1	0
97	256	0.8				
97	257	7.4				
97	258	0.8				
97	275	1.2				
97	283	38.2	4.4	0.2	6.4	2.1
97	284	1.4				
97	285	0.2				
97	287	6.8				
97	288	0.4				
97	289	1				
97	305	0.6				
97	309	2.8				
97	316	11.6				
97	320	2.2				
97	331	0.8				
97	332	15.8	1.8	0	2.6	0
97	339	0.4				
97	355	2				
97	356	9.2				
97	357	7.2				
97	358	5.2				
98	1	71.6	20	0.6	26	0.4
98	2	6				
98	5	0.4				
98	6	11	0	0	2.2	0.1
98	7	36	12	2.3	18	10
98	8	5.6				
98	13	1.4				
98	14	25	4	2.5	9	4.8
98	18	1.4				
98	19	0.2				
98	23	3				
98	29	9.4				
98	30	0.2				
98	32	1.6				
98	38	8				
98	39	1				
98	40	7				
98	41	10	2.8	0.3	3.2	0.2
98	43	14	1.6	0.1	4.3	0.5
98	47	83	5.6	2.9	8	5.5
98	48	10				
98	56	8				
98	58	5				
98	59	5				
98	60	8.5				
98	65	12	2.2	2	2.9	2.5
98	67	24	12	12	11	11
98	73	4				
98	75	1				
98	81	1				
98	82	3				
98	83	2				
98	84	8	0.2	0	1	0
98	85	27	10.8	10.5	7	5.8
98	113	8.4				
98	129	3				
98	155	0.4				
Total		588.6	80.2	33.4	105.7	42.9
runoff as % of rainfall for the recorded period			13.63	5.67	17.96	7.29

* Estimated values as measuring system became inoperative due to flooding

Rainfall and runoff on the minimum surface storage (MSS) and total soil tillage (TST) runoff plots on Bo and Sw during the 1998/99 rain season

Year	DOY	Rain (mm)	Runoff (mm)			
			Bonheim		Swartland	
			MSS	TST	MSS	TST
98	299	17.5	0.7	0	1.1	0
98	306	18	0.5	0	0.6	0
98	323	24	0.4	0	1.8	0
98	330	15.5	0.60	0	0.8	0
98	334	3	1.3	0	0	0
98	336	21.2	11.03	0.06	9.5	0.2
98	341	3	0	0	0.6	0
98	342	4	0	0	0.1	0
98	344	3.9	0	0	0.2	0
98	348	7.6	1.5	0	0.4	0
98	353	8.4	0.8	0	0.5	0
98	363	24	9.7	1.5	2.5	0.5
98	364	11.8	7.6	0.4	7.4	0.5
99	10	3.6	0	0	0.3	0.1
99	11	9.2	3.8	0.6	4.6	0
99	22	22.8	8.5	0	7.2	0
99	23	11	6.6	0	6.3	0
99	33	10	3.5	0.06	2.6	0
99	50	8.8	0.2	0.01	3.8	0
99	52	5.2	0.06	0	1.8	0
99	56	5.8	0.2	0.1	1.7	0
99	74	6.4	1.5*	0	1.0	0
99	80	9.8	0.2	0	0.7	0
99	84	3.2	0.2	0	0.4	0
99	118	6.8	0.2	0	0.5	0
99	138	18.8	1.5	0.9	1.3	0.8
99	139	20	1.6	3.7	1.6	0.3
Total		462.2	60.69	7.42	59.26	2.4
Runoff as % of rainfall			13.1	1.6	12.8	0.5

*Estimated value; measuring apparatus defective

Comparison between predicted annual runoff using equation 4.3, and the measured values of Du Plessis and Mostert (1965)

Season	Rain [*1] (mm)	Cum. Rain (mm)	Estimated Runoff [*2] (mm)	Cum. Runoff (mm)	Runoff as % of Rain	Rain [*3] (mm)	Cum. Rain (mm)	Measured Runoff [*4] (mm)	Cum. Runoff (mm)	Runoff as % of Rain
37/38	348.7	348.7	68.7	68.7	19.7	353	353	55.1	55.1	15.6
38/39	449	797.7	105.6	174.3	23.5	392	745	79.5	134.6	20.3
39/40	576.5	1374.2	145.1	319.4	25.2	654	1399	143.8	278.4	22.0
40/41	642.4	2016.6	197.7	517.2	30.8	643	2042	201.9	480.3	31.4
41/42	409.4	2426.0	96.9	614.1	23.7	398	2440	85.7	566.0	21.5
42/43	963.5	3389.5	265.4	879.5	27.5	952	3392	318.2	884.2	33.4
43/44	701	4090.5	194.8	1074.3	27.8	651	4043	214.2	1098.3	32.9
44/45	393	4483.5	93.0	1167.3	23.7	356	4399	67.3	1165.7	18.9
45/46	539.6	5023.1	168.8	1336.1	31.3	523	4922	159.1	1324.7	30.4
46/47	349.9	5373.0	72.9	1409.0	20.8	318	5240	49.0	1373.7	15.4
47/48	699.9	6072.9	225.2	1634.2	32.2	701	5941	203.8	1577.5	29.1
48/49	223.5	6296.4	26.8	1660.9	12.0	223	6164	47.7	1625.2	21.4
49/50	545.4	6841.8	121.0	1781.9	22.2	504	6668	127.3	1752.5	25.3
50/51	532.5	7374.3	146.2	1928.1	27.4	523	7191	142.6	1895.0	27.3
51/52	360.9	7735.2	75.2	2003.3	20.8	327	7518	73.4	1968.5	22.5
52/53	469.7	8204.9	138.2	2141.5	29.4	516	8034	177.4	2145.9	34.4
53/54	575.1	8780.0	157.6	2299.1	27.4	542	8576	188.0	2333.9	34.7
				mean	**25.0**				mean	**25.7**

*1 Measured rainfall obtained from the ISCW weather data bank

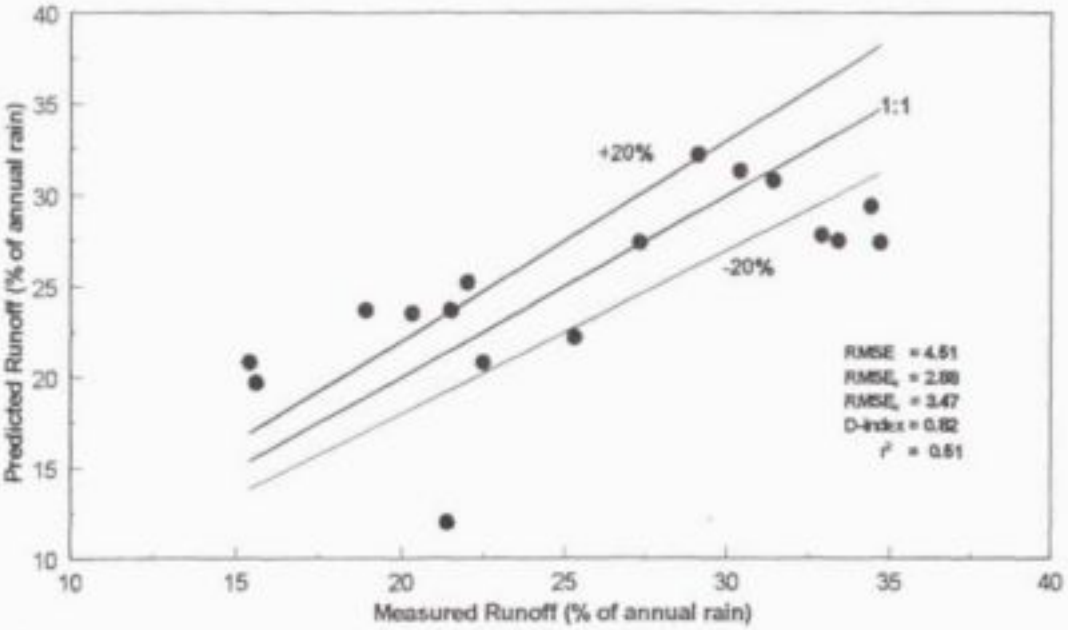
*2 Predicted runoff calculated by applying Equation 4.3 to rainfall events greater than 8 mm

*3 Annual rainfall measured by du Plessis and Mostert (1965); obtained by interpolation on their published graphs, as this was the only source of their data available.

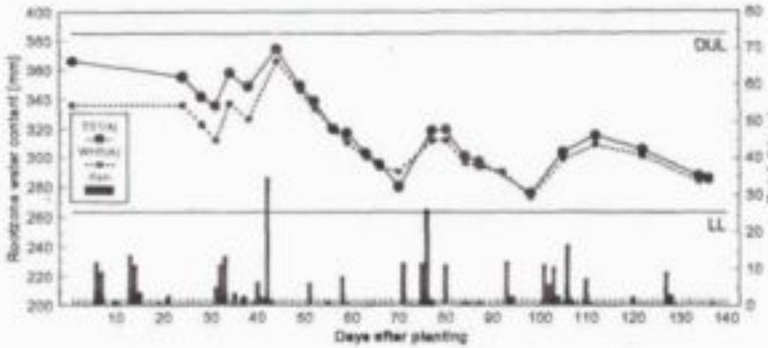
*4 Annual runoff measured by du Plessis and Mostert (1965)

Appendix 4.5

Measured versus predicted runoff as % of rain for the data presented in Appendix 4.4

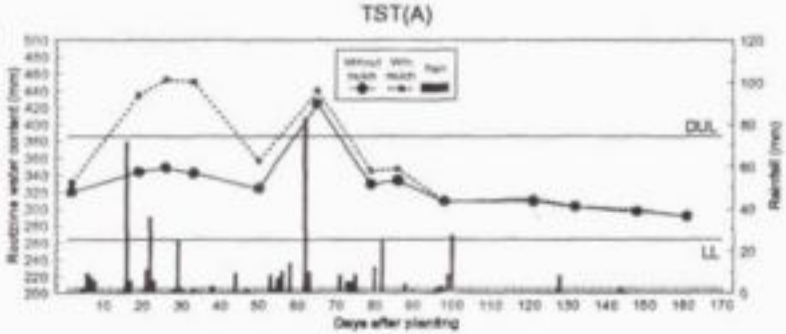


Appendix 5.1.1.1 Measured changes in the soil water content of the rootzone during the 1996/97 season on the Glen / Bonheim ecotope : Maize

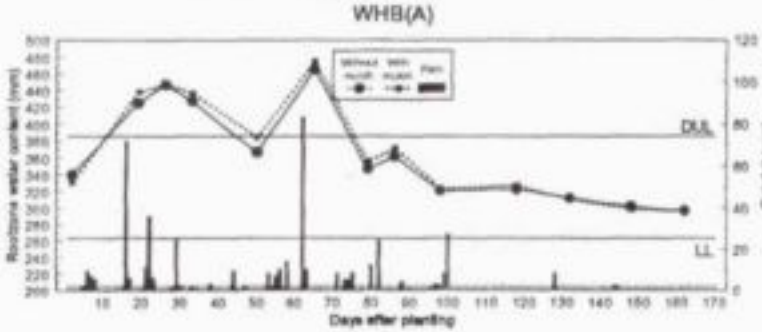


Appendix 5.1.1.2 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Glen / Bonheim ecotope : Maize

a

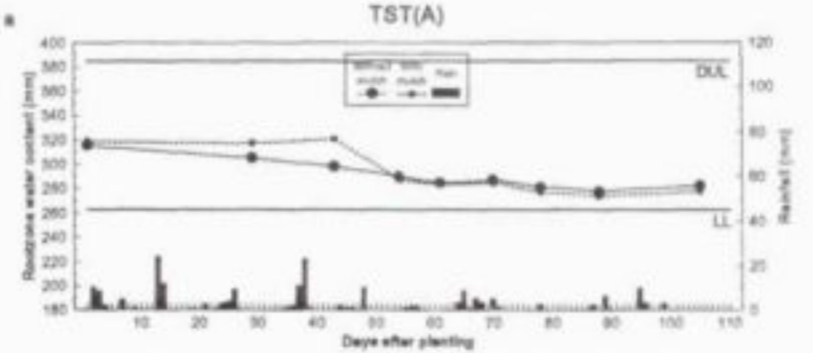


b

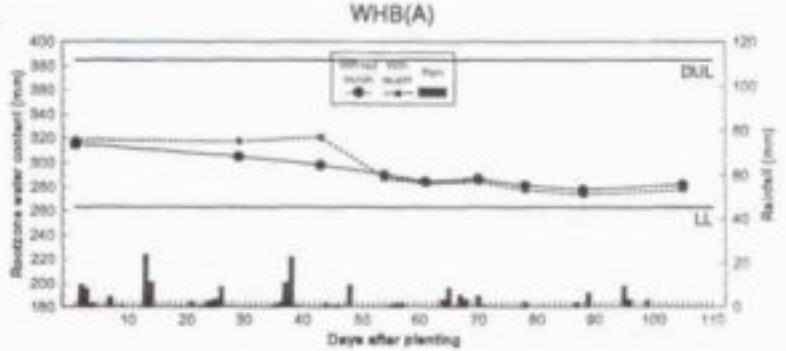


Appendix 5.1.1.3 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Glen / Bonheim ecotope : Maize

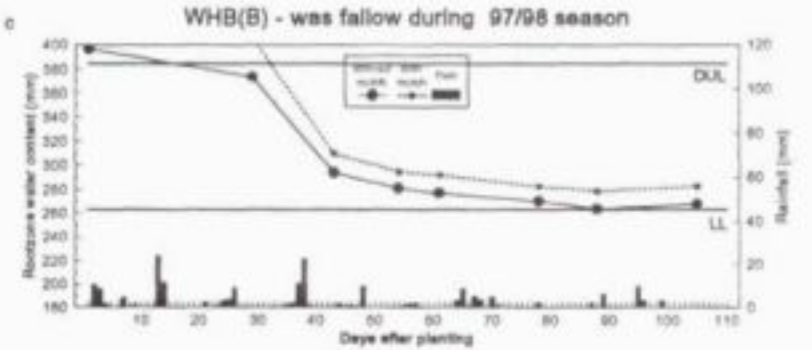
a



b

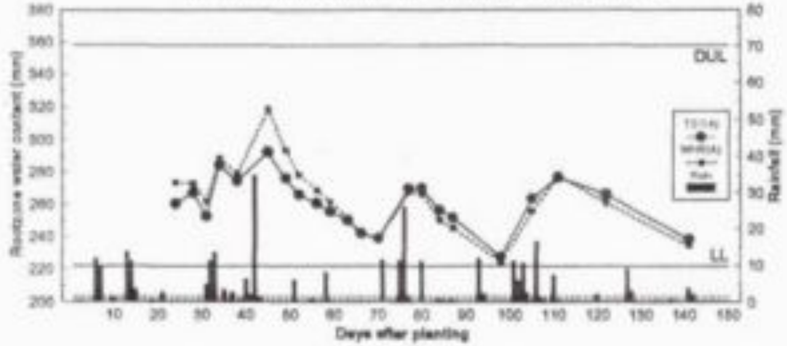


c



Appendix 5.1.2.1 Measured changes in the soil water content of the rootzone during the 1996/97 season on the Glen / Swartland ecotope : Maize

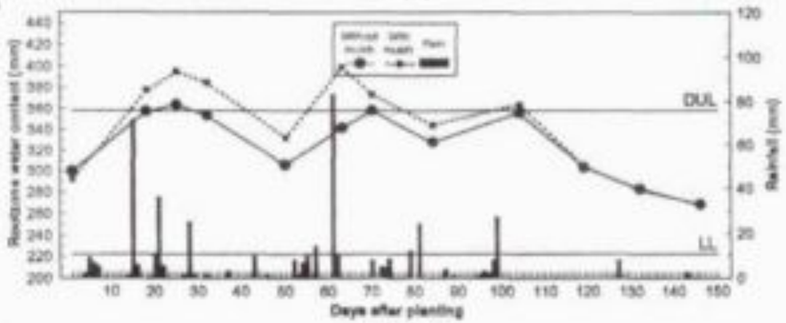
a



Appendix 5.1.2.2 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Glen / Swartland ecotope : Maize

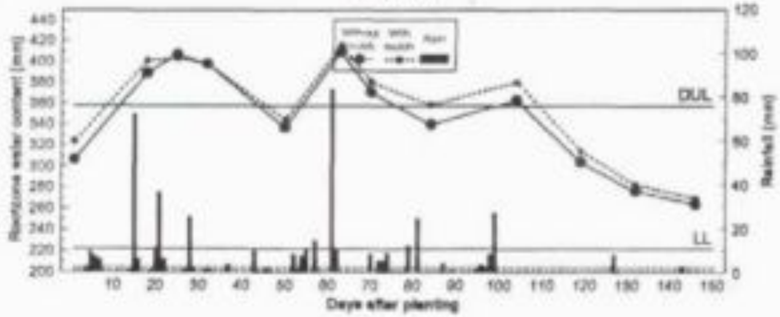
a

TST(A)



b

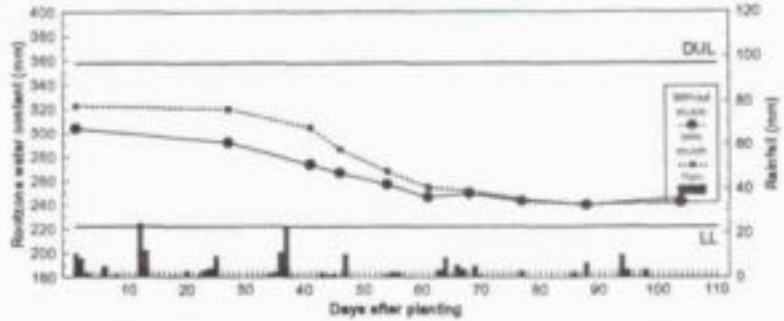
WHB(A)



Appendix 5.1.2.3 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Glen / Swartland ecotope : Maize

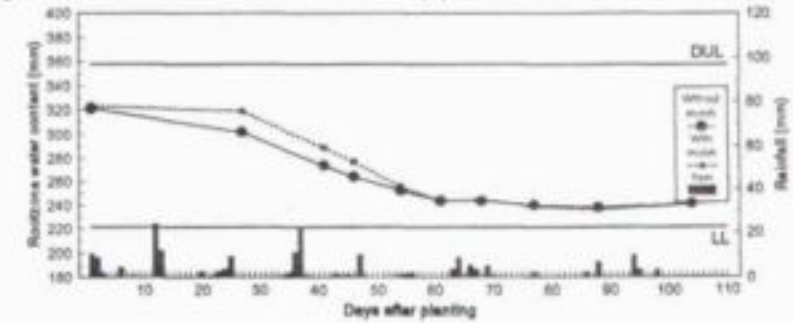
a

TST(A)



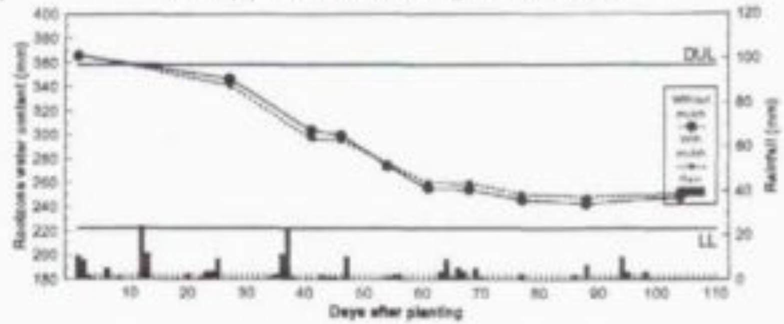
b

WHB(A)



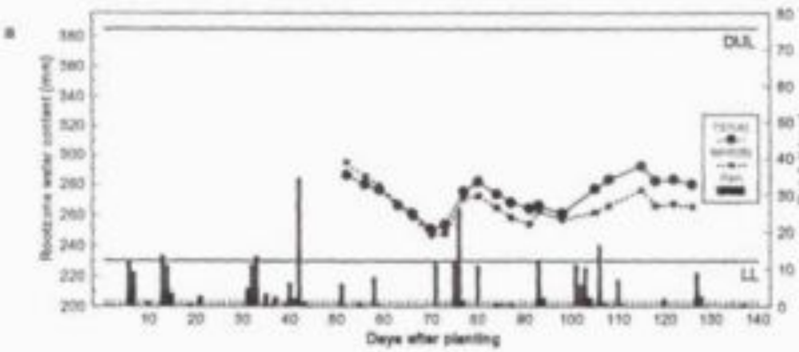
c

WHB(B) - was fallow during 97/98 season



Appendix 5.2.1.1 Measured changes in the soil water content of the rootzone during the 1996/97 season on the Glen / Bonheim ecotope : Sunflower

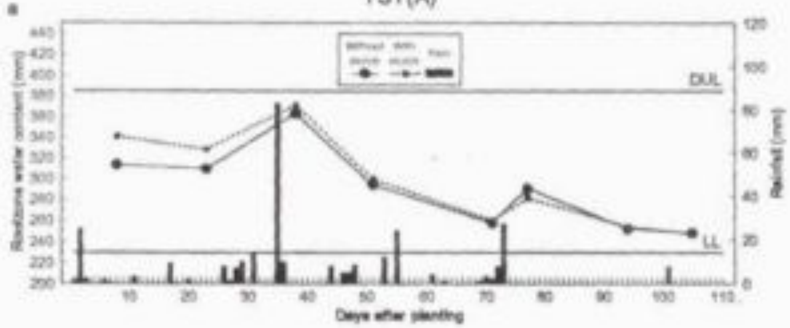
a



Appendix 5.2.1.2 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Glen / Bonheim ecotope : Sunflower

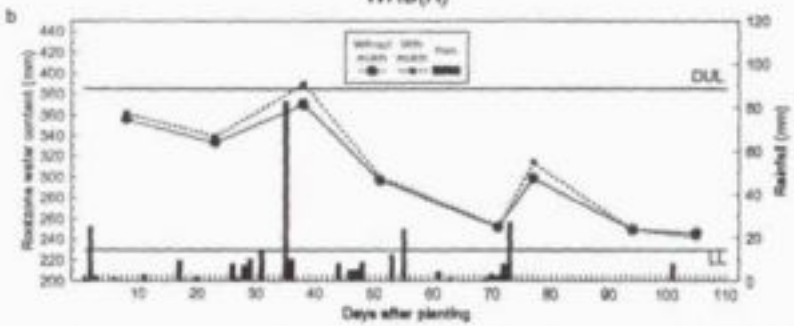
a

TST(A)



b

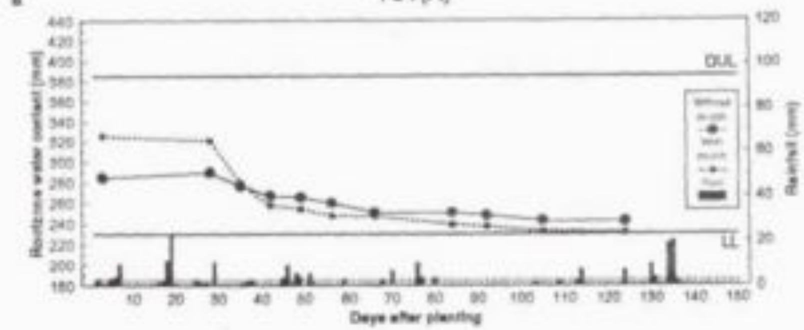
WHB(A)



Appendix 5.2.1.3 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Glen / Bonheim ecotope : Sunflower

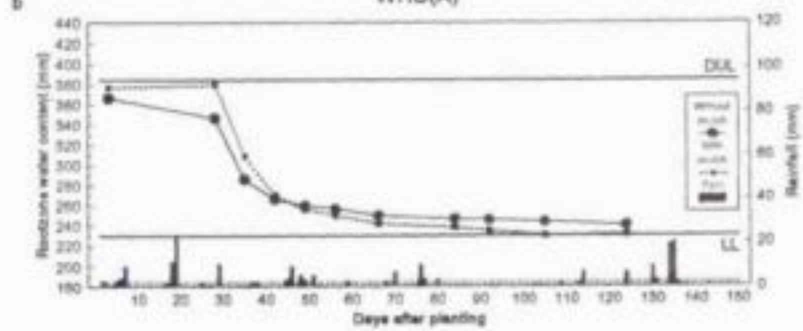
a

TST(A)



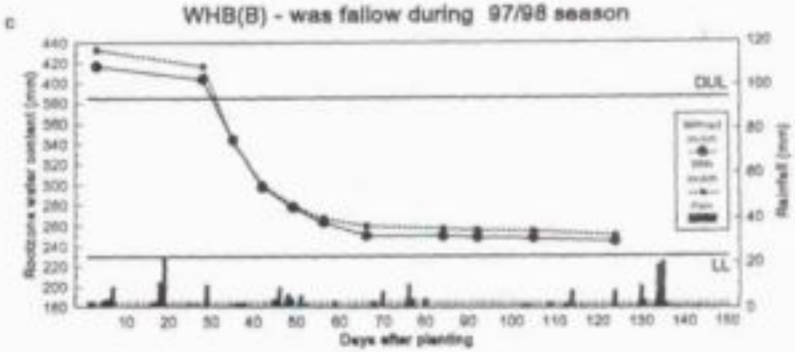
b

WHB(A)

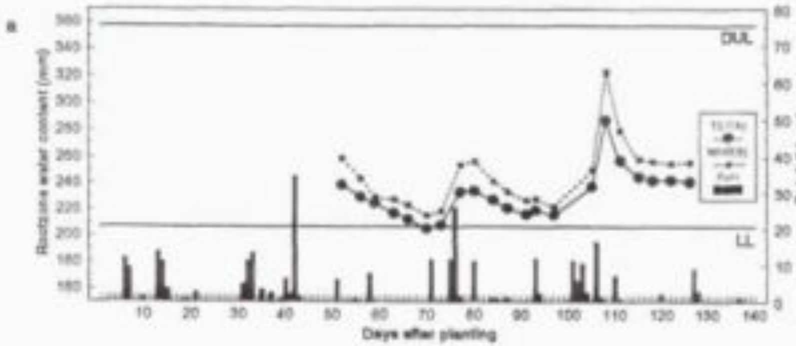


c

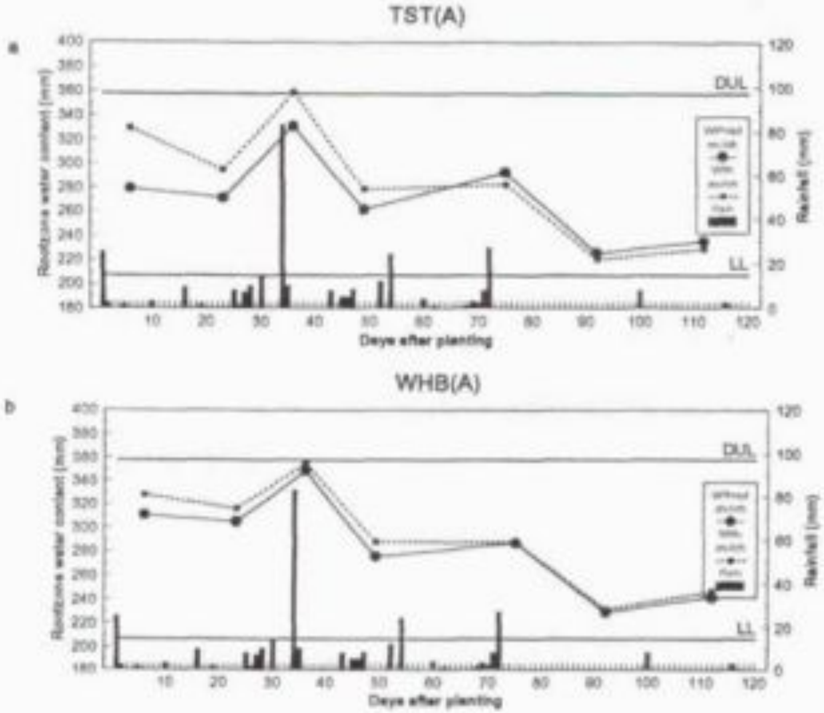
WHB(B) - was fallow during 97/98 season



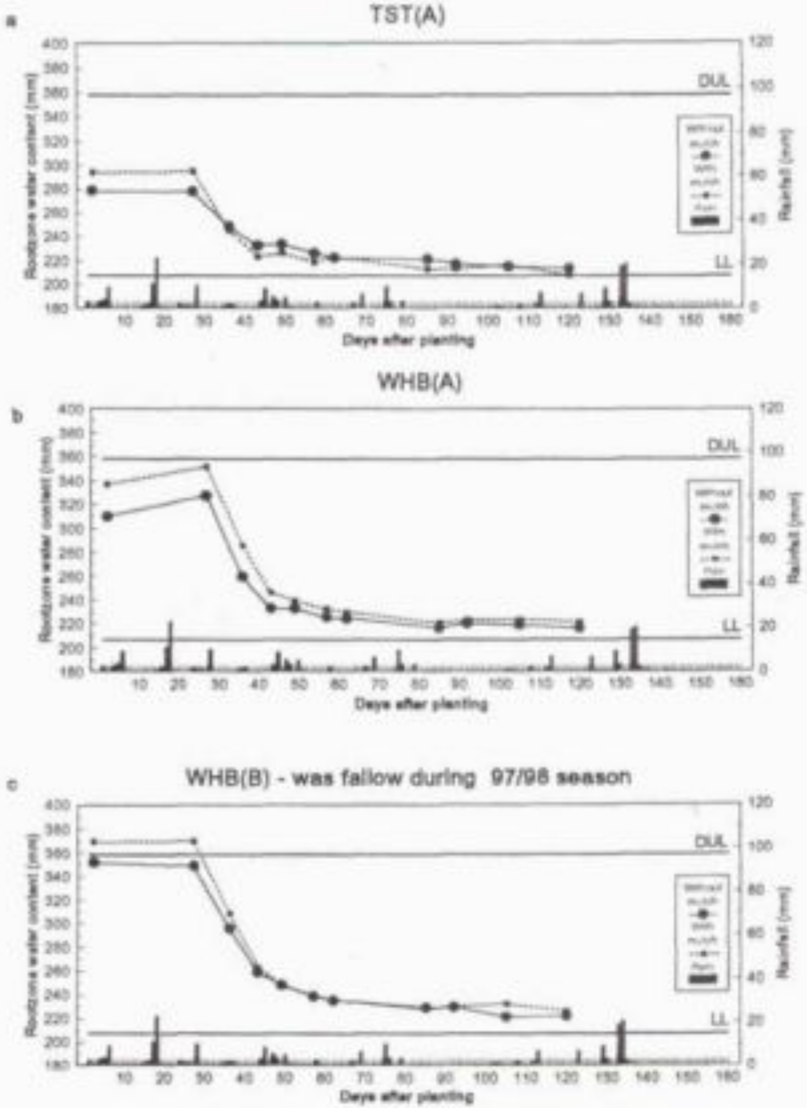
Appendix 5.2.2.1 Measured changes in the soil water content of the rootzone during the 1996/97 season on the Glen / Swartland ecotope : Sunflower



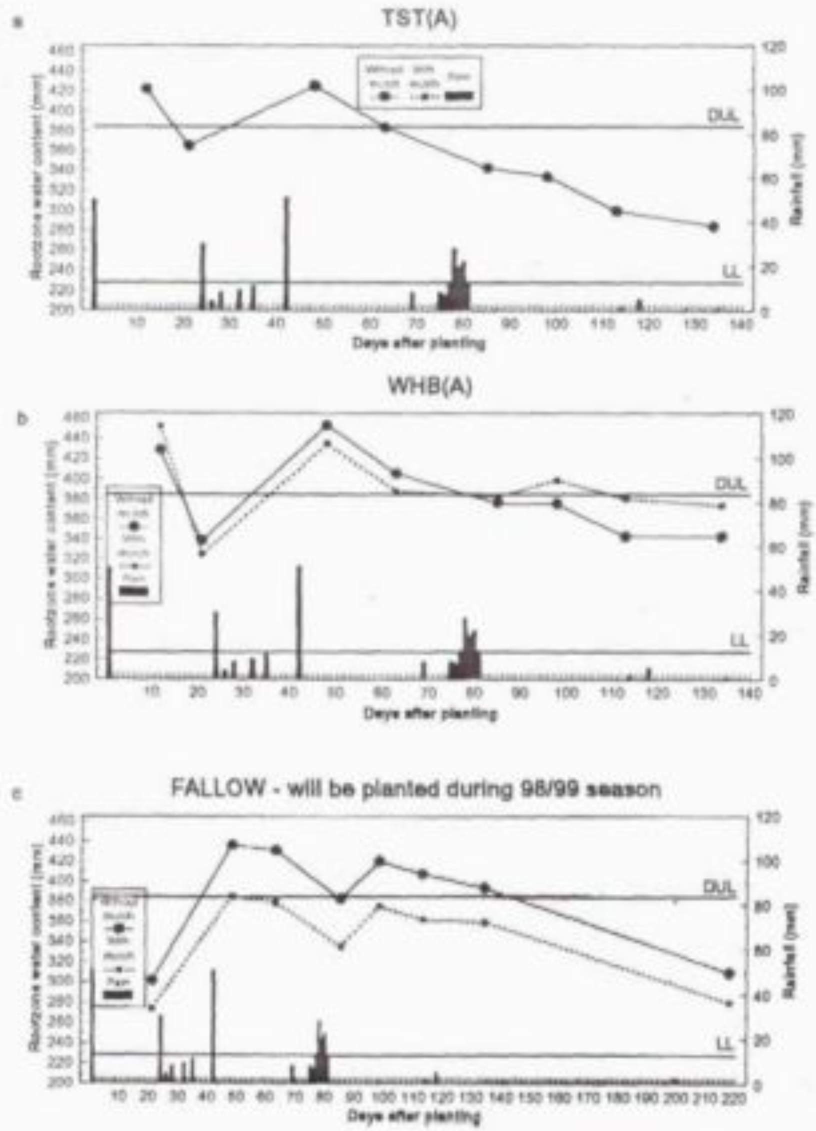
Appendix 5.2.2.2 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Glen / Swartland ecotope : Sunflower



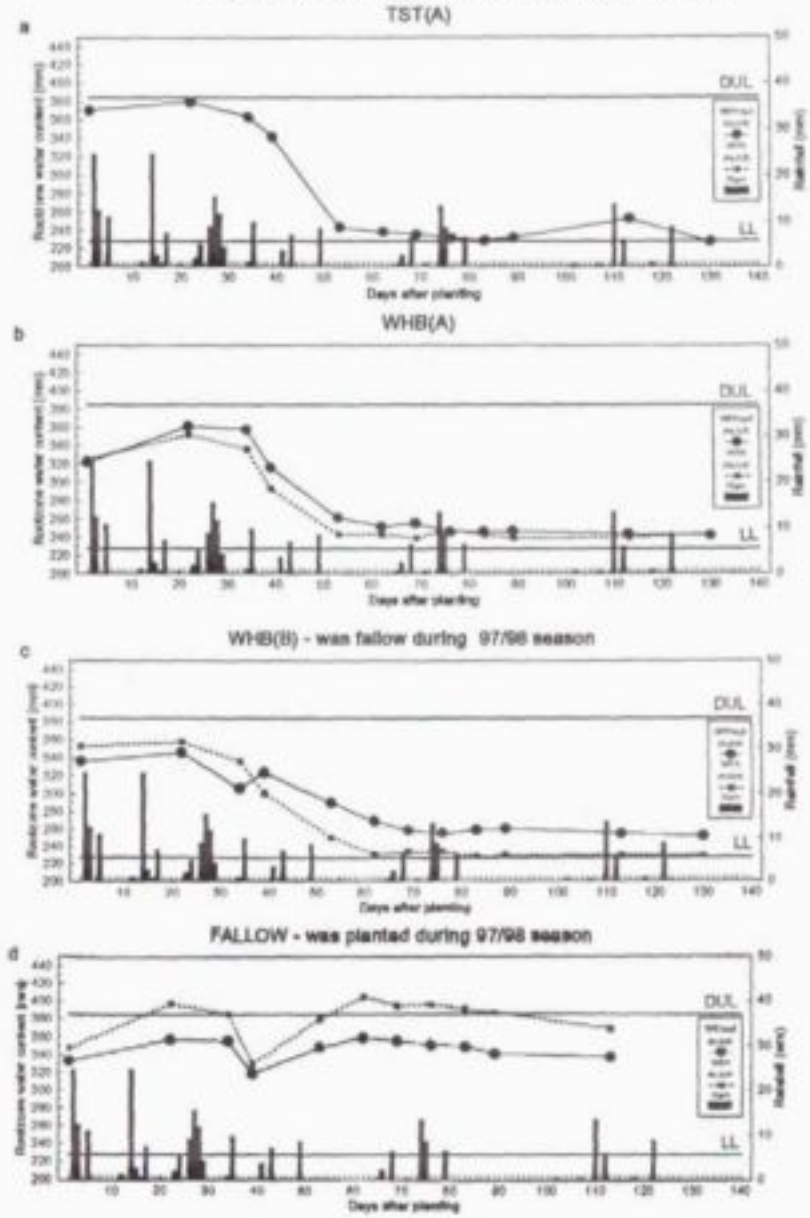
Appendix 5.2.2.3 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Glen / Swartland ecotope : Sunflower



Appendix 5.2.3.1 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Khumo / Swartland ecotope : Sunflower

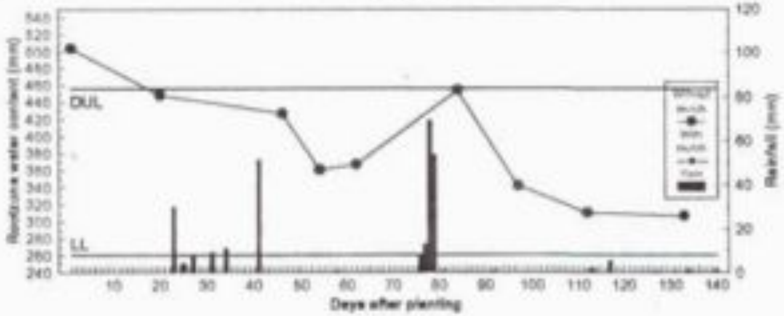


Appendix 5.2.3.2 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Khumo / Swartland ecotope : Sunflower

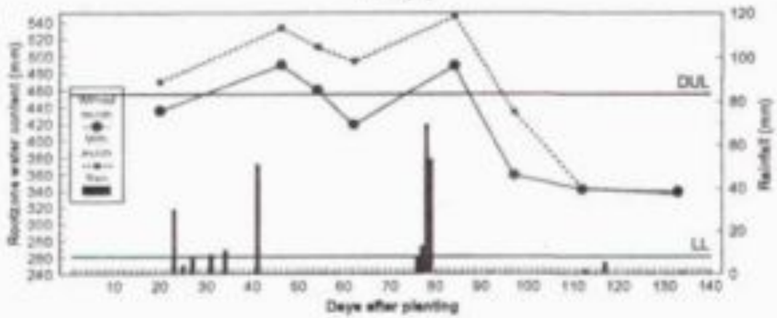


Appendix 5.2.4.1 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Vlakspruit / Arcadia ecotope : Sunflower

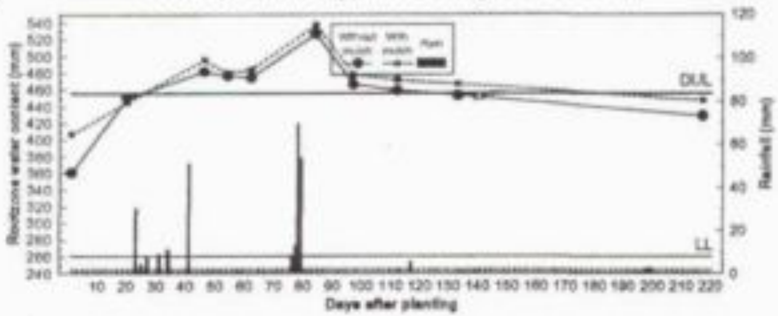
a TST(A)



b WHB(A)

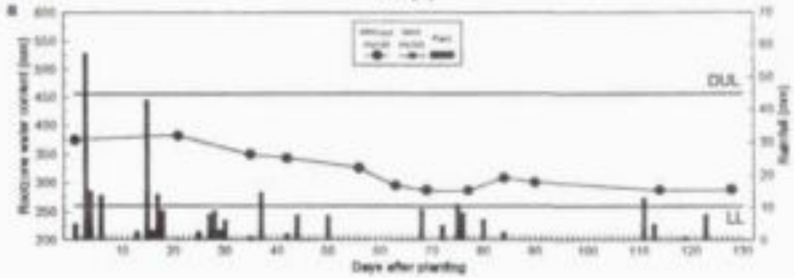


c FALLOW - will be planted during 98/99 season

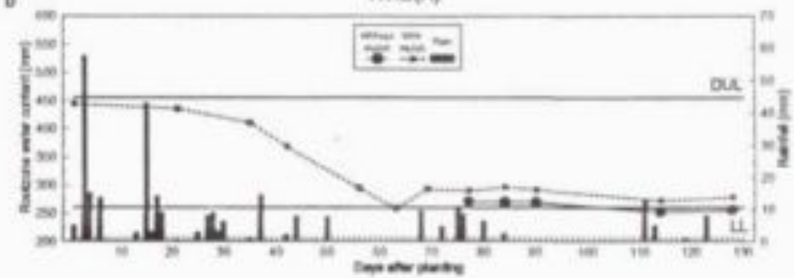


Appendix 5.2.4.2 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Vlakspruit / Arcadia ecotope : Sunflower

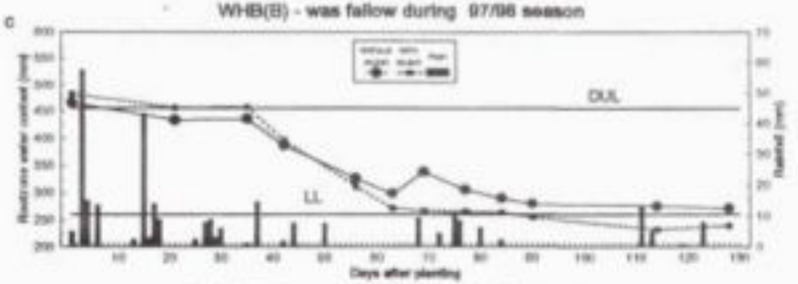
a TST(A)



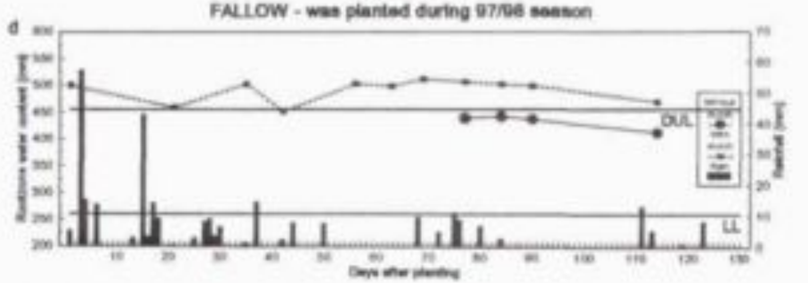
b WHB(A)



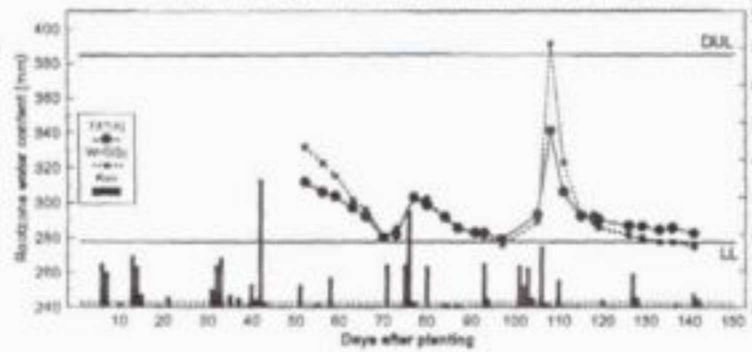
c WHB(B) - was fallow during 97/98 season



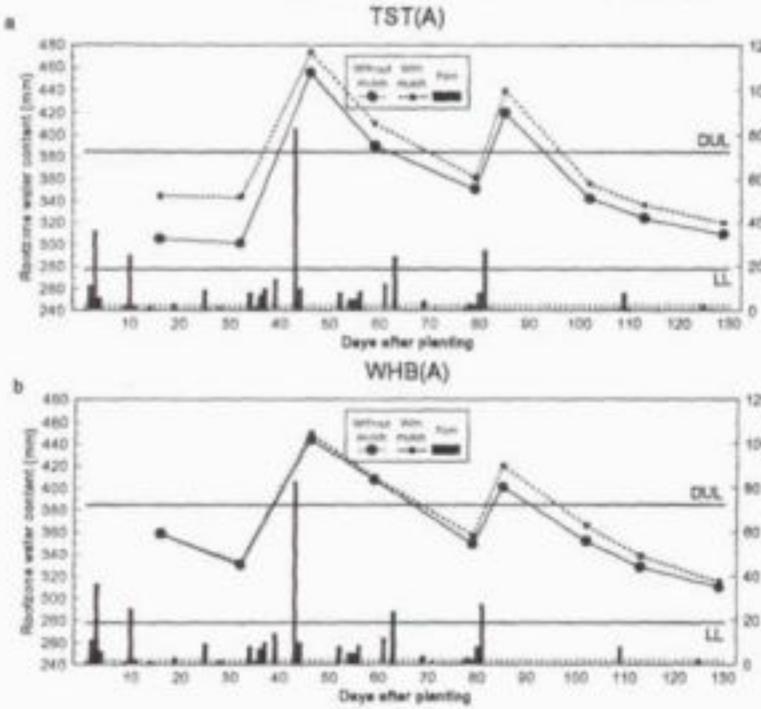
d FALLOW - was planted during 97/98 season



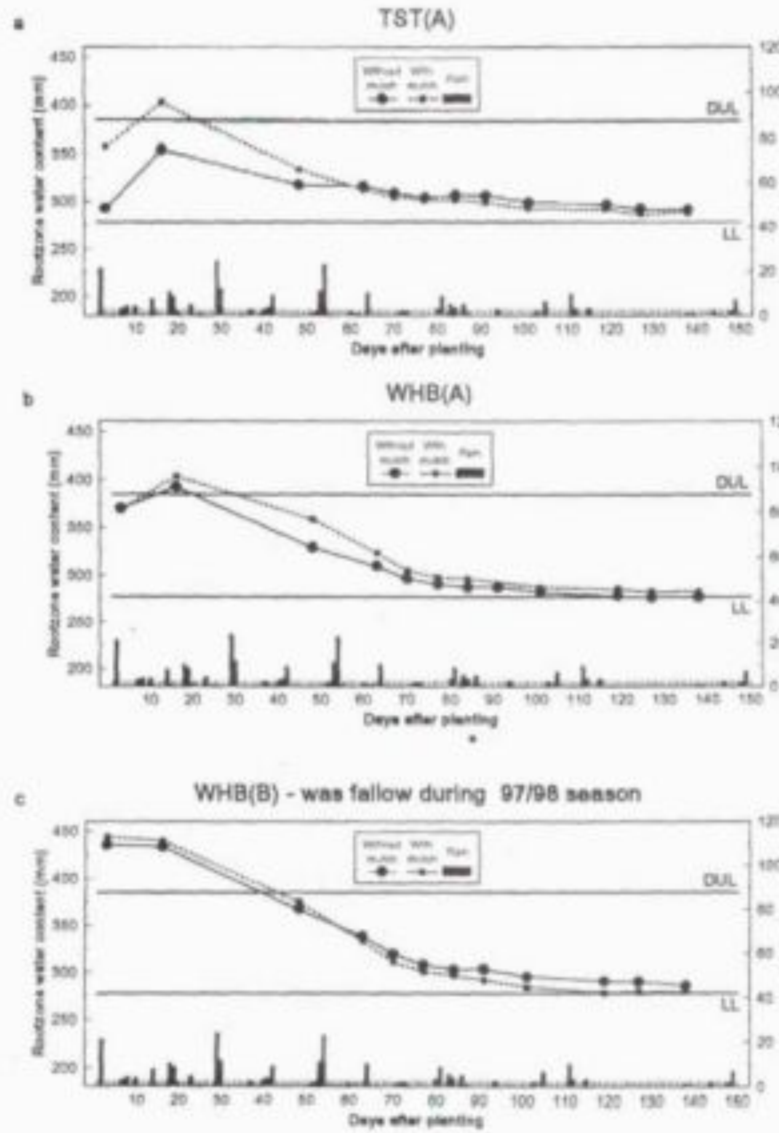
Appendix 5.3.1.1 Measured changes in the soil water content of the rootzone during the 1996/97 season on the Glen / Bonheim ecotope : Sorghum



Appendix 5.3.1.2 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Glen / Bonheim ecotope : Sorghum

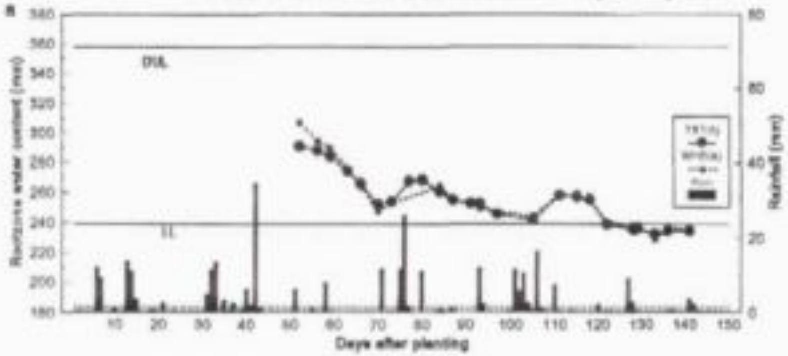


Appendix 5.3.1.3 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Glen / Bonheim ecotope : Sorghum



Appendix 5.3.2.1 Measured changes in the soil water content of the rootzone during the 1996/97 season on the Glen / Swartland ecotope : Sorghum

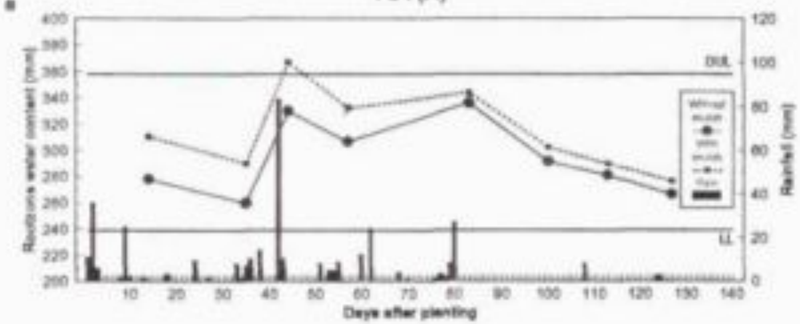
a



Appendix 5.3.2.2 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Glen / Swartland ecotope : Sorghum

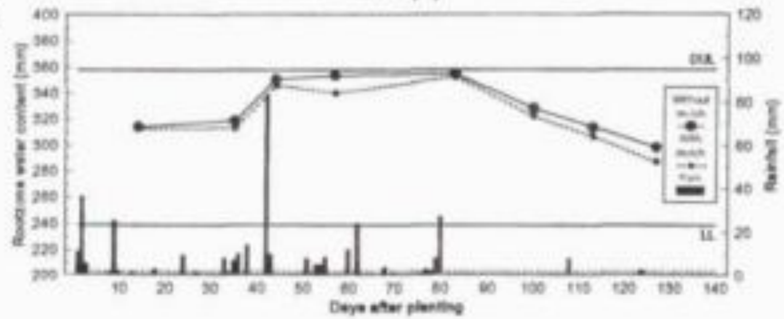
TST(A)

a



WHB(A)

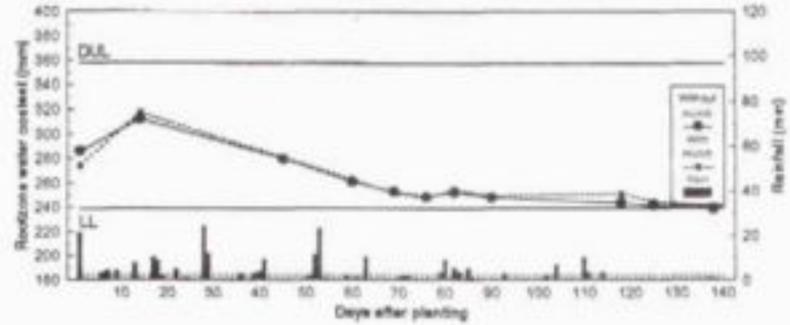
b



Appendix 5.3.2.3 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Glen / Swartland ecotope : Sorghum

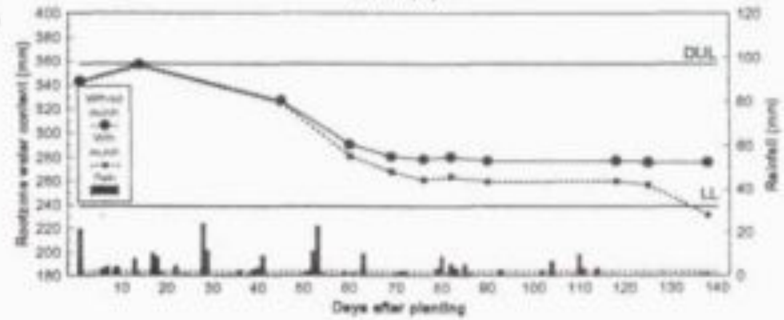
TST(A)

a



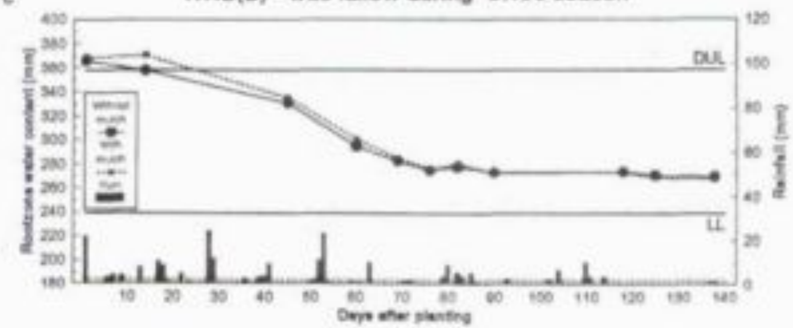
WHB(A)

b



WHB(B) - was fallow during 97/98 season

c



BRIEF DESCRIPTION OF THE DSSAT-V3 MODEL (From Tsuji, Uehara & Balas, 1994)

CHAPTER THREE.
DSSAT V3 OVERVIEW

SHELL

The DSSAT v3 Shell is a menu-driven program which enables users to easily select and use any of the DSSAT components. The Shell has five main menu items, each with various options: DATA, MODELS, ANALYSES, TOOLS and SETUP/QUIT.

The DATA main menu item provides users access to weather, soil and experiment data, similar to that of DSSAT v2.1. One major change is that the new data are all stored in ASCII files so that users can access and manipulate them more easily than in the v2.1 system. Some temporary dBase files are created to allow users to search for data or information contained in the data, also a new capability. There is also a program, Convert, in DSSAT v3 to convert ASCII model input files from DSSAT v2.1 into the new v3 file formats for crop management inputs, soil and weather data. This will allow users to more easily adapt to v3. Although there is no program to convert genetic coefficient data from the old system to the new formats, genetic coefficients for all crop models have been converted and are available in DSSAT v3 for simulation with the new model versions.

New data sections have also been added under the DATA main menu item. Now there is a CLIMATE section which deals with monthly data, which can be used to simulate daily weather data if daily data are not available for a site. This new feature allows users to input monthly data from published sources, such as FAO, and simulate crop performance. There is also a GENOTYPE section, which contains a new genetic coefficient calculation program to assist users when they have cultivars that are not in the genetic coefficient data file. There is a BACKGROUND section which allows users to obtain general information on the data contained in their system, and sections on PEST and ECONOMIC to store and handle pest and economic data. The new data definitions and crop model inputs and outputs are fully described in Volume 2-1 (Jones et al. 1994) of this book.

Under the MODELS section, users can access models for calibration, validation and sensitivity analysis purposes as before. Currently, models are available for various cereal crops (maize, wheat, sorghum, millet, rice and barley), three grain legume crops (soybean, peanut, and dry bean), and cassava. Generally, the three grain legume models operate using one program and the cereal crops operate with another set of code, except for the rice model. The crop models now have a more modular structure with a separate input module that processes the new files to reduce program size and complexity.

A new crop model graphics program is also available. It is mouse-driven and creates plots of simulated and observed variables similar to the graphics package in DSSAT v2.1. This package, called Graphing of Simulated and Experiment Data, is much more flexible and can output graphs to printers or to files for inserting into other software. Also under each crop model section is a selection for REVIEWing the results from simulation runs. This feature allows users to view results on the screen, or print them out to save them for other purposes. It accesses an ASCII editor which is supplied with DSSAT v3, or one which is specified by the user during setup. This allows users to "install" their own editor into DSSAT or use a default one that is supplied.

Under the ANALYSES section, two choices appear: Season and Sequence. The Season option allows users to setup simulation experiments, simulate them and analyze the results, similar to the strategy evaluation mode in DSSAT v2.1. It provides access to the interactive model input creation program, XCreate, which sets up one or more strategies to compare, for one or more crops. As was the case in DSSAT v2.1, the initial conditions are reset in this mode for each run, so that results represent the variability expected if the practices were implemented with fixed starting conditions. In addition to having the new XCreate program to setup runs and new crop model versions, DSSAT v3 also has a new seasonal evaluation program which will be described in more detail below. The second option under ANALYSES is to simulate sequences of crops, such as in crop rotations, for studying the long term effects of practices on crop and soil performance, with emphasis on time trends and uncertainty.

Under the TOOLS section, users can access their disk manager (such as XTREE), their editor and spreadsheet, or go to the DOS prompt temporarily without leaving DSSAT. These tool options were not available in DSSAT v2.1, and users found it inconvenient to exit and restart DSSAT when some other task had to be performed.

The SETUP/QUIT section is similar to the SETUP menu option in DSSAT v2.1, but more items can be setup or installed in DSSAT v3, such as the tools described above and managers of the different types of data, in addition to the models and analyses programs.

For a comprehension description of the DSSAT v3 Shell and its operation, see Part 3 of this Volume (Volume 1-3, Hunt et al 1994) .

Crop Models

The crop models in DSSAT v3 are new versions created by modifying models from DSSAT v2.1. The cereal crop models were basically integrated into one program referred to as the generic CERES model, and includes maize, wheat, sorghum, millet and barley. The rice model is a stand-alone model based on a CERES-Rice v2.1 conversion to v3 data files and formats. The grain legume models (SOYGRO, PNUTGRO, and BEAN-GRO) all operate using a generic grain legume model structure, called CROPGRO. The aroid and potato crop models have not yet been converted to the DSSAT v3 file and format structures. The cassava model uses the CROPSIM model structure, which is similar to the CERES models.

CERES

The five cereal models were combined to run with a single set of code by incorporating the development and growth sections from each individual model into a single module with a single soil component. This new module, called CERES, uses the DSSAT v3 input/output file structures and formats, and it is fully compatible with the graphics program, genetic coefficient calculator, and season analysis programs in v3. The input file for genetic coefficients, formerly referred to as GENETICS.MZ9 for maize, has been modified to adapt it to the genetic coefficient calculator program. The new genetic coefficient data file for maize is called MZCER940.CUL, to note that this file is for maize using the generic CERES model version 94-0. The genetic coefficients themselves have not been modified for the cereal crops, but their formats have been. Genetic coefficients for all cultivars in v2.1 have been converted and are available for simulation with the new crop model versions.

CROPGRO

The three grain legume models were also combined to operate under a single module, CROPGRO. In this new module, nitrogen components for the soil and plant system were added, including simulation of nitrogen uptake, fixation and mobilization. The crop carbon and nitrogen balance sections were restructured, and an option was added to simulate photosynthesis at the leaf level, using hourly time steps. Simulation of vegetative and reproductive development were modified, allowing more flexibility for defining the effects of temperature, photoperiod, drought and nitrogen stresses on development during the various soybean growth phases. Other new features include options to simulate the effect of a potential climate change on soybean growth and the effect of pest interactions on soybean productivity.

Evapotranspiration Calculations

In the CERES, CROPGRO and the other DSSAT v3 models, options exist for the Priestly-Taylor method for computing potential evapotranspiration, and for the Penman method using the FAO definitions of the wind term. The Priestly-Taylor method is the same as used by Ritchie (1985). The use of the Penman method requires daily humidity and wind speed data. The new weather file format includes columns for these data when they are available. When they are not available, users should select the Priestly-Taylor method.

Carbon Dioxide Effects

The new models have the capability to simulate the effects of CO_2 on photosynthesis and water use. Daily potential transpiration is modified by CO_2 concentration based on the effects of CO_2 on stomata conductivity (Peart et al., 1989). A multiplicative modification is made to daily canopy photosynthesis as described by Curry et al. (1988).

Climate Change Studies

The DSSAT v3 models have the capability to modify daily weather data that are read in from the weather file, as well as day length. Each weather variable can be modified, by multiplying a constant times the input value and/or adding a constant to it. This gives one the flexibility to change one or all weather variables and includes the capability to make them constant, as in constant environment experiments. Users can specify the date that a given modification is to begin, and can have more that one entry if the experiment included environment switching of any type. These options are available in FILEX for any experiment and are also available interactively during any model run.

Weather Generators

The new models have built-in capabilities for simulating weather using either one of two generators. Coefficients for generating weather are in *.CLI files, such as UFGA.CLI, where UFGA is the site of the weather station. One generator is SIMMETEO (Geng 1986) which requires only monthly averages of solar radiation, maximum and minimum temperatures, precipitation, and days with precipitation. This model then computes coefficients and uses the WGEN to simulate daily data. The second generator is WGEN (Richardson 1985), which requires more statistics which are computed from daily data from a number of years. This ability to simulate weather internally, using only monthly averages of variables will greatly expand the application of the models to areas where the monthly data are all that are available.

CROP ROTATIONS

An option in the models allows users to select whether to reinitialize soil variables after each run or to use ending conditions from one run as inputs to the next run. This allows for crop rotations to be studied in the new models, with carry over effects in the soil currently limited to crop residue, soil N, carbon and water with depth. A sequence model "driver" is available to run the different crops in sequence, including a fallow period between crops. Any number of years of a crop rotation can be simulated in multiple replications, as specified by the user. A sequence analysis program analyzes time trends and variability in crop performance of the sequences.

For a comprehension description of the DSSAT v3 crop models, see Volume 2-2 (Hoogenboom et al. 1994) of this book.

Appendix 6.2

Sunflower Model: Bo TST (A) 1997/98 season

Plant_Date	Har_date	NUL	LL	TEAW
15-01-98	12-05-98	300	200	100

DAP	P	P-R	Eo	CF	EoCF	G_s	ETW	FTEAW	FTEAW	SWB	SL	Dr	ETW
1	25.0	21.1	4.50	0.01	0.10	304	122.80	0.88	1.00	21.34	325.34	325.3	122.34
2	0.0	0.0	10.85	0.03	0.36		122.94	0.87	0.87	-1.76	326.80	326.8	123.80
3	0.0	0.0	7.38	0.04	0.44		123.80	0.88	0.88	-0.30	326.50	326.5	123.50
4	0.0	0.0	9.25	0.06	0.84		122.90	0.88	0.88	-0.87	325.80	325.8	122.83
5	1.4	1.4	7.59	0.12	0.94		122.83	0.88	0.88	0.77	325.70	325.7	123.70
6	0.2	0.2	9.06	0.16	1.44		123.70	0.88	0.88	-0.78	325.92	325.9	122.92
7	0.0	0.0	11.88	0.20	2.38		122.92	0.88	0.88	-1.56	324.33	324.3	121.33
8	0.0	0.0	12.28	0.23	2.87		121.33	0.87	0.87	-1.91	322.42	322.4	119.42
9	0.0	0.0	8.87	0.27	2.41		119.42	0.86	0.86	-1.58	320.84	320.8	117.84
10	3.0	3.0	8.83	0.31	2.14		117.84	0.86	0.75	0.86	321.71	321.7	118.71
11	0.0	0.0	12.17	0.35	4.24		118.71	0.85	0.85	-3.76	318.85	318.9	115.85
12	0.0	0.0	12.09	0.39	4.69		115.95	0.84	0.84	-2.97	315.88	316.0	112.88
13	0.0	0.0	9.72	0.42	4.11		112.90	0.82	0.82	-2.55	313.43	313.4	110.43
14	0.0	0.0	8.81	0.46	4.51		110.43	0.81	0.81	-3.74	310.69	310.7	107.69
15	0.0	0.0	8.51	0.50	5.22		107.69	0.59	0.59	-1.81	308.78	308.8	105.78
16	9.4	8.5	8.21	0.53	4.36		105.78	0.58	0.85	4.45	313.24	313.2	110.24
17	0.2	0.2	11.79	0.56	6.65		110.24	0.61	0.61	-3.83	309.41	309.4	106.41
18	0.0	0.0	11.80	0.60	7.08		106.41	0.58	0.58	-4.19	305.27	305.3	102.27
19	1.8	1.8	10.28	0.63	6.48		102.27	0.56	0.56	-2.03	303.24	303.2	100.24
20	0.0	0.0	11.80	0.66	7.84		100.24	0.55	0.55	-4.21	299.03	299.0	96.03
21	0.0	0.0	11.79	0.69	8.11		96.03	0.53	0.53	-4.28	294.75	294.8	91.75
22	0.0	0.0	11.79	0.72	8.44		91.75	0.50	0.50	-4.25	290.50	290.5	87.50
23	0.0	0.0	8.21	0.74	6.08		87.50	0.48	0.48	-2.93	287.57	287.6	84.57
24	0.0	0.0	8.40	0.77	6.44		84.57	0.46	0.46	-2.99	284.58	284.6	81.58
25	8.0	7.4	7.17	0.79	5.67		81.58	0.45	0.79	2.87	287.45	287.4	84.45
26	1.0	1.0	8.40	0.81	6.84		84.45	0.46	0.46	-2.17	285.27	285.3	82.27
27	7.2	7.0	8.30	0.84	6.94		82.27	0.45	0.72	2.00	287.27	287.3	84.27
28	10.0	8.0	8.40	0.86	7.19		84.27	0.46	0.82	1.06	290.33	290.3	87.33
29	0.0	0.0	10.09	0.87	8.83		87.33	0.48	0.48	-4.24	286.09	286.1	83.09
30	14.5	12.2	8.87	0.88	7.82		83.09	0.46	0.84	4.79	290.88	290.9	87.88
31	0.0	0.0	3.48	0.91	3.17		87.88	0.48	0.48	-1.53	289.35	289.3	86.35
32	0.0	0.0	11.52	0.92	10.47		86.35	0.47	0.47	-4.98	284.38	284.4	81.38
33	0.0	0.0	6.32	0.94	5.93		81.38	0.45	0.45	-2.66	281.71	281.7	78.71
34	83.0	66.2	4.15	0.95	3.95		78.71	0.43	1.00	64.21	345.92	345.9	142.92
35	10.0	8.0	2.00	0.96	1.93		142.92	0.79	1.00	7.00	352.97	353.0	149.97
36	0.0	0.0	0.28	0.97	0.28		149.97	0.82	0.82	-0.23	352.74	352.7	149.74
37	0.0	0.0	8.02	0.98	7.89		149.74	0.82	0.82	-6.46	346.28	346.3	143.28
38	0.0	0.0	4.63	0.99	4.59		143.28	0.79	0.79	-3.61	342.67	342.7	139.67
39	0.0	0.0	8.88	1.00	8.86		139.67	0.77	0.77	-6.29	337.35	337.4	134.35
40	0.0	0.0	11.13	1.01	11.22		134.35	0.74	0.74	-8.28	329.07	329.1	126.07
41	0.0	0.0	11.23	1.01	11.34		126.07	0.69	0.69	-7.88	321.19	321.2	118.19
42	0.0	0.0	10.94	1.02	11.14		118.19	0.65	0.65	-7.24	313.95	314.0	110.95
43	8.0	7.4	8.11	1.02	8.29		110.95	0.61	1.00	-0.14	313.81	313.8	110.81
44	0.0	0.0	3.88	1.03	3.87		110.81	0.61	0.61	-2.53	313.28	313.3	110.28
45	0.0	0.0	9.19	1.03	9.45		110.28	0.61	0.61	-2.09	311.18	311.2	108.18
46	0.0	0.0	9.06	1.03	9.32		108.18	0.59	0.59	-1.95	309.24	309.2	106.24
47	8.0	7.6	7.45	1.03	7.66		106.24	0.58	0.93	0.60	309.84	309.8	106.84
48	0.0	0.0	11.13	1.03	11.47		106.84	0.59	0.59	-6.73	303.11	303.1	100.11
49	0.0	0.0	11.23	1.03	11.58		100.11	0.55	0.55	-6.36	296.75	296.7	93.75
50	0.0	0.0	10.75	1.03	11.06		93.75	0.52	0.52	-5.70	291.05	291.1	88.05
51	0.0	0.0	10.94	1.03	11.23		88.05	0.48	0.48	-5.43	285.62	285.6	82.62
52	12.0	10.6	1.61	1.03	1.66		82.62	0.45	1.00	4.61	290.23	290.2	87.23
53	0.0	0.0	6.41	1.02	6.53		87.23	0.48	0.48	-4.61	285.81	285.8	82.81
54	24.0	20.3	1.80	1.02	1.82		82.81	0.45	1.00	18.41	304.02	304.0	101.02
55	0.0	0.0	11.64	1.01	11.78		101.02	0.56	0.56	-6.20	297.81	297.8	94.81
56	0.0	0.0	11.75	1.01	11.72		94.81	0.52	0.52	-5.90	291.92	291.9	88.92
57	0.0	0.0	10.94	1.00	10.95		88.92	0.49	0.49	-5.36	286.56	286.6	83.56
58	0.0	0.0	10.47	1.00	10.44		83.56	0.46	0.46	-4.79	281.78	281.8	78.78
59	0.0	0.0	9.53	0.99	9.44		78.78	0.43	0.43	-4.06	277.67	277.7	74.67
60	4.0	4.0	9.34	0.98	9.20		74.67	0.41	0.81	-0.70	276.98	277.0	73.98
61	0.0	0.0	10.19	0.98	9.98		73.98	0.41	0.41	-4.05	272.93	272.9	69.93
62	1.0	1.0	10.09	0.97	9.80		69.93	0.38	0.38	-2.78	270.18	270.2	67.18
63	0.0	0.0	10.38	0.96	10.00		67.18	0.37	0.37	-3.69	266.47	266.5	63.47
64	0.0	0.0	10.57	0.96	10.09		63.47	0.35	0.35	-3.52	262.95	263.0	59.95
65	0.0	0.0	10.57	0.95	10.01		59.95	0.33	0.33	-3.30	259.65	259.7	56.65
66	0.0	0.0	10.38	0.94	9.74		56.65	0.31	0.31	-3.03	256.62	256.6	53.62
67	0.0	0.0	8.40	0.93	7.80		53.62	0.29	0.29	-2.33	254.30	254.3	51.30
68	1.0	1.0	6.04	0.92	5.56		51.30	0.28	0.28	-0.57	253.73	253.7	50.73
69	3.0	3.0	5.88	0.91	5.40		50.73	0.28	1.00	2.40	256.13	256.1	53.13
70	0.0	0.0	7.29	0.90	6.56		53.13	0.29	0.33	-2.17	253.96	254.0	50.96
71	8.0	7.4	3.67	0.89	3.27		52.96	0.28	0.89	3.84	259.80	259.8	56.80
72	27.0	22.8	3.50	0.88	3.08		56.80	0.31	1.00	19.87	279.84	279.8	76.84
73	0.0	0.0	3.56	0.87	3.09		76.58	0.42	0.42	-1.29	278.29	278.3	75.29
74	0.0	0.0	4.34	0.86	3.76		75.29	0.41	0.41	-1.56	276.73	276.7	73.73
75	0.0	0.0	7.82	0.85	6.78		73.73	0.41	0.41	-2.74	273.99	274.0	70.99
76	0.0	0.0	2.82	0.84	2.47		70.99	0.39	0.39	-0.96	273.03	273.0	70.03
77	0.0	0.0	10.06	0.83	8.55		70.03	0.38	0.38	-3.20	269.82	269.8	66.82
78	0.0	0.0	9.16	0.82	7.52		66.82	0.37	0.37	-2.78	267.06	267.1	64.06
79	0.0	0.0	10.38	0.81	8.42		64.06	0.35	0.35	-2.97	264.09	264.1	61.09
80	0.0	0.0	10.16	0.80	8.16		61.09	0.34	0.34	-2.74	261.35	261.4	58.35
81	0.0	0.0	10.16	0.79	8.06		58.35	0.32	0.32	-2.58	258.77	258.8	55.77
82	0.0	0.0	10.28	0.78	8.02		55.77	0.31	0.31	-2.46	256.31	256.3	53.31
83	0.0	0.0	10.28	0.77	7.91		53.31	0.29	0.29	-2.30	254.00	254.0	51.00
84	0.0	0.0	10.00	0.76	7.58		51.00	0.28	0.28	-2.13	251.87	251.9	48.87
85	0.0	0.0	10.28	0.75	7.69		48.87	0.27	0.27	-2.06	249.81	249.8	46.81
86	0.0	0.0	9.34	0.74	6.88		46.81	0.26	0.26	-1.77	248.04	248.0	45.04
87	0.0	0.0	4.53	0.73	3.29		45.04	0.25	0.25	-0.81	247.22	247.2	44.22
88	0.0	0.0	5.83	0.72	4.18		44.22	0.24	0.24	-1.02	246.21	246.2	43.21
89	0.0	0.0	8.59	0.70	6.05		43.21	0.24	0.24	-1.44	244.77	244.8	41.77
90	0.0	0.0	10.06	0.69	6.94		41.77	0.23	0.23	-1.59	243.18	243.2	40.18
91	0.0	0.0	8.21	0.68	5.61		40.18	0.22	0.22	-1.24	241.94	241.9	38.94
92	0.0	0.0	10.06	0.67	6.73		38.94	0.21	0.21	-1.44	240.50	240.5	37.50
93	0.0	0.0	8.72	0.66	5.43		37.50	0.21	0.21	-1.33	239.18	239.2	36.18
94	0.0	0.0	8.48	0.65	5.53		36.18	0.20	0.20	-1.10	238.08	238.1	35.08
95	0.0	0.0	7.82	0.64	5.02		35.08	0.19	0.19	-0.98	237.10	237.1	34.10
96	0.0	0.0	8.82	0.63	5.57		34.10	0.19	0.19	-1.14	235.96	236.0	32.96
97	0.0	0.0	10.29	0.62	6.39		32.96	0.18	0.18	-1.13	234.83	234.8	31.83
98	0.0	0.0	8.81	0.61	5.04		31.83	0.17	0.17	-1.06	233.77	233.8	30.77
99	0.2	0.2	4.72	0.60	2.83		30.77	0.17	0.17	-0.28	233.46	233.5	30.44
100	8.0	7.4	5.69	0.59	3.12		30.40	0.17	0.44	6.11	238.61	238.6	35.61
101	0.0	0.0	8.81	0.58	5.65		35.61	0.20	0.20	-0.81	237.80	237.8	34.80
102	0.0	0.0	8.81	0.57	5.03		34.80	0.19	0.19	-0.97	236.83	236.8	33.83
103	0.0	0.0	5.53	0.56	3.13		33.83	0.19	0.18	-0.96	235.84	235.8	32.84
104	0.0	0.0	5.81	0.55	3.45		32.84	0.18	0.18	-0.88	234.87	234.7	31.87
105	0.0	0.0	5.81	0.54	3.30		31.87	0.17	0.17	-0.83	233.74	233.7	30.74
106	0.0	0.0	5.81	0.53	3.20		30.74	0.17	0.17	-0.88	232.87	232.9	29.87
107	0.0	0.0	5.81	0.52	3.11		29.87	0.16	0.16	-0.84	232.03	232.0	29.03
108	0.0	0.0	3.77	0.51	1.93		29.03	0.16	0.16	-0.31	231.72	231.7	28.72
109	0.0	0.0	4.72	0.50	2.37		28.72	0.16	0.16	-0.37	231.38	231.3	28.38
110	0.0	0.0	4.72	0.49	2.33		28.38	0.16	0.16	-0.36	230.98	231.0	27.98
111	0.0	0.0	3.77	0.48	1.83		27.98	0.15	0.15	-0.28	230.72	230.7	27.71
112	0.0	0.0	3.77	0.47	1.79		27.72	0.15	0.15	-0.27	230.43	230.4	27.43
113	0.0	0.0	4.25	0.47	1.99		27.43	0.15	0.15	-0.30	230.13	230.1	27.13
114	0.0	0.0	4.72	0.46	2.18		27.13	0.15	0.15	-0.32	229.81	229.8	26.81
115	0.0	0.0	3.20	0.45	1.46		26.81	0.15	0.15	-0.22	229.59	229.6	26.59
116	2.4	2.4	1.42	0.44	0.62		26.59	0.15	0.76	1.93	231.52	231.5	28.52
117	0.2	0.2	3.30	0.43	1.43		28.52	0.16	0.16	-0.02	231.49	231.5	28.49
118	0.0	0.0	3.30	0.42	1.40		28.49	0.16	0.16	-0.22	231.28	231.3	28.28
119	0.0	0.0	1.69	0.42	0.78		28.28	0.16	0.16	-0.12	231.15	231.2	28.15

SF

0.88

0.83

0.73

0.62

0.49

0.30

0.21

0.20

ISF 0.84

Yield 1716

Appendix 6.3

Measured and predicted sunflower yields (kg ha^{-1}) on four different ecotopes

Ecotope	Season	Treatment	Measured yield	Predicted yield
Sw	96/97	TST(A)	1540	1534
		WHB(A)	1751	2693
	96/97	TST(A)	2028	1458
		TSTM(A)	2281	1964
		WHB(A)	2462	1971
		WHBM(A)	2558	2059
	98/99	TST(A)	505	444
		TSTM(A)	617	621
		WHB(A)	661	996
		WHBM(A)	815	1123
		WHB(B)	1418	1075
		WHBM(B)	1571	119
Bo	96/97	TST(A)	1612	2076
		WHB(A)	1853	3224
	97/98	TST(A)	2098	1716
		TSTM(A)	2476	2087
		WHB(A)	2773	3106
		WHBM(A)	2806	3175
	98/99	TST(A)	594	404
		TSTM(A)	626	751
		WHB(A)	651	1345
		WHBM(A)	804	1472
		WHB(B)	1547	1466
		WHBM(B)	1561	1523

Appendix 6.3

Ecotope	Season	Treatment	Measured yield	Predicted yield
Ks	97/98	TST(A)	1216	1127
		WHB(A)	1734	2504
		WHBM(A)	1876	2578
	98/99	TST(A)	1096	1336
		WHB(A)	1260	1918
		WHBM(A)	1628	1978
		WHB(B)	1607	1925
		WHBM(B)	1658	1986
Va	97/98	TST(A)	2134	871
		WHB(A)	2835	2217
		WHBM(A)	2937	2252
	98/99	TST(A)	1045	1270
		WHB(A)	1588	2197
		WHBM(A)	1977	2248
		WHB(B)	1994	2197
		WHBM(B)	2581	2248