AN IRRIGATION MANAGEMENT TOOL
FOR
PROCESSING TOMATO PRODUCTION

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Report to the

WATER RESEARCH COMMISSION

DEPARTMENT OF PLANT PRODUCTION AND SOIL SCIENCE

UNIVERSITY OF PRETORIA

WRC Report No 646/1/01

ISBN: 1 86845 763X

May 2001

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EXECUTIVE SUMMARY

Background

This project, which was funded by the Water Research Commission, Langeberg Foods and the University of Pretoria, was aimed at the *maximisation of economic water use efficiency in processing tomato production.* A computer program, TOM-MAN, was developed as a prototype model with processing tomatoes as an example, and will eventually be incorporated in the SWB (Soil Water Balance) irrigation scheduling program which is currently under development by the University of Pretoria.

It is indisputably clear from numerous reports that irrigation management is the most important factor towards economic optimization of processing tomato production. *The most crucial decision about irrigation management for processing tomatoes is to decide on when and to what extent irrigation should be reduced in order to apply the right amount of stress.* This "right" amount of stress is not only a function of the physical situation, but is determined to a great extent by the economic situation as far as expected costs and benefits are concerned. In order to optimize economic water use efficiency for the processing tomato industry, the total cost of the global process (production as well as processing) should be minimised. In order to achieve this, the processor's quality based price for the producer's tomatoes, should be structured in a way that the farmer's profit is maximised at the yield/quality combination where the total cost of the global process is minimised. Producers need to be able to identify this optimum for their own situations and must then be able to manage the production system to achieve the target set. Optimization of this system requires integration of all variables and constants affecting the crop-soil-climate-irrigation-management system, as well as the economic situation of the producer and processor.

A modelling approach seemed to be the only practical way of integrating all the different variables into a single decision making process. Therefore, in order to facilitate this integration, a management tool in the form of a computer program was developed. The TOM-MAN program integrates the TOMYIELD crop growth model, which is based on SWB, and an economic optimization model, TOM-ECON, which was developed during this project.

Approach

In order to create a management tool which could be applied under a wide range of climatic and soil conditions, a mechanistic modelling approach was followed. Several growth analyses were conducted at various localities and during different seasons to generate data sets of growth and development as well as climate and the soil water balance. Data from some of the data sets were used to calculate input parameters during model development. The model was evaluated by running it with the calculated input parameters and the initial soil water content, rain, irrigation and weather data from the evaluation sites in the Western Cape Province and Northern Province. Simulated results of growth, development, yield and quality are compared to measured data to determine the accuracy of the model.

TOMYIELD differs from SWB mainly in its ability to simulate fresh yield and quality of processing tomatoes, as SWB only simulates dry matter yield of the different plant components. In order to simulate fresh yield and quality of processing tomatoes, procedures were developed for the following processes:

* loss and gain of fruit water;
* translocation of a portion of the dry matter from senesced leaves to fruits;
* partitioning of fruit dry matter to the various fruit components;
* fruit ripening;
* maintenance and climacteric respiration of fruits; and
* final fresh yield and percentage of soluble solids (brix).

Other modifications were also introduced to improve the accuracy of the simulation of growth and development, as well as the soil water balance procedure of SWB:

* improved simulation of seedling growth rate;
* influence of shading on the senescence rate of leaves;
* storage of assimilates in the leaves;
* changes in canopy structure during the season;
* hastening influence of water stress on ripening; and
* senescence rate.

Results

The structure and functioning of the model is described, with full details on all the modifications to SWB.

The input parameters needed to run TOMYIELD were established and evaluated. The model is evaluated by simulating the fresh yield, brix and water use of the Vredendal, Platskraal and Messina trials. The simulation of development rate according to thermal time was not sufficiently accurate to enable using a single set of thermal time parameters. Individual, site specific requirements were instead determined.

The water use efficiency, as well as the radiation extinction coefficient also varied between localities and individual parameters are recommended. Simulated versus measured data indicated that the following aspects were simulated fairly accurately:

* leaf area index;
* fractional interception of solar radiation;
* total and harvestable dry matter; and
* cumulative evapotranspiration and drainage.

The simulation of fresh yield and brix still needs attention, especially if the model is not calibrated for the area of use.

The function of TOM-ECON is to establish the desired irrigation strategy for processing tomatoes for application by TOM-MAN during routine scheduling. The user can define a set of potential irrigation strategies in terms of the allowable depletion levels of soil water during the different growth stages of the tomato crop. For each of these strategies a simulation of required irrigation and the resulting yield and quality is simulated by TOM-MAN.

TOM-ECON quantifies the costs of the TOMYIELD simulated inputs required for different strategies, as well as the income generated from the simulated outputs (yield and quality). In order to optimize a specific situation, the user can enter the cost of inputs and the applicable tomato price structure. Because TOM-ECON's simulation of the net benefit is based on TOMYIELD's simulation of the yield and quality, the accuracy of TOMYIELD's simulation is of utmost importance.

For the calculation of the total variable production cost, variable running costs and the cost of risk are calculated.

Net income is calculated per unit of land area, water, and the contracted tonnage of yield, in order to enable the user to select the optimum irrigation strategy according to the factor, which is most limiting to increased profits. The user selects the criteria (land, water or contract tonnage of yield) on which basis he would like to optimize net income. TOM-ECON will then sort the irrigation strategies, based on the selected criteria, in a descending order. The user then selects the best irrigation strategy from the sorted list, which is applicable to his particular situation. The selected strategy is then applied as the irrigation guideline for scheduling irrigation.

Application

TOM-MAN, as a management tool for the optimization of the production of processing tomatoes, can be applied to assist management of both producers and processing companies in the following respects:

* selection of optimal irrigation schedules by producers; and
* routine scheduling of irrigation.
* optimization of the price structure for processing tomatoes;

Conclusion

It is concluded that:

* Integration of an irrigation scheduling model and an economic optimization model is appropriate and feasible;
* Simulations of canopy development and dry matter production of processing tomatoes are fairly accurate;
* The simulation of the water balance is good and practical irrigation scheduling can be implemented with confidence; and
* The simulation of fresh yield and brix are not yet accurate enough and fine tuning of the parameters and/or a more mechanistic approach is required.

Further research needs

Various needs for further research have been identified during the project. The priority for further development is to enhance technology transfer through improved user friendliness and wider applicability to other crops through the establishment of model crop parameters.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission.

The Steering Committee, responsible for this project, consisted of the following persons:

Dr GR Backeberg	Water Research Commission
Dr GC Green	Water Research Commission
Prof H J Sartorius von Bach	University of Pretoria
Dr R P de Villiers	ARC: Vegetable and Ornamental Plant Institute, Roodeplaat
Mr F B Reinders	ARC: Institute of Agricultural Engineering, Silverton
Prof A Singels	University of the Orange Free State
Mr FPJ van der Merwe	ARC: Institute of Agricultural Engineering; Silverton
Mr R Schmidt	Tomato producer, Weipe
Mr F Prinsloo	Langeberg Foods (Pty) Ltd.
Mr A C Frits	Water Research Commission (Secretary)

The financing of the project by the Water Research Commission and Langeberg Foods and the contribution of the members of the Steering Committee is gratefully acknowledged.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to the following:

Producers on whose farms data sets were collected:

Mr Evert du Plessis (Marble Hall);
Mr Ludan Sieberhagen (Vredendal);
Messrs Jean and Samuel Aggenbach (Platskraal);
Mr Rudi Schmidt (Messina); and

Mrs Breitenbach and Mr Samuel Schmidt (Weipe).

Langeberg Foods for close co-operation with the planning and execution of the project and for their contribution towards the financing of the project.

The Department of Plant Production and Soil Science, University of Pretoria, for the use of their facilities and especially for the support of **Mr Johan de Beer** and **Mr Gene Beyers**.
Mr William Sefara for his dedication in conducting the Hatfield growth analysis.
Mr Kobus Le Roux for technical work.

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LIST OF ABBREVIATIONS AND SYMBOLS

a	-	Empirical parameter varying with salinity and cultivar
ActualTrsp	-	Simulated crop water use (mm d^{-1})
ADDgddi	-	Additional day degrees (d °C)
ADWC	-	Air dry water content (volumetric fraction)
b	-	Empirical parameter varying with salinity and cultivar
brix	-	Gravimetric percentage of soluble solids in fruits
BrixPrice	-	Brix based price per ton (R t^{-1})
BrixPriceMin	-	Minimum price for lowest brix (R t^{-1})
BrixPriceMax	-	Maximum price for highest brix (R t^{-1})
CanopyInt	-	Parameter indicating the maximum intercepted amount for a full canopy of the specific crop (mm)
CanopyWetted	-	Fraction of the canopy which is wetted during irrigation
ClimRr	-	Respiration rate during climacterium (g dry matter g^{-1} organ dry mass d^{-1})
CrateMass	-	Average mass of tomatoes in a picking crate (kg $crate^{-1}$)
CumETD	-	Cumulative evapotranspiration and drainage (mm)
CumIrrig	-	Cumulative simulated irrigation requirement (mm)
D	-	Willmot's index of agreement
DAP	-	Days after transplanting (d)
Daylength	-	Day length (hours)
DailyLAIAge[k]	-	Age of LAIAge group (d °C)
DailyLAIAge[k-1]	-	Age of the LAIAge group on the previous day (d °C)
$DailyLAI_k$	-	LAI which was grown on a specific day as demarcated by the counter k
Dday	-	Physiological day increment (physiological day) (d °C)
de	-	Maximum humidity deficit (g m^{-3})
DistDepot	-	Distance to the depot (km)
DM	-	Total dry mass of the organ (g)
dmi	-	Daily increment of assimilates produced (kg m^{-2})
dmis	-	Daily dry matter increment based on FI and air temperature (kg m^{-2})
dmiw	-	Daily dry matter increment based on soil water uptake (kg m^{-2})
DWR	-	Dry matter-water ratio (kPa)
dz	-	Depth of the evaporation layer (m)
E	-	Evaporation rate (g m^{-2} s^{-1})
ElecPriceIncrease	-	Factor by which unit electricity cost increased since previous season
EmDD	-	Emergence day degrees (d °C)
EndSeedlDDFrac	-	Ratio of day degrees at the end of seedling and day degrees at flowering
EndSeedlingDD	-	Day degrees until end of seedling growth stage (d °C)
Energy	-	Cost of energy converted to R m^{-3} irrigation (R m^{-3})

$FcWc_{Evap}$	-	Field water capacity of the evaporation layer (volumetric fraction)
FI	-	Fractional interception of radiation
FI_{evap}	-	Fractional interception for evaporation from the soil surface
FI_{Transp}	-	Fractional interception of solar radiation by green leaves
F_{fD}	-	Daily fruit dry matter increment (g cm^{-2} d^{-1})
FixedHDM	-	All HDM excluding SolHDM (kg m^{-2})
F_{fW}	-	Daily import rate of fruit water per unit fruit surface area (g cm^{-2} d^{-1})
FixHDMi	-	Daily increment of fixed fruit solids (kg m^{-2})
f_{fruit}	-	Fruit partitioning factor
FlDD	-	Cumulated thermal time units required for flowering (physiological day) (d °C)
f_{leaf}	-	Leaf partitioning factor
fr	-	Fraction of assimilates partitioned to roots
FreshYield	-	Fresh yield (t ha^{-1})
f_{root}	-	Root partitioning factor
f_{top}	-	Vegetative partitioning factor
F_{TW}	-	Daily fruit transpirational water loss (kg m^{-2})
FullFertCost	-	Cost for a tomato yield of 130 t ha^{-1} (R m^{-2})
GDD	-	Cumulated thermal time units (physiological day) (d °C)
GDD_{EJG}	-	Thermal time at the end of juvenile growth (d °C)
gddi	-	Growing day degrees increment (d °C)
GenIrrCost	-	Cost of general irrigation items converted to R m^{-3} irrigation (R m^{-3})
GenIrrPriceIncrease	-	Factor by which general irrigation cost increased since previous season
GpDD	-	Growth transition period parameter from flowering until the termination of leaf growth (d °C)
GpSensStress	-	Parameter representing the average reduction in GpDD on days with water stress (d °C Stress day^{-1})
GLA	-	Rate of increase in leaf area during juvenile growth (m^2 leaves m^{-2} land d^{-1})
GrossIncome	-	Total income per unit area (R m^{-2})
g_s	-	Surface conductance to water vapour (m s^{-1})
HDM	-	Harvestable dry matter (kg m^{-2})
hdmDissi	-	Daily increment of dissolved dry matter (kg m^{-2})
HDMDissFrac	-	Fraction of fixed dry matter which dissolves when NettHdmi < 0
hdmi	-	Daily harvestable dry matter increment of assimilates allocated to fruits (kg m^{-2})
hdmFixRate	-	Fraction of net import of solids which are fixed (kg m^{-2})
hdmRespi	-	Dry matter lost to respiration (kg m^{-2})
HeatBrixDropSens	-	Average drop in brix with untimely heat waves (brix)
HeatProb	-	Probability of a heat wave during ripening (fraction)
HWC	-	Harvestable (fruit) water content (gravimetric fraction)

HwcGainCoef	-	Average relative rate of water gain after relief of water stress (d^{-11})
hwci	-	Daily increment in future fruit water content (fraction)
HwcLossCoef	-	Average relative rate of water loss after relief of water stress
InitBrix	-	Parameter indicating the initial brix of tomatoes which were not stressed (brix)
InitSeedPeelFrac	-	Parameter indicating the initial fraction of fixed HDM that is part of seeds and peels (kg m^{-2})
$IrrInf_{Evap}$	-	Irrigation infiltrated into the evaporation layer (mm)
k	-	A counter indicating days after planting (d)
KC	-	Canopy extinction coefficient for solar radiation
$KC_{initial}$	-	Canopy extinction coefficient for solar radiation from transplanting until the change in canopy structure commences (stage when the first fruits ripen)
KC_{max}	-	Maximum canopy extinction coefficient for solar radiation
$KC_{modified}$	-	Modified canopy extinction coefficient for solar radiation due to changed canopy structure
LAI	-	Leaf area index
LAI_{avg}	-	Average leaf area during the period between measurements
LAI_{d-1}	-	LAI of previous day
LAI_k	-	Leaf area index on day k after planting (m^2 kg^{-2})
LAI_{EJG}	-	Leaf area index at the end of juvenile growth
LAIi	-	Leaf area index increment for the current day
LDM	-	Leaf dry matter (kg m^{-2})
ldmi	-	Leaf dry matter increment (kg leaf m^{-2} d^{-1})
LSPP	-	Leaf-stem partition parameter (m^2 kg^{-1})
m	-	Empirical parameter varying with salinity and cultivar (g cm^{-2} d^{-1})
MAE	-	Mean absolute error
MaxHWC	-	Average water content of tomatoes which were not stressed (fraction)
MaxInterDOY	-	Daily calculated maximum amount of water in mm that can be intercepted by the canopy (mm)
MaxIrrIntDOY	-	Daily calculated maximum amount of irrigation that can be intercepted by the canopy (mm)
MaxLeafAge	-	Maximum leaf age (d °C)
MaxYield	-	Maximum yield for processing tomatoes (t ha^{-1})
M_F	-	Fruit mass (kg m^{-2})
MinFertCost	-	Fertiliser cost for a tomato yield of 25 t ha^{-1} (R m^{-2})
MinHWC	-	Minimum fruit water content
MinYield	-	Minimum yield for processing tomatoes (t ha^{-1})
MRi	-	Daily maintenance respiration increment per organ (g d^{-1})
MRr	-	Daily respiration rate (g dry matter g^{-1} organ dry mass d^{-1})
MtDD	-	Maturity day degrees (d °C)
$MtDD_{NoStress}$	-	Day degrees at maturity for non-stressed tomatoes in the same trial (d °C)

$MtDD_{Stressed}$	-	Day degrees at maturity for stressed tomatoes (d °C)
MtSensStress	-	Parameter representing the average reduction in MtDD on days with water stress (d °C Stress day^{-1})
N	-	Number of observations
NettHDMi	-	Net daily harvestable dry matter increment (kg m^{-2})
NILand	-	Net income per square meter (R m^{-2})
NIWater	-	Net income per cubic meter of water (R m^{-3})
NIYield	-	Net income per ton of fresh yield (R t^{-1})
NMRi	-	Normal daily maintenance respiration for fruits (g d^{-1})
p	-	Empirical parameter varying with salinity and cultivar (g cm^{-3} d^{-1})
PAR	-	Photosynthetically active radiation
PAR_{above}	-	PAR above the canopy
PAR_{below}	-	Average PAR below the canopy
Payload	-	Mass of a truck load (kg)
PET	-	Potential evapotranspiration (mm d^{-1})
PickCost	-	Wage paid per crate (R $crate^{-1}$)
PotentialEvap	-	Potential evaporation from a completely wet soil surface (mm d^{-1})
PT	-	Potential transpiration (mm d^{-1})
PWC_d	-	Profile water content on day d (mm)
PWC_{d-1}	-	Profile water content on day d-i (mm)
PWPWC	-	Permanent wilting point water content (volumetric fraction)
$Q10_c$	-	Sensitivity to temperature
R	-	Fruit radius (cm)
r^2	-	Coefficient of determination
RainBrixDropSens	-	Average drop in brix with untimely rain (brix)
RainProb	-	Probability of rain during ripening (fraction)
RCHeat	-	Average cost of the risk of untimely heat waves during ripening (R m^{-2})
RCRain	-	Average cost of the risk of untimely rain during ripening (R m^{-2})
RD	-	Root depth (m)
RDM	-	Cumulative root dry matter (kg m^{-2})
RDmax	-	Maximum root depth (m)
RelGrwStg	-	Expired fraction of the development time towards maturity
RelHwcGainRate	-	Relative fruit water content gain rate (d^{-1})
RelHwcLossRate	-	Relative fruit water content loss rate (d^{-1})
RGR	-	Root growth rate (m^2 $kg^{-0.5}$)
RGR_{leaf}	-	Relative leaf growth rate (m^2 leaf increment m^{-2} existing leaf area $(°C\ d)^{-1}$)
RipeDD	-	Ripening day degrees (d °C)
$RipeDD_{NoStress}$	-	Day degrees at first ripening for non-stressed tomatoes in the same trial (d °C)
$RipeDD_{Stressed}$	-	Day degrees at first ripening (d °C)
RipenessFactor	-	Variable representing the fraction of fruits that are ripened

RipeningPeriod	-	Length of the ripening period (physiological days) (d °C)
RipeSensStress	-	Parameter representing the sensitivity for stress (d °C Stress day^{-1})
RMSE	-	Root mean square error
RUE	-	Radiation use efficiency (kg MJ^{-1})
s	-	slope of the linear regression
SDI	-	Mean stress day index (based on the matric potential of the soil)
SDM	-	Stem dry matter (kg m^{-2})
SeedPeelFrac	-	Fraction of net import fixed (kg m^{-2})
SeedPeelHDM	-	Harvestable dry matter of seeds and peels (kg m^{-2})
SeedPeelHDMi	-	Daily dry matter growth in seeds and peel (kg m^{-2})
SenesceRate	-	Leaf senescence rate (d^{-1})
$Senesci_k$	-	The senesced LAI increment of the LAI which was grown on a specific day as indicated by the counter k
ShadeSenesceCoef	-	Empirical constant parameter indicating the relationship between senescence rate and FI_{evap} (d^{-1})
SI	-	Stress index
SLA	-	Specific leaf area (m^2 kg^{-1})
SLACoef	-	Daily decrease in SLA during the season (m^2 kg^{-1} d^{-1})
SLA_k	-	Specific leaf area for day k (m^2 kg^{-1})
SLA_{k-1}	-	Specific leaf area for the day before day k (m^2 kg^{-1})
Solar	-	Total daily solar radiation (MJ m^{-2} d^{-1})
SolHDM	-	Soluble pool of harvestable dry matter (kg m^{-2})
SolHDMi	-	Daily soluble harvestable dry matter increment (kg m^{-2})
StressDays	-	Total number of days with SI $<$ 0.95 (Stress day)
SurfaceWetted	-	Fraction of the soil surface which is wetted by the irrigation and sideways movement of soil water in the evaporation layer
SWB	-	Soil Water Balance model
Tavg	-	Average daily temperature (°C)
Tb	-	Base temperature (°C)
Tcutoff	-	Temperature above which development rate is constant (°C)
TDM	-	Total dry matter (kg m^{-2})
Tfact	-	Factor indicating temperature effect on dmis
T_{lo}	-	Light limited optimum temperature (°C)
Tmin	-	Minimum temperature (°C)
Tn	-	Long term average daily minimum temperature (°C)
Topt	-	Optimum temperature (°C)
TotCumIrrig	-	Total cumulated irrigation for all fields during the previous season (m^3)
TotElectBill	-	Total electricity cost for all fields during the previous season (R)
TotI	-	Total irrigation for the period from day d-i to d (mm)
TotP	-	Total precipitation for the period from day d-i to d (mm)
TotRiskCost	-	Total risk cost due to untimely rain and/or heat waves (R m^{-2})
TotVarProdCost	-	Total variable production cost (R m^{-2})
TotVRC	-	Total variable running costs (R m^{-2})

CHAPTER 1

INTRODUCTION

Irrigation management has a direct influence on the production and processing cost of factory tomatoes. This is due to the fact that irrigation costs and yields are increased by increased irrigation, whilst quality in terms of total soluble solids (TSS), measured in degrees brix, is lowered. The lowered quality results in an increase in processing cost due to an increased amount of water that has to be evaporated off during processing and the additional processing capacity taken up by the increased mass of fresh tomatoes that has to be processed per ton of paste.

In order to optimize the economic water use efficiency for the processing tomato industry, the total cost of the global process (production as well as processing) should be minimised. In order to achieve this, the quality based fruit price should be structured in a way that maximizes the producer's profit at that yield/quality combination where the total cost of the global process is minimised. For the producer to strive towards the optimum yield/quality combination, he must be able to identify this optimum for his specific circumstances and must then be able to manage the production system to achieve the set target.

There are three problems in the industry which need to be addressed in order to enable the optimization of water use efficiency of processing tomatoes:

* The price structure is not perceived by producers to optimize their profits at the yield/quality combination that is promoted by processors;
* Producers need a procedure or "tool" for determining the optimum yield/quality combination; and
* Producers need a management "tool" to enable them to manage or schedule the irrigation towards achieving the set yield/quality targets.

The aim of the project was to *maximise the economic water use efficiency of processing tomato production* by creating an irrigation management tool (the TOM-MAN computer

program) for processing tomatoes.

TOM-MAN can be used for determining optimum target yield and quality which is mainly influenced by irrigation management and for the scheduling of irrigation towards achieving the targets set. A modelling approach is followed in order to create a mechanistic tool which will be applicable under a wide range of conditions.

The program, TOM-MAN, is basically an irrigation scheduling tool, based on SWB (Soil Water Balance) as described by Benadé, Annandale & Van Zijl (1995). TOM-MAN consists of two sub-models namely:

* TOM-YIELD, which simulates the growth and development of processing tomatoes, as well as the soil water balance; and
* TOM-ECON, which applies a cost benefit analysis to determine the optimum irrigation schedule.

In order to apply the cost benefit analysis, both the costs (water use) and benefits (yields and quality) of the crop need to be simulated and therefore the following objectives had to be achieved:

* To simulate the growth and development of the crop;
* To simulate the soil water balance; and
* To quantify the costs and benefits of different irrigation schedules.

TOM-MAN is developed as a prototype model with processing tomatoes as an example. The model will be incorporated in the SWB irrigation scheduling program which is currently under development by the University of Pretoria. In its final form the technology will be transferred to the tomato producers through the extension services of Langeberg Foods and/or through the services of irrigation scheduling consultants. Initially the program will probably be applied by only a few producers on limited areas until confidence is gained in its performance. Apart from being transferred to the tomato industry, the technology will also be useful to producers of all other crops, once the input parameters are established.

CHAPTER 2

LITERATURE REVIEW

One of the main problems in the tomato industry is that there seems to be conflict between the interests of producers and processors. This conflict originates from the negative correlation between yield and quality of factory tomatoes (Rudich, Klamar, Geizenberg & Harel, 1977; Sanders, Hile, Hodges, Meek & Phene, 1989; May, Walcott, Peters & Grimes, 1990; Mitchell, Shannon, Grattan & May, 1991; Sefara, 1994; Dumas, Leonie, Portas & Bièche, 1994). The typical relationship between yield and quality is demonstrated in Figure 2.1.

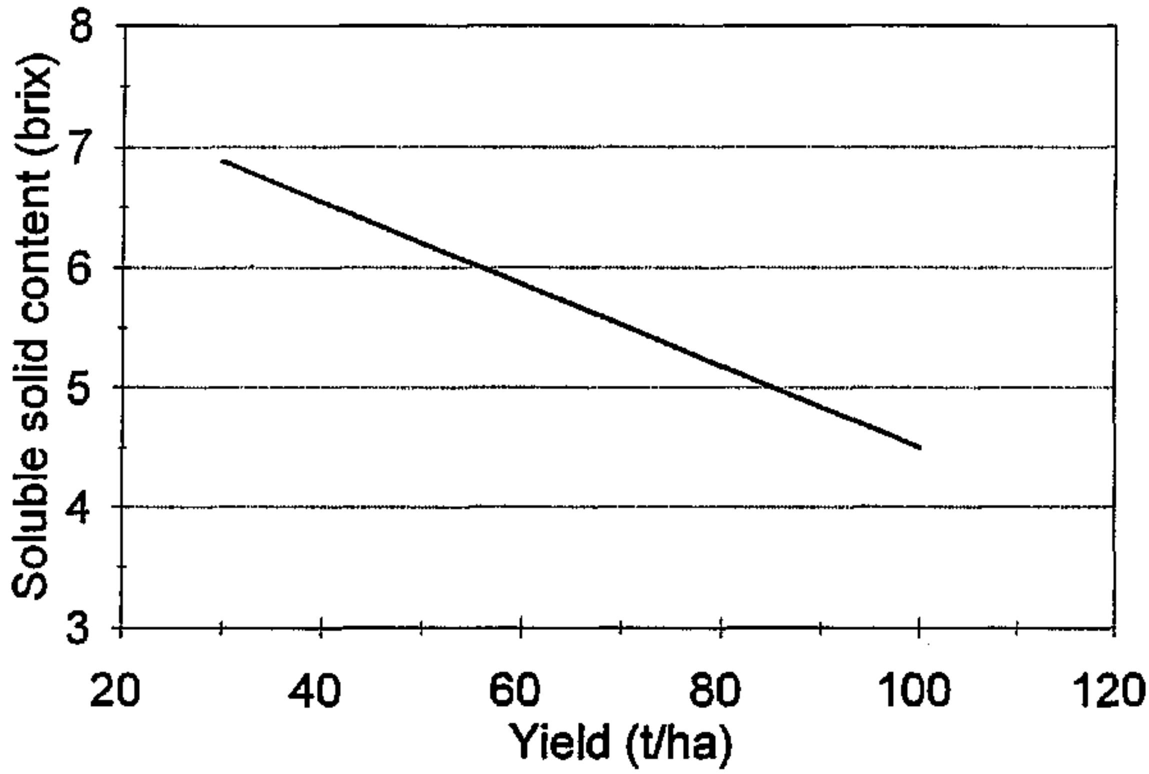


Figure 2.1 The typical relationship between yield and quality (brix) of processing tomatoes according to Mitchell *et al.* (1991).

Higher yields are normally associated with higher yields of total soluble solids per hectare and are produced by applying high irrigation levels (Dumas *et al.*, 1994). With a constant price the producer's production cost per ton of fresh tomatoes is at it's lowest with high yields. According to producers, profits are maximised at high yield levels and therefore they tend to ignore processor's requests for improved quality, unless higher prices are offered. The costs of the processor, on the other hand, are high with high yields per ha, due to the fact that the paste yield (tons of paste per ton of fresh tomatoes) is low and more water has to be evaporated off during processing. Processing costs are therefore increased at high yields per hectare due to the additional tomatoes purchased and transported, additional energy consumed during processing and additional processing capacity taken up by low brix tomatoes.

Payments based on quality are considered to be the best way of stimulating the production of high quality tomatoes (Dadomo, 1994; Dumas *et al.*, 1994). When a quality based price scale was introduced by Langeberg Foods in South Africa in 1994, with an increase of R 20.00 per degree brix, it was insufficient to convince growers to improve quality. The same occurred after the price was revised for the 1995 season to increase the premium to R 45.00 per degree brix. This indicates the complexity of the need for a compromise between producers and processors. This apparent conflict should be solved by minimizing costs per ton of paste for the industry as a whole. This can be done by structuring the price in such a way that the producer's profit is maximised at the same yield/quality combination which minimises total cost for the industry.

Numerous authors report on management strategies aimed at optimizing water use efficiency and profits (Rudich *et al.*, 1977; Alvino, Frusciante & Monti, 1980; Bar-Yosef & Sagiv, 1982; Giardini & Borin, 1990; Hedge & Srinivas, 1990; Mitchell *et al.*, 1991; Sefara, 1994; Baselga Yrissary, Prieto Losada & Rodriguez Del Rincon, 1993; May, 1993; Dadomo, 1994; Dumas *et al.*, 1994). From these reports it is indisputably clear that irrigation management is the most important factor towards the economic optimization of processing tomato production. Another factor reported on in many of these studies is nitrogen fertilisation. May (1993) summarises the influence of nitrogen on yield and quality as being variable and debatable, but usually of little importance. According to May (1993) the influence of fertilisation is normally seen only when nutrients are lacking or not well balanced. This is confirmed clearly by Dumas *et al.* (1994). It is clear from the reports referred to that water stress reduces yield and improves quality. Moderate stress increases viscosity significantly but severe stress leads to unacceptably high viscosity. Maximum benefit is achieved with moderate stress, but this optimum level of stress is not easily quantified. *The most crucial decision about irrigation management for processing tomatoes is to decide on when and to what extent irrigation should be reduced in order to apply the right amount of stress* (Rudich *et al.*, 1977).

The problem with optimum timing and level of water stress is summarized in the statement of May (1993): " *Not knowing the relative economic value of each factor* (fresh yield, solids yield, soluble solids yield and viscosity), *it is impossible to determine the best combination of yield and quality* (managed by stress) *to suit both growers and processors.*" This statement refers to the economic values of inputs and outputs of the production and processing system which influence decisions. Another problem which complicates decisions, is the variation in space and time in the production systems, which makes it impossible to come up with recipes like cut off dates for irrigation. An example of these types of recommendations is found in Dumas *et al.* (1994): *"The cut-off must occur between 10 and 50% fruit maturity, depending on the soil, type of planting, the variety, the climate and the irrigation technique adopted."* The problem seems to be that there are numerous variables, differing with location, climate, season, soil type, cultivar, price structure, input costs, etc., which have to be integrated in order to optimize decisions.

A modelling approach seems therefore, to be the only practical way of integrating all the different variables into the decision making process. *It was decided to develop a simulation model as a management tool in order to integrate the technical and economic variables into a real time decision making tool with which the production of processing tomatoes can be optimized.* This aim implies that in order to maximise net benefit, all the inputs (irrigation requirements) and outputs (yield and quality) must be simulated for the quantification of costs and income. The most important requirements for the model were:

* accurate simulation of crop water use and soil water balance, because water availability or stress is a prominent factor in growth, development, yield and quality;

* accurate simulation of growth and development as well as the fresh yield and quality of processing tomatoes, which influences water use;
* to optimize irrigation strategies economically by calculating the net benefit of different irrigation strategies; and
* in order to be able to apply the model to a wide range of circumstances, it should be mechanistic.

Three existing tomato models and a soil water balance model of particular interest were found:

* TOMSIM (Van Laar, Goudriaan & Van Keulen, 1992);
* TOMGRO (Dayan, Van Keulen, Jones, Zipori, Shmeul & Challa, 1991);
* TOMMOD (Wolf, Rudich, Marani & Rekah, 1986); and
* NEWSWB (Annandale, Campbell, Olivier & Van der Westhuizen, 1994).

Both TOMSIM and TOMGRO simulate the growth and development of table tomatoes for conditions of unlimited water supply in plastic tunnels. Neither of these models nor TOMMOD simulates water use. All the models use a thermal time approach to simulate development rate. Both TOMSIM and TOMGRO simulate only dry matter accumulation in the different organs, while fresh yield and quality are not simulated. TOMMOD only simulates development rate of processing tomatoes from seeding to harvest. NEWSWB, on the other hand, was developed as a generic crop, soil water balance model. Although some empiricisms are used, the soil water balance, soil water uptake, and crop growth and development are mostly simulated mechanistically. Like the other models, only dry matter production of different plant components is simulated. It was decided to base the development of the new model TOM-MAN on NEWSWB.

Simulation of crop water use and the soil water balance

NEWSWB simulates water uptake based on the most limiting of water supply from the soil and evaporative atmospheric demand. The water balance is simulated through either the standard cascading (tipping bucket) soil water balance procedure or a one-dimensional matric flux potential finite difference solution of the water flow equations. The simulation of crop water uptake and the soil water balance has been evaluated and was found to be accurate (Annandale *et al.*, 1994). The fact that a mechanistic modelling approach is followed enables the application of the model to a wide variety of conditions.

Simulation of the growth, development, fresh yield and quality of processing tomatoes

Both TOMSIM and TOMGRO simulate the growth and development of table tomatoes for conditions of unlimited water supply in plastic tunnels. Both of these models simulate dry matter accumulation in the different organs only, while fresh yield and quality are not simulated (De Koning, 1994; Jones, Dagan, Allen, van Keulen & Challa, 1991). These models are very complex and simulate the processes of photosynthesis, respiration and dry matter accumulation per truss for indeterminate varieties.

Fruit growth and development of processing tomatoes were studied from numerous reports (Walker & Ho, 1976; Walker & Thornley, 1976; Ho, 1979; Dinar & Stevens, 1981; Ho & Hewitt, 1986; Ho, Grange & Picken, 1986; Wolf & Rudich, 1987; Ho, 1988), and are summarised as follows.

Simulation of development rate

One of the most important aspects of simulating crop growth is the correct simulation of development rate as this strongly influences assimilate partitioning. The use of linear thermal time is applied with varying success for processing tomatoes. Austin & Ries (1968) and Warnock (1970) concluded that their simulations based on thermal time were worse than empirical calendar time estimates, while Wolf *et al.* (1986), Warnock & Isaacs (1969) and Calado & Portas (1987) reported in favour of the use of the thermal time approach. From these reports it is concluded that the thermal time approach can be applied in the simulation of development rate of processing tomatoes.

Wolf *et al.* (1986) developed TOMMOD which simulates development rate of processing tomatoes from seeding to harvest. According to Wolf *et al.* (1986) the varying accuracy resulting from the use of the approach is due to the following factors:

- the possibility of different base temperatures for different development stages;
- the hastening influence of low night temperatures on flowering;
- the non-linear influence of high average daily temperatures on development rate; and
- the accelerating influence of water stress on development rate.

The simulation procedures used in the TOMMOD model will be described below.

Different base temperatures for different development stages

Wolf *et al.* (1986) used different base temperatures for different development stages. From emergence to first flowering a temperature of 8 °C was used while 10 °C was used from flowering to harvesting.

The hastening influence of low night temperatures on flowering dates

During the period before flowering starts the initiation of flowering is hastened if the daily minimum temperature falls below 15 °C. This is done by adding additional day degrees to the normally calculated day degrees according to Eq. 2.1.

If Tmin < 15 °C then

ADDgddi - 0.25 * (Topt - Tb) 2.1

where:	Tmin	-	Minimum temperature (°C)
	ADDgddi	-	Additional day degrees (d °C)
	Topt	-	Optimum temperature (°C)
	Tb	-	Base temperature (°C)

(Note that gddi stands for daily growing day degrees increment)

The non-linear influence of high average daily temperatures on development rate

During the reproductive stage, for days with average temperatures above 20 °C, a quadratic equation (Eq. 2.2), instead of the normal linear equation is applied in order to calculate the accumulated thermal time units at high temperatures (GDD). According to this approach, the daily increment of day degrees (Dday) reaches a maximum value at 26 °C.

If GDD > FIDD and Tavg > 20 °C then

Dday = (6.0304 + 0.5408 * Tavg - 0.0104 *Tavg^2) * Daylength/24 ..... 2.2

where:	GDD	-	Cumulated thermal time units (physiological day) (d °C)
	FIDD	-	Cumulated thermal time units required for flowering (physiological day) (d °C)
	Dday	-	Physiological day increment (physiological day) (d °C)
	Tavg	-	Average daily temperature (°C)
	Daylength	-	Day length (hours)

A physiological day is defined as a day with an average temperature equal to the optimum temperature and can be converted to day degrees by multiplication by the difference between the base temperature and the optimum temperature.

In NEWSWB the calculation of thermal time is calculated according to Eqs. 2.3 to 2.5.

If Tavg < Tb then gddi = 0 .... 2.3

If Tb <Tavg < Tcutoff then gddi = Tavg - Tb 2.4

If Tavg > Tcutoff then gddi = Tcutoff - Tb 2.5

where:	Tcutoff	-	Temperature above which development rate is constant (°C)
	gddi	-	Growing day degrees increment (d °C)

The daily gddi was calculated according to the procedures of TOMMOD and also NEWSWB for an optimum temperature of 26 °C and a Tb of 10 °C. The equations (Figure 2.2) indicate that the TOMMOD procedure results in an increased day degrees increment for temperatures between 20 °C and Topt. This increased thermal time is not supported by Wolf *et al.* (1986) nor by any other information at our disposal and is therefore not accepted. Apart from this the calculations are very similar, and therefore the procedure of NEWSWB is accepted.

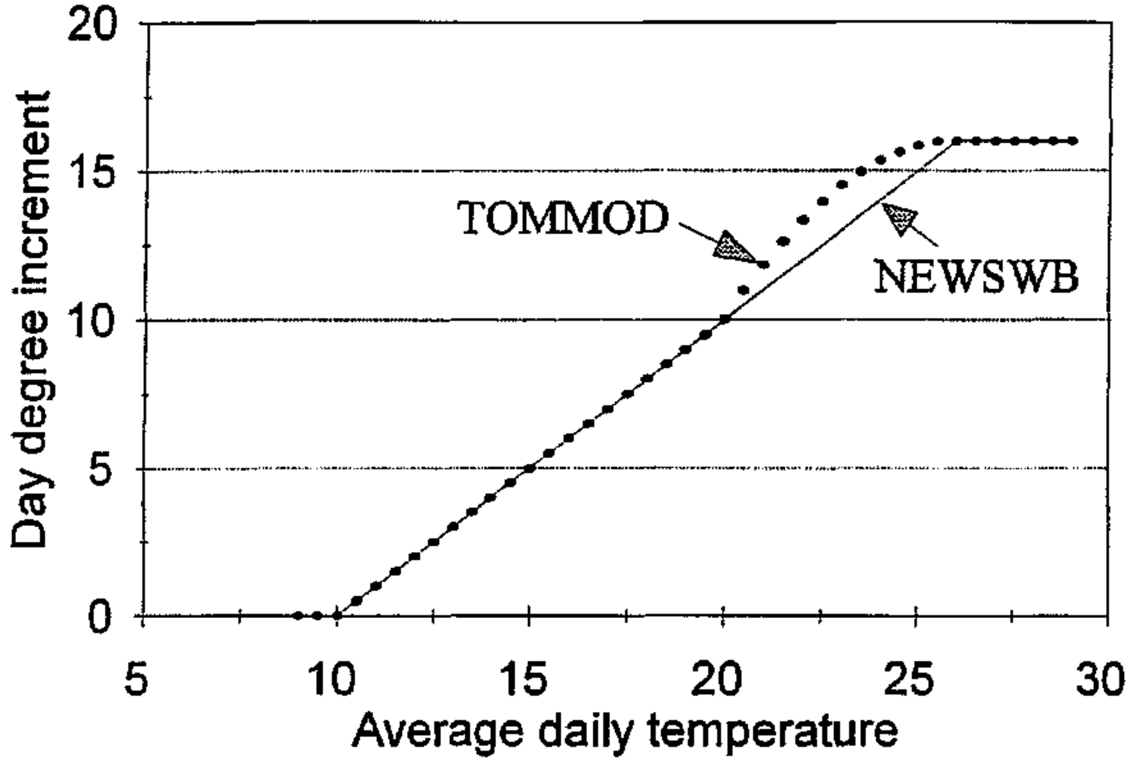


Figure 2.2 The simulation of thermal time increments by TOMMOD and NEWSWB.

The accelerating influence of water stress on development rate

In TOMMOD the ripening period is shortened according to Eq. 2.6 if water stress occurs once ripening has commenced.

If ripening commenced and water stress occurs then

RipeningPeriod = 31.017 - 5.958 * SDI 2.6

where: RipeningPeriod - Length of the ripening period (physiological days) (d °C)

SDI - Mean stress day index (based on the matric potential of the soil)

(Note that the constant with a value of 31.017 is actually the amount of physiological days required for a ripening period without water stress, while the reduction of thermal time per day of water stress is represented by the slope of -5.958).

This equation simulates the effect of the mean water stress during the ripening period, while the effect of daily stress is required for a real time model. The use of soil matric potential to simulate plant water stress is also very empirical. The stress index (SI) as simulated on a daily basis according to Eq. 2.7 in NEWSWB is much more mechanistic and therefore more suitable for real time modelling of the influence of water stress on the shortening of the ripening period. The procedure developed will be discussed in more detail in Chapter 6.

SI = ActualTrsp / PT 2.7

where: ActualTrsp - Simulated crop water use (mm d^{-1})
PT - Potential transpiration (mm d^{-1})

From the literature reviewed, it is concluded that the thermal time approach holds for processing tomatoes. The thermal time procedures of NEWSWB are acceptable, but could be modified to simulate the influence of low temperatures before flowering and of water stress after ripening on the length of the ripening period.

Assimilate production

TOMSIM simulates growth during the seedling stage separately from the simulation for the remaining development stages, while NEWSWB and TOMGRO use only one procedure for all stages. TOMSIM's procedures are described below.

Assimilate production during seedling growth

According to TOMSIM (Van Laar *et al.*, 1992) temperature is the overriding factor in regulating juvenile growth rate as the rate of leaf appearance and final leaf size are constrained by temperature through its effect on cell division and extension, rather than by the supply of assimilates. The juvenile stage, during which leaf area increases exponentially over time, applies until leaf area index (LAI) exceeds 0.75 and/or when accumulated growing day degrees exceed three tenths of the required thermal time for flowering. The exponential leaf area growth rate is described for a daily time step in

Eq. 2.8.

$$\mathbf{GLA = LAI_{d-1} * [\,exp\,(RGR_{leaf} * gddi) - 1\,]} \quad \text{.......................} \quad 2.8$$

where: GLA - Rate of increase in leaf area during juvenile growth (m^2 leaves m^{-2} land d^{-1})

RGR_{leaf} - Relative leaf growth rate (m^2 leaf increment m^{-2} existing leaf area (°C d)$^{-1}$)

LAI_{d-1} - LAI of previous day

The parameter RGR_{leaf} is determined according to Eq. 2.9 and a value of 0.009 (d °C)$^{-1}$ is used in TOMSIM.

$$\mathbf{RGR_{leaf} = LAI_{EJG} / GDD_{EJG}} \quad \text{..............................} \quad 2.9$$

where: LAI_{EJG} - Leaf area index at the end of juvenile growth

GDD_{EJG} - Thermal time at the end of juvenile growth (d °C)

The daily increment in assimilates is calculated according to Eq. 2.10.

$$\mathbf{ldmi = GLA / SLA} \quad \text{....................................} \quad 2.10$$

where: SLA - Specific leaf area (m^2 kg^{-1})

ldmi - Leaf dry matter increment (kg leaf m^{-2} d^{-1})

<u>Normal assimilate production</u>

In NEWSWB the daily production of assimilates is a function of plant water uptake (Eq. 2.11), as well as a function of intercepted solar radiation and temperature (Eq. 2.12). The smaller of the two is accepted by NEWSWB as the actual assimilate produced:

$$\mathbf{dmiw = ActualTrsp * DWR / VPD} \quad \text{.........................} \quad 2.11$$

where: dmiw - Daily dry matter increment based on soil water uptake (kg m^{-2})

DWR - Dry matter-water ratio (kPa)

VPD - Average daily vapour pressure deficit (kPa)

$$\mathbf{dmis = Tfact * RUE * FI_{Transp} * Solar} \quad \text{......................} \quad 2.12$$

where: dmis - Daily dry matter increment based on FI and air temperature (kg m^{-2})

Tfact	-	Factor indicating temperature effect on dmis
RUE	-	Radiation use efficiency (kg MJ^{-1})
FI_{Transp}	-	Fractional interception of solar radiation by green leaves
Solar	-	Total daily solar radiation ($MJ\ m^{-2}\ d^{-1}$)

If Tavg > T_{lo} then Tfact = 1

If T_{lo} > Tavg > Tb then Tfact = (Tavg - Tb) / (T_{lo} - Tb)

If Tavg < Tb then Tfact = 0 . . . . 2.13

where: T_{lo} - Light limited optimum temperature (°C)

For average daily temperatures above T_{lo}, temperature does not limit dry matter production and Tfact equals one. For average daily temperatures below T_{lo}, however, temperature limits dry matter production and Tfact is reduced linearly to zero at and below the base temperature (Tb). Because the assimilate production procedure in NEWSWB takes the possibility of limitations in the atmospheric evaporative demand, soil water supply, solar radiation and low temperatures into account, it is preferred above that of Spitters, van Keulen & van Kraalingen (1989).

Assimilate partitioning

In TOMSIM and TOMGRO, which simulate the growth and development of indeterminate tomato cultivars, assimilates are partitioned according to the relative sink strengths of the different organs. According to Heulevink & Bertin (1994) this approach is essential with the relatively complex partitioning of indeterminate cultivars, whilst the use of empirical partitioning factors is acceptable for determinate growers. It is expected therefore, that the partitioning of assimilates of processing tomatoes, which are determinate growers, will be simulated reasonably well by NEWSWB. The partitioning of assimilates by NEWSWB is described in Chapter 6.

Simulation of fresh yield

Fresh yield accumulation is due to the increase in fruit dry mass and water content. Fruit water is imported through the xylem and is lost by transpiration through the peel. Dry matter is imported from leaves in the form of soluble sugars (mainly sucrose). During metabolic processes the soluble dry matter is fixed into insoluble substances in the paste or into seed and peel components. Respiration causes a loss of soluble dry matter because the soluble sugars are the main substrate for respiration. Dry matter in fruits can be considered to be in one of three pools, namely:

* soluble dry matter;
* fixed dry matter in the paste; and
* seed and peel dry matter.

Bussières (1994) simulated the increment of fresh yield for the second phase of fruit growth only. His simulation is based on the following:

* Daily fresh yield increment includes daily water and dry matter increments;
* The daily water increment includes daily water import and loss; and
* The daily dry matter increment is the difference between the daily import of assimilates and the daily loss of assimilates due to respiration.

Fruit water loss is simulated as a linear function of fruit mass according to Eq. 2.14. This approach suggests that fruit water loss is a function of fruit water supply and that atmospheric evaporative demand is not a limiting factor.

$$F_{TW} = 0.012 * M_F \qquad 2.14$$

where: F_{TW} - Daily fruit transpirational water loss (kg m^{-2})

M_F - Fruit mass (kg m^{-2})

Fruit water import is simulated as a function of fruit surface area according to the linear function in Eq. 2.15.

$$F_{IW} = m - p*R \qquad 2.15$$

F_{IW} - Daily import rate of fruit water per unit fruit surface area (g cm^{-2} d^{-1})

m - Empirical parameter varying with salinity and cultivar (g cm^{-2} d^{-1})

p - Empirical parameter varying with salinity and cultivar (g cm^{-3} d^{-1})

R - Fruit radius (cm)

The import of assimilates is simulated as a function of water import according to Eq. 2.16 and this suggests that sink strength or fruit size, indicated by the radius (R) in Eq. 2.15 is the only limiting factor.

$$F_{ID} = a * F_{IW} - b \quad \ldots \quad 2.16$$

where: F_{ID} - Daily fruit dry matter increment (g cm^{-2} d^{-1})

a - Empirical parameter varying with salinity and cultivar

b - Empirical parameter varying with salinity and cultivar

It should be noted that in this research by Bussières (1994) the influence of salinity on fruit growth was studied and that the influence of water stress as caused by salinity, is simulated using the empirical parameters m, p, a and b.

This approach is not acceptable because the influence of supply and demand of water is simulated too empirically. Water loss from any evaporating surface is known to be a function of evaporative demand and water supply at the surface. The water loss rate will therefore decrease with either a decreased evaporative demand or a reduced fruit water content, which will result in a decreased osmotic potential of the fruit sap. The decreased osmotic potential of fruit sap will lower the difference in vapour pressure between the evaporating fruit surface and the atmosphere. The rate of import of fruit water on the other hand will be influenced by the water supply to the plant as well as the evaporative demand.

Jones & Higgs (1982) simulated the water loss from apple fruits mechanistically according to Eq. 2.17.

$$E = 2.36 * g_s * de * 10^4 \quad \ldots \quad 2.17$$

where: E - Evaporation rate (g m^{-2} s^{-1})

g_s - Surface conductance to water vapour (m s^{-1})

de - Maximum humidity deficit (g m^{-3})

The surface conductance of the apples decreased from about 1 m s^{-1} to less than 0.1 m s^{-1} over time during the season. No detailed information was found on a change in the surface conductance for water of tomato peels and therefore it was assumed that a similar decrease in surface conductance would occur with tomatoes. This assumption should be investigated in the future.

An empirical approach was applied to simulate water import and loss as a function of current fruit water content, maximum and minimum allowable water contents, stress index and the development stage of the crop. This procedure is described in Chapter 6.

Fruit maintenance respiration and the climacterium

NEWSWB does not simulate maintenance respiration explicitly, and therefore reductions in fruit dry matter under conditions where respiration rate exceeds assimilate import rate cannot be simulated. A clear decrease in both total dry matter and harvestable dry matter (HDM) was measured in the growth analysis trials towards maturity (Chapter 4). Both TOMGRO and TOMSIM simulate maintenance respiration of tomato roots, stems, leaves and fruits separately according to Eq. 2.18. This procedure has been incorporated in TOMYIELD in order to simulate maintenance respiration of fruits only.

$$\mathbf{MRi = MRr * DM * Q10_c * exp\,(0.01 * (Tavg - T_{ref}))} \quad \ldots\ldots\ldots\ldots \quad \mathbf{2.18}$$

where:

MRi	-	Daily maintenance respiration increment per organ ($g\ d^{-1}$)
MRr	-	Daily respiration rate (g dry matter g^{-1} organ dry mass d^{-1})
DM	-	Total dry mass of the organ (g)
$Q10_c$	-	Temperature sensitivity to respiration (Spitters *et al.*, 1989, in Bertin & Heuvelink, 1993) (Q_{10c}= 2 in TOMSIM and 1.4 in TOMGRO, i.e. respiration doubles in TOMSIM and increases by 40% in TOMGRO with every 10 °C increase in temperature)
T_{ref}	-	Q10c reference temperature (°C)

In TOMSIM and TOMGRO the coefficients are assumed to be constant. Although maintenance respiration per unit of biomass is likely to decrease with crop size (Ho & Hewitt, 1986; Grierson & Kader, 1986; McGlassen, 1976), there is according to Bertin & Heuvelink (1993) no quantitative basis for the introduction of this effect in TOMSIM and TOMGRO. According to Ho & Hewitt (1986) the respiration rate falls from 0.5 mg CO_2 g^{-1} fresh weight h^{-1}

in a two week old fruit to 0.06 mg $g^{-1} h^{-1}$ in a mature green fruit just prior to the onset of the climacterium. This decreasing trend is also shown by McGlassen (1976), as reported by Nevins & Jones (1986), to be a reduction of around 50% from that soon after fruit initiation until just before ripening commences. It is concluded that the downward trend in maintenance respiration rate should be simulated as a function of fruit development stage and that the maintenance respiration rate should decrease to between 10 and 50% of its initial value.

The climacterium is a sudden increase and then subsequent decrease in respiration rate which starts with the onset of ripening. According to Grierson & Kader (1986) the climacterium is the result and not the cause of ripening because non-climacteric crops do not show this behaviour during ripening. During the climacterium of processing tomatoes, respiration rate increases sharply by a factor of two and then declines slowly again. This trend in respiration rate applies to a single tomato fruit and therefore one could expect that for a tomato field where individual tomatoes are gradually ripening and are being harvested as soon as the majority of fruits are ripened, the gradual decline will be absent.

Based on this information it is concluded that climacteric respiration can be simulated separately from maintenance respiration and that the climacteric respiration rate can be taken as a constant value of double that of the normal respiration rate at the onset of ripening.

CHAPTER 3

EXPERIMENTAL PROCEDURES

3.1 Modelling approach

In order to create a management tool which could be applied under a wide range of climatic and soil conditions, a mechanistic modelling approach was followed. Existing models, which are relevant to the system that had to be simulated, were studied. The sub-model, TOMYIELD, which simulates the growth and development, as well as the fresh yield and quality of processing tomatoes, was based on the unpublished NEWSWB model developed by G.S. Campbell (Washington State University).

Several growth analyses were conducted at various localities and during different seasons in order to generate data sets of growth and development as well as weather and the soil water balance. Some of the data sets were used to calculate input parameters for the model. The model was evaluated by running it with the calculated input parameters and the initial water content, rain, irrigation and weather data from the evaluation sites in the Western Cape Province and the Northern Province. The simulated results of growth, development, yield and quality are compared to the measured data from the evaluation sites to determine the accuracy of the simulations.

3.2 Trials and localities

For the purpose of model development, most of the "trials" were conducted in the form of growth analyses. Comprehensive data sets were collected in order to be able to calculate parameters for the simulation of the processes of growth and development. For this reason, the focus was on generating data sets for varying environmental conditions rather than repeating treatments at a particular location or during a particular season.

The following trials or growth analyses were conducted:

Locality	*Latitude*	*Longitude*	*Year*	*Trial/Growth analysis*
Marble Hall	25°01' S	29°25' E	1992	Growth analysis
Pretoria	25°44' S	28°20' E	1992/93	Water stress trial (Sefara)
Pretoria	25°44' S	28°20' E	1992/93	Growth analysis
Pretoria	25°44' S	28°20' E	1994/95	Water stress trial
Vredendal	31°36' S	18°26' E	1994/95	Growth analysis
Platskraal	31°10' S	18°17' E	1994/95	Growth analysis
Messina	22°14' S	29°55' E	1995	Growth analysis

As illustrated in Figure 3.1, the localities where the research was conducted are situated from the most northern border of South Africa to the south western coastline.

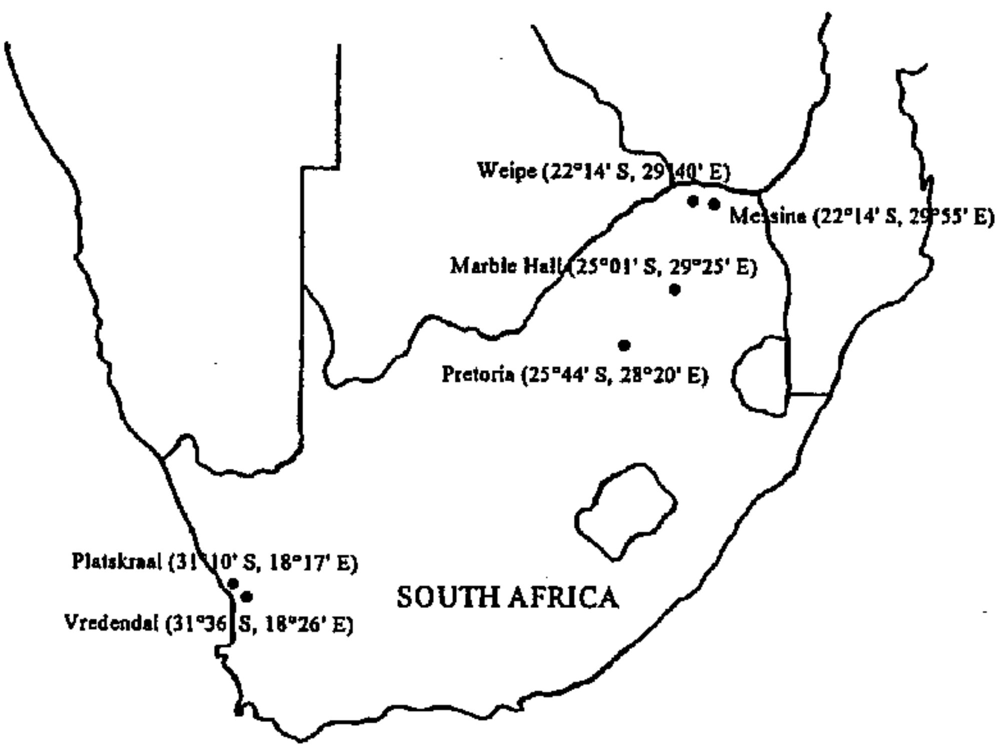


Figure 3.1 The situation of the different localities.

Major climatic differences:

Average daily temperatures at Platskraal were 3 °C lower than at Vredendal, mainly due to lower night temperatures caused by the cooling effect of air flowing in from the cold Atlantic ocean at night, as Platskraal is situated closer to the sea than Vredendal. For the same reason, the average daily temperatures for the Western Cape localities are markedly lower than those of the other localities. Days in the Western Cape are also noticeably longer than those at the other localities due to the higher latitude and summer production period. The soil characteristics varied greatly between the different localities. The main characteristics are summarised in Table 3.1.

Table 3.1 The silt plus clay content, measured water content at field capacity, calculated water content at -75 kPa according to Bennie, Coetzee, van Antwerpen, van Rensburg & Burger (1988), as well as soil depth at the different localities.

Locality	Silt+Clay (%)	Water content		Soil depth (mm)
		Field capacity (mm m^{-1})	-75 kPa (mm m^{-1})	
Marble Hall	55	380	300	1000
Pretoria	35	202	150	1200
Vredendal	10	195	55	1500+
Platskraal	10	220	55	1500+
Messina	12	164	70	500

The soils differed in water holding capacity from as much as 380 mm m^{-1} in Marble Hall to 164 mm m^{-1} in Messina while profile depths varied from only 500 mm in Messina to more than 1500 mm in Vredendal and Platskraal. All of the soils are well drained.

3.3 Trial descriptions

Marble Hall growth analysis (1992/93)

A commercial field of sprinkler irrigated processing tomatoes was monitored on plot J11 of Mr Evert du Plessis. The tomatoes were transplanted on 13 August 1992 and were harvested on 18 December 1992.

The aim of this Marble Hall growth analysis was to generate a data set from a locality different in weather and soil characteristics from that of Pretoria. The data set was needed for the calculation of crop parameters. The cultivar UC82 was planted.

Pretoria stress trial (1992/93)

This drip irrigated water stress trial was conducted under a rain shelter on the Hatfield experimental farm in Pretoria. A full report on the trial was given by Sefara (1994). The aim was to quantify the influence of water stress on canopy development, yield and quality of processing tomatoes. The cultivar planted was UC82.

Five treatments without replications were applied. Three treatments were irrigated after the average reading of two 30 cm deep tensiometers in the crop row reached either -20 kPa, -50 kPa or -75 kPa. These treatments were termed wet, medium and dry respectively. The remaining two treatments were also irrigated at -20 kPa, but irrigation was terminated (cut off) when 1% and 20% of fruits ripened. The treatment combinations of matric potential and irrigation cutoff at different ripeness stages are shown in Table 3.2.

Pretoria growth analysis (1992/93)

This growth analysis on drip irrigated tomatoes was conducted on the Hatfield experimental farm in Pretoria. The aim was to generate more detailed data, especially on the relationship between leaf area index and fractional interception (FI) of photosynthetically active radiation (PAR) for the cultivar UC82.

Data was collected as for the Marble Hall growth analysis, except that an additional technique was used to measure fractional interception of PAR for the purpose of the calculation of the specific leaf area.

Table 3.2 Treatment combinations of soil matric potential at which irrigations took place and ripeness stages at which irrigation was terminated for the Pretoria stress trial (1992/93).

Tensiometer reading (T) (kPa)	% Fruit ripeness (R)		
	1%	20%	100%
-20	T20R01	T20R20	T20R100
-50	-	-	T50R100
-75	-	-	T75R100

Pretoria stress trial (1994/95)

This water stress trial was also drip irrigated and was conducted under the rain shelter on the Hatfield experimental farm in Pretoria. The aim of the trial was to quantify the influence of water stress and its timing on canopy development, fruit yield and quality. The cultivar Brigade was used in this trial because UC82 was replaced with Brigade by the industry.

Four different irrigation treatments with three replications were applied after all plots were irrigated daily for ten days to ensure proper seedling establishment.

All plots were brought to field capacity before the trial commenced. The treatments were:

Treatment	*Vegetative stage*	*Reproductive stage*
WW (WetWet):	ψ > -30 kPa	ψ > -30 kPa
WS (WetStress):	ψ > -30 kPa	No irrigation or rain
SW (StressWet):	No irrigation or rain	ψ > -30 kPa
SS (StressStress)*:	No irrigation or rain	No irrigation or rain

ψ - matric potential (kPa)

* This treatment could only deplete about 100 mm of water from the soil profile.

Although a weekly spray program for the prevention of pests and diseases was followed, an unknown virus, which could not be identified by the Diagnostic Service of the Institute for Vegetable and Ornamental Plants, caused severe damage to the canopy at the stage when 20 to 40% ripeness occurred in the different treatments. The trial had to be terminated because of the disease. In spite of the premature termination of this trial, very valuable data was collected on all aspects measured.

Vredendal growth analysis (1994/95)

A commercial field of drip irrigated tomatoes (cultivar Brigade) was monitored on the farm of Mr Ludan Sieberhagen, situated 10 km north of Vredendal. The tomatoes were transplanted on 10 October 1994 and harvested on 4 February 1995.

The aim of the growth analysis was to generate a data set from the Vredendal area, which differs markedly from the other localities in respect of weather and soil characteristics. The data set was needed for the evaluation of the simulation model.

Data was collected as for the 1992/93 Pretoria growth analysis. As a result of the long distance between Pretoria and the Western Cape, growth analysis data could only be collected every two to three weeks.

Platskraal growth analysis (1994/95)

Similar to the Vredendal growth analysis, this analysis was conducted on the farm of Mr Jean Aggenbagh, situated in Platskraal, 5 km north of Koekenaap. The tomatoes were also transplanted on 10 October 1994 but were harvested on 14 February 1995.

Messina growth analysis (1995)

The same procedure as described for the Vredendal and Platskraal trials was repeated in Messina. The Messina growth analysis was conducted on the farm of Mrs Esterhuyse which is situated 30 km west of Messina along the Limpopo river. The Brigade tomatoes were transplanted on 21 February 1995 and harvested on 6 September 1995.

The data collected are summarized for all trials in Table 3.3.

Table 3.3 Data collected at the different trials.

Data collected	Pretoria 1992/93 Stress trial	Pretoria 1994/95 Stress trial	Marble Hall 1992/93 Growth analysis	Pretoria 1992/93 Growth analysis	Vredendal 1994/95 Growth analysis	Platskraal 1994/95 Growth analysis	Messina 1994/95 Growth analysis
Soil water content	Daily except weekends	Daily except weekends	Daily except weekends	weekly	weekly	weekly	weekly
Soil matric potential	Daily except weekends	Daily except weekends	Daily except weekends	Daily except weekends	Daily except weekends	Daily except weekends	Daily except weekends
Irrigation + precipitation	daily	daily	daily	daily	daily	daily	daily
Weather data	hourly	hourly	hourly	hourly	hourly	hourly	hourly
Leaf area	weekly	weekly	weekly	weekly	2-3 weekly	2-3 weekly	2-3 weekly
FI	weekly	weekly	weekly	weekly	2-3 weekly	2-3 weekly	2-3 weekly
Yield+quality	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Root depth	No	No	Yes	No	No	No	No

Data from the two Pretoria stress trials and the Marble Hall (1992/93) and Pretoria

(1994/95) growth analyses was used for calibration of the model, while data from Vredendal, Platskraal and Messina were used for model evaluation.

3.4 Measurement techniques

Weather data

Hourly weather data was monitored with three automatic weather stations using CR10 data loggers from Campbell Scientific Incorporated (Logan, Utah, USA). One station was used on the Hatfield experimental farm in Pretoria, while the other two were moved from trial to trial.

Humidity was initially measured with Xnam humidity sensors, but due to frequent problems with drifting calibrations, wet bulb temperatures were used later on in the project. Both air and wet bulb temperatures were measured with thermocouples. Solar radiation was measured with LI-200X pyranometers from Licor (Lincoln, Nebraska, USA), while cup anemometers from RM Young (Traverse City, Michigan, USA) were used for measurement of wind speed. Precipitation was measured with tipping bucket rain gauges.

Fractional interception of photosynthetically active radiation

FI was measured manually with a sunfleck ceptometer from Decagon (Pullman, Washington, USA). In order to account for variation within the canopy, at least 20 measurements were taken below the canopy. Only one measurement was taken above the canopy, where no variation in PAR was expected. In order to establish the average FI for a field, the different measurements were taken at random in the field. Where the relationship between FI and LAI had to be calculated, all of the 20 FI measurements and the leaf area measurement were made on the same 1 m^2 plot.

The 0.8 m long probe of the ceptometer was positioned diagonally with one end at the centre between two rows while the other end was in the row. After each of the 10 measurements on one side of the row, the probe was moved on by 100 mm along the row to cover 1 m of row length. By repeating this on both sides of the row, 20 measurements were obtained and the average calculated. In the case of the Messina trial, where a 2.0 m row width was planted, only 1.6 m of the row width could be covered using this technique. Because the tomatoes did not cover the centre 0.4 m strip between the rows, the FI of that area was equal to zero. The FI was measured as described above but with the ceptometer perpendicular to the row. The final FI was then calculated as the weighted average of the FI measured in the 1.6 m row width, which was covered by the measurement, and the two 0.2 m strips with no intercepted radiation.

FI was calculated according to Eq. 3.1

$$\mathbf{FI^* = (PAR_{above} - PAR_{below}) / PAR_{above}} \quad \ldots\ldots \quad \mathbf{3.1}$$

* For Messina: $\mathbf{FI = (PAR_{above} - PAR_{below}) / PAR_{above} * 1.6/2}$

where: PAR_{above} - PAR above the canopy

PAR_{below} - Average PAR below the canopy

Leaf area

Leaf area was measured destructively on 1 m^2 plots. All above ground material was harvested and separated into leaves, stems, flowers and fruits. The area of the leaves was measured with a Licor LI-3100 leaf area meter (Lincoln, Nebraska, USA).

Soil water content

Volumetric soil water content was monitored with a Campbell Pacific Nuclear hydroprobe (Model CPN 503). The probe was calibrated according to the field method described by Greacen, Correl, Cunningham, Johns & Nicols (1981). In the 1992/93 trials two access tubes were installed per plot. One was installed on the planted ridge and the other midway between rows. For all the other trials three tubes were used per plot and the additional tube was placed halfway between the above mentioned positions.

Soil water matric potential

The matric potential of soil water was measured with vacuum gauge tensiometers, which were installed in the planting ridge at depths of 300 and 600 mm. In the Vredendal, Platskraal and Messina trials, additional tensiometers were installed in the same positions as the neutron probe access tubes.

Irrigation

The Marble Hall trial was irrigated with overhead sprinklers and two manually read rain gauges were installed in each plot to measure the irrigation and precipitation. These rain gauges were positioned at each of the two sets of access tubes where the soil water content and the soil matric potential was measured.

All other trials were drip irrigated and either manual or automatic rain gauges were installed in order to monitor precipitation. In Pretoria the amount of water applied by drip irrigation was measured manually by collecting and weighing the water from the last dripper in each row. In the Vredendal, Platskraal and Messina trials the irrigation was automatically monitored by two tipping bucket drip meters per plot which were mounted on the drip lines. The water application was not disturbed as water was channelled through the meters onto the soil and therefore the measurements could be made at the actual points where the soil water measurements were made. The meters were monitored by the data logger in the automatic weather station.

Fresh yield, dry matter and fruit quality (brix)

Fresh yield was determined by harvesting and weighing all harvestable fruits on a 1.0 m row length close to the point where the soil water measurements were taken.

The dry matter content of fruits and vegetative material was determined by weighing before and after complete drying at 65 °C.

Fruit quality was monitored by measuring brix of tomato samples with an Atago digital refractometer (DBX 55).

CHAPTER 4

RESULTS AND DISCUSSION

Results of growth analyses, water use and weather data are presented only in summarised form in order to indicate the similarities and differences between the different data sets. It should be noted that standard statistical analysis is not imperative because of the modelling approach followed.

4.1 Growth analyses

Phenological development and thermal time

The phenological stages that are of importance in the simulation of the development of tomatoes are flowering, ripening and maturity (>90% fruit ripeness). With the cardinal temperatures as established from the literature (Tb = 10 °C and Tcutoff = 26 °C), the day degrees for each of the development stages is calculated for all the data sets.

It should be noted that seedlings are used and that by the time that they are transplanted, the different batches of seedlings may already vary in age. Seedlings used in these trials/growth analyses were normally more or less six weeks old, but their exact age (days after seeding or day degrees) was not known.

The measured days from transplanting to the various phenological stages as well as the measured day degrees for the trials/growth analyses, which were used for calibration of the model, are presented in Table 4.1 and Figure 4.1, while those for the trials/growth analyses, which were used for evaluation, are presented in Table 4.2.

Table 4.1 Measured thermal time requirements (d °C) and days after transplanting (DAP) to different phenological stages for the trials/growth analyses which were used for calibration of the model.

Cultivar	Trial/Treatment	Development time					
		Flowering		First ripeness		Maturity	
		DAP	FlDD (d °C)	DAP	RipeDD (d °C)	DAP	MtDD (d °C)
UC82	Marble Hall 1992/93	27	203	80	874	127	1537
	Pretoria 1992/93 Growth analysis	22	295	67	763	98	1080
	Pretoria 1992/93 Stress trial (treatment avg)	22	241	70	797	98	1080
Brigade	Pretoria 1994/95 Stress trial: WetWet	30	278	62	778	107	1035
	Pretoria 1994/95 Stress trial: WetStress	30	278	54	675	103	1007
	Pretoria 1994/95 Stress trial: StressWet	30	278	60	747	105	1019
	Pretoria 1994/95 Stress trial: StressStress	30	278	54	675	103	1007
Average		27	265	64	758	106	1109

Where: DAP - Days after transplanting FlDD - Flowering day degrees

RipeDD - Ripening day degrees (d °C) MtDD - Maturity day degrees (d °C)

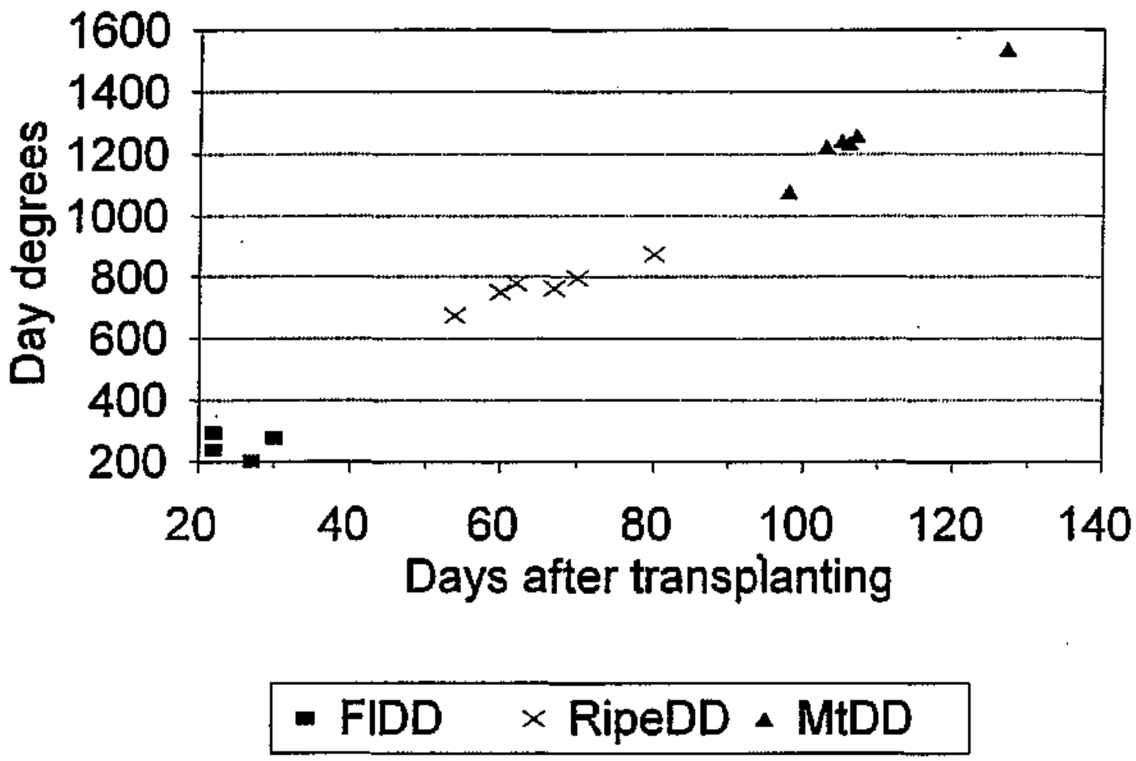


Figure 4.1 Measured thermal time requirements (day degrees) and days after transplanting for different phenological stages for the different trials.

Table 4.2 Measured thermal time requirements (d °C) and days after transplanting (DAP) to different phenological stages for the growth analyses which were used for evaluation of the model.

Cultivar	Trial/Treatment	Development time					
		Flowering		First ripeness		Maturity	
		DAP	FIDD (d °C)	DAP	RipeDD (d °C)	DAP	MtDD (d °C)
Brigade	Vredendal 1994/95	40	391	66	673	119	1347
	Platskraal 1994/95	39	305	85	818	126	1254
	Messina 1995	21	297	92	963	147	1340

Accumulated dry matter of plant components

The accumulated dry matter of different plant components, namely leaves, stems and fruits, was measured periodically during the season and included in the database of the model. As an example, measured accumulated dry matter for the 1992/93 growth analysis trial in Pretoria is presented in Figure 4.2.

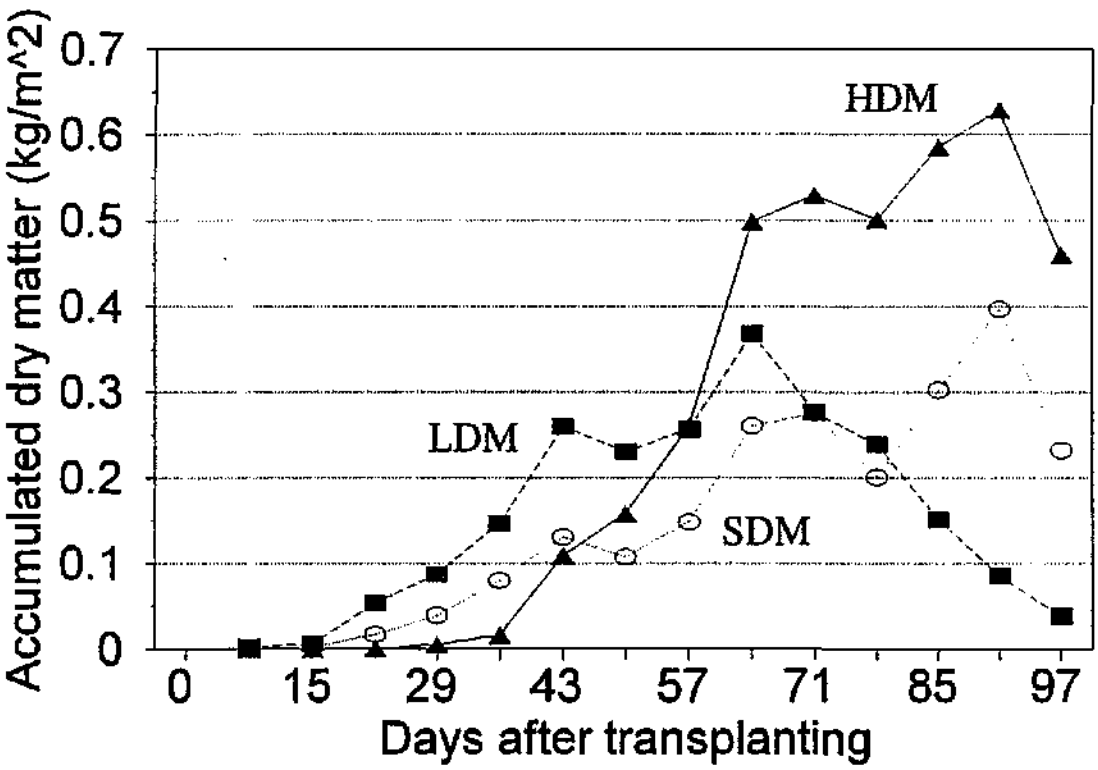


Figure 4.2 Measured dry matter accumulation of leaves (LDM), stems (SDM) and harvestable fruit dry matter (HDM) for the 1992/93 growth analysis in Pretoria.

Fractional interception of photosynthetically active radiation and leaf area index

FI was measured periodically during the season in all trials, while LAI, which is a destructive measurement, was measured only in the growth analysis trials. The FI and LAI results were included in the database of the model. As an example, FI data measured for the various treatments of the 1994/95 stress trial in Pretoria is presented in Figure 4.3 and LAI data at 78 days after transplanting (DAP) of the 1992/93 growth analysis in Figure 4.4.

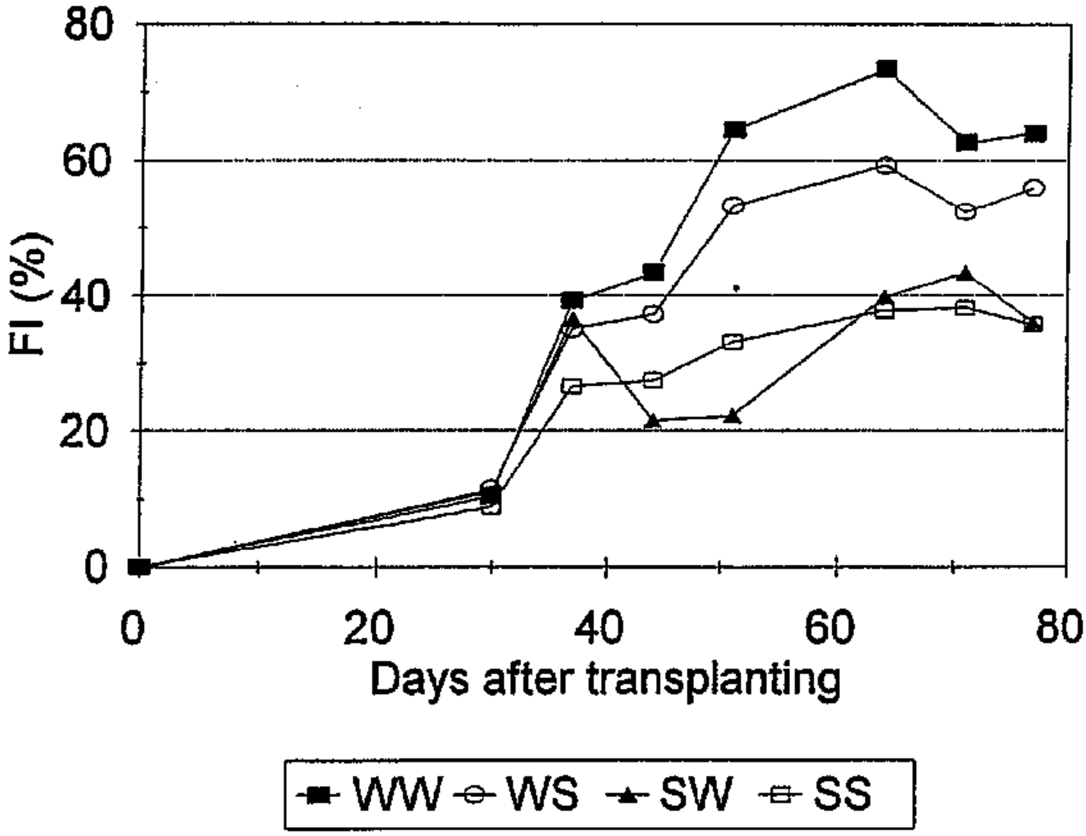


Figure 4.3 Measured fractional interception (FI) for the various treatments of the 1994/95 Pretoria stress trial.

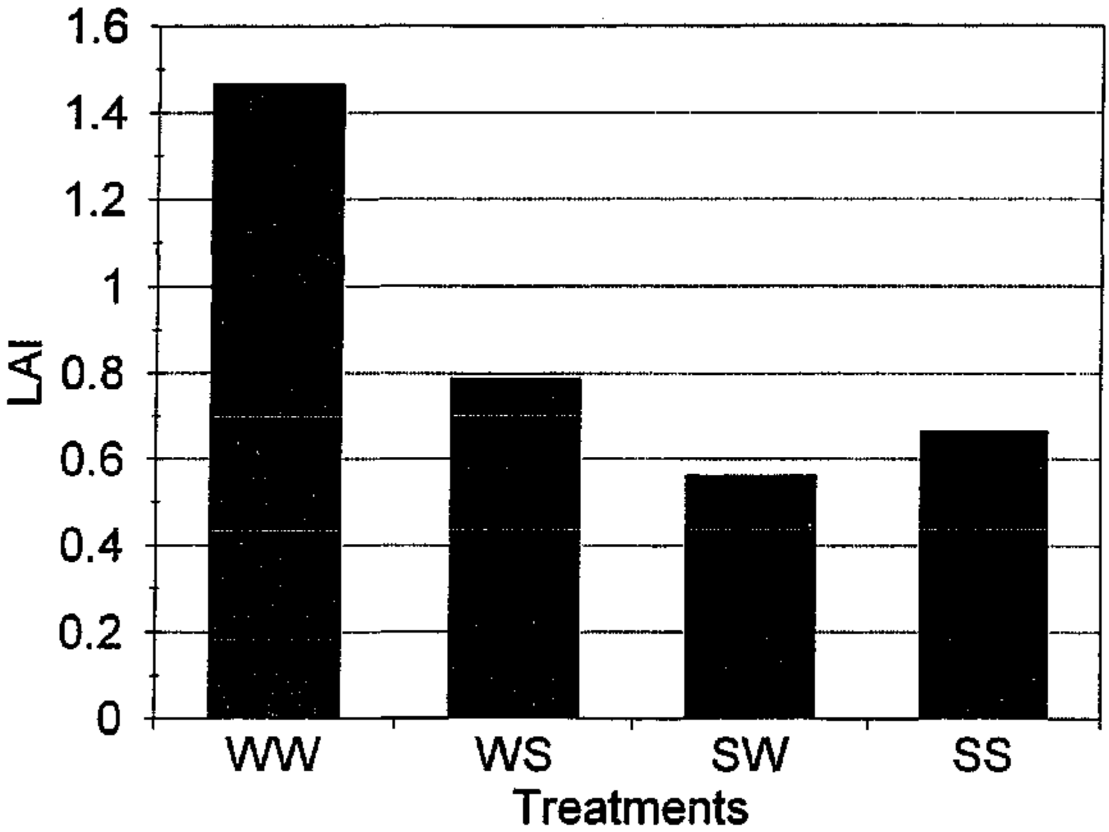


Figure 4.4 Measured LAI at 78 days after transplanting for the 1992/93 growth analysis in Pretoria.

4.2 Water use, yield and quality

The measured cumulative evapotranspiration and drainage (CumETD) as well as the final yield, average brix and water use efficiencies (WUE) are presented in Table 4.3 for the 1994/95 stress trial in Pretoria.

There was no runoff in the Pretoria stress trials, where drip irrigation and a rain shelter was used. All of the field trials were conducted on fairly level fields which were drip

Table 4.3 Measured cumulative evapotranspiration plus drainage (CumETD), fresh yield, brix and calculated water use efficiencies of the different trials.

Trial	Treatment	CumETD (mm)	Fresh yield (t ha^{-1})	brix Avg	$WUE_{Fresh\ yield}$ (kg m^{-3})	WUE_{TSS} (kg m^{-3})
Marble Hall 1992/93	-	621	81.1	3.6	13.1	0.47
Pretoria 1992/93 stress trial	T20R01	398	66	3.5	16.6	0.58
	T20R20	466	71	3.7	15.2	0.56
	T20R100	536	73	3.7	13.6	0.51
	T50R100	437	64*	3.9	14.6	0.57
	T75R100	399	53	4.2	13.3	0.56
Pretoria 1994/95 stress trial**	WetWet	242	64.3	4.3	26.6	1.14
	WetStress	193	38.6	5.5	20.0	1.10
	StressWet	156	23.4	5.7	15.0	0.92
	StressStress	122	17.0	6.3	13.8	0.87
Vredendal 1994/95	-	502	109	4.8	21.7	1.04
Platskraal 1994/95	-	444	98.8	4.8	22.3	1.07
Messina 1995	-	992	80.6	5.3	8.1	0.43

* This yield was measured as 50 t ha^{-1} and corrected to an estimated 64 t ha^{-1} because some fruit was likely stolen from this specific plot.

** This trial was harvested at 76 days after transplanting as a result of an unknown virus disease. Although much higher yields could be expected if harvesting had taken place at full maturity, the measured yields were not corrected.

irrigated and monitored closely. Although runoff was not measured specifically, no visible runoff was noted on any of the field trials.

Drainage was prevented completely in the 1994/95 stress trial in Pretoria by excluding rain with the rain shelter and by replacing only the measured deficits in soil water content. The CumETD values for the 1992/93 stress trial in Pretoria includes some drainage, as discussed below. CumETD was calculated according to Eq. 4.1 for different periods.

CumETD = $(PWC_d - PWC_{d-i})$ + TotP + TotI 4.1

where:	PWC_d	-	Profile water content on day d
	PWC_{d-i}	-	Profile water content on day d-i
	TotP	-	Total precipitation for the period from day d-i to d
	TotI	-	Total irrigation for the period from day d-i to d

The water use efficiencies based on fresh yield ($WUE_{Fresh\ yield}$) and total soluble solids (WUE_{TSS}) are also indicated in Table 4.3 and were calculated according to Eqs. 4.2 and 4.3 respectively.

$WUE_{Fresh\ yield}$ = FreshYield*100 / CumETD 4.2

where:	$WUE_{Fresh\ yield}$	-	Water use efficiency based on fresh yield (kg fresh yield m^{-3} water)
	FreshYield	-	Fresh yield (t ha^{-1})

WUE_{TSS} = FreshYield * brix / CumETD 4.3

where:	WUE_{TSS}	-	WUE based on total soluble solids (kg soluble solids m^{-3} water)
	brix	-	Gravimetric percentage of soluble solids in fruits

From the data above it is clear that the WUE of the treatments of the 1994/95 stress trial in Pretoria and the growth analyses in Vredendal and Platskraal are much higher than that of the rest. This was due to inefficient irrigation in the case of the rest of the trials/growth analyses.

The high water use in the Marble Hall growth analysis is mainly due to the use a sprinkle irrigation system, while drip irrigation was used in all the other trials.

In the 1992/93 Pretoria stress trial, although the irrigations were properly timed with the aid of tensiometers, too large volumes were likely applied. This was due to the calculation of the required irrigation as the average deficit was measured at only two access tubes, one in the tomato row and the other halfway in between the rows. This procedure overestimated the required irrigation because the soil water deficit in the top part of the profile between the rows, which was not wetted by the drip irrigation system, was included in the calculated irrigation quantities. By applying these irrigation quantities on the row, drainage was caused under the rows. The over irrigation can be seen in the data of Sefara (1994).

The high WUE in Vredendal and Platskraal, compared to that of the other growth analyses, is partly due to the scheduling of the irrigation based on calculated water use. The scheduling was done with the irrigation scheduling program, called Besproeiingsbestuursprogram (BBP). BBP was run by the farmer on his own computer. BBP calculates evaporative demand according to a simple, empirical but locally calibrated regression model, while evapotranspiration is calculated according to the crop factor approach as described by Burgers (1982).

The high water use in Messina was partly due to a longer growing season (147 days vs 110 days in most other cases) and partly to over irrigation. It should be noted that in this case irrigation was only monitored and not scheduled.

Data of the harvestable yield and brix for the 1994/95 stress trial in Pretoria is presented in Figure 4.5 to confirm the general trend of decreasing brix with increasing yield.

4.3 Storage of weather data

Historic monthly weather data for all localities are presented in Table A1 of Appendix A. Daily weather data with calculated PET for the trial periods at all localities and measured hourly data will be stored on CD at the University of Pretoria.

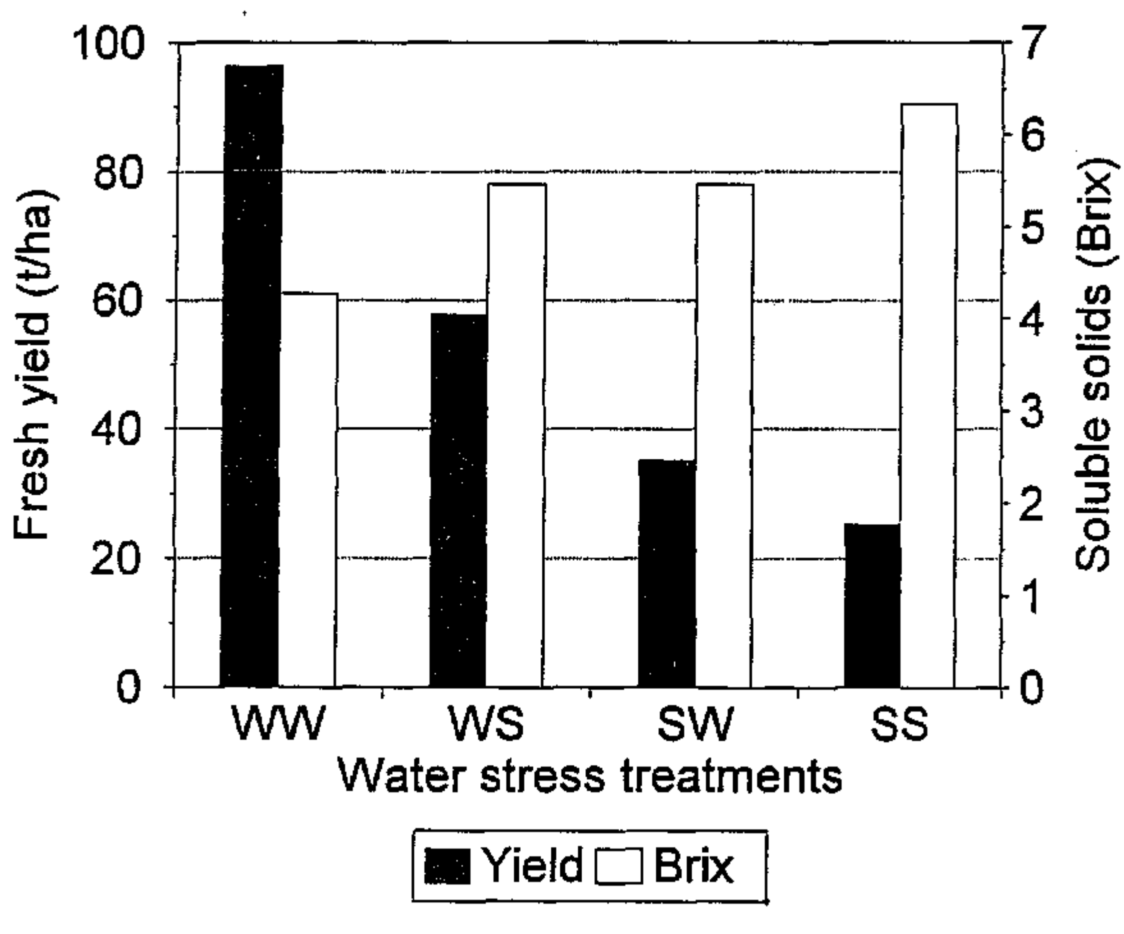


Figure 4.5 Measured yield and brix for the various treatments of the 1994/95 stress trial in Pretoria.

CHAPTER 5

THE TOMATO MANAGEMENT PROGRAM (TOM-MAN)

5.1 Introduction

The functional operation of TOM-MAN and especially the role of each of the sub-models are discussed in this Chapter while the details of the sub-models are dealt with in Chapters 6 and 7. The various applications of TOM-MAN are described in Chapter 8.

5.2 Functions of TOM-MAN and the sub-models TOMYIELD and TOM-ECON

The main function of TOM-MAN is to integrate the crop simulation and real time irrigation scheduling model (TOMYIELD) and the economic optimization model (TOM-ECON) to perform either or both of the following tasks:

* TOMYIELD simulates expected crop growth and development from soil and weather input data for a set of different irrigation strategies. The required inputs of irrigation and resulting outputs of yield are simulated for the different irrigation strategies. Given the simulated required inputs and outputs of TOMYIELD, TOM-ECON calculates the costs and benefits for each of the strategies and selects the optimum one; and
* TOM-MAN manages (schedules) the irrigation on a real time basis according to the selected optimum strategy.

The flow diagram in Figure 5.1 indicates the main routes that the TOM-MAN user can follow in order to perform either or both of the two main tasks described above.

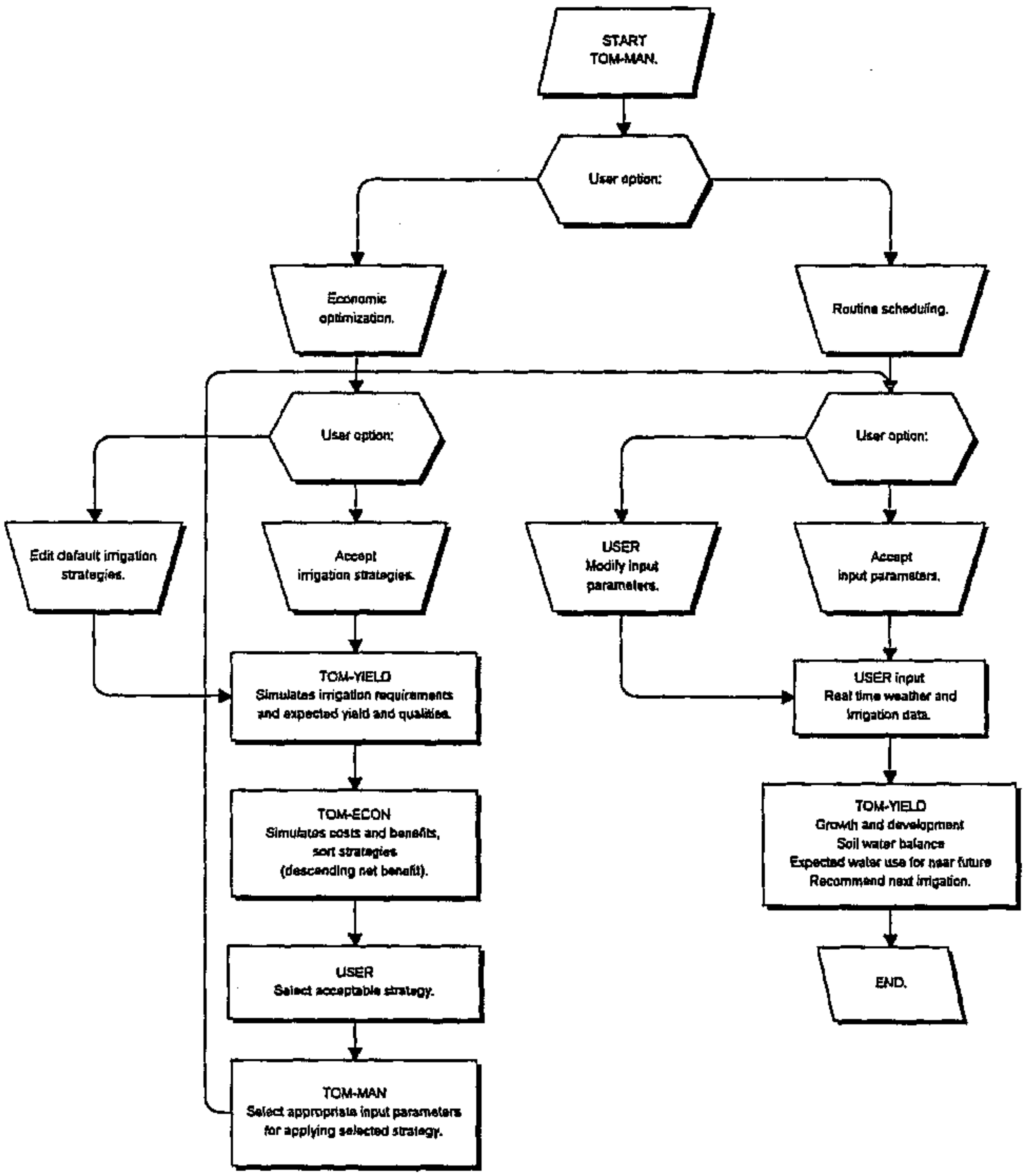


Figure 5.1 Flow diagram of the main functions of TOM-MAN.

For the selection of the optimal irrigation schedule, the user will be prompted with a range of irrigation schedules or strategies, which he/she will be able to edit. The schedule indicates the allowable soil water depletion level (in matric potential) over time during the season on a thermal time scale. This enables the user to specify the allowable depletion levels for specific development stages. The application of the different schedules will result in differing levels of water stress during the various development stages. TOMYIELD simulates the growth and development according to each of the different irrigation strategies. The required irrigation and the expected yield and quality is also quantified for use by TOM-ECON. TOM-MAN then applies TOM-ECON to simulate the costs of the required inputs (irrigation, fertilisation, labour, harvesting and transport), as well as the benefits (income) resulting from the outputs (yield and quality). The expected benefit over costs is then calculated for each of the strategies in order to select the optimal strategy.

Once the optimal strategy is selected, the input parameters concerning the irrigation guidelines of the optimal irrigation schedule are accepted and used during routine scheduling. The user then only needs to supply irrigation and weather data on a daily basis. Apart from recommending required timing and quantities of irrigation to apply according to the selected strategy, the program keeps record of all the simulated and measured values.

CHAPTER 6

DESCRIPTION OF TOMYIELD, THE GROWTH SIMULATION MODEL

6.1 Introduction

TOMYIELD is based on the NEWSWB model, which is described by Benadé *et al.* (1995). TOMYIELD differs from NEWSWB mainly in its ability to simulate fresh yield and quality of processing tomatoes, as NEWSWB only simulates dry matter yield of the different plant components.

In order to simulate fresh yield and quality of processing tomatoes, modifications were needed to account for:

* fruit ripening as hastened by water stress;
* maturity as enhanced by water stress;
* maintenance respiration of fruits;
* loss and gain of fruit water;
* partitioning of fruit dry matter to the various fruit components;
* the simulation of final fresh yield; and
* the percentage of soluble solids (brix).

Minor modifications were also introduced to the following aspects of the model in order to increase the accuracy of the simulation of canopy growth and development:

* simulation of seedling growth rate;
* translocation of a portion of the dry matter from senesced leaves to fruits;
* influence of water stress on the termination of leaf growth;
* influence of self shading on senescence rate of leaves;
* storage of assimilates in the leaves; and
* changes in canopy structure during the season.

The modifications mentioned above, are discussed as part of the description of the complete crop growth and development unit of TOMYIELD under item 6.3. The construction of this part of the program is shown in Figure 6.1.

The soil water balance procedures were modified in order to enable the model to simulate the water balance of drip and micro irrigation systems. These modifications will be described in Chapter 6.4.

6.2 Time step

TOMYIELD, like NEWSWB, runs on a daily time step.

6.3 The crop growth and development unit of TOMYIELD

After the crop is planted the simulation will run until maturity is reached. Maturity is described by the parameter MtDD, which indicates the day degree requirements until maturity. The first step after planting is the calculation of thermal time on which the development rate is based.

Thermal time is calculated in TOM-MAN as described in Chapter 2 for NEWSWB.

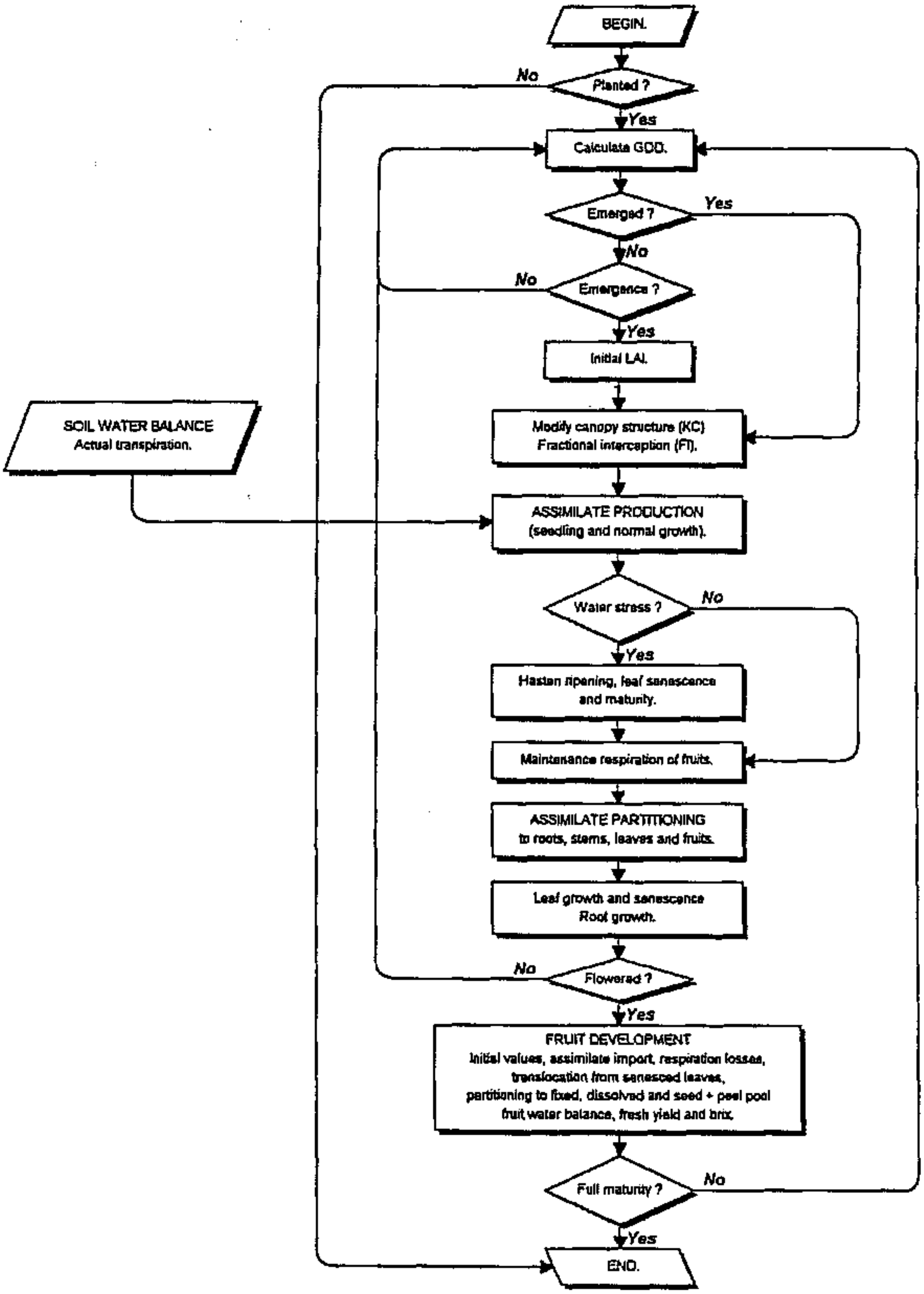


Figure 6.1 Flow diagram of the crop growth simulation process in TOMYIELD.

Calculation of thermal time

The growing day degrees (GDD) are calculated daily and accumulated from planting onwards for the rest of the season. The average daily temperature is calculated as the average of daily maximum and minimum temperatures.

The cardinal temperatures were found from literature studies to be:

Base temperature (T_{base})	10 °C
Cutoff temperature (T_{cutoff})	26 °C

These temperatures were assumed correct but will be refined through use. The results of elapsed day degrees until the various development stages varied considerably and indicate that refinement is still needed in this respect. The minimum, maximum and average growing day degrees are presented in Table 6.1.

Table 6.1 Minimum, maximum and average day degrees to the various development stages for all trials and growth analyses.

Development stages	Parameter	Day degree requirement		
		Minimum	Average	Maximum
Flowering	FlDD	203	284	391
First ripening	RipeDD	673	777	963
Maturity	MtDD	1080	1259	1537

According to Wolf *et al.* (1986) there are several other factors, which are not taken into account in TOMYIELD, which influence development rate considerably. At least two of these factors, namely high average day temperatures (above 26 °C) and fairly big differences in day length between localities, could have an important influence. The incorporation of the principles applied in TOMMOD (Wolf *et al.*, 1986) is therefore identified as a development need for the near future. As TOMMOD simulates development rate from seeding onwards, provision can be made for the simulation of the physiological age of seedlings in order to eliminate error resulting from seedlings which differ in age at transplanting. The user will then have to acquire weather data for the period from seeding to transplanting.

In order to prevent errors in the simulation of development rate influencing the simulated results of the rest of the model, the measured growing day degrees were used in the simulations.

Emergence

In NEWSWB thermal time commences with an initial value of zero at planting. Emergence normally takes place when the required day degrees for emergence (EmDD) are accumulated. Because seedlings are transplanted, the parameter EmDD is taken as zero. The simulation of canopy development and assimilate production commences only after emergence.

For processing tomatoes, however, seedlings are transplanted at the age of about 6 weeks. At this stage seedlings could already have accumulated around 50 day degrees before emergence and another ±300 day degrees after emergence. This aspect is identified as a development need as discussed before.

Fractional interception of solar radiation

In TOMYIELD, as in NEWSWB, fractional interception of solar radiation is simulated according to Eq. 6.1, in which the canopy extinction coefficient for solar radiation (KC) describes or represents the canopy structure.

$$FI = 1 - e^{-KC * LAI} \quad \ldots\ldots \quad 6.1$$

KC is an input parameter, and should have a fixed value throughout the season if the canopy structure remains unchanged. It should be kept in mind that if the row width is altered, KC will also be affected. Row widths varied from 1.25 m to 2.0 m in the different trials. This aspect will be investigated fully at a later stage in order to develop a procedure to estimate KC more mechanistically.

The value for KC is calculated from measured LAI and FI data according to Eq. 6.2, which is derived from Eq. 6.1.

$$KC = -\ln(1 - FI) / LAI \quad \text{........} \quad 6.2$$

Calculated values for KC, as shown in Figure 6.2, indicates a huge drop towards the end of seedling stage, followed by an upward trend during the rest of the season.

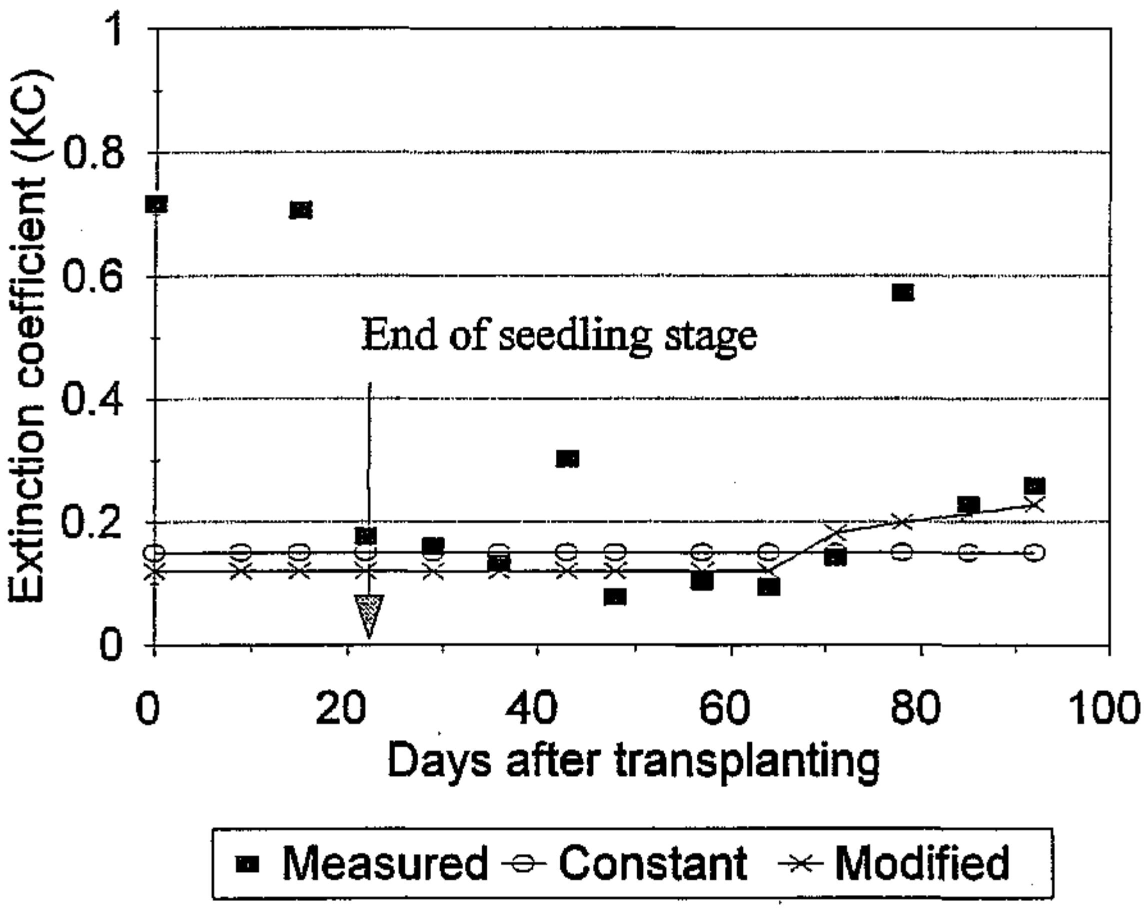


Figure 6.2 Calculated extinction coefficient (KC) values from the 1992/93 Pretoria growth analysis trial.

In NEWSWB, a fixed value of KC is used throughout the season. With this approach, a KC value of 0.15 resulted in the best fit between simulated and measured values of FI (Figure 6.3). The simulation procedure with a constant KC over estimates FI during the mid season while it under estimates towards the end. This inaccuracy is due to a change in canopy structure and the increase in interception by stems and fruits. The canopy structure of processing tomatoes

changes during the growing season to such an extent that it is easily noticed visually. During the early vegetative stage the canopy is fairly closed and the young fruits are not exposed to sunlight. Close to the first ripeness stage the canopy opens up, probably because the stems are bending downwards into a more horizontal position due to increased fruit mass.

In order to account for the observed change in canopy structure of processing tomatoes, TOMYIELD was adapted and the extinction coefficient is assumed to be a fixed parameter ($KC_{initial}$) from planting until the change in canopy structure commences at the stage when the first fruits ripen. After this, KC is increased according to Eq. 6.3.

If GDD > RipeDD then

$KC_{modified} = KC_{initial} * GDD / (RipeDD * 0.7)$

If $KC_{modified}$ > KC_{max} then $KC_{modified}$ = KC_{max} 6.3

where: $KC_{modified}$ - Modified canopy extinction coefficient for solar radiation due to changed canopy structure

KC_{max} Maximum canopy extinction coefficient for solar radiation

The use of the modified KC resulted in more accurate simulation of FI, especially later during the season, as shown in Figure 6.3.

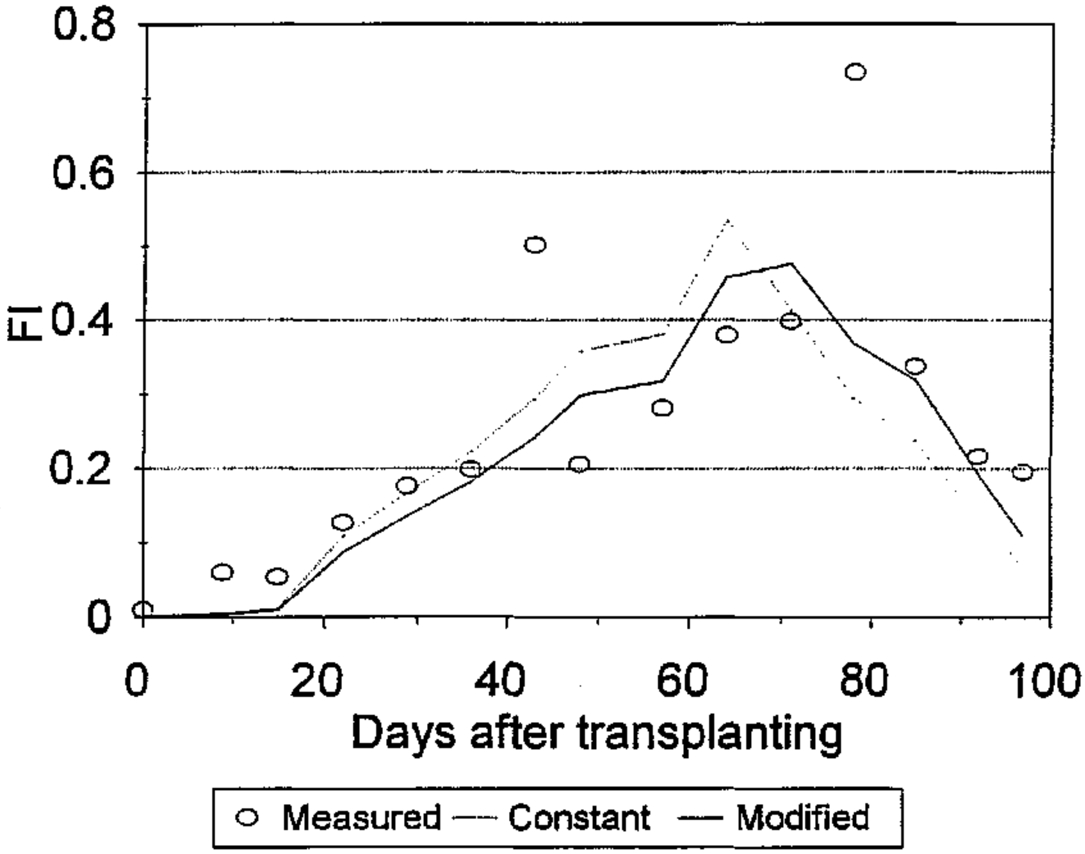


Figure 6.3 Simulated and measured FI over time for the Pretoria 1992/93 growth analysis.

Assimilate production

Daily assimilate production is calculated according to the normal NEWSWB procedure for the period from the end of the seedling stage to maturity, while it is modified slightly for the seedling growth period.

NEWSWB assimilate production

The basic principle that production may be either water limited or radiation limited, as described in the literature review in Chapter 2, is applied. The description is repeated here only for the convenience of the reader. Transpiration is simulated in the soil unit of the model, while energy limited growth is simulated from intercepted solar radiation and radiation use efficiency (RUE). Daily assimilate production is calculated separately based on both water (Eq. 6.4) and energy (Eq. 6.5) and then the most limiting value is accepted as the final daily dry matter increment (dmi).

dmiw = ActualTrsp * DWR / VPD 6.4

dmis = Tfact * RUE * FI_{Transp} * Solar 6.5

If Tavg > T_{lo} then Tfact = 1
If Tlo > Tavg > Tb then Tfact = (Tavg - Tb) / (T_{lo} - Tb)
If Tavg < Tb then Tfact = 0 . . . . 6.6

The procedures imply that for average daily temperatures above Tlo, temperature does not limit dry matter production. For average daily temperatures below Tlo, however, temperature limits dry matter production as Tfact is reduced linearly from a value of one to zero at the base temperature (Tb).

Assimilate production during seedling growth

After transplanting, seedlings normally display symptoms of temporary wilting and slow growth. During this period a balance between root water supply and evaporative demand is created or restored by growing proportionally more roots at the expense of leaf growth. During the seedling stage, while leaf expansion rate is temperature limited (Van Laar *et al.*, 1992), leaf area increases exponentially as a function of temperature, until growth becomes assimilate supply limited. The simulation of seedling growth requires the simulation of the duration of the seedling stage as well as the rate of growth.

Duration of the seedling stage:

In TOMSIM (Van Laar *et al.*, 1992), for indeterminate tomatoes with longer periods before flowering, the end of the seedling stage is taken as the point in time when LAI exceeds 0.75 or GDD exceeds 0.3 of the day degree requirement for flowering (FIDD). This fraction is defined in TOMYIELD as the parameter EndSeedIDDFrac. With determinate tomatoes, which flower much sooner, it could be expected that the seedling stage will last for a greater portion of the period before flowering.

The distinctive feature of the seedling stage is a sharply increasing specific leaf area which stabilises at the end of the seedling stage. This can be seen in Figure 6.4 for the 1992/93 Pretoria growth analysis. The trend is drawn in the graph.

From the change in the SLA-trend, the end of seedling stage is taken as 22 days after transplanting, or the equivalent 249 growing day degrees for the specific data set. This represents 0.84 of the measured FIDD for this data set, while the measured LAI was 0.77 m^2 leaves m^{-2} soil. From this data it is concluded that an LAI of 0.75 or 84% of FIDD can be used as reasonable indicators for the end of the seedling stage until a more detailed study is performed.

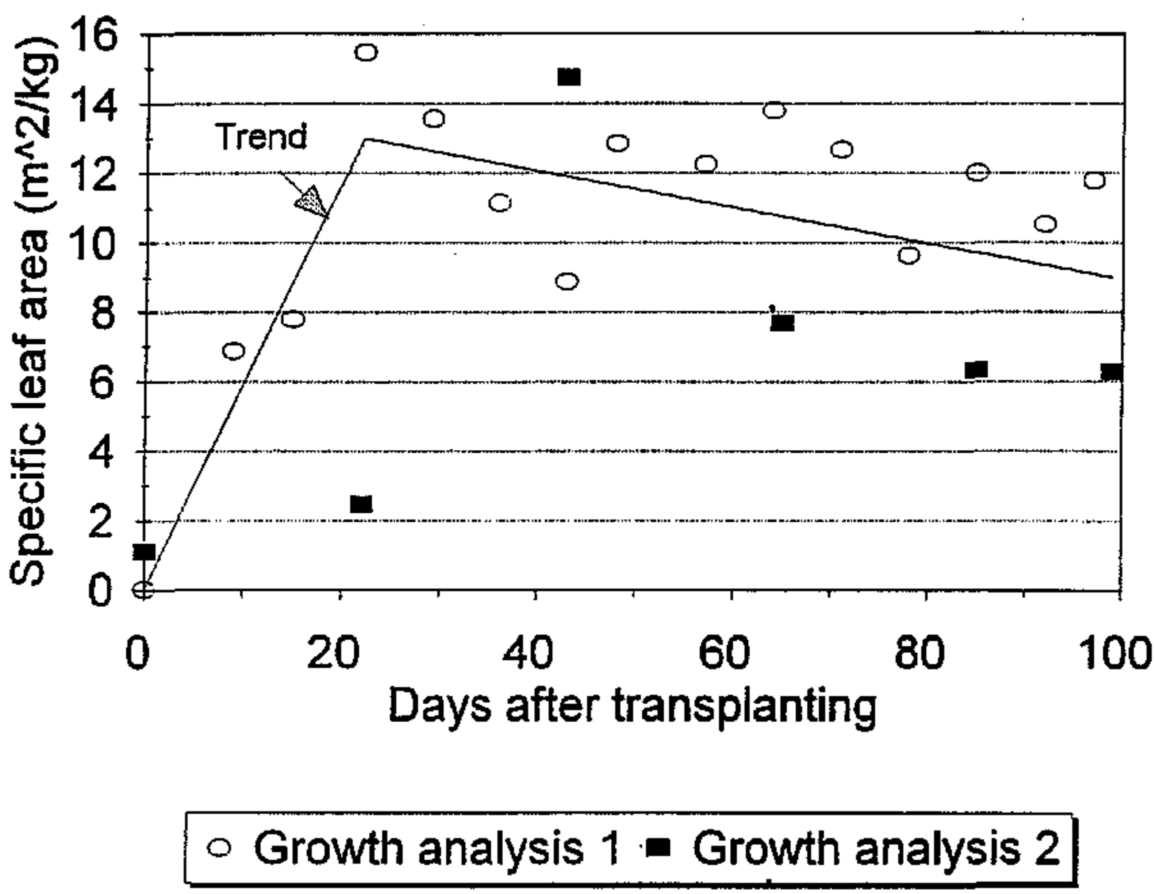


Figure 6.4 The trend in SLA during the season, indicating the end of the seedling stage for the Pretoria 1992/93 growth analysis.

TOMYIELD is adapted by adding the parameter EndSeedlDDFrac and the value of 0.84 is allocated. The duration of the seedling stage is calculated according to Eq. 6.7. This procedure will enable the generic model to simulate crops or cultivars with varying seedling stage lengths by using different values for the EndSeedlDDFrac parameter.

EndSeedlingDD = FlDD * EndSeedlDDFrac 6.7

where: EndSeedlingDD	-	Day degrees until end of seedling growth stage (d °C)
EndSeedlDDFrac	-	Ratio of day degrees at the end of seedling and day degrees at flowering

Growth rate during the seedling stage:

The procedure for simulating seedling growth rate as a temperature function as described by Van Laar *et al.* (1992) is accepted and incorporated. The daily increment in LAI (LAIi) is determined by the LAI at the end of the previous day, the RGR_{leaf} and the temperature or gddi. LAIi is calculated according to Eq. 6.8.

$$\mathbf{LAIi = LAI_{d-1} * [\ exp(RGR_{leaf} * gddi) - 1]} \qquad 6.8$$

where: LAIi - Leaf area index increment for the current day

The relative growth rate of leaf area (RGR_{leaf}) is a parameter which is calculated according to Eq. 6.9. A value of 0.15 resulted as the average of several periods. This value is clearly higher than the 0.009 used in TOMSIM.

$$\mathbf{RGR_{leaf} = (LAI_d - LAI_{d-1}) / LAI_{avg} \ * gddi} \qquad 6.9$$

where: LAI_d - Leaf area at end of period between measurements

LAI_{d-1} - LAI at beginning of period between measurements

LAI_{avg} - Average leaf area during the period between measurements

The resulting simulation of LAI over time after transplanting is plotted with the measured data in Figure 6.5. This shows that leaf area growth is simulated accurately for the seedling stage (first 22 days after planting). After this the normal simulation of growth according to assimilate supply should commence.

The hastening influence of water stress on fruit ripening

The parameter RipeDD was defined as the number of day degrees required until first ripening. The number of day degrees which elapsed until first ripening was calculated for the non-stressed treatments of the Pretoria 1994/95 trials and found to be 779. First ripening occurred sooner in all the treatments where stress was induced. This effect is probably due to an increased canopy temperature with water stress and is simulated by reducing the required amount of day degrees for ripening according to the approach

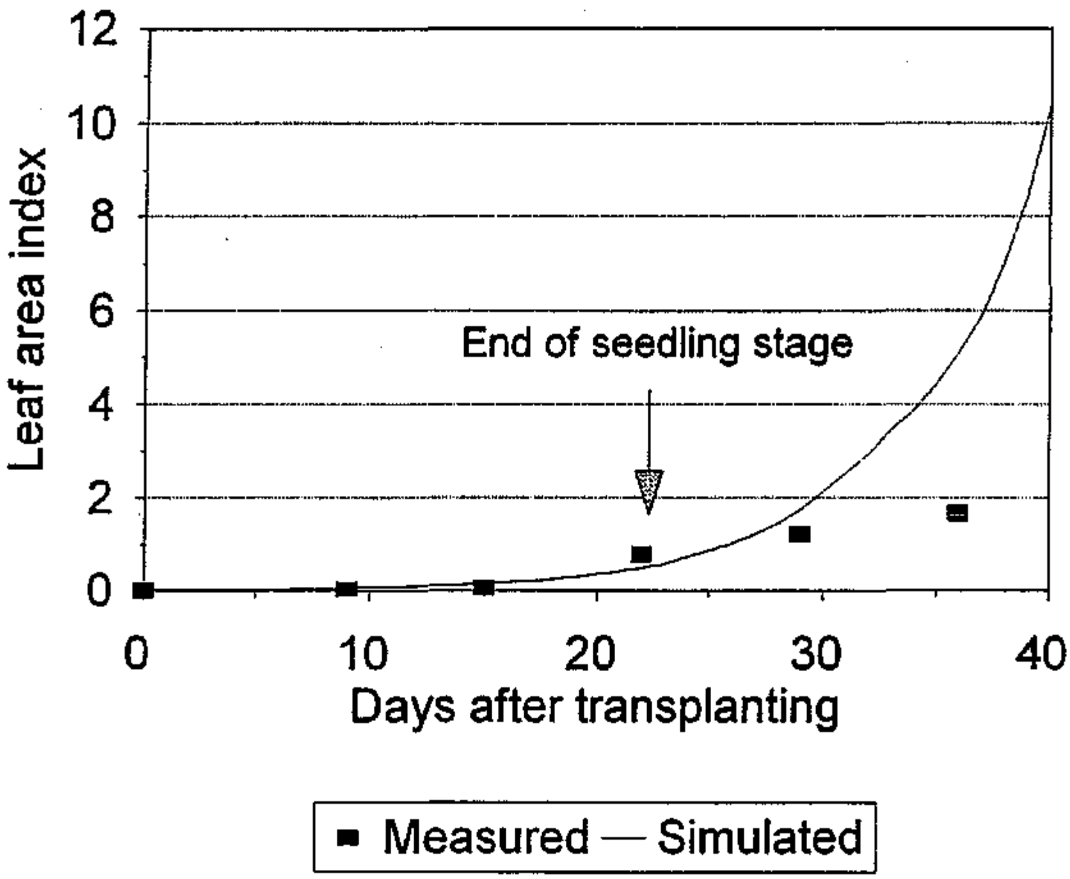


Figure 6.5 Measured and simulated LAI for the seedling stage of the 1992/93 Pretoria growth analysis.

followed by Wolf *et al.* (1986) in TOMMOD. In TOMMOD the length of the ripening period (the required number of physiological days for the period from first flowering to first ripening) is calculated according to Eq. 6.10.

RipeningPeriod = RipeDD - RipeSensStress * SDI **6.10**

where: RipeSensStress - Parameter representing the sensitivity for stress (d °C Stress day^{-1})

In TOMMOD an empirically determined value of 5.958 is used for the parameter RipeSensStress in this report. This represents the number of physiological days by which ripening is enhanced per unit SDI. In TOMMOD a stress index, SDI, is calculated as a linear function based on soil matric potential only. This does not necessarily represent a water stress condition to the plant, because stress also depends on evaporative demand and root resistance. The stress index, SI, calculated by TOMYIELD (NEWSWB) is more suitable for this purpose, as it takes both soil water supply and demand into consideration.

The RipeSensStress parameter is defined as the reduction in day degree requirement in day degrees (when SI<0.95). RipeSensStress is calculated empirically from the data for the three stressed treatments according to Eq. 6.11.

$RipeSensStress = (RipeDD_{NoStress} - RipeDD_{Stressed})/StressDays$ 6.11

where: $RipeDD_{NoStress}$ - Day degrees at first ripening for non-stressed tomatoes in the same trial (d °C)

$RipeDD_{Stressed}$ - Day degrees at first ripening (d °C)

StressDays - Total number of days with $SI < 0.95$ (Stress day)

The RipeSensStress parameter is calculated for the WS, SW and SS treatments of the 1992/93 stress trial in Pretoria as 2.17, 4.6 and 3.01 (d °C Stress day^{-1}) respectively. The average value of 3.26 is used in TOMYIELD.

The reduction in RipeDD is finally calculated in TOMYIELD according to Eq. 6.12.

If $SI < 0.95$ then

$RipeDD := RipeDD - RipeSensStress * StressDays$ 6.12

In the daily calculation procedure in TOMYIELD, StressDays equals one and RipeDD becomes RipeDD-RipeSensStress on days with $SI < 0.95$.

The influence of water stress on the termination of leaf growth

As with ripening, the termination of leaf growth is hastened by water stress. The same approach is followed as with ripening. The growth transition period parameter (GpDD), which indicates the duration (in day degrees) of the transition period from flowering until the termination of leaf growth, is therefore decreased according to Eq. 6.13 on days when SI < 0.95.

If SI < 0.95 then

GpDD := GpDD - GpSensStress * StressDays 6.13

where: GpDD - Growth transition period from flowering until the termination of leaf growth (d °C)

GpSensStress - Parameter representing the average reduction in GpDD on days with water stress (d °C Stress day^{-1})

As sufficient detailed data is not available for the calculation of the parameter GpSensStress, it is assumed that the GpDD is reduced to the same extent as the period to first ripeness. Therefore GpSensStress was taken as equal to RipeSensStress until it can be quantified properly.

The hastening of maturity by water stress

Maturity is defined as the stage when 95% of the fruits are ripened and is hastened by water stress. As in the case of the simulation of the timing of first ripening and the termination of leaf growth, the day degree requirement for maturity (MtDD) is reduced when the calculated SI indicates that water stress occurs. MtDD is decreased according to Eq. 6.14 on days when SI<0.95.

MtDD := MtDD - MtSensStress * StressDays 6.14

where: MtSensStress - Parameter representing the average reduction in MtDD on days with water stress (d °C Stress day^{-1})

MtSensStress is calculated according to Eq. 6.15 from the data of the three stressed treatments of the 1994/95 Pretoria stress trial.

$$\mathbf{MtSensStress = (MtDD_{NoStress} - MtDD_{Stressed})/StressDays} \quad \ldots\ldots\ldots\ldots \quad 6.15$$

where: $MtDD_{NoStress}$ - Day degrees at maturity for non-stressed tomatoes in the same trial (d °C)

$MtDD_{Stressed}$ - Day degrees at maturity for stressed tomatoes (d °C)

The MtSensStress parameter is calculated for the SW, WS and SS treatments of the 1992/93 stress trial in Pretoria as 0.6, 1.1 and 0.4 (d °C stress day^{-1}) respectively. The average value of 0.72 is used in TOMYIELD.

Maintenance respiration of fruit and the increased respiration rate due to the climacterium

A decrease in HDM close to maturity, as shown in Figure 4.2 in Chapter 4, is typical. This decrease is due to maintenance respiration which causes a reduction of assimilates towards the end of the growing season. The daily increment of maintenance respiration (NMRi) is simulated according to the same equation (Eq. 6.16) used in TOMSIM and TOMGRO.

If $T_{ave} > T_{ref}$ then

$$\mathbf{NMRi = MRr * HDM * Q10_c * exp\ (0.01 * (T_{ave} - T_{ref}))} \quad \ldots\ldots\ldots\ldots \quad 6.16$$

where: NMRi - Normal daily maintenance respiration for fruits (g d^{-1})

According to the Marble Hall and Pretoria data sets the maintenance respiration rate increases during fruit development even before fruit ripening. The relative growth stage variable, RelGrwStg, of which the value increases linearly from zero at planting to one at maturity, is calculated according to Eq. 6.17.

$$\mathbf{RelGrwStg = GDD / MtDD} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 6.17$$

where: RelGrwStg - Expired fraction of the development time towards maturity

In TOMYIELD maintenance respiration increment (MRi) is calculated according to

Eq. 6.18 and its value therefore increases from a fraction of about 0.23 of normal maintenance respiration at flowering to 1.0 or full maintenance respiration at maturity.

If GDD > FlDD then

MRi = NMRi * RelGrwStg 6.18

The input parameter MRr was determined by running the model with different values for MRr, starting with the value of 0.01 used by both TOMSIM and TOMGRO. The measured and simulated data fitted satisfactorily with an MRr value of 0.005 g dry matter respired g^{-1} HDM d^{-1}.

As described in Chapter 2, the climacterium is a sudden increase and a subsequent decrease in respiration rate which starts with the onset of ripening. This increased respiration during ripening is simulated in addition to the normal respiration according to the same basic formula as shown in Eq. 6.16. Instead of MRr, a new parameter, ClimRr was defined to indicate the respiration rate due to the climacterium. While in TOMSIM and TOMGRO respiration of individual ripened fruits is simulated with Eq. 6.16, in TOMYIELD the respiration of all green and ripened fruits is simulated. A modification had to be introduced to represent the increasing percentage of ripened fruits towards full ripeness. As a first approach, a linear increase in ripeness is assumed in calculating the RipenessFactor with Eq. 6.19.

If GDD > RipeDD then

RipenessFactor = (GDD - RipeDD) / (MtDD - RipeDD) 6.19

where: RipenessFactor - Variable representing the fraction of fruits that are ripened

The ClimRr which was established by running the model with different values was found to be 0.013 for the cultivar Brigade (Pretoria, 1995 data) and 0.017 for UC82 (Marble Hall data).

Assimilate partitioning

The partitioning of assimilates is the same as for NEWSWB. Priority for assimilates is assigned firstly to fruits if present, then to roots and the remainder is available for leaf and stem growth. The fraction of the assimilates allocated to fruits is increased from zero before flowering to one (all assimilates allocated to fruits) at the end of the transition period between vegetative and reproductive growth. The model allocates a fixed fraction to the roots until the maximum rooting depth is reached. Under conditions of water stress, 50% of the assimilates normally allocated to leaf growth, are re-allocated to root growth, while the other 50% is allocated to stem growth. This results in a smaller canopy which is a realistic water stress response.

The partitioning factors indicate the fraction of the daily dry matter increment which is allocated to the different plant organs. The following partition parameters are used:

* Fruit partitioning fraction (f_{fruit});
* Root partitioning fraction (f_{root});
* Vegetative fraction (f_{top});
* Leaf fraction (f_{leaf}); and
* Leaf stem partition parameter (LSPP).

Partitioning to fruits:

The first priority for assimilates is fruits. Fruit partitioning is calculated according to Eq. 6.20.

If GDD > FIDD then

$$f_{fruit} = (GDD - FIDD) / GtpDD \qquad 6.20$$

The amount of assimilates allocated to fruits is calculated according to Eq. 6.21.

hdmi = dmi * f_{fruit} 6.21

where: hdmi - Daily harvestable dry matter increment of assimilates allocated to fruits (kg m^{-2})

dmi - Daily increment of assimilates produced (kg m^{-2})

Partitioning to roots:

During the period before flowering and before the maximum rooting depth (RDmax), is attained, a constant fraction (f_{root}) of the available assimilates is allocated to root growth. Another variable, fr, is used in the model in order to describe the variable value of the fraction to the roots during the period after flowering. Before flowering, while roots grow at a fixed rate, depending on availability of assimilates, fr equals f_{root}. From flowering until maximum rooting depth is reached, fr declines linearly to zero as a result of the higher priority assigned to fruit. If insufficient assimilates are available due to water stress, priority is assigned to fruits and fr equals zero.

Partitioning to vegetative dry matter:

The remaining assimilate, after fruit and root growth are "satisfied", is available for vegetative growth and is calculated according to Eq. 6.22. This vegetative dry matter increment (vdmi) is partitioned to leaf and stem growth. The fraction allocated to leaves (f_{leaf}) is calculated from the leaf stem partition parameter (LSPP) according to Eq. 6.23.

vdmi = dmi - hdmi - (fr * dmi) 6.22

where: vdmi - Top (vegetative i.e. leaves and stem) dry matter (kg m^{-2})

fr - Fraction of assimilates partitioned to roots

$f_{leaf} = 1 / (1 + LSPP * VDM)^2$ 6.23

where: VDM - Vegetative (leaves + stem) dry matter (kg m^{-2})

LSPP is an input parameter which is determined from experimental data according to Eq. 6.24. LSPP is calculated from data of several growth analyses as indicated in Figure 6.6.

$$LSPP = [(SLA * VDM / LAI) - 1] / VDM \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 6.24$$

According to Figure 6.6 the value of LSPP is initially high but decreases sharply during the early part of the season. After about twenty days after transplanting, which also indicates the end of the seedling stage, LSPP becomes fairly constant for the rest of the season.

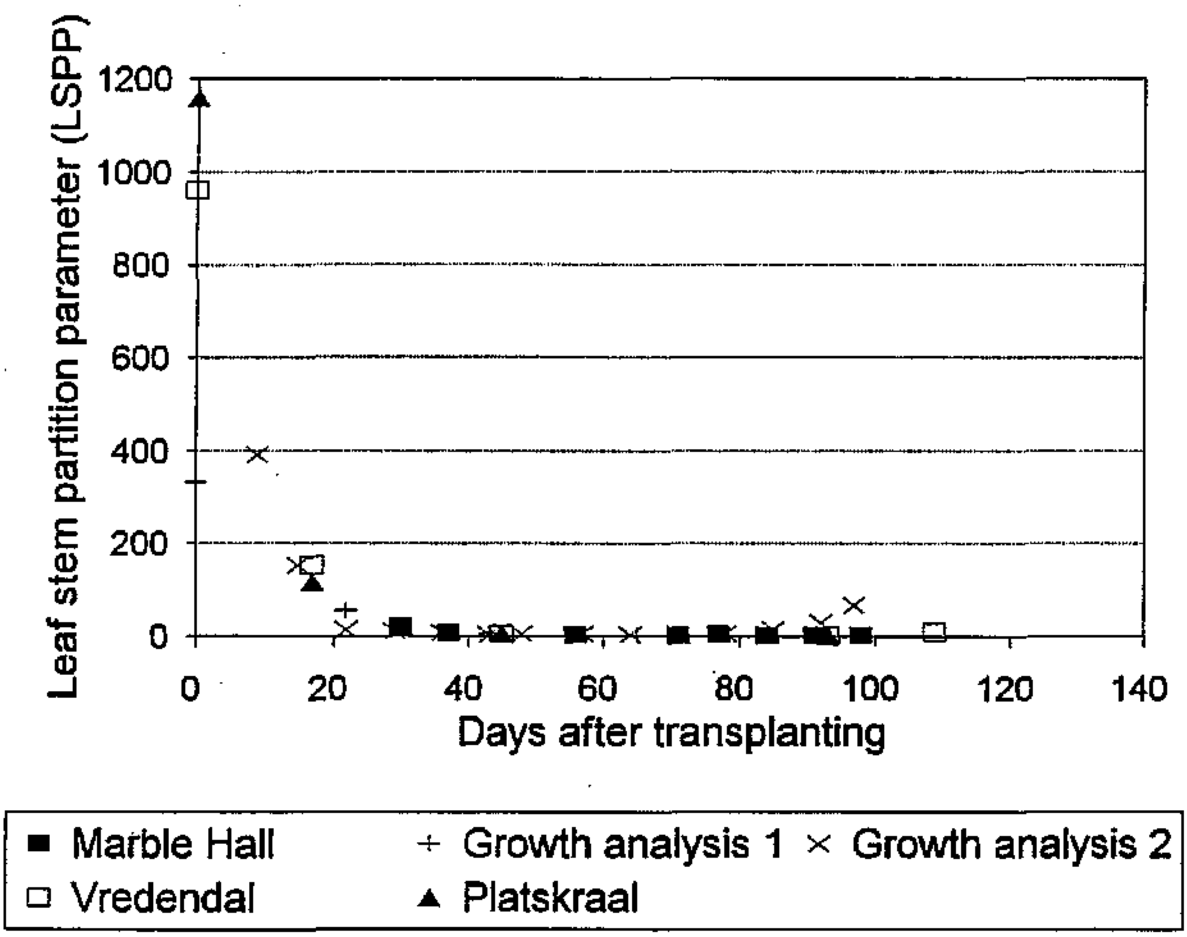


Figure 6.6 Leaf stem partition parameter (LSPP) calculated from several growth analyses.

As in NEWSWB, a constant value for LSPP is used throughout the season. The average LSPP of 3.9 was calculated from the Marble Hall and Pretoria data sets by ignoring the data of the first 20 days. Constant values for LSPP (3.9 $m^2 kg^{-1}$) and SLA (12.4 m^2 leaves kg^{-1} leaf) were used in order to evaluate the simulations of LAI for the Vredendal and Platskraal data sets. LAI is calculated according to Eq. 6.25 from the accumulated dry matter of leaves and SLA.

LAI = LDM * SLA **6.25**

where: LDM - Leaf dry matter (kg m^{-2})

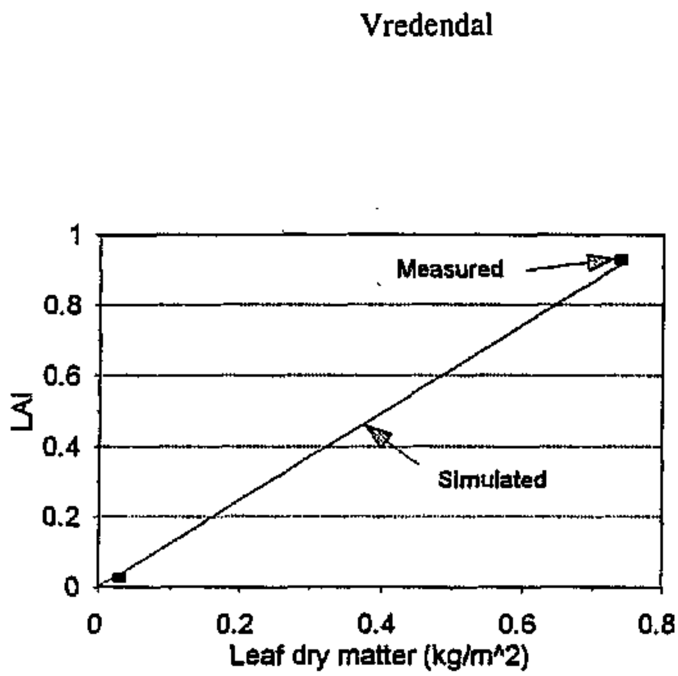
LAI calculated using Eq. 6.25 for different masses of vegetative dry matter, is compared with measured LAI in Figure 6.7. LAI is predicted reasonably well from vegetative dry matter. The single Platskraal data point, which is far above the simulated line, is probably due to measurement or sampling error, because it does not fit the tendency of the measured curve for the Platskraal data either.

The partitioning process is summarised in Figure 6.8.

Leaf senescence

The commencement of senescence has not been modified in TOMYIELD. Senescence of leaves of a given age group still commences when the maximum leaf age (GDD > MaxLeafAge) is achieved.

In NEWSWB and in TOMYIELD the ageing of leaves is accelerated on days when the crop is subjected to water stress. This is done by calculating a variable "water stress factor" (wsf) according to Eq. 6.26 from the stress index (SI), which is calculated in the soil unit.



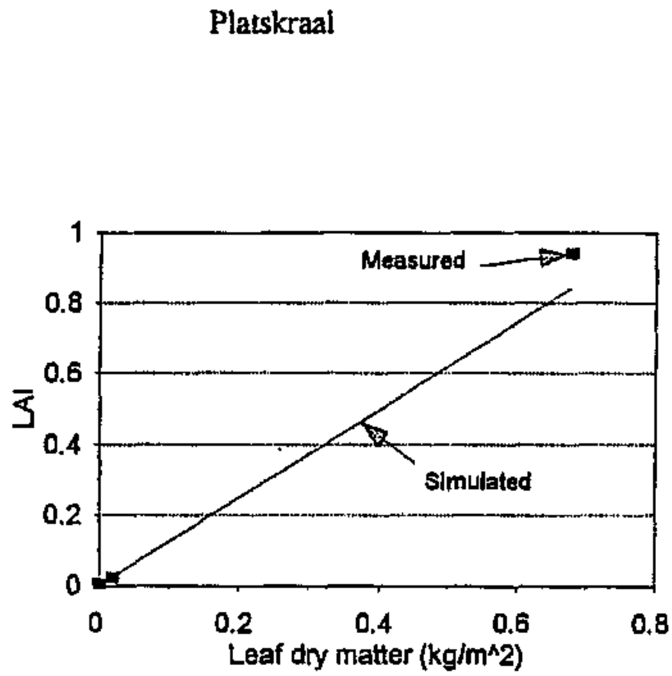


Figure 6.7 Measured versus simulated LAI for the period before the onset of senescence for the Vredendal and Platskraal growth analyses.

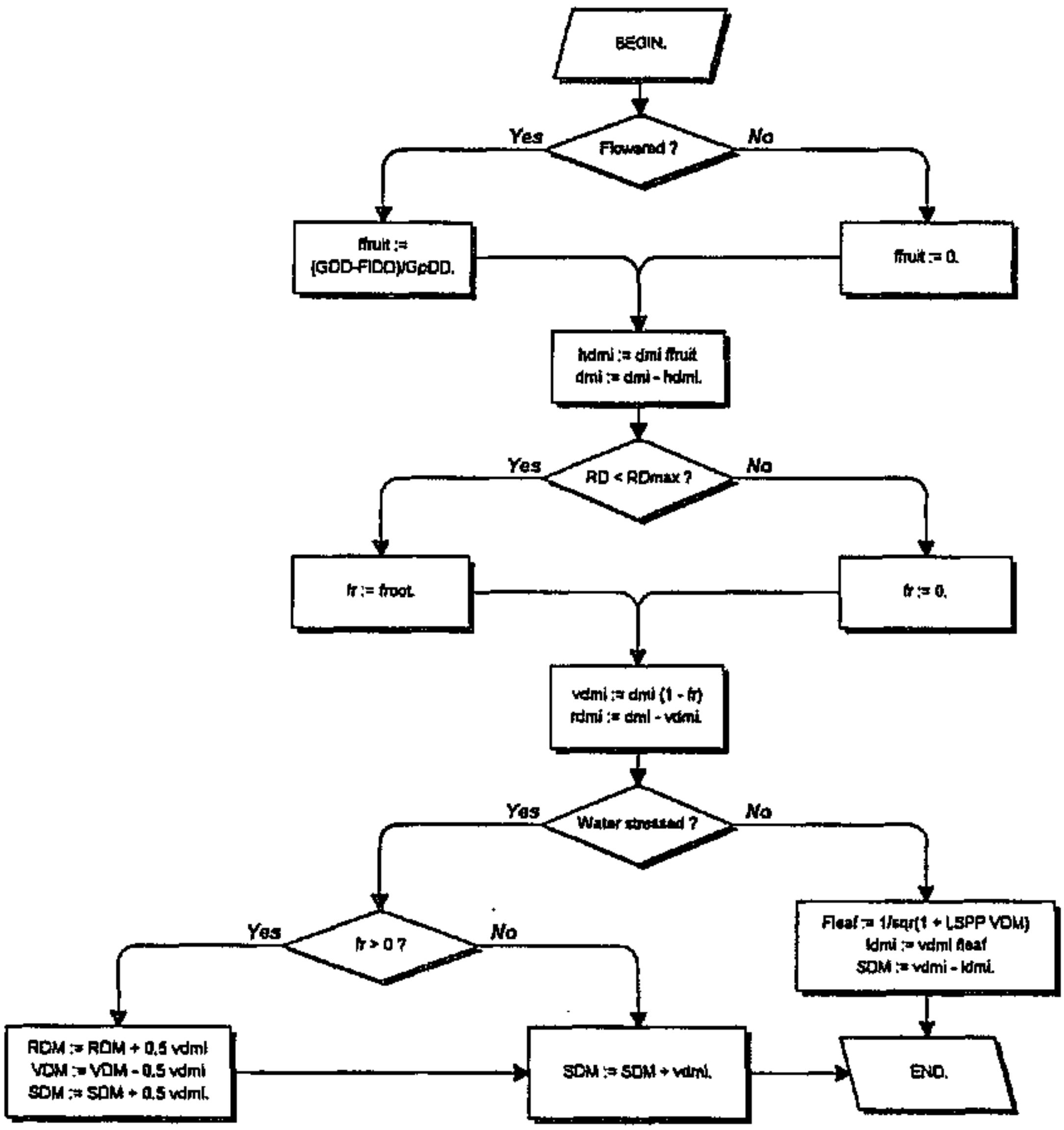


Figure 6.8 Assimilate partitioning in NEWSWB and TOMYIELD.

If SI < 0.95 then wsf = 1 / SI

If wsf > 2 then wsf = 2 . . . . 6.26

The age of all LAI grown on a given day is simulated by adding the daily growing day degree increment (gddi), which is modified by the wsf (Eq. 6.27) when water stress occurs on the given day. This implies that leaf ageing is accelerated when water stress occurs, but this does not influence the termination of leaf growth.

DailyLAIAge[k] = DailyLAIAge[k-1] + gddi * wsf 6.27

where: DailyLAIAge[k] - Age of LAIAge group (d°C)

DailyLAIAge[k-1] - Age of the LAIAge group on the previous day (d °C)

Senescence rate

NEWSWB over estimated senescence rate by senescing all leaves of a certain age group completely as soon as the maximum leaf age (parameter: MaxLeafAge in day degrees) is reached. According to Van Laar *et al.* (1992) senescence rate of tomatoes is partly due to leaf age and partly to self shading. The relative death rate (fraction of leaves which senesce per day) due to self shading is taken as zero for LAI values lower than 4 and is increased linearly to 0.03 when LAI reaches 8 m^2 leaves m^{-2} soil. This means that leaves of a certain age group will senesce in TOMSIM at a rate of zero to 3 percent per day depending on shading. Senescence rate due to self shading is simulated in TOMYIELD as a function of fractional interception for evaporation (FI_{evap}) according to Eq. 6.28.

SenesceRate = ShadeSenesceCoef * FI_{evap} 6.28

where: SenesceRate - Leaf senescence rate (d^{-1})

ShadeSenesceCoef - Empirical constant parameter indicating the relationship between senescence rate and FI_{evap} (d^{-1})

The value of 0.05 for the empirical constant, ShadeSenesceCoef, was found by running the model with values increasing from 0.03, which was used by Van Laar *et al.* (1992), until the decrease in simulated LAI and FI matched the measured values for the

Loskop data set.

The daily senesced LAI increment ($Senesci_k$) is calculated according to Eq. 6.29 for each age group of leaves.

$$\mathbf{Senesci_k - SenescRate * DailyLAI_k} \quad \ldots \quad \mathbf{6.29}$$

where:	$Senesci_k$	-	The senesced LAI increment of the LAI which was grown on a specific day as indicated by the counter k
	$DailyLAI_k$	-	LAI which was grown on a specific day as demarcated by the counter k

The result of the modification is that not all the leaf area of the particular age group (as in NEWSWB), but only a fraction of it senesces on each day after senescence commences. The total senescence for a day is calculated by summing all the senesced LAI increments for a given day.

Storage of assimilates in the leaves

The ratio between leaf area and leaf dry mass (SLA) is considered to be a crop specific constant in NEWSWB. Data from all the localities (Figure 6.9) indicates a decrease in SLA during the season.

This data confirms that assimilate storage in leaves occurs. This is accounted for in TOMSIM. The data indicates that more assimilates are stored in the leaves towards the end of the season. This is probably due to the reduced demand for assimilates as leaf growth stops and proportionally more and more fruits mature. This is also in agreement with results from Heuvelink & Bertin (1994). TOMYIELD therefore decreases SLA during the season according to Eq. 6.30.

$$\mathbf{SLA_k = SLA_{k-1} + SLACoef * k} \quad \ldots \quad \mathbf{6.30}$$

where	SLA_k	-	Specific leaf area for day k ($m^2\ kg^{-1}$)
	SLA_{k-1}	-	Specific leaf area for the day before day k ($m^2\ kg^{-1}$)
	SLACoef	-	Daily decrease in SLA during the season ($m^2\ kg^{-1}\ d^{-1}$)

k - A counter indicating days after planting (d)

The influence of the decreasing SLA during the season on LAI is that the leaf area of a given mass of leaves erroneously decreases over time which results in a decrease in FIT. This is prevented by the daily updating of LAI according to Eq. 6.31.

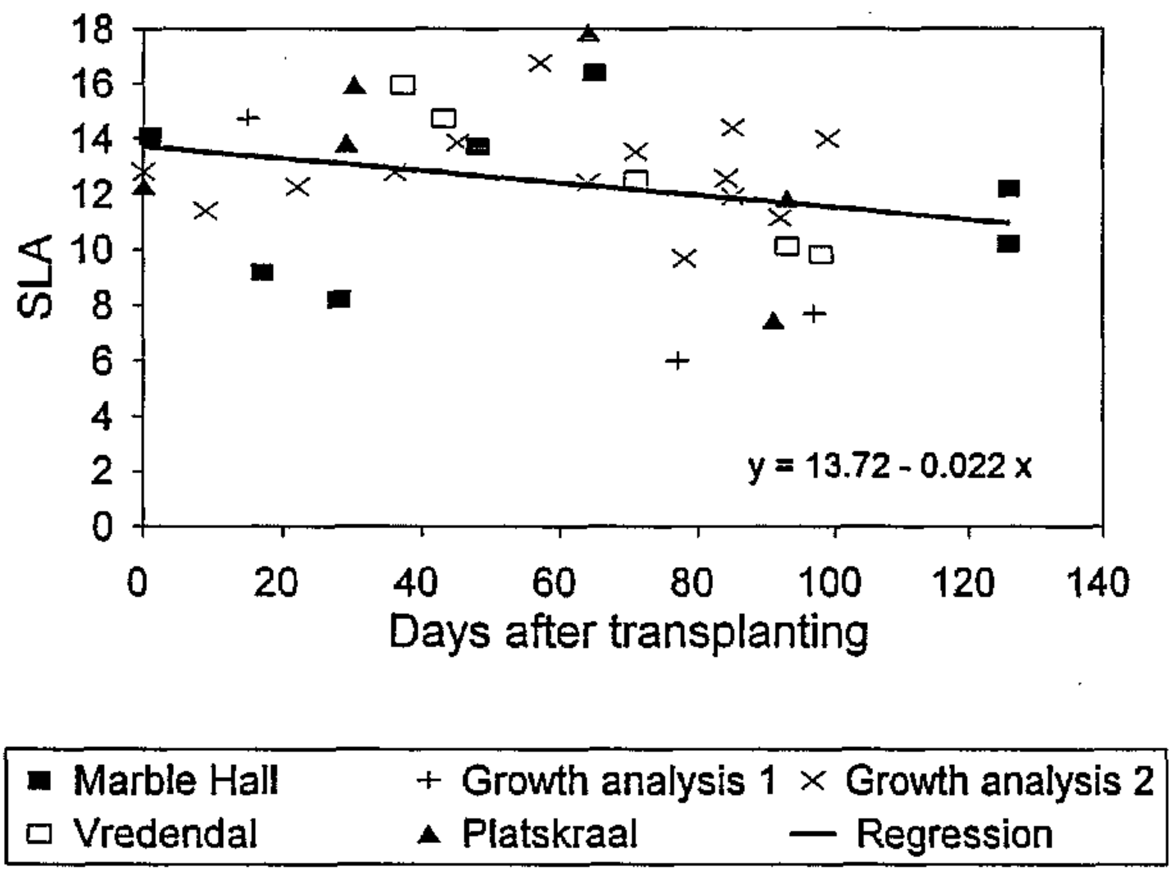


Figure 6.9 Data from all growth analyses showing the declining tendency in SLA during the season.

$LAI_k = LAI_k * SLA_{k-1} / SLA_k$ **6.31**

where: LAI_k - Leaf area index on day k after planting (Eq. 6.28) (m^2 kg^{-1})

Root growth

Root dry matter is increased by accumulating the assimilates which are partitioned to roots. The depth of root growth is simulated, as a function of root dry matter, according to Eq. 6.32. Root growth is stopped as soon as the maximum rooting depth is reached.

$RD = RDM^{0.5} * RGR$ **6.32**

where: RD - Root depth (m)
RDM - Cumulative root dry matter (kg m^{-2})
RGR - Root growth rate (m^2 $kg^{-0.5}$)

Fruit Growth

Although the simulation of fruit growth is mostly empirical, it attempts to simulate at least the basic processes of fruit water loss and gain and the fixing, dissolving and respiration losses of fruit solids which influence the final percentage of soluble solids in tomatoes. The different components and processes are defined below while the approach followed is demonstrated in Figure 6.10.

Components:

*	SolHDM	the soluble dry matter in the fruit paste;
*	FixedHDM	the fixed parts in the fruit paste
*	Seed&PeelHDM	the dry matter in seeds and peels
*	Fruit water	all of the water contained in the fruit

Processes (Figure 6.10):

* Normal respiration loss - the loss of dry matter due to respiration during the period before ripening;
* Climacteric respiration loss - the loss of dry matter due to respiration during ripening;
* Assimilate import - the import of newly produced assimilates into fruits;
* Translocation import from senesced leaves - the import of translocated assimilates from senesced leaves into fruits;
* Water import - The import of water from roots into fruits;
* Fixing - the process of fixing soluble dry matter into fixed dry matter;
* Growth - the growth of seeds and peel by utilizing fixed dry matter;
* Dissolving - the dissolving of fixed dry matter to soluble dry matter; and
* Transpiration loss - the loss of water through the process of transpiration.

The daily time step simulation of fruit growth is discussed according to the flow diagram in Figure 6.11.

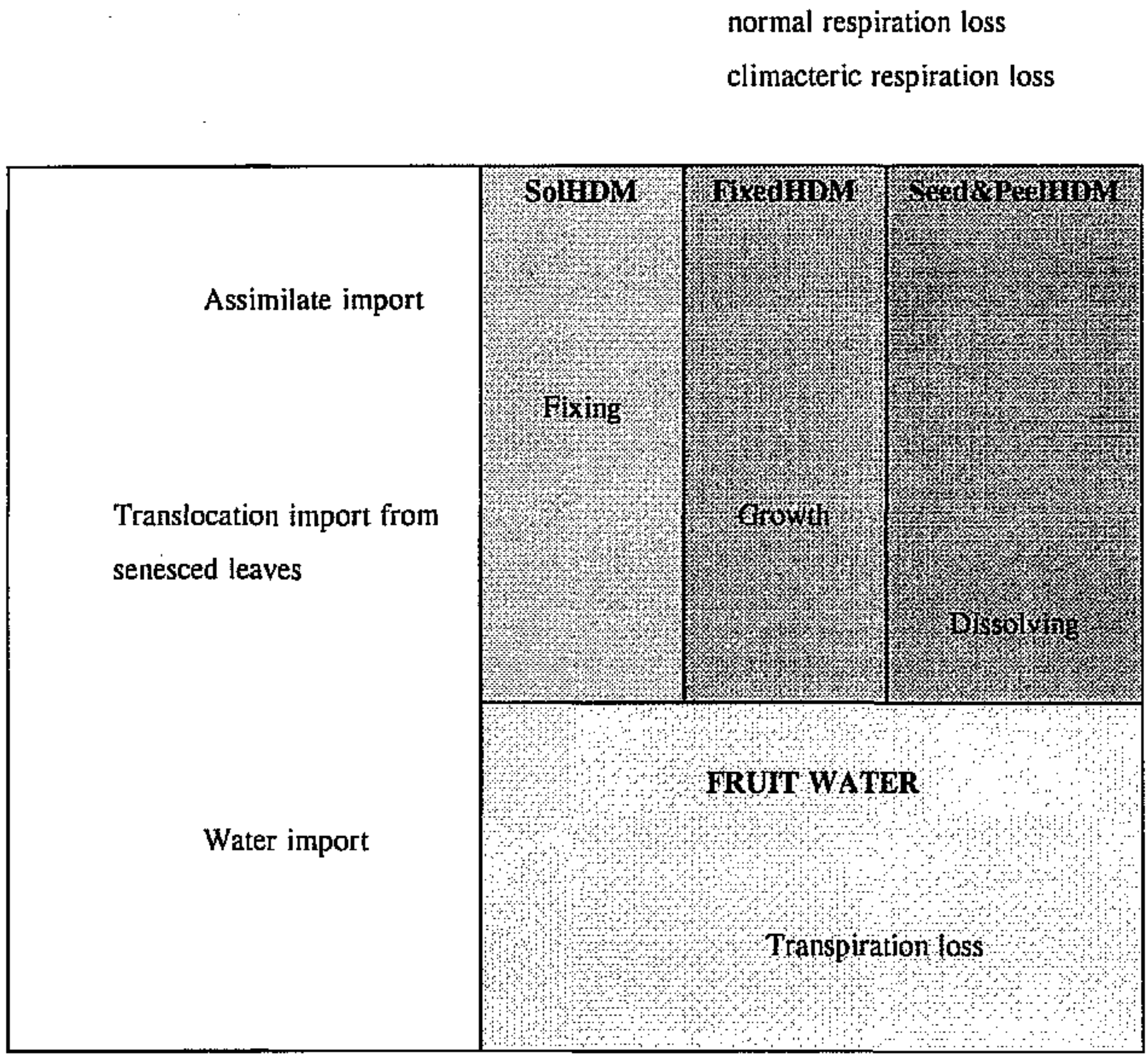


Figure 6.10 The different fruit components and processes simulated by TOMYIELD.

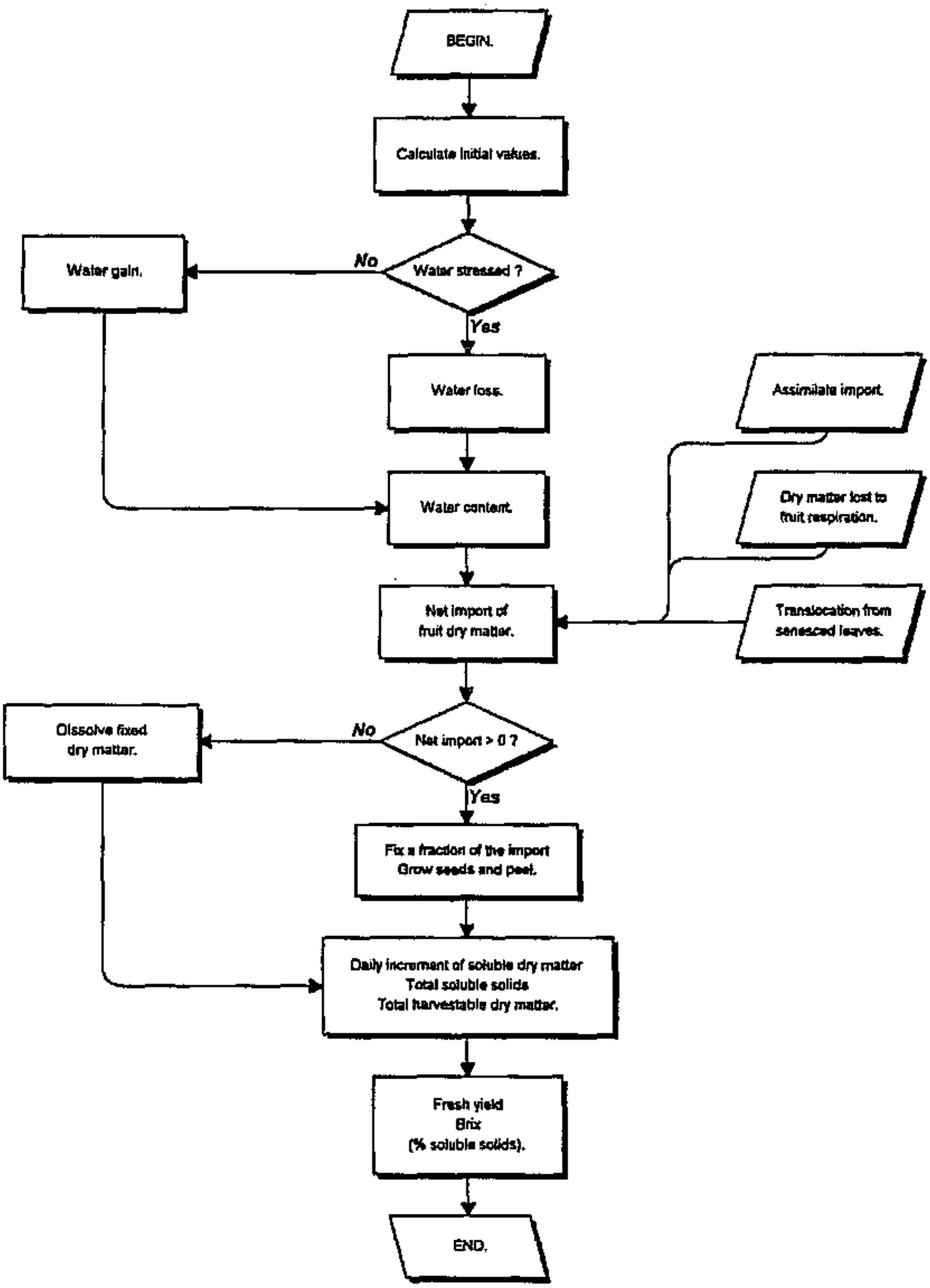


Figure 6.11 Flow diagram of the simulation of fresh yield and brix.

Calculation of initial values for variables

On the first day of flowering the initial values are calculated according to Eq. 6.33 to 6.38 for all the variables used in the simulation of fresh yield and brix.

HWC = MaxHWC 6.33

Where: HWC - Harvestable (fruit) water content (gravimetric fraction)
MaxHWC - Average water content of tomatoes which were not stressed (fraction)

HDM = Transl * SDM 6.34

Where: Transl - Parameter indicating the fraction of stem dry matter translocated to harvestable dry matter on day of first flowering
SDM - Stem dry matter (kg m^{-2})

FreshYield = HDM *10 / (1 - HWC) 6.35

Where: 10 - Factor to convert from kg m^{-2} to t ha^{-1}

SolHDM = FreshYield * InitBrix / 100 . . . . 6.36

Where: SolHDM - Soluble pool of harvestable dry matter (kg m^{-2})
InitBrix - Parameter indicating the initial brix of tomatoes which were not stressed

SeedPeelHDM = InitSeedPeelFrac * (HDM - SolHDM) 6.37

Where: SeedPeelHDM - Harvestable dry matter of seeds and peels (kg m^{-2})
InitSeedPeelFrac - Parameter indicating the initial fraction of fixed HDM that is part of seeds and peels (kg m^{-2})

FixedHDM = HDM - SolHDM - SeedPeelHDM 6.38

Where: FixedHDM - All HDM excluding SolHDM (kg m^{-2})

Daily fruit water loss and gain

The water content (HWC) of fruits is simulated by starting off with an initial water content equal to the maximum fruit water content (MaxHWC). This parameter is measured as 0.94 which is the average fruit water content found in fruits which were never stressed.

The influence of the level of the simulated fruit water content on the rate of water loss or gain is simulated through the use of two variables, RelHwcGainRate and RelHwcLossRate. The values for RelHwcGainRate and RelHwcLossRate as shown in Figure 6.12 are calculated according to Eqs. 6.39 and 6.40 an depend on the level of simulated water content in relation to the maximum and minimum limits.

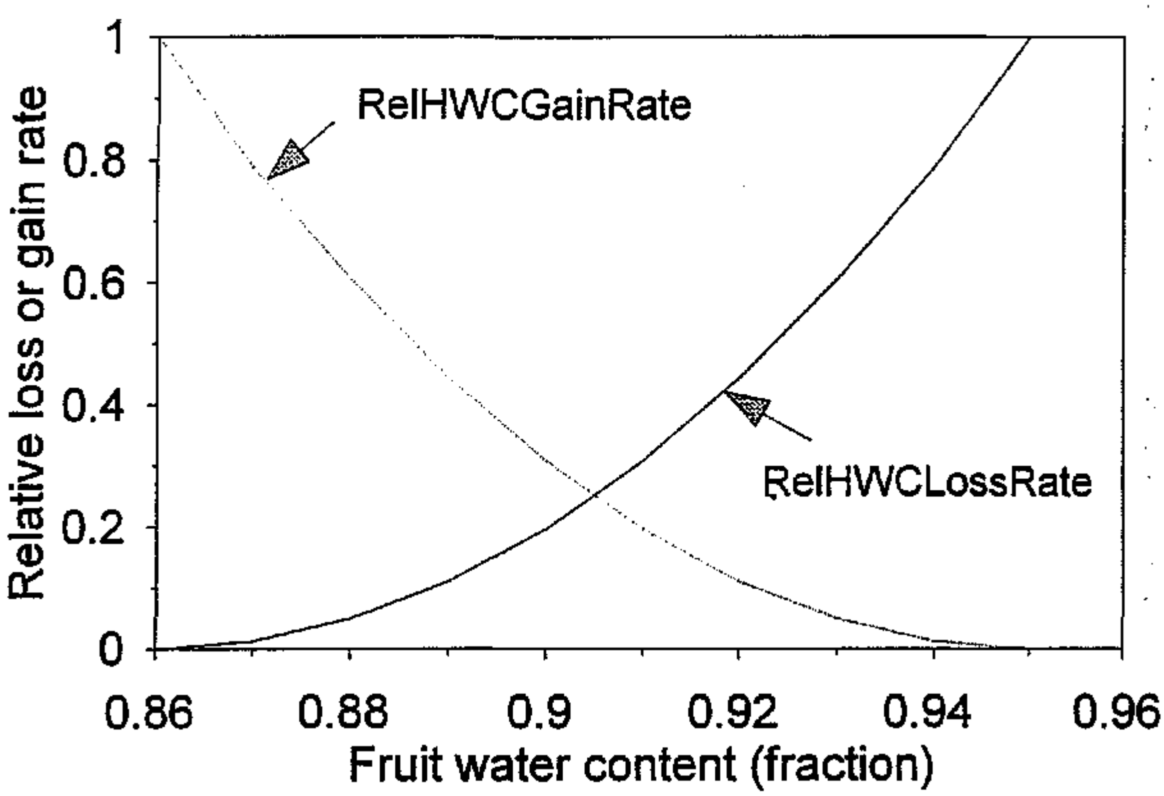


Figure 6.12 RelHwcGainRate and RelHwcLossRate with different simulated values of HWC.

RelHwcGainRate = (MaxHWC - HWC) / 0.5*(MaxHWC - MinHWC) . 6.39

where: RelHwcGainRate - Relative fruit water content gain rate (d^{-1})

HWC - Simulated fruit water content

MaxHWC - Maximum fruit water content

MinHWC - Minimum fruit water content

RelHwcLossRate = (HWC - MinHWC) / 0.5 * (MaxHWC - MinHWC) . 6.40

where: RelHwcLossRate - Relative fruit water content loss rate (d^{-1})

The influence of the timing of stress in relation to the development stage of the crop is accounted for by the multiplication with the variable RelGrwStg, which is calculated according to Eq. 6.41.

RelGrwStg = GDD / MtDD 6.41

The calculated value of RelGrwStg increases from zero at planting to one at maturity and is ± 0.125 at start of flowering.

The daily fruit water increment is calculated according to Eqs. 6.42 and 6.43 for stressed and non-stressed conditions respectively.

If SI < 0.95 then

hwci = -HwcLossCoef * RelHwcLossRate * RelGrwStg / SI 6.42

where: hwci - Daily increment in future fruit water content (fraction)

HwcLossCoef - Average relative rate of water loss after relief of water stress

If SI > 0.95 then

hwci = HwcGainCoef * RelHwcGainRate * RelGrwStg 6.43

where: HwcGainCoef - Average relative rate of water gain after relief of water stress (d^{-1})

The HWC is updated daily by cumulating the daily values of hwci. The simulated value for HWC is limited to the range of water contents found in tomato fruits. The maximum and minimum water contents are indicated by the parameters MaxHWC and

MinHWC and values of 0.96 and 0.86 are used.

Daily net import of fruit dry matter

The daily net import of fruit dry matter is calculated by adding the daily assimilates partitioned to harvestable dry matter (hdmi) and the dry matter translocated to fruits from senesced leaves (TranslTDMi) and by subtracting the dry matter lost to fruit respiration (hdmRespi). This done according to Eq. 6.44.

NettHDMi = hdmi + TranslTDMi - hdmRespi 6.44

where:	NettHDMi	-	Net daily harvestable dry matter increment (kg m^{-2})
	hdmi	-	Harvestable dry matter increment from partitioning of assimilates (kg m^{-2})
	TranslTDMi	-	Translocated dry matter from senesced leaves (kg m^{-2})
	hdmRespi	-	Dry matter lost to respiration (kg m^{-2})

Redistribution of dry matter within fruits

The basic processes of fixing imported dry matter, or remobilising fixed dry matter is empirically simulated through the following three basic processes:

* Fixing of dry matter in the FixedHDM pool;
* The growth of seeds and peels in the SeepPeelHDM pool; and
* The dissolution of fixed dry matter from the FixedHDM pool.

All imported dry matter is added to the soluble pool (SolHDM). Respiration losses are also taken from the soluble pool. In order to simplify the simulation, it is assumed that only on days when there is a net import of dry matter, dry matter is fixed and seeds and peel grown. On days with a negative net import, no fixing or seed and peel growth occurs and fixed dry matter is dissolved and added to the pool of soluble solids again.

Fixing of dry matter in the FixedHDM pool

The parameter hdmFixRate is defined as the fraction of a positive nett import of dry matter which is fixed. The daily increment of fixed harvestable dry matter (FixHDMi) is calculated according to Eq. 6.45.

FixHDMi = NettHDMi * hdmFixRate 6.45

where: FixHDMi - Daily increment of fixed fruit solids (kg m^{-2})
hdmFixRate - Fraction of nett import of solids which are fixed (kg m^{-2})

The growth of seeds and peels in the SeepPeelHDM pool

The seeds and peel are grown from the pool of fixed harvestable dry matter by allocating a fraction of the daily FixHDMi (Eq. 6.46). This process is considered to be irreversible.

If NettHDMi > 0 then

SeedPeelHDMi = FixHDMi * SeedPeelFrac 6.46

where: SeedPeelHDMi - Daily dry matter growth in seeds and peel (kg m^{-2})
SeedPeelFrac - Fraction of nett import fixed (kg m^{-2})

The dissolving of fixed dry matter from the FixedHDM pool

The dissolving of fixed solids, which is assumed to happen only when the daily import of harvestable solids is negative, is calculated according to Eq. 6.47. It is assumed that dissolution will be proportional to the size of the complete pool of fixed soluble solids and a parameter HDMDissFrac is defined as the fraction of the fixed pool which will dissolve if NettHDMi becomes negative.

If NettHDMi < 0 then

hdmDissi = HDMDissFrac * FixHDMi 6.47

where: hdmDissi - Daily increment of dissolved dry matter (kg m^{-2})
HDMDissFrac - Fraction of fixed dry matter which dissolves when

NettHdmi < 0

Total soluble solids

The total soluble solids are simulated by adding the daily increments of soluble harvestable dry matter (SolHdmi), which is calculated according to Eq. 6.48.

SolHdmi = NettHDMi - FixHDMi + hdmDissi 6.48

where: SolHDMi - Daily soluble harvestable dry matter increment (kg m^{-2})

Simulation of total harvestable dry matter

The total harvestable dry matter (HDM) is simulated by adding daily increments of nett harvestable dry matter (NettHDMi).

Simulation of fresh yield and brix (% soluble solids)

The variable FreshYield is calculated from simulated total harvestable dry matter (HDM) and the harvestable water content (HWC) according to Eq. 6.49.

FreshYield = 10 * HDM / (1 - HWC) 6.49

where: 10 - Factor to convert from kg m^{-2} to t ha^{-1}

The variable brix indicates the gravimetric content of soluble solids of the fruit. Brix is calculated from simulated FreshYield and soluble harvestable dry matter (SolHDM) according to Eq. 6.50.

brix =SolHDM / FreshYield * 100 . . . . 6.50

The results of simulated versus measured yield and brix for the various trials will be presented under item 6.6 (model evaluation)

6.4 Modification to the soil water balance routine to enable simulation of drip irrigation

In NEWSWB, as described by Benadé *et al.* (1995), it is assumed that an overhead irrigation system is used and therefore precipitation and irrigation can be summed before simulation of interception, infiltration and evaporation. Because all but the Marble Hall trial were drip irrigated, and only a portion of the soil surface was wetted by the irrigation, while precipitation wets the complete surface, modifications were required to the soil water balance routine in TOMYIELD. The following modifications were introduced:

* Separate infiltration simulation for precipitation and irrigation;
* No canopy interception of drip irrigation; and
* The simulation of evaporation with incomplete wetting of the soil surface

Separate infiltration simulation for precipitation and irrigation

Although a mechanistic simulation model was developed by Annandale (1991) for the simulation of a two dimensional water balance, the incorporation of such a model into NEWSWB would be complex and was not attempted during this project. A more simple approach was taken to solve the problem temporarily.
In TOMYIELD the infiltration of precipitation is simulated according to the normal procedure as described by Benadé *et al.* (1995).

Infiltration of irrigation, however, is simulated as follows: a new parameter, SurfaceWetted, indicates the fraction of the soil surface which is wetted by the irrigation system and the lateral movement of applied water. For sprinkle irrigation which applies irrigation to the whole surface, SurfaceWetted = 1.0, while the value for drip irrigation systems depends on soil type (hydraulic conductivity) and dripper spacing. With a line spacing of 1.5 m and a wetted strip of 0.4 m along the line, SurfaceWetted = 0.4/1.5 = 0.267.

During full surface infiltration, if the irrigation is sufficient, the amount of water needed to fill the evaporation layer to field capacity is calculated according to Eq. 6.51

$$\mathbf{IrrInf_{Evap} = (FcWc_{Evap} - Wc_{Evap})*\rho_w*dz} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{6.51}$$

where:	$IrrInf_{Evap}$	-	Irrigation infiltrated into the evaporation layer (mm)
	$FcWc_{Evap}$	-	Field water capacity of the evaporation layer (volumetric fraction)
	Wc_{Evap}	-	Water content of the evaporation layer (volumetric fraction)
	ρ_w	-	Density of water (kg m^{-3})
	dz	-	Depth of the evaporation layer (m)

Eq. 6.51 has been modified to reduce the amount of infiltration proportionally to allow for the fact that irrigation water can only fill the fraction of the evaporation layer which is wetted. This implies that even if there is still a deficit in the non-wetted part of the evaporation layer, the additional irrigation water will be passed on as infiltration to the deeper layers. The infiltration of irrigation for the evaporation layer is thus calculated according to Eq. 6.52.

$$\mathbf{IrrInf_{Evap} = (FcWc_{Evap} - Wc_{Evap})*\rho_w*dz*SurfaceWetted} \quad \ldots\ldots\ldots \quad \mathbf{6.52}$$

where:	SurfaceWetted	-	Fraction of the soil surface which is wetted by the irrigation and sideways movement of soil water in the evaporation layer

Infiltration of irrigation for the deeper layers is calculated according to the normal procedure. Although this procedure is not very mechanistic, it is considered to be a reasonable assumption in the absence of a two or three dimensional simulation of water movement and root distribution and it is considered to be a temporary solution.

Interception of irrigation by the canopy

In NEWSWB the maximum interception was calculated according to Eq. 6.53 and the assumption was made that the complete canopy was wetted by both precipitation and irrigation.

$$\mathbf{MaxInterDOY = FI_{evap} * CanopyInt} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{6.53}$$

where:	MaxInterDOY	-	Daily calculated maximum amount of water in mm that can be intercepted by the canopy (mm)
	FI_{evap}	-	Daily simulated fractional interception of solar radiation
	CanopyInt	-	Parameter indicating the maximum intercepted amount for a full canopy of the specific crop (mm)

The modified simulation of interception is based on the assumption that if the canopy is not wetted completely, the daily maximum interception should be reduced proportionally to the fraction of the canopy which is wetted during irrigation. A new parameter, CanopyWetted, is therefore created to indicate the fraction of the canopy which is wetted during irrigation. If the whole canopy is not wetted during irrigation, the daily maximum interception is reduced by Eq. 6.54.

MaxIrrIntDOY = MaxInterDOY * CanopyWetted 6.54

where:	MaxIrrIntDOY	-	Daily calculated maximum amount of irrigation that can be intercepted by the canopy (mm)
	MaxInterDOY	-	Daily calculated maximum amount of water which can be intercepted by the canopy (mm)
	CanopyWetted	-	Fraction of the canopy which is wetted during irrigation

Evaporation with incomplete wetting of the soil surface

In TOMYIELD the normal evaporation simulation procedure of NEWSWB is applied for evaporation following precipitation, while evaporation of irrigation water is simulated by the modified procedure described below.

In NEWSWB the potential evaporation from a completely wet soil surface is calculated according Eq. 6.55.

PotentialEvap = (1- FI_{evap}) * PET 6.55

where:	PotentialEvap	-	Potential evaporation from a completely wet soil surface (mm d^{-1})
	FI_{evap}	-	Fractional interception of solar radiation for evaporation
	PET	-	Potential evapotranspiration (mm d^{-1})

If irrigation water is applied by a drip irrigation system to the shaded area under the plant canopy, evaporation will be reduced due to a smaller evaporating area and an increased fractional interception (FI_{evap}) of the wetted area, compared to the average FI of the field. While the existing model simulates the water balance in only one dimension (depth), the real situation is clearly three dimensional, with 1.25 to 2 m wide crop row spacing and drippers spaced at 0.3 to 0.6 m apart. The surface layer should at least be divided into an irrigated area and a non-irrigated area. The infiltration and evaporation of each portion should be simulated separately. Modifications of this nature will require major modifications to the database of the model and could not be introduced at this point in time. The problem is solved by the development of a fairly accurate empirical approach, which does not complicate the input data requirements, and does not involve modifications to the data base. If surface wetted is less than one, evaporation of irrigation water is reduced in proportion to the fraction of the soil surface which is wetted and as a function of the fractional interception for evaporation (Eq. 6.56). The term $(1\text{-}FI)^2$ is an empirical factor which represents the influence of the fact that the portion of the soil surface which is wetted area is in the shaded area and is not exposed normally to the non-intercepted radiation.

If SurfaceWetted < 1 then

PotentialEvap = $(1 - FI_{evap})^2$ * PET * SurfaceWetted 6.56

In order to allow for the "complete" drying off of the non-irrigated soil surface after precipitation (through normal evaporation), it is assumed that if sufficient time is allowed for the normal evaporation, the soil surface will be dry and the evaporation rate will become insignificant. Only after this period of normal evaporation (FullEvapPeriod) has elapsed after each occurrence of precipitation, will evaporation be simulated according to the procedure for irrigation again. The required period for normal evaporation will be a function of evaporative demand, soil type and crop canopy and could be calculated. In this empirical approach, however, a parameter, FullEvapPeriod, is introduced and a value of three days is used. This value was established by simulating the water content of the evaporation layer for the various trials. It was found that for the soil-climate-crop systems of this project, three days was sufficient to allow for drying off of the water content to below permanent wilting point.

In SWB the evaporation rate is based on both evaporative demand and soil water supply. This procedure (Eq. 6.57) reduces evaporation rate when the water content of the evaporation layer decreases to below permanent wilting point, and evaporation ceases once air dry water content is reached. This procedure is also used in TOMYIELD.

If WC < PWPWC then

$$\text{Evap} = \text{PotentialEvap} * ((\text{WC} - \text{ADWC})/(\text{PWPWC} - \text{ADWC}))^2 \quad \ldots\ldots\ 6.57$$

Where: WC - Water content (volumetric fraction)
ADWC - Air dry water content (volumetric fraction)
PWPWC - Permanent wilting point water content (volumetric fraction)

6.5 Input parameters and data required

The parameters needed to run TOMYIELD are those used by SWB and the additional parameters which were created in the development of TOMYIELD. The parameters are listed below.

SWB crop parameters:

KC	Tb	RUE	Total dry matter at emergence
FlDD	DWR	Transl	Minimum leaf water potential
EmDD	Tcutoff	SI	Maximum transpiration
GpDD	Leaf senescence	RDmax	
MtDD	Canopy storage	RGR	
SLA	LSPP	f_{root}	

Additional crop parameters required by TOMYIELD:

InitBrix	Maximum brix	Minimum brix	InitSeedPeelFrac
SeedPeelFrac	EndSeedIDDFrac	hdmFixRate	HDMDissFrac
RipeDD	HwcLossCoef	Initial HWC	MaxHWC

MinHWC	HwcGainCoef	ClimRr	HDM respiration rate
MRr	$Q10_c$	T_{ref}	Initial f_{leaf}
SLACoef	Maximum KC	TranslTDMi	ShadeSenesceCoef
RipeSensStress	GpSensStress	MtSensStress	SurfaceWetted
CanopyWetted	Full evaporation period		

Input data requirements to run the model:

The minimum data requirements to run the model with the calculation of evaporative demand by the Priestley-Taylor formula is:

* Latitude and longitude;
* Daily minimum and maximum temperature (°C); and
* Daily irrigation and precipitation (mm).

In order to utilise the more accurate Penman-Monteith equation for the calculation of evaporative demand, the following additional data is required:

* Total daily radiation;
* Average vapour pressure deficit (VPD); and
* Average wind speed.

6.6 Model evaluation

The model is evaluated by simulating the fresh yield, brix and water use of the Vredendal, Platskraal and Messina trials. Three problems were identified during the initial evaluation:

* The simulation of development rate according to thermal time was not accurate;
* The use of the DWR parameter which was established from the original Marble Hall data set lead to the over estimation of growth at the other localities; and

* The extinction coefficient (KC) which was established from the Marble Hall data set did not apply to the evaluation data sets.

These problems are probably the result of one or more of the empirical approaches used. A permanent solution to these problems would be the identification of their causes, and the application of more mechanistic modelling procedures. Temporary solutions are discussed briefly.

Thermal time

The thermal time requirements, as established from each trial, are used for the evaluation of the model for that data set. By doing this, any error in development rate, caused by incorrect thermal time estimations, does not cause errors in the evaluation of other parameters and/or procedures.

Overestimation of growth at the evaluation localities

The over estimation of growth indicated too great an efficiency of water(DWR) or radiation (RUE) use. The model was run with the other data sets (initial soil water content, weather, irrigation and precipitation) and various DWR values to establish a suitable DWR for the different localities. Although DWR should be a universal parameter for all localities, the following values are recommended until the problem, most likely the empirical VPD estimate, is solved.

Locality	*DWR*
Marble Hall	4.8
Messina	3.5
Vredendal and Platskraal	2.4

Extinction coefficient

An extinction coefficient of 0.45 resulted in the best fit between measured and simulated FI values for Marble Hall. When this value was used in the other localities, FI was under estimated in all cases. This is partly due to the fact that measured FI was in the PAR waveband, whilst the model actually needs a solar radiation fractional interception. A value of 0.59 resulted in good fits between simulated and measured data for all the other locations. This difference may also be due to the fact that the cultivar UC82 was planted in Marble Hall, while Brigade was used at the other sites. All other parameters were kept at constant values as indicated in Table 6.2.

The comparisons of measured and simulated data is shown below for:

* Leaf area index;
* Fractional interception of radiation;
* Total dry matter;
* Fresh yield and brix; and
* Cumulative evapotranspiration plus drainage.

Statistical analyses of measured and simulated data is summarized in Table 6.3 (p. 94). The parameters of the statistical analysis are number of observations (N), coefficient of determination (r^2), slope of the linear regression (s), Willmot's index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE). These parameters were recommended by de Jager (1994) to test model's accuracy.

Table 6.2 Parameters for TOMYIELD evaluation.

TOMYIELD parameters				
	Marble Hall	Messina	Vredendal	Platskraal
KC	0.45	0.59	0.59	0.59
DWR	4.8	3.5	2.4	2.5
EmDD	0	0	0	0
FlDD	203	260	260	250
RipeDD	874	570	620	963
GpDD	1100	500	500	700
MaxLeafAge	1000	700	800	1200
MtDD	1537	1150	1300	1560
CanopyWetted	1.0	0	0	0
SurfaceWetted	1.0	0.3	0.3	0.3

Tb	10	RGR	3.5	Tcutoff	26
Topt	20	RUE	0.0015	Minimum leaf water	
Maximum transpiration	10	EndSeedlDDFrac	0.3	potential	-1250
GpSensStres	3.187	Maximum KC	0.6	SI	0.95
RipeSensStress	3.187	Canopy storage	1.0	Full evaporation	
SLA	15.2	InitBrix	4.5	period	3
SLACoef	-0.022	Maximum brix	8	Initial HWC	0.95
ShadeSenescCoef	1.0	Minimum brix	3.5	MaxHWC	0.96
f_{root}	0.15	InitSeedPeelFrac	0.2	MinHWC	0.86
LSPP	1.1	SeedPeelFrac	0.65	HwcLossCoef	0.00075
Transl	0.2	hdmFixRate	0.2	HwcGainCoef	0.0006
Total dry matter at		HDMDissFrac	0.06	hdmRespi	0
emergence	0.007	MtSensStress	0.72	ClimRr	0.015
Initial f_{leaf}	0.4	RDmax	1.1	Q10c	1.4
TranslTDMi	0.3			T_{ref}	10

Leaf area index

Measured and simulated LAI for Vredendal, Platskraal and Messina is presented in Figure 6.13.

The simulated LAI values compared reasonably well with the measured data. It should be kept in mind that the measurement of LAI is a destructive technique and the variation in measured data is mostly due to variation found in the commercial fields. The low LAI values of 1 in Messina, compared to the values of 2.5 to 3 in Vredendal and Platskraal is the result of differences in row spacing. In Messina the row width was 2 m while rows was 1.2 m apart in Vredendal and 1.5 m in Platskraal.

Fractional interception of radiation

Measured and simulated FI for Vredendal, Platskraal and Messina is presented in Figure 6.14.

Although it appears that the model is underestimating FI, it should be borne in mind that measurements were made in the PAR waveband, whilst it is the interception of solar radiation that needs to be simulated. Radiation interception of fruits and vines will also cause measurements to be larger than simulated values.

Total dry matter

Measured and simulated total dry matter (TDM) for Vredendal, Platskraal and Messina is presented in Figure 6.15.

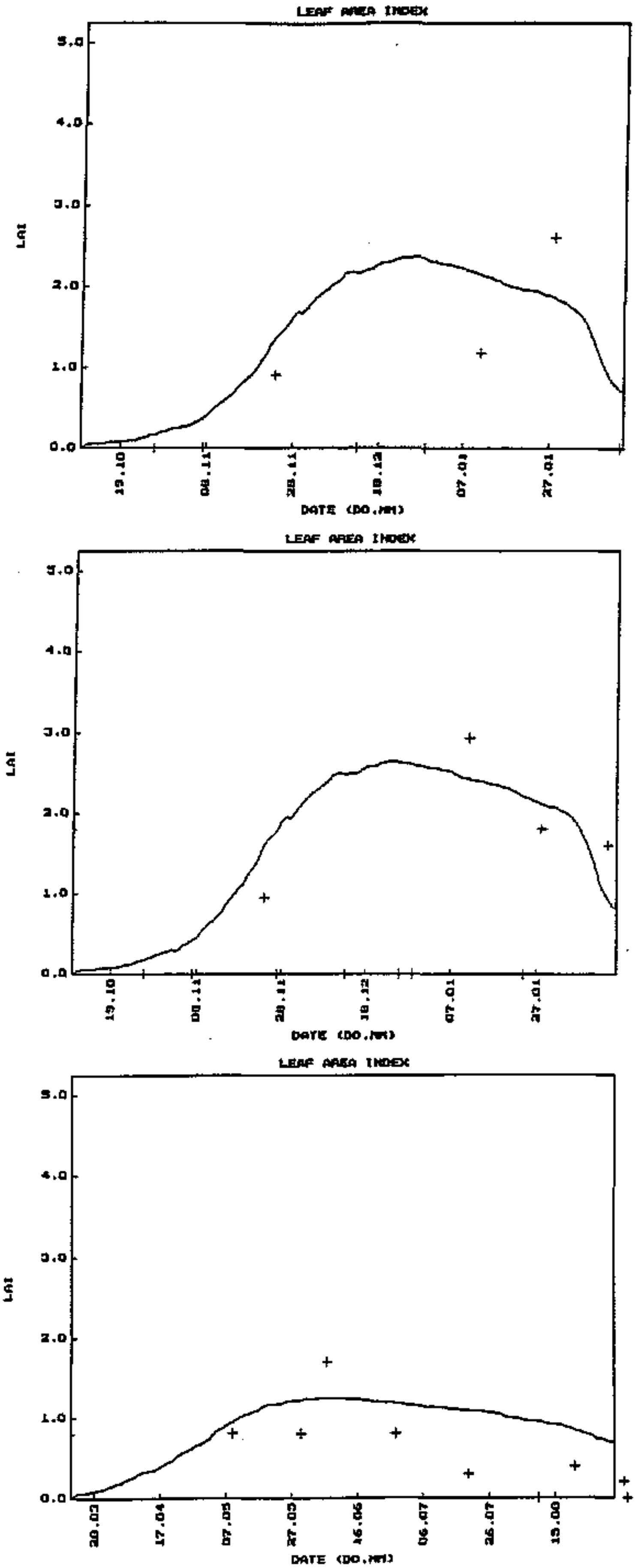


Figure 6.13 Measured and simulated LAI for Vredendal (top), Platskraal (centre) and Messina (bottom graph).

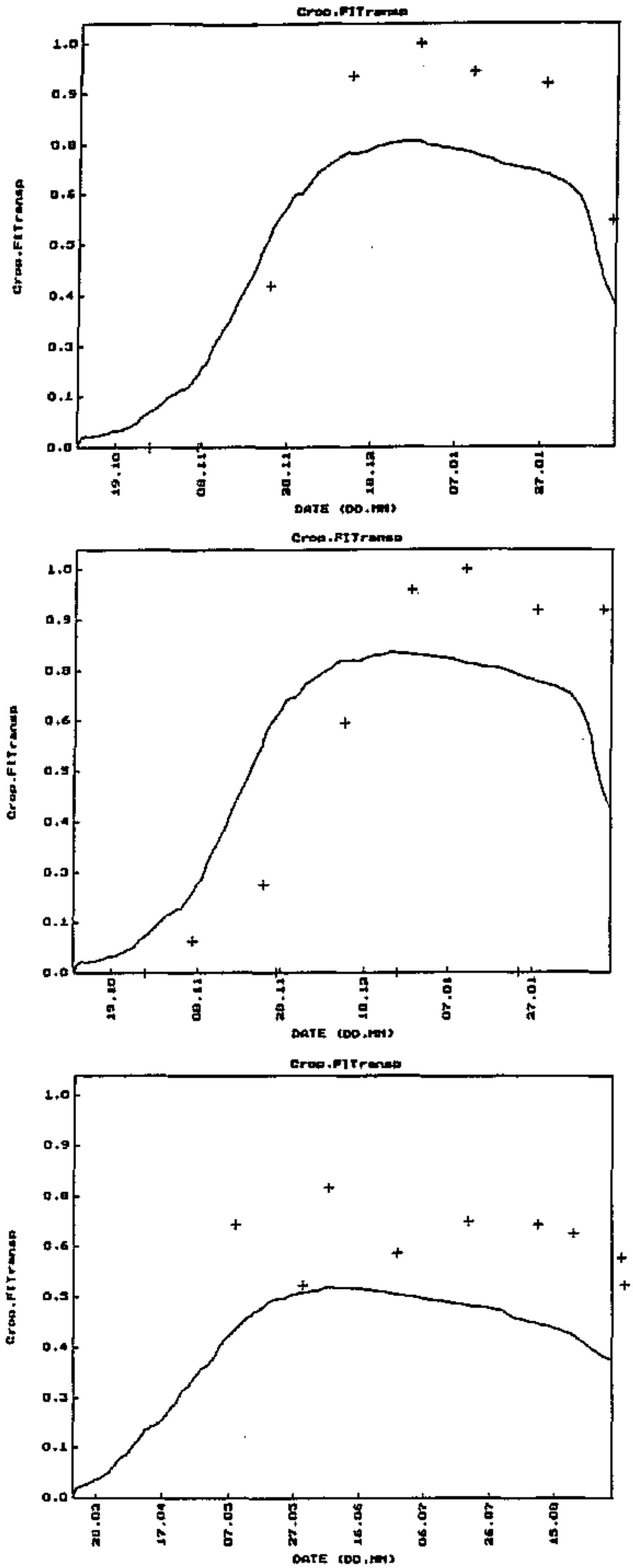


Figure 6.14 Measured and simulated FI for Vredendal (top), Platskraal (centre) and Messina (bottom graph).

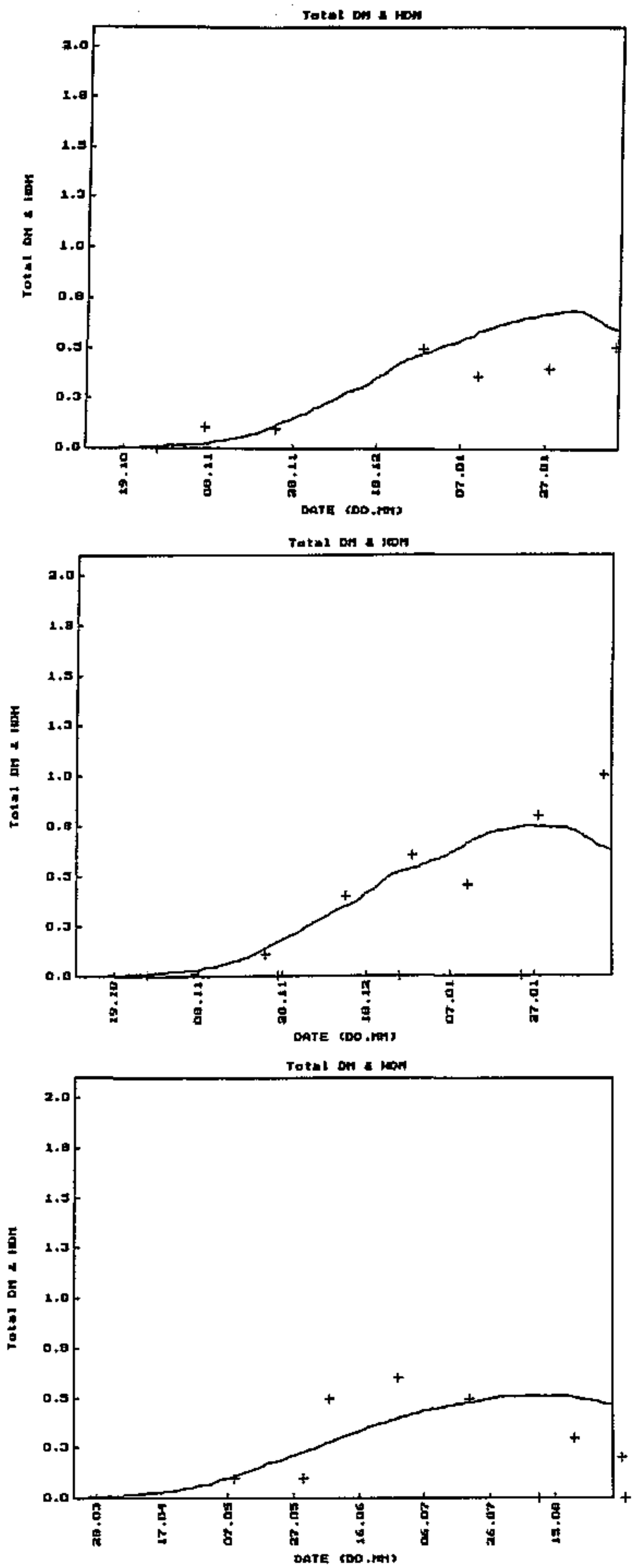


Figure 6.15 Measured and simulated TDM for Vredendal (top), Platskraal (centre) and Messina (bottom graph).

Fresh yield and brix

Measured and simulated fresh yield and brix for Vredendal, Platskraal and Messina is presented in Figure 6.16.

It is clear that fresh yield and brix simulations still require some attention. This is not too surprising, considering the many complex interactions that need to be taken into account.

Cumulative evapotranspiration plus drainage

Measured and simulated cumulative evapotranspiration plus drainage for Vredendal, Platskraal and Messina are shown in Figure 6.17.

It is clear that the model is simulating the water balance well, and this gives one confidence in using it as an irrigation scheduling tool.

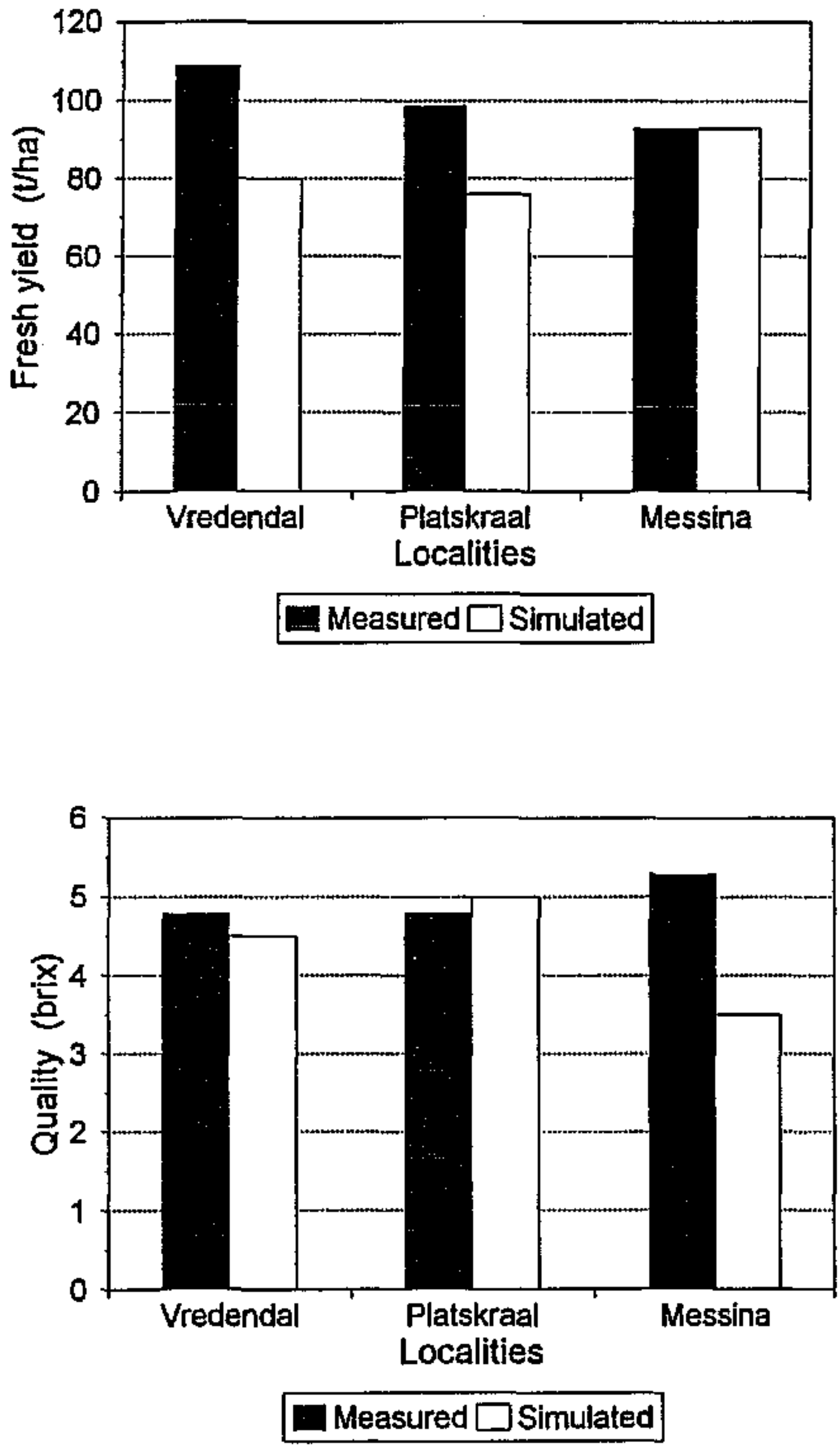


Figure 6.16 Measured and simulated fresh yield and brix.

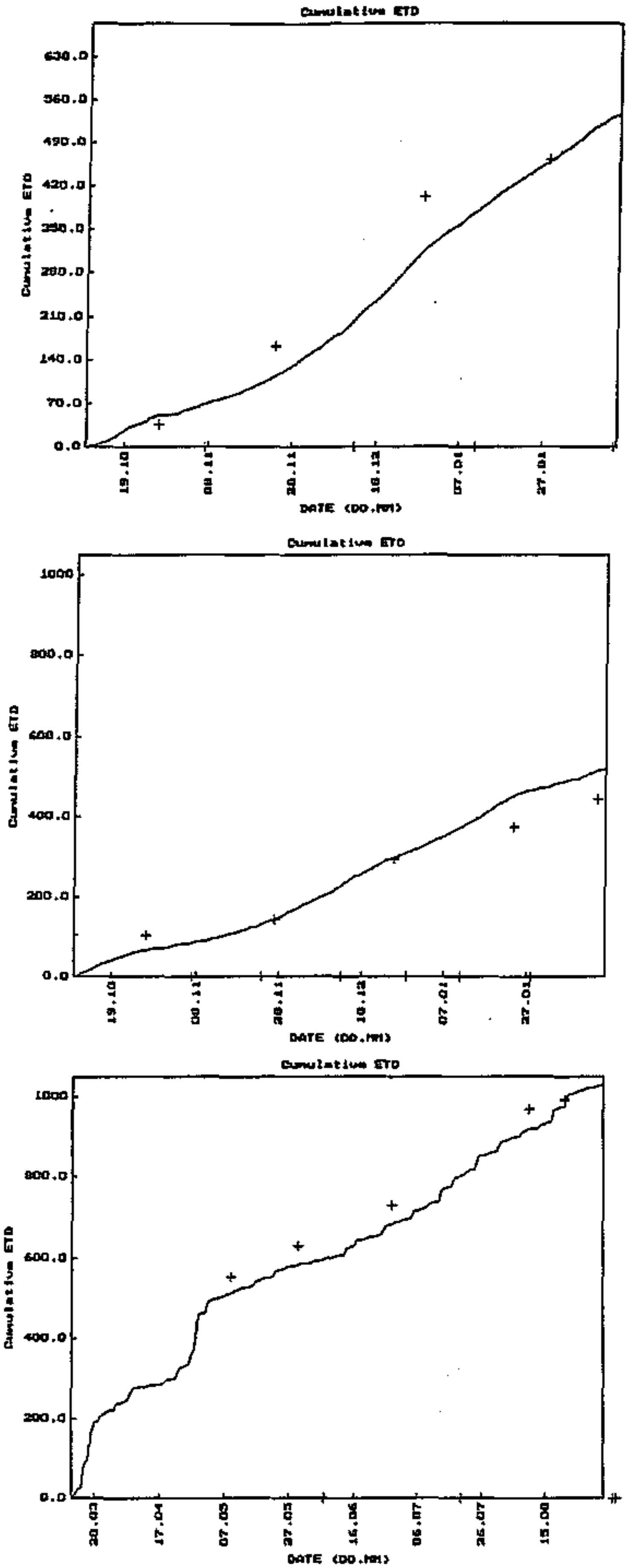


Figure 6.17 Measured and simulated cumulative evapotranspiration plus drainage for Vredendal (top), Platskraal (centre) and Messina (bottom graph).

Table 6.3 Statistical analysis of measured and simulated data for LAI, FI, TDM and CumETD at three locations (Vredendal, Platskraal and Messina).

		N	r^2	s	D	RMSE	MAE
LAI	Vredendal	3	-4.08	0.96	0.49	0.97	72.58
	Platskraal	4	0.10	0.90	0.76	0.67	41.10
	Messina	6	-7.36	1.13	0.57	0.53	67.66
FI	Vredendal	6	0.67	0.81	0.81	0.19	25.57
	Platskraal	7	0.17	0.84	0.82	0.26	37.65
	Messina	7	-2.72	0.72	0.34	0.21	31.23
TDM	Vredendal	6	0.83	0.74	0.87	0.16	31.94
	Platskraal	8	0.80	0.87	0.94	0.16	25.40
	Messina	6	-0.03	0.88	0.79	0.15	39.08
CumETD	Vredendal	4	0.96	0.90	0.98	54.57	16.68
	Platskraal	5	0.97	1.12	0.98	49.53	15.33
	Messina	5	0.99	0.97	0.99	29.00	3.68

CHAPTER 7

THE SIMULATION MODEL TOM-ECON

7.1 Introduction

The function of TOM-ECON is to establish the optimum irrigation strategy for processing tomatoes, once the decision has been made to go for processing tomatoes. The model integrates the numerous parameters and variables affecting the soil-plant-atmosphere continuum and the economic environment, in order to quantify net benefit of a variety of scheduling strategies. The optimum strategy, the one with the highest net income per unit of limited resource (land, yield contract or water) is selected and applied using TOM-MAN during scheduling.

It is important to realise that TOM-ECON's simulation of the net benefit is based on TOMYIELD's simulation of the yield, quality and irrigation requirements. For this reason the accuracy of simulation in TOMYIELD is of utmost importance.

TOM-ECON quantifies the costs of TOMYIELD simulated inputs required by the different strategies, as well as the income generated from the simulated outputs (yield and quality). In order to enable a user to optimize a specific situation, which may differ from region to region, farm to farm and even field to field, he or she is able to enter his or her own cost of inputs and the applicable tomato price structure.

Different irrigation scheduling strategies may cause differences in expected costs or benefits as a result of the risk of certain events, which are beyond the control of the user or farmer. There are at least two possible events which need to be taken into account in quantifying the net benefit of scheduling strategies for processing tomatoes. Firstly, rain during periods when the crop should be stressed in order to improve quality or to maintain a certain quality level can cause a rapid decline in quality due to increased fruit water uptake. Secondly, heat waves when fruit is already ripening, can cause very high respiration rates leading to rapid reductions in soluble solids and therefore brix.

Irrigation schedules will influence costs related to non-irrigation production factors because economic optimum levels of plant populations, fertiliser requirements, required spray programs and harvesting costs will vary for different yield levels.

Because the relationship between irrigation schedules and some of these costs is complex, some of these costs are not accounted for in TOM-ECON. The influence of irrigation schedules on fertiliser costs, however, can be estimated because fertilisation programs are normally based on yield targets and this is known for the different irrigation schedules. Harvesting costs, labour and transport, can also be calculated if the yield is known and therefore TOM-ECON simulates expected fertiliser, harvesting labour and transport costs for different irrigation strategies.

7.2 Model Structure

The structure of TOM-ECON is shown in Figure 7.1. TOM-ECON is run as a sub-model of TOM-MAN only on the users request. Before TOM-ECON can be applied, TOMYIELD is run for the different irrigation strategies to simulate the required irrigation as well as the expected fresh yield and quality for each.

The user then enters the information regarding the unit costs of inputs and the product price structure.

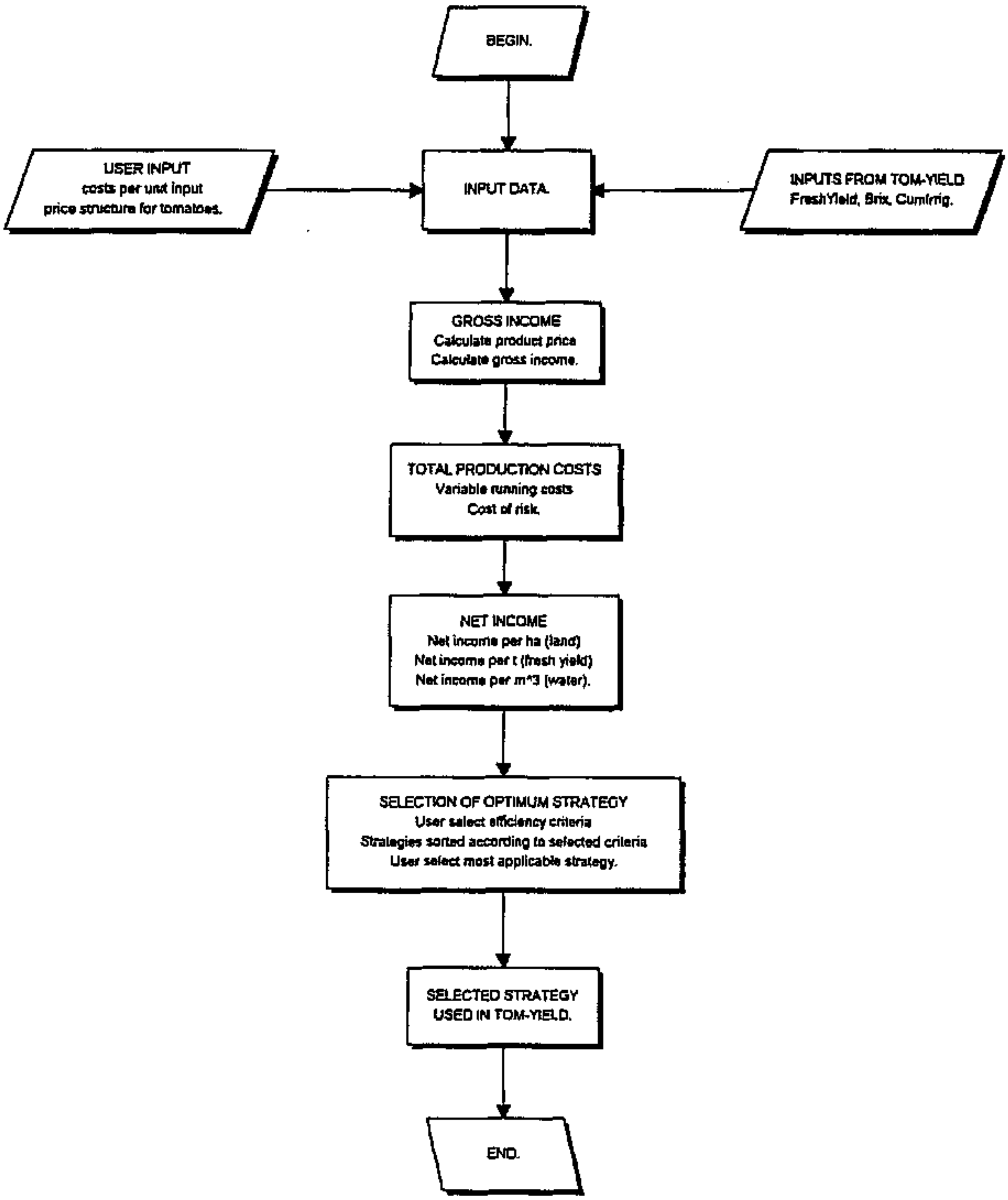


Figure 7.1 Flow diagram of TOM-ECON.

7.3 Model description

Input data

Inputs from TOMYIELD:

The required cumulative irrigation (CumIrrig), expected fresh yield (FreshYield) and percentage soluble solids (brix) for each irrigation strategy are simulated outputs of TOMYIELD which are used as inputs to TOM-ECON.

User inputs

The user enters the required input data in respect of the following:

* Quality based price structure for the season; and
* Applicable production costs and costs per unit input of water.

Calculation of gross income

Both the price and the yield have to be known in order to calculate the total income. For processing tomatoes, the price is based on quality (brix) and needs to be calculated, according to Eq. 7.1.

If brix < 3.9 then BrixPriceMin = (R 170 t^{-1}, 1995)
If brix > 7.5 then BrixPriceMax = (R 400 t^{-1}, 1995)
If 3.9 < brix < 7.5 then
BrixPrice = BrixPriceMin + (BrixPriceMax - BrixPriceMin) / (7.5 - 3.9)
*** (brix - 3.9) 7.1**

where: BrixPrice - Brix based price per ton (R t^{-1})
BrixPriceMax - Maximum price for highest brix (R t^{-1})
BrixPriceMin - Minimum price for lowest brix (R t^{-1})

This price structure with a gradient of R 63.80 $brix^{-1}$ t^{-1} was applicable for Langeberg Foods contractors in 1995. If a non-linear price scale is introduced in future, then the model will be adapted to accommodate it.

The gross income per unit area can be calculated with Eq. 7.2, while the nett income is calculated per square meter, per cubic meter of irrigation water and per ton of yield contract respectively in Eqs. 7.18 to 7.20.

GrossIncome = FreshYield/10000 * BrixPrice 7.2

where: GrossIncome - Total income per unit area (R m^{-2})

Calculation of variable production costs

Two cost classes were considered. These are defined (with examples) below:

Variable running costs are those costs, whose values will vary depending on the irrigation strategy followed. Examples: Irrigation, fertilisation, harvesting labour, transport of the crop.

Risk costs are costs which may or may not be incurred, depending on the occurrence of events which are beyond the control of the manager. Examples: Damage due to untimely rain or heat waves.

Variable running costs:

The following costs vary with irrigation schedule followed because their input levels are linked either to the amount of water applied or to the expected yield. The calculations are shown in Eqs. 7.3 to 7.10 and are summed in Eq. 7.11. These cost items are the following:

* Irrigation water;
* Irrigation energy;

* General variable irrigation costs;
* Fertilisation;
* Labour for harvesting; and
* Transport for delivering crop to depot.

VRCWater = CumIrrig / 1000 * WaterCost 7.3

where: VRCWater - Irrigation water cost (R m^{-2})
CumIrrig - Cumulative simulated irrigation requirement (mm)
WaterCost - Cost of water (R m^{-3})

For the purpose of this study the energy cost per cubic meter of water applied is assumed to be constant. The value of the variable Energy can be calculated with Eq. 7.4.

Energy = TotElectBill / TotCumIrrig * ElecPriceIncrease 7.4

where: Energy - Cost of energy converted to R m^{-3} irrigation (R m^{-3})
TotElectBill - Total electricity cost for all fields during the previous season (R)
TotCumIrrig - Total cumulative irrigation for all fields during the previous season (m^3)
ElecPriceIncrease - Factor by which unit electricity cost increased since previous season

The variable energy cost is calculated with Eq. 7.5.

VRCEnergy = CumIrrig / 1000 * Energy 7.5

where: VRCEnergy - Irrigation energy cost (R m^{-2})

The cost of general irrigation items per cubic meter of water applied can be calculated with Eq. 7.6.

GenIrrCost = TotGenIrr / TotCumIrrig * GenIrrPriceIncrease . . . 7.6

where: GenIrrCost - Cost of general irrigation items converted to R m^{-3}

		irrigation (R m^{-3})
TotGenIrr	-	Total general irrigation cost for maintenance and labour for the previous season (R)
GenIrrPriceIncrease	-	Factor by which general irrigation cost increased since previous season

The variable running cost for general irrigation items such as irrigation system maintenance and labour is calculated in Eq. 7.7.

VRCGenIrr = CumIrrig / 1000 * GenIrrCost 7.7

where:	VRCGenIrr	-	General irrigation cost excluding water and energy (R m^{-2})

The calculation of the fertilisation cost is based on the assumption that for yields between a minimum of 25 and a maximum of 130 t ha^{-1}, the fertiliser cost is a linear function of the FreshYield as shown in Eq. 7.8. This simplification is used until this development need is addressed by another specialist in this field.

VRCFert = MinFertCost + (FreshYield - MinYield) * (FullFertCost - MinFertCost) / (MaxYield - MinYield)

If VRCFert > FullFertCost then VRCFert = FullFertCost 7.8

where:	VRCFert	-	Cost of fertilisers (R m^{-2})
	MinFertCost	-	Fertiliser cost for a tomato yield of 25 t ha^{-1} (R m^{-2})
	FullFertCost	-	Cost for a tomato yield of 130 t ha^{-1} (R m^{-2})
	MaxYield	-	Maximum yield for processing tomatoes (t ha^{-1})
	MinYield	-	Minimum yield for processing tomatoes (t ha^{-1})

The input values for MinFertCost and FullFertCost are obtained by calculating the costs for recommended fertiliser programs for target yields of 25 t ha^{-1} and 130 t ha^{-1} respectively.

VRCHarvLabour = 0.1 * FreshYield / CrateMass * PickCost . . . 7.9

where:	VRCHarvLabour	-	Variable labour cost for picking tomatoes (R m^{-2})

CrateMass	-	Average mass of tomatoes in a picking crate (kg $crate^{-1}$)
PickCost	-	Wage paid per crate (R $crate^{-1}$)

VRCHarvTransp = 0.1 * FreshYield / Payload * DistDepot * TruckRunCost 7.10

where:	VRCHarvTransp	-	Cost of transport to deliver harvest to depot (R m^{-2})
	Payload	-	Mass of a truck load (kg)
	DistDepot	-	Distance to the depot (km)
	TruckRunCost	-	Running cost of the truck (R km^{-1})

TotVRC = VRCWater + VRCEnergy + VRCGenIrr + VRCFert + VRCHarvLabour + VRCHarvTransp 7.11

where:	TotVRC	-	Total variable running costs (R m^{-2})

Risk costs:

The major risks that are accounted for are untimely rain and heat waves. Both will cause a drop in the content of soluble solids (brix). If rain occurs the brix will be decreased primarily as a result of the uptake of additional fruit water. During heat waves an increased respiration rate causes a loss of soluble solids, resulting in a lowered brix.

The cost of these events is a function of the probability of their occurrence as well as the sensitivity of the quantity and quality of yield due to the event. The probability of the occurrence of these events, is a function of the climate of the region and the time of year during which the crop is grown. It is assumed that the higher the brix before the event commences, the more sensitive it will be to the event. The best approach to calculate these probabilities and to integrate the changing risk of occurrence of the event during the season and the changing susceptibility to damage of the crop is to run the model for a long period using either historic real or simulated weather data. This approach will be possible in the near future by using the proposed Climate Generation function of the SWB model.

For this report, however, due to a lack of adequate data, an empirical approach was developed to estimate the drop in brix after untimely rain and/or heat waves. It is assumed that the probability of occurrence of untimely rain or heat waves is known or estimated by the user and that the sensitivity for a decrease in brix after untimely rain and/or heat waves is a function of the brix level before the event. This sensitivity is accounted for by the variables, RainBrixDropSens and HeatBrixDropSens, which is calculated according to Eq 7.12 and 7.13. The value declines from one to zero with brix decreasing from 8 to 3.5. The values of these parameters can only be estimated at this stage and should be quantified during future research.

RainBrixDropSens = (InitBrix - 3.5) / 4.5 . . . . 7.12

where: RainBrixDropSens - Average drop in brix with untimely rain (brix)

It is estimated that if brix is increased to a level of 5.5 by water stress, it will drop by 1 unit to 4.5 if rain occurs and therefore a value of 1/4.5 is estimated for RainBrixDropSens.

HeatBrixDropSens = (InitBrix - 3.5) / 4.5 . . . . 7.13

where: HeatBrixDropSens - Average drop in brix with untimely heat waves (brix)

It is estimated that if brix is increased to a level of 5.5 by water stress, it will drop by 1.25 units to 4.25 if a heat wave occurs. A value of 1.25/4.5 is therefore estimated for HeatBrixDropSens.

The average cost per square meter per season of these risks are calculated according to Eqs. 7.14 and 7.15. The total risk cost is calculated with Eq. 7.16.

RCRain = RainBrixDropSens * RainProb * (BrixPriceMax - BrixPriceMin) / (7.5 - 3.9) * FreshYield / 10000 . . . . 7.14

where: RCRain - Average cost of the risk of untimely rain during ripening (R m^{-2})

RainProb - Probability of rain during ripening (fraction)

RCHeat = HeatBrixDropSens * HeatProb * (BrixPriceMax - BrixPriceMin) / (7.5 - 3.9) * FreshYield / 10000 .... 7.15

where: RCHeat - Average cost of the risk of untimely heat waves during ripening ($R\ m^{-2}$)

HeatProb - Probability of a heat wave during ripening (fraction)

The figures 7.5 and 3.9 represent the upper and lower limit of brix for the price structure applicable to Langeberg Foods contractors in 1995 (Eq. 7.1).

TotRiskCost = RCRain + RCHeat... 7.16

where: TotRiskCost - Total risk cost due to untimely rain and/or heat waves ($R\ m^{-2}$)

Increase in yield quantity due to untimely rain, and decrease in yield quantity due to untimely heat should also be accounted for.

The total variable production cost is calculated by adding the variable running cost items and the risk cost in Eq. 7.17.

TotVarProdCost = TotVRC + TotRiskCost 7.17

where: TotVarProdCost - Total variable production cost ($R\ m^{-2}$)

Calculation of net income

Net income is calculated per unit of land area, irrigation water, and contract yield, to enable the user to select the optimum irrigation strategy according to the factor which is most limiting to profits.

The calculations are done according to Eqs. 7.18 to 7.20.

NILand = GrossIncome - TotVarProdCost 7.18

where: NILand - Net income per square meter (R m^{-2})

NIWater = NILand / CumIrrig * 1000 .... 7.19

where: NIWater - Net income per cubic meter of water (R m^{-3})

NIYield = NILand / FreshYield * 10000 .... 7.20

where: NIYield - Net income per ton of fresh yield (R t^{-1})

Selection of the optimal strategy

The user selects the criteria (land, contract or water), on which basis he would like to optimize net income. TOM-ECON then sorts the irrigation strategies, based on the selected criteria. The first (best) irrigation strategy is automatically selected by TOM-ECON and applied as the irrigation guideline for scheduling irrigation with TOMYIELD.

CHAPTER 8

APPLICATION OF TOM-MAN

8.1 Introduction

The production cost per ton of tomatoes rises with improved quality, while the processing cost decreases. Because the output quality of a farmer's processing tomatoes is the input quality of the raw product for processing, the optimization of the global process requires that inefficiencies are eliminated in processing as well as in production. The aim with the quality based price structure is to motivate producers to grow tomatoes of optimum quality for both parties. For producers to be willing to adapt their production strategies, they should expect maximum profits at the new "optimum" quality levels and they will need to adapt their existing management systems to achieve the targets set. TOM-MAN, as a management tool for the optimization of the production of processing tomatoes, can be applied by producers to:

- select the optimal irrigation schedules; and
- to schedule irrigations according to the identified optimum schedule.

Procedures for the two different applications are described below.

8.2 Selection of optimal irrigation schedules by producers

For any given price structure, there are numerous variables which will determine the optimum yield/quality target and the accompanying irrigation schedule with which the net income of the producer will be maximised. As a result of the variation in climate between different areas, soil types and planting dates, the use of average guidelines which are applied to the industry as a whole, can simply not be optimal for all the individual producers. Through the use of TOM-MAN, as described in Chapter 7, the producer can establish economically optimal irrigation guidelines, which apply to his own individual situation. His own set of input data will reflect both the physical production aspects (climate, soil and planting date) as well as the economic situation (actual price structure, simulated required input, real input costs, fixed costs, opportunity costs, etc.).

Examples of practical applications:

In order to demonstrate the intended application of the model, it is assumed that the crop simulation part of TOM-MAN will finally be able to simulate the yield, quality and water use of different irrigation schedules accurately. The two data sets from the 1992/93 and 1994/95 Pretoria stress trials will be used as if they were simulated. These data sets include widely differing schedules which resulted in different levels of water use, yields and quality.

The input data and calculated outputs for the two trials are shown in Tables 8.1 and 8.2. The water use, yield and quality data is measured in the trials while the data on costs is taken from information gathered during 1995 from co-operating farmers.

Results of the 1992/93 Pretoria stress trial (Table 8.1):

Depending on which of land, water or yield contract is the most limiting factor, the T20R100, T20R01 or T75R100 treatment should be selected. If land is limiting the selection of the best strategy should be based on the net income per unit land (NILand). The T20R100 treatment would then be best with a net income of R9907 per ha, which is R902 more than that of the T20R01 treatment. If water would be limiting, which is the situation on most farms, the selection should be based on the calculated net income per unit water (NIWater). In this case the T20R01 is best as it earns R0.41 per cubic meter of water (22.2%) more than the T20R100 treatment. It should be recognized that the T20R100 treatment which generated the highest income per unit of land had the lowest income per unit of water. If the tonnage of the contract would be limiting, then the T75R100 treatment should be selected.

Table 8.1 Input data and calculated outputs for the 1992/93 Pretoria stress trial.

PTA Stress trial 1992/93

INPUT DATA	Units	1	2	3	4	5
		T20R01	T20R20	T20R100	T50R100	T75R100
Fresh yield	t/ha	66.00	71.00	73.00	64.00	53.00
Brix	%	3.5	3.7	3.7	3.9	4.2
CumIrrig	mm	398	466	536	437	399
TotElectBill	R	33540	33540	33540	33540	33540
TotCumIrrig	m3	22722232	22722232	22722232	22722232	22722232
General irrigation cost (Maintenance)	R	3000	3000	3000	3000	3000
General irrigation cost (Labour)	R	2500	2500	2500	2500	2500
Minimum brix	%	3.9				
Price if brix < minimum brix	R/t	170	ElecPriceIncrease		%	5
BrixPriceMin	R/t	170	Payload		kg	20000
(BrixPriceMax-BrixPriceMin)/(7.5-3.9)	R/brix	63.8	DistDepot		km	15
Price if brix > maximum brix	R/t	400	TruckRunCost		R/km	4.5
Maximum brix	%	7.5	RainBrixDropSens		%	1
MinFertCost	R/m2	0.05	InitBrix		%	5.5
FullFertCost	R/m2	0.15	Final brix		%	4.5
CrateMass	kg/crate	28	RainProb			0.01
PickCost	R/crate	0.35	HeatBrixDropSens		%	1.25
WaterCost	R/m3	0.05	InitBrix		%	5.5
			Final brix		%	4.25
			HeatProb			0.01

OUTPUT

		Units	1	2	3	4	5
	Price	R/t	170	170	170	170	189.14
	GrossIncome	R/m2	1.122	1.207	1.241	1.088	1.002
TotVRC	VRCWater	R/m2	0.0199	0.0233	0.0268	0.0219	0.0200
	VRCEnergy	R/m2	0.0006	0.0007	0.0008	0.0007	0.0006
	VRCGenIrr	R/m2	0.0001	0.0001	0.0001	0.0001	0.0001
	VRCFert	R/m2	0.0738	0.0794	0.0816	0.0716	0.0593
	VRCHarvLabour	R/m2	0.0825	0.08875	0.09125	0.08	0.06625
	VRCHarvTransp	R/m2	0.0446	0.0479	0.0493	0.0432	0.0358
	RCRain	R/m2	0.0000	0.0002	0.0002	0.0004	0.0005
	RCHeat	R/m2	0.0000	0.0002	0.0002	0.0004	0.0005
	TotVarProdCost	R/m2	0.2215	0.2406	0.2503	0.2181	0.1830
	NILand	R/m2	0.9005	0.9664	0.9907	0.8699	0.8194
	NIWater	R/m3	2.26	2.07	1.85	1.99	2.05
	NIYield	R/t	136	136	136	136	155

According to this trial the following irrigation guidelines are recommended:

For a land limiting situation: Irrigate at a depletion level of 20 kPa for the whole season (T20R100)

For a water limiting situation: Irrigate at a depletion level of 20 kPa until the first fruits ripen, then stop irrigations (T20R01).

For a contract limiting situation: Apply moderate water stress during the whole season.

Results of the 1994/95 Pretoria stress trial (Table 8.2):

The treatments of the 1994/95 stress trial and the 1992/93 stress trial are similar in nature and can be considered to be equivalent as follows:

1992/93	T20R100	T20R01	T75R100	T75R01
1994/95	WetWet	WetStress	StressWet	StressStress

In the 1992/93 trial it was intended to apply a T20R01 treatment, but the ripening was to quick and all fruits ripened before any stress could be induced during ripening.

For the 1994/95 trial the WetWet treatment (equivalent of the T20R100 treatment) should be selected if land is limiting. The net income of the WetStress treatment was only slightly lower by R189 per ha. If water would be limiting, the WetStress treatment (equivalent of T20R01) is best as it earns R0.44 per cubic meter of water more (20.7%) than the next best treatment. If the tonnage of the contract would be limiting, then the StressStress (equivalent of T75R01) should be selected.

Table 8.2 Input data and calculated outputs for the 1994/95 Pretoria stress trial.

Pta Stress trial 1994/95

INPUT DATA	Units	1 WetWet	2 WetStress	3 StressWet	4 StressStress			
Fresh yield	t/ha	64.30	38.60	23.40	17.00			
Brix	%	4.3	5.5	5.7	6.3			
CumIrrig	mm	242	193	156	122			
TotElectBill	R	13368.8	13368.75	13368.75	13368.75			
TotCumIrrig	m3	8912.5	8912.5	8912.5	8912.5			
General irrigation cost (Maintenance)	R	3000	3000	3000	3000			
General irrigation cost (Labour)	R	2500	2500	2500	2500			
Minimum brix	%	3.9						
Price if brix < minimum brix	R/t	170				ElecPriceIncrease	%	5
BrixPriceMin	R/t	170				Payload	kg	20000
(BrixPriceMax-BrixPriceMin)/(7.5-3.9)	R/brix	63.8				DistDepot	km	15
Price if brix > maximum brix	R/t	400				TruckRunCost	R/km	4.5
Maximum brix	%	7.5				RainBrixDropSens	%	1
MinFertCost	R/m2	0.05				InitBrix	%	5.5
FullFertCost	R/m2	0.15				Final brix	%	4.5
CrateMass	kg/crate	28				RainProb		0.01
PickCost	R/crate	0.35				HeatBrixDropSens	%	1.25
WaterCost	R/m3	0.05				InitBrix	%	5.5
						Final brix	%	4.25
						HeatProb		0.01

OUTPUT

			WetWet 1	WetStress 2	StressWet 3	StressStress 4
	Price	R/t	195.52	272.08	284.84	323.12
	Gross Income	R/m2	1.257	1.050	0.667	0.549
TotVRC	VRCWater	R/m2	0.0121	0.0097	0.0078	0.0061
	VRCEnergy	R/m2	0.3812	0.3040	0.2457	0.1922
	VRCGenIrr	R/m2	0.1493	0.1191	0.0963	0.0753
	VRCFert	R/m2	0.0738	0.0443	0.0269	0.0195
	VRCHarvLabour	R/m2	0.08038	0.04825	0.02925	0.02125
	VRCHarvTransp	R/m2	0.0434	0.0261	0.0158	0.0115
	RCRain	R/m2	0.0007	0.0011	0.0007	0.0007
	RCHeat	R/m2	0.0007	0.0011	0.0007	0.0007
	TotVarProdCost	R/m2	0.7416	0.5535	0.4231	0.3271
	NILand	R/m2	0.5156	0.4967	0.2434	0.2222
	NIWater	R/m3	2.13	2.57	1.56	1.82
	NIYield	R/t	80	129	104	131

According to this trial the following irrigation guidelines should be recommended:

For a land limiting situation:	Keep well watered (wet) for the early season and apply little or no stress during the latter part of the season.
For a water limiting situation:	Irrigate at a depletion level of 20 kPa until the first fruits ripen, then apply stress during ripening.
For a contract limiting situation:	Apply moderate water stress during the whole season.

8.3 Routine scheduling

The guidelines which were selected as the best should be quantified in terms of kPa of tension allowed during different weeks of the season. This recommended schedule is then used in TOM-MAN to schedule the irrigation during production on a real time basis. This means that weather and irrigation has to be monitored and this daily input data needs to be entered into TOM-MAN. TOM-MAN then simulates the evaporative demand, the complete soil water balance and the growth and development of the crop. The model indicates the soil water deficit which indicates the required irrigation to fill the soil profile.

8.4 Optimization of the price structure by processors

The processor can use TOM-MAN to determine the price structure which will optimize producer's net income per unit area at the quality level which minimises the total costs and maximises profits for the industry. TOM-MAN simulates the role of the producer in the pricing issue and generates valuable information on the influence of the price structure on the producer's optimum target yield.

The processor's cost for the production of a ton of tomato paste and the paste yield (tons of paste per ton of fresh tomatoes) with varying qualities of raw material (fresh tomatoes) should be quantified beforehand by the processor. TOM-MAN is used to simulate the production of processing tomatoes of varying qualities as well as the net income per unit of the limiting resource. This is done by simulating the yield, quality and the resulting net income per unit of limiting resource at various quality levels and for a range of prices according to the proposed price structure. The range of different quality levels is generated by simulating a range of irrigation strategies. Producers are represented by using either a single set or various sets of input data of soil, climate and input costs.

During the simulations TOM-MAN generates all the data required for the calculation of the total costs per unit of the limiting resource of the producer. The processor can therefore use TOM-MAN to find the price structure which will be efficient in motivating the producer to produce the optimum quality. Apart from using TOM-MAN for establishing the price structure, it will also be an appropriate tool for convincing farmers to produce the optimum quality.

It should be realised that the optimum price structure, which is established for the average producer, does not mean that the net income of all producers will be optimized at this optimum quality.

CHAPTER 9

PROGRAMMING IN USER FRIENDLY FORMAT

TOM-MAN and SWB, is written in Turbo Pascal in a fairly user friendly format. Further programming is needed in the following respects:

* The incorporation of the procedures for simulating development rate according to the principles applied in TOMMOD (Wolf *et al.*, 1986) is required to improve the accuracy of the model in this respect;
* A procedure for routine scheduling of irrigation and the prediction and recommendation of irrigation is needed;
* The parameters created for TOMYIELD and TOM-ECON need to be incorporated in the user interface;
* A procedure for user input of data for TOM-ECON; and
* TOM-MAN needs to be incorporated into SWB to enable users to schedule any irrigated crop.

The further development of the user friendliness of the program should be considered as one of the major priorities in the development of the program for the transferral of the technology developed.

CHAPTER 10

CONCLUSIONS

The approach of the integration of a growth simulation model and an economic optimization model seems to be appropriate and feasible.

Simulations of canopy development and dry matter production are fairly accurate.

The accuracy of the simulation of water use is acceptable for practical irrigation scheduling.

The simulation of fresh yield and brix are not yet accurate and fine tuning of the parameters and /or a more mechanistic approach is required.

The priority for further development is to enhance technology transfer through improved user friendliness and wider applicability through the establishment of crop parameters for other irrigated crops.

CHAPTER 11

NEEDS FOR FURTHER RESEARCH AND DEVELOPMENT

Various needs for further research have been identified during the project. These needs are listed below:

1 Parameters for other irrigated crops have to be determined in order to enhance the transfer of the technology. The majority of farmers are growing a variety of crops and need to schedule irrigation on all of them.

2 User friendliness should be defined by identifying the main users and their needs. The needs should be prioritised and the program development then needs to focus on these priorities.

3 The soil water balance procedure needs to be adapted to be able to simulate the soil water balance for partial wetting of the soil profile.

4 A sensitivity analysis is needed to quantify the influences of inaccuracies in TOMYIELD on the validity of the optimization procedures of TOM-ECON.

5 Risk of occurrence of heat waves and rain should be quantified for the main tomato producing areas and the procedure for the quantification of risk cost needs to be improved. At this stage, the risk cost is calculated as if it is a single event, but it should be improved in order to integrate (during the season) the changing risk of the occurrence of the event and the changing susceptibility of damage to the crop. More information is also required on the effect of heat waves and untimely rain on crop yield and quality.

6 The influence of different row widths on the extinction coefficient should be investigated.

7 Thermal time requirements for different processing tomato cultivars should be quantified.

8 The influence of water stress on thermal time requirements needs to be quantified properly.

9 A more mechanistic approach to the simulation of fruit water import and export needs to be developed

10 The change in canopy structure with maturity needs to be investigated in more detail in order to simulate the process more mechanistically.

11 Seedling growth should be studied in more detail in order to refine the procedure for its simulation.

CHAPTER 12

SUMMARY

This project, which was funded by the Water Research Commission, Langeberg Foods and the University of Pretoria, was aimed at the *maximisation of economic water use efficiency in processing tomato production.* A computer program, TOM-MAN, was developed as a prototype model with processing tomatoes as an example, and will eventually be incorporated in the SWB irrigation scheduling program which is currently under development by the University of Pretoria.

It is indisputably clear from numerous reports that irrigation management is the most important factor towards economic optimization of processing tomato production. *The most crucial decision about irrigation management for processing tomatoes is to decide on when and to what extent irrigation should be reduced in order to apply the right amount of stress.* This "right" amount of stress is not only a function of the physical situation, but is determined to a great extent by the economic situation as far as expected costs and benefits are concerned. In order to optimize economic water use efficiency for the processing tomato industry, the total cost of the global process (production as well as processing) should be minimised. In order to achieve this, the processor's quality based price for the producer's tomatoes, should be structured in a way that the farmer's profit is maximised at the yield/quality combination where the total cost of the global process is minimised. Producers need to be able to identify this optimum for their own situations and must then be able to manage the production system to achieve the target set. Optimization of this system requires integration of all variables and constants affecting the crop-soil-climate-irrigation-management system, as well as the economic situation of the producer and processor.

A modelling approach seemed to be the only practical way of integrating all the different variables into a single decision making process. Therefore, in order to facilitate this integration, a management tool in the form of a computer program was developed. The TOM-MAN program integrates the TOMYIELD crop growth model, which is based on SWB, and an economic optimization model, TOM-ECON, which was developed during this project.

In order to create a management tool which could be applied under a wide range of climatic and soil conditions, a mechanistic modelling approach was followed. Several growth analyses were conducted at various localities and during different seasons to generate data sets of growth and development as well as climate and the soil water balance. Data from some of the data sets were used to calculate input parameters during model development. The model was evaluated by running it with the calculated input parameters and the initial soil water content, rain, irrigation and weather data from the evaluation sites in the Western Cape Province and Northern Province. Simulated results of growth, development, yield and quality are compared to measured data to determine the accuracy of the model.

TOMYIELD differs from SWB mainly in its ability to simulate fresh yield and quality of processing tomatoes, as SWB only simulates dry matter yield of the different plant components. In order to simulate fresh yield and quality of processing tomatoes, procedures were developed for the following processes:

* loss and gain of fruit water;
* translocation of a portion of the dry matter from senesced leaves to fruits;
* partitioning of fruit dry matter to the various fruit components;
* fruit ripening;
* maintenance and climacteric respiration of fruits; and
* final fresh yield and percentage of soluble solids (brix).

Other modifications were also introduced to improve the accuracy of the simulation of growth and development, as well as the soil water balance procedure of SWB:

* improved simulation of seedling growth rate;
* influence of shading on the senescence rate of leaves;
* storage of assimilates in the leaves;
* changes in canopy structure during the season;
* hastening influence of water stress on ripening; and
* senescence rate

The structure and functioning of the model is described, with full details on all the modifications to SWB.

The input parameters needed to run TOMYIELD were established and evaluated. The model is evaluated by simulating the fresh yield, brix and water use of the Vredendal, Platskraal and Messina trials. The simulation of development rate according to thermal time was not sufficiently accurate to enable using a single set of thermal time parameters. Individual, site specific requirements were instead determined. The water use efficiency (DWR), as well as the radiation extinction coefficient (KC) also varied between localities and individual parameters are recommended. Simulated versus measured data indicated that the following aspects were simulated fairly accurately:

* leaf area index;
* fractional interception of solar radiation;
* total and harvestable dry matter; and
* cumulative evapotranspiration and drainage.

The simulation of fresh yield and brix still needs attention, especially if the model is not calibrated for the area of use.

TOM-ECON

The main function of TOM-ECON is to establish the optimum irrigation strategy for processing tomatoes for application by TOM-MAN during routine scheduling.
TOM-ECON quantifies the costs of TOMYIELD simulated inputs required for different strategies, as well as the income generated from the simulated outputs (yield and quality). In order to optimize for a specific situation, which may differ from region to region, farm to farm and even field to field, the user can enter the cost of inputs and the applicable fruit price structure. Because TOM-ECON's simulation of the net benefit is based on TOMYIELD's simulation of the yield and quality, the accuracy of TOMYIELD's simulation is of utmost importance.

For the calculation of the total production cost, the following classification of cost items was used:

* Fixed overhead costs;
* Fixed running costs;
* Variable running costs;
* Cost of risk; and
* Opportunity cost.

Net income is calculated per unit of land area, water, and tonnage of yield, to enable the user to select the optimum irrigation strategy according to the factor which is most limiting to increased profits. The user selects the criteria (land, water or tonnage of contract), on which basis he would like to optimize net income. TOM-ECON will then sort the irrigation strategies, based on the selected criteria, in a descending order and the user selects the best irrigation strategy which is applicable to his particular situation. The strategy which is finally selected in TOM-ECON is then taken as the irrigation guideline for scheduling irrigation with TOMYIELD.

Application

TOM-MAN, as a management tool for the optimization of the production of processing tomatoes, can be applied to assist management of both processing companies and producers in the following respects:

* optimization of the price structure for processing tomatoes;
* selection of optimal irrigation schedules; and
* routine scheduling of irrigation.

Conclusions

It is concluded that:

* Integration of an irrigation scheduling model and an economic optimization model is appropriate and feasible;
* Simulations of canopy development and dry matter production of processing tomatoes are fairly accurate;
* The simulation of the water balance is good and practical irrigation scheduling can be implemented; and
* The simulation of fresh yield and brix are not yet accurate enough and fine tuning of the parameters and/or a more mechanistic approach is required.

Further research needs

Various needs for further research have been identified during the project. The priority for further development is to enhance technology transfer through improved user friendliness and wider applicability to other crops through the establishment of crop model parameters.

CHAPTER 13

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APPENDIX A

Weather data

Table A1 Long term average daily maximum (Tx) and minimum (Tn) temperatures as well as the calculated monthly average vapour pressure deficit (VPD) for the different localities.

Month	Marble Hall			Pretoria			Lutzville			Messina		
	Tx	Tn	VPD	Tx	Tn	VPD	Tx	Tn	VPD	Tx	Tn	VPD
Jan	32.1	19.3	0.43	28.5	15.8	0.42	29.9	14.8	0.50	33.0	20.9	0.41
Feb	32.4	19.1	0.45	28.2	15.5	0.42	30.8	14.9	0.53	32.4	20.5	0.40
Mar	30.8	17.4	0.45	27.0	13.7	0.44	30.1	14.0	0.54	31.5	19.0	0.42
Apr	28.4	13.2	0.50	24.7	9.7	0.49	28.0	12.5	0.51	30.1	15.9	0.47
May	26.0	8.1	0.59	21.8	4.3	0.57	24.7	10.3	0.47	27.6	10.8	0.56
Jun	22.5	4.3	0.59	19.3	0.6	0.60	22.2	8.9	0.43	24.8	7.1	0.58
Jul	22.6	4.4	0.59	19.7	0.5	0.62	21.6	7.8	0.45	24.9	7.0	0.59
Aug	24.9	7.0	0.59	22.5	3.1	0.63	22.0	7.9	0.46	27.1	9.7	0.57
Sep	28.3	11.8	0.55	25.7	8.1	0.58	23.6	9.1	0.48	29.6	13.8	0.53
Oct	28.8	15.0	0.46	27.3	12.2	0.50	26.0	10.6	0.51	31.7	17.5	0.48
Nov	30.2	17.2	0.44	27.4	13.9	0.45	28.0	12.5	0.51	32.2	19.4	0.43
Dec	31.2	18.7	0.42	28.2	15.2	0.43	28.6	13.9	0.49	32.8	20.3	0.42

Lutzville is situated between Platskraal and Vredendal, with Platskraal closer to the sea than Lutzville and Vredendal. Average daily temperatures at Platskraal was 3 °C lower than at Vredendal, mainly due to lower night temperatures. The days in the Western Cape are also markedly longer than that in the other localities.

From the data in Table A1 it can be seen that the average VPD was much lower in Vredendal (close to the sea) than at Messina. The minimum temperatures at Vredendal are also lower than at the other localities, because of cooling at night.

Measured hourly weather data will be stored on diskette by the project leader at the University of Pretoria.

APPENDIX B

Source code for programs

WEATHER UNIT

```
unit _IWeathr;

interface

uses
   Dos,
   PXEngine,
   PXMsg,
  _IPXEng,
  _Math,
  _InOut,
  _IGlob,
  _IPET,
  _FldTbl,
  _WIDTbl,
  _DayWTbl,
  _PrcpTbl,
  _IInpWRD;

type
  WeatherRecord = record
    Rni,              {Net isothermal radiation W/m2}
    SVP,              {Saturation vapour pressure kPa}
    VP,               {Vapour pressure kPa}
    Eac,              {Emissivity Atmosphere}
    Ea,               {Clear sky emissivity}
    Ta,               {Air temperature  C}
    Tw,               {Wet bulb temperature  C}
    Latitude: Double;
  end; {WeatherRecord}

var
  PET,
  MeanTemp,
  Lni,                {Net isothermal long wave radiation}
  Slope:   Real;
  Weather:  WeatherRecord;

procedure InitWeather;
function PotSolar(DOY: Integer): Real;
function WeatherDayStep(WeatherID: Integer;
                   DOYDate:   DateStr;
                   DOY:       Integer): Integer;

implementation

uses
  _IInpPr;
```

```
var
  HalfDay: Real;           {Half day length}

procedure InitWeather;

Begin {Procedure InitWeather}
  FillChar(Weather,SizeOf(Weather),#0);
end; {Procedure InitWeather}

function PotSolar(DOY: Integer): Real;

var
  x,
  Lat,Dec,RelDist,HrAngle,
  SinDec,CosDec,Sinhs,Coshs,
  SinLatSinDec,CosLatCosDec: Real;

Begin {Function PotSolar}

  Lat      := -WeathrID.Latitude*Pi/180;          {Latitude in radians}
  Dec      := -0.4093*Sin(2*Pi*(284 + DOY)/365);  {Southern hemisphere}
  SinDec   := Sin(Dec);
  CosDec   := Cos(Dec);
  RelDist  := 1 + 0.033*Cos(2*Pi*DOY/365);
  HrAngle  := ArcCos(-Tan(Lat)*Tan(Dec));         {Sunset hour angle}

  x        := -Sin(Lat)*SinDec/(Cos(Lat)*CosDec);  {#}
  HalfDay  := Pi/2 - ArcTan(x/Sqrt(1-x*x));        {#}

  PotSolar := 118.08*RelDist/Pi*(HrAngle*Sin(Lat)*SinDec +
                                 HrAngle*Cos(Lat)*CosDec);
(*
  Lat          := WeathrID.Latitude*Pi/180;  {Converts latitude to radians}
  SinDec       := 0.39785*Sin(4.869 + 0.0172*DOY + 0.03345*Sin(6.224 + 0.0172*DOY));
  CosDec       := Sqrt(1 - Sqr(SinDec));
  SinLatSinDec := Sin(Lat)*SinDec;
  CosLatCosDec := Cos(Lat)*CosDec;
  Coshs        := -SinLatSinDec/CosLatCosDec;
  Sinhs        := Sqrt(1 - Sqr(Coshs));
  HalfDay      := Pi/2 - ArcTan(Coshs/Sinhs);  {#}
  PotSolar     := 117.5*(HalfDay*SinLatSinDec + CosLatCosDec*Sinhs)/pi;
*)
end; {Function PotSolar}

function WeatherDayStep(WeatherID: Integer;
                        DOYDate:   DateStr;
                        DOY:       Integer): Integer;
var
  k,
  PxErr: Integer;
  dt,
  Tr,          {Atmospheric transmissivity}
  PSR:   Real;

Begin {Function WeatherDayStep}
  IrrigDOY   := 0;        {#}
  PrecipDOY  := 0;        {#}
  PxErr := FindWDay(WDayID,DOYDate);
```

```
  if PxErr = PXERR_RECNOTFOUND then
    Begin
      InputWDayProc(WDayID,DOYDate);
      PxErr := FindWDay(WDayID,DOYDate);
    end; {if}
  if PxErr = PxSuccess then
    Begin
      PxErr := FindPrecip(Field.PerseelID,DOYDate);
      if PxErr = PXERR_RECNOTFOUND then
        Begin
          InputPrecipProc(Field.PerseelID,DOYDate);
          PxErr := FindPrecip(Field.PerseelID,DOYDate);
        end; {if}
    end; {if}
  if PxErr = PxSuccess then
    Begin
      IrrigDOY  := Precip.Irrig;
      PrecipDOY := Precip.Precip;
     {Precip.Precip := Precip.Precip + Precip.Irrig;}   {#}
      PSR := PotSolar(DOY);
      dt := WDayData.MaxTemp - WDayData.MinTemp;
      if dt < 2 then
        dt := 2;
      k := DOY - 30;
      if k < 1 then
        k := k + 365;
      if WDayData.Solar = 0 then
        Begin
          Tr := 0.7*(1 - Exp(-0.329*Sqr(dt)/PotSolar(k)));
          WDayData.Solar := PSR*Tr;
        end
      else
        Tr := WDayData.Solar/PotSolar(k);
      MeanTemp := (WDayData.MaxTemp + WDayData.MinTemp)/2;
      Slope := ((0.00223*MeanTemp + 0.0549)*MeanTemp + 2.97)*
                              MeanTemp + 45.3;     {Gives Slope in Pa}
      Lni   := (HalfDay/pi)*(0.96 - 1/(1 + 0.048*Exp(7.1*Tr)))*
                                          (0.026*MeanTemp - 9.2);

      if WDayData.VPD = 0 then
        WDayData.VPD := 0.7*Slope*dt
      else
        WDayData.VPD := WDayData.VPD*1000;    {Converts kPa to Pa}
    end; {if}
  if PxErr = PxSuccess then
    if WDayData.PET = 0 then
      PET := CalcPriestlyPET
    else
      PET := WDayData.PET;
  WeatherDayStep := PxErr;
end; {Function WDayDayStep}

end. {unit _IWeathr}
```

SOIL UNIT

```
unit _ISoil;

interface

uses
  PXEngine,
  PXMsg,
  _Math,
  _InOut,
  _IGlob,
  _Strings,
  _IWeathr,
  _FldTbl,
  _CropTbl,
  _SoilTbl,
  _DayWTbl,
  _PrcpTbl,
  _ICrop,
  _StraTbl,
  _ResTbl;

type
  SoilRecord = record
    ActualTrsp,
    Adwc,                  {Air dry water content}
    SI:       Real;
    a,
    b,
    Spsi:     SoilArray;
  end; {SoilRecord}

var
{InitStorage: Real;}
  dz:  SoilArray;    {Soil layers}
  Soil: SoilRecord;

procedure CalcSoildz(z:     SoilArray;
                var dz: SoilArray);
procedure InitSoil;
procedure SoilDayStep;
function SoilStoredWater(WC,dz: SoilArray;
                  RD:   Real): Real;
function AllowableDepletionProc(FCWC,PWPWC,dz:    SoilArray;
                        RD:           Real;
                        PercentDepletion: Real): Real;

implementation

var
  IrrigFlag,
  PrecipFlag:    Boolean;
  PrecipEvapCount: Byte;

procedure CalcSoildz(z:     SoilArray;
                var dz: SoilArray);
var
```

```
 i: Integer;

Begin {Procedure CalcSoildz}
 dz[1] := z[1];
 for i := 2 to NrOfLayers do
   dz[i] := z[i] - z[i-1];
end; {Procedure CalcSoildz}

procedure InitSoil;

var
 i: Integer;

Begin {Procedure InitSoil}
 IrrigFlag      := False;
 PrecipFlag     := False;
 PrecipEvapCount := 0;
 CalcSoildz(SoilData.z,dz);
 for i := 1 to NrOfLayers do
   Begin
     Soil.b[i] := ln(Field.PsiPWP/Field.PsiFC)/ln(SoilData.fcwc[i]/SoilData.pwpwc[i]);
     Soil.a[i] := Exp(ln(-Field.PsiPWP) + Soil.b[i]*ln(SoilData.pwpwc[i]));
     SoilData.pwpwc[i] := Exp(-ln(-3*Psilm/(2*Soil.a[i]))/Soil.b[i]);    {Plant lower limit}
     if SoilData.wc[i] > SoilData.fcwc[i] then
       Begin
         SoilData.wc[i] := SoilData.fcwc[i];
         OutputErrorMsg(Field.PerseelID+': Initial WC['+IntToStr(i)+'] exceeds field capacity',Nil);
       end; {if}
   end; {for}
 Soil.Adwc := 0.3 * SoilData.pwpwc[1];   {Air dry water content}
 ProfileFC := SoilStoredWater(SoilData.FCWC,dz,SoilData.z[NrOfLayers]{CropData.RDmax});
end; {Procedure InitSoil}

procedure CalcInterception;  {Calculates interception by canopy}

var
  MaxInterDOY, MaxIrrIntDOY  : real;  {Maximum interception}

Begin {Procedure CalcInterception}
 InterDOY := 0;
 PreIntDoy := 0;
 IrrIntDoy := 0;

 if (Precip.Precip > 0) or (Precip.Irrig > 0) then
   Begin
     MaxInterDOY := Crop.FIevap * Cropdata.CanopyInt;

     If PrecipDOY > 0 then
       Begin
         If Precip.Precip < MaxInterDOY then
           Begin
             PreIntDOY := Precip.Precip;
             Precip.Precip := 0;
             end {Precip.precip < MaxInterDOY}
           else
             Begin
             PreIntDoy := MaxInterDOY;
             Precip.Precip := Precip.Precip - PreIntDOY;
```

```
        end; {Precip.precip < MaxInterDOY}
      end; {PrecipDOY > 0 then}

     MaxIrrIntDOY := MaxInterDOY * CropData.CanopyWetted; {Maximum IrrIntDOY}

     if (IrrigDOY > 0) then
       Begin
        If precip.Irrig < MaxIrrIntDOY then
          Begin
           IrrIntDOY := Precip.irrig;
           Precip.Irrig := 0;
           end {Precip.irrig < MaxInterDOY}
          else
           Begin
           IrrIntDoy := MaxIrrIntDOY;
           Precip.Irrig := Precip.Irrig - IrrIntDOY;
          end; {Precip.irrig < MaxIrrIntDOY}
       end; {if (IrrigDOY > 0)}
   end; {if (Precip.Precip > 0) or (Precip.Irrig > 0)}

  InterDOY := IrrIntDOY + PreIntDOY;
  CumPreInt := CumPreInt + PreIntDoy;
  CumIrrInt := CumIrrInt + IrrIntDoy;
end; {Procedure CalcInterception}

procedure CalcRunOff;

Begin {Procedure CalcRunOff}
  RunOffDOY := 0;
  if Precip.Precip > 0 then
   Begin
    if Precip.precip <= 0.2 * SoilData.Rop then
      RunOffDOY := 0
    else
      RunOffDOY := Sqr(Precip.precip - 0.2 * SoilData.Rop)
                 /(Precip.precip + 0.8 * SoilData.Rop);
    Precip.precip := Precip.precip - RunOffDOY;
   end; {if}
end; {Procedure CalcRunOff}

procedure CalcInfiltration;

var
  i              : Integer;
  SimIntDay         : real;

Begin {Procedure CalcInfiltration}
  i            := 1;
  DrainDOY       := 0;
  PreDrainDOY    := 0;
  IrrDrainDOY    := 0;
  IrrInfEvapLayer := 0;

  while (Precip.precip > 0) and (i <= NrOfLayers) do
   Begin
    if Precip.precip >= (SoilData.fcwc[i]-SoilData.wc[i])*Rho_w*dz[i] then
      Begin
       Precip.precip := Precip.precip - (SoilData.fcwc[i] -
```

```
                                  SoilData.wc[i]) * Rho_w*dz[i];
      SoilData.wc[i] := SoilData.fcwc[i];
    end
   else
    Begin
      SoilData.wc[i] := SoilData.wc[i] + Precip.precip/(Rho_w*dz[i]);
      Precip.precip := 0;
    end;
   Inc(i);
  End; {while (Precip.precip > 0) and (i <= NrOfLayers)}

 if (Precip.precip > 0) and (not SimEcon) then
  Begin
   PreDrainDOY := Precip.precip;
   Precip.precip := 0;
   CumPreDrain := CumPreDrain + PreDrainDOY;
  end; {if}

 if SimEcon then
  Begin
   if Strat.DAPkPa < Abs(Soil.Spsi[Strat.Layer]) then
    Begin
      Precip.Irrig := MaxOfFloat(ProfileFC - ResultData.ProfileWC,0);
      SimIntDay := Crop.FIevap*Cropdata.CanopyInt*CropData.CanopyWetted;
      Precip.Irrig := Precip.Irrig + SimIntDay;
{OutputErrorMsg('Precip: '+IntToStr(DOY)+'  '+FloatToStr(Precip.irrig,10,3),nil);}
    end
   else
    Precip.Irrig := 0;
   Precip.precip := 0;
   IrrigDOY  := Precip.Irrig;
   PrecipDOY := Precip.Precip;
  end; {if}

 i := 1;
 while (Precip.Irrig > 0) and (i <= NrOfLayers) do
  Begin
   if i = 1 then

    Begin
      IrrInfEvapLayer := (Soildata.Fcwc[i] - SoilData.wc[i]) *
                         Rho_w * dz[i] * CropData.SurfaceWetted;
      SoilData.wc[i] := SoilData.wc[i] + (IrrInfEvapLayer/(Rho_w*dz[i]));
      Precip.Irrig := Precip.Irrig - IrrInfEvapLayer;
    End; {if i = 1 then}

   if i > 1 then
    Begin
      if Precip.Irrig >= (SoilData.fcwc[i] - SoilData.wc[i]) *
                                          Rho_w * dz[i] then
       Begin
         Precip.Irrig := Precip.Irrig
                 - (SoilData.fcwc[i] - SoilData.wc[i]) * Rho_w*dz[i];
         SoilData.wc[i] := SoilData.fcwc[i];
       end
      else
       Begin
         SoilData.wc[i] := SoilData.wc[i] + Precip.Irrig/(Rho_w*dz[i]);
```

```
          Precip.Irrig := 0;
        end;
      End;
     Inc(i);
   End; {while (Precip.Irrig > 0) and (i <= NrOfLayers)}

   IrrDrainDOY := Precip.Irrig;
   Precip.Irrig := 0;
   CumIrrDrain := CumIrrDrain + IrrDrainDOY;
   Draindoy := PreDrainDOY + IrrDrainDOY;
end; {Procedure CalcInfiltration}

Procedure CalcEvaporation;

var
  nwc,
  PotentialEvap: Real;

Begin{Procedure CalcEvaporation}
  EvapDOY := 0;        {#}
  PotentialEvap := 0;
  PrecipFlag := PrecipDOY > 0;
  if PrecipFlag or (PrecipEvapCount > 0) then
    Begin
      if PrecipFlag then PrecipEvapCount := 0;
      inc(PrecipEvapCount);
      if PrecipEvapCount = 4 then PrecipEvapCount := 0;
      PrecipFlag := False;
      PotentialEvap := (1 - Crop.Flevap) * PET;
      end
  else
    Begin
      PotentialEvap := CropData.SurfaceWetted * sqr(1 - Crop.Flevap) * PET;
    end;
  if SoilData.wc[1] <= SoilData.pwpwc[1] then
    Begin
      PotentialEvap := PotentialEvap
        * Sqr((SoilData.wc[1] - Soil.Adwc)/ (SoilData.pwpwc[1] - Soil.Adwc));
    end;
  nwc := SoilData.wc[1] - PotentialEvap / (Rho_w * dz[1]);
  if nwc <= Soil.Adwc then
    nwc := Soil.Adwc;
  EvapDOY := (SoilData.wc[1] - nwc) * Rho_w * dz[1];
  SoilData.wc[1] := nwc;
end; {Procedure CalcEvaporation}

procedure CalcTranspiration;

var
  i,m:     Integer;
  z,
  ust,
  est,
  estar,
  Psix,
  Loss,
  AvePstar,
  AvePsi:  Real;
```

```
 f:      SoilArray;

Begin {Procedure CalcTranspiration}
 TransDOY := 0;              {#}
 Soil.Spsi[1] := 0;
 Soil.ActualTrsp := 0;
 AvePsi := 0;
 z := dz[2];                 {z:=0;}
 i := 2;                     {rdd:=Crop.RD/4.6;}
 if (Crop.RD > 0) and (Crop.Fltransp > 0) then
   Begin
     repeat
       Soil.Spsi[i] := -Soil.a[i] * Exp(-Soil.b[i]*ln(SoilData.wc[i]));
       if z <= Crop.RD then
         f[i] := dz[i]*(2*(Crop.RD - z) + dz[i])/Sqr(Crop.RD)
       else
         f[i] := Sqr((Crop.RD - z + dz[i])/Crop.RD);
                        {f[i] := Exp(-z/rdd)*(1-Exp(-dz[i]/rdd));}
       AvePsi := AvePsi + f[i]*Soil.Spsi[i];
       Inc(i);
       if i <= NrOfLayers then
         z := z + dz[i];
     until (i > NrOfLayers) or (z - dz[i] > Crop.RD);
     AvePstar := AvePsi/Psilm;
     if AvePstar < 1.5 then
       ust := 1 - 0.67*AvePstar
     else
       ust := 0;
     est := PET/CropData.MaxTrans;  {if est < 0 then est := 0;}
     if est < ust then
       estar := est
     else
       estar := ust;
     if estar < 0 then
       estar := 0;
     Psix := Psilm * (AvePstar + 0.67 * estar);
     m := i - 1;
     for i := 2 to m do
       Begin
         Loss := (Crop.Fltransp * CropData.MaxTrans * f[i] *
                 (Psix - Soil.Spsi[i]) / (0.67 * Psilm)) / (Rho_w*dz[i]);
(*
         if Loss < 0 then
           Begin
             OutputErrorMsg('Loss ('+IntToStr(DOY)+'):
                                 '+FloatToStr(Loss,8,2),Nil);
             Loss := Abs(Loss);
           end; {if}
*)
         if SoilData.wc[i] - Loss < SoilData.pwpwc[i] then
           Loss := SoilData.wc[i] - SoilData.pwpwc[i];
         Soil.ActualTrsp := Soil.ActualTrsp + Loss * Rho_w*dz[i];
         SoilData.wc[i] := SoilData.wc[i] - Loss;
       end; {for}
     Soil.ActualTrsp := MaxOfFloat(0,Soil.ActualTrsp);
     TransDOY := Soil.ActualTrsp;
   end; {if}
 if Crop.Fltransp > 0 then
```

```
    Soil.SI := Soil.ActualTrsp/(Crop.FItransp*PET)
  else
    Soil.SI := 0;
end; {Procedure CalcTranspiration}

procedure SoilDayStep;

Begin {Procedure SoilDayStep}
  CalcEvaporation;
  CalcTranspiration;
  CalcInterception;
  CalcRunOff;
  CalcInfiltration;
end; {Procedure SoilDayStep}

function SoilStoredWater(WC,dz: SoilArray;
                         RD:    Real): Real;
var
  z,
  StoredWater: Real;
  i:          Integer;

Begin {Function SoilStoredWater}
  i := 0;
  z := 0;
  StoredWater := 0;
  repeat
    Inc(i);
    StoredWater := StoredWater + WC[i]*dz[i]*Rho_w;
    z := z + dz[i];
  until (i >= NrOfLayers) {or (z >= RD)};
  SoilStoredWater := StoredWater;
end; {Function SoilStoredWater}

function AllowableDepletionProc(FCWC,PWPWC,dz:   SoilArray;
                                RD:              Real;
                                PercentDepletion: Real): Real;
var
  z,
  Depletion: Real;
  i:        Integer;

Begin {Function AllowableDepletionProc}
  z := 0;
  i := 0;
  Depletion := 0;
  repeat
    Inc(i);
    Depletion := Depletion + (FCWC[i]-PWPWC[i])*dz[i]*Rho_w;
    z := z + dz[i];
    if z > RD then
      Depletion := Depletion - (z - RD)*(FCWC[i]-PWPWC[i])*Rho_w;
  until (i >= NrOfLayers) or (z >= RD);
  AllowableDepletionProc := -Depletion*PercentDepletion/100;
end; {Function AllowableDepletionProc}

end. {unit _Isoil}
```

CROP UNIT

```
unit _lCrop;

interface

uses
  _lGlob,
  _lWeathr,
  _CropTbl,
  _DayWTbl;

type
  CropRecord = record
    TDM,        {Vegetative (top) dry matter, leafs + stems}
    SDM,        {Stem dry matter}
    HDM,        {Havestable dry matter}
    PHDM,       {Potential HDM, not used anywhere}
    LAI,        {Leaf area index}
    yLAI,       {(yellow) LAI of dead leafs}
    GDD,        {Growing day degrees}
    FItransp,   {Fractional inteception of solar radiation for evaporation}
    FIevap,     {Fractional inteception of solar radiation for evaporation}
    RD,         {Root depth}
    RDM,        {Root dry matter}
    gpf,        {Grain (fruit) partition factor, fraction to HDM}
    MaxLAI,     {Maximum leaf area index}
    FDD:        {For vernalization (instead of GDD), not used}
      Real;

    DFE,       {Days from emergence}
    LeavesDead: {Senesced leaves}
      Integer;

    DailyLAI,   {Leaf area of dmi produced on a given day}
    DailyLAIAge: {Age of corresponding DailyLAI}
      Array[0..400] of Real;

    CropPlanted,
    Mature,
    Flowered,
    Vegetative,
    Emerged:       Boolean;

  end; {CropRecord}

var
  Crop: CropRecord;

procedure InitCrop;
procedure PlantCrop;
procedure CropDayStep;

implementation

uses
  _lSoil;
```

```
var
  SeedlingStg,
  LDMCorrected: Boolean;

Procedure InitCrop;

var
  i: Integer;

Begin {Procedure InitCrop}
  Crop.TDM         := 0;
  Crop.LAI         := 0;
  Crop.yLAI        := 0;
  Crop.RD          := initRD;
  Crop.FIevap      := 0;
  Crop.FItransp    := 0;
  Crop.PHDM        := 0;
  Crop.HDM         := 0;
  Crop.GDD         := 0;
  Crop.FDD         := 0;
  Crop.SDM         := 0;
  Crop.CropPlanted := False;
  Crop.DFE         := 0;
  Crop.LeavesDead  := 0;
  Crop.Emerged     := False;
  Crop.Flowered    := False;
  Crop.Vegetative  := Crop.Emerged and not Crop.Flowered;
  Crop.Mature      := False;
  Crop.MaxLAI      := 0;
  LDMCorrected     := False;
  FillChar(Crop.DailyLAI,SizeOf(Crop.DailyLAI),#0);
  FillChar(Crop.DailyLAIAge,SizeOf(Crop.DailyLAIAge),#0);

end; {Procedure InitCrop}

Procedure PlantCrop;
Begin {Procedure PlantCrop}
  Crop.CropPlanted := True;
  Crop.GDD         := 0;
  Crop.FDD         := 0;
  Crop.HDM         := 0;
  Crop.TDM         := CropData.TDMstart;
  Crop.RDM         := CropData.froot * Crop.TDM / (1 - CropData.froot);
  Crop.FItransp    := 0;
  Crop.SDM         := 0;
  Crop.DailyLAI[0] := CropData.SLA * Crop.TDM * InitFleaf;
  Crop.LAI         := Crop.DailyLAI[0];
  Crop.DFE         := 0;
  Crop.LeavesDead  := 0;
  Crop.Emerged     := False;
  Crop.Flowered    := False;
  Crop.Mature      := False;
  Crop.MaxLAI      := 0;
  Crop.RD          := InitRD;

end; {Procedure PlantCrop}

Procedure CropDayStep;
```

```
var
 i            : Integer;
 gddi,     {Daily increment of growin degree days}
 tfact,    {Temperature effect on growth rate}
 dmiw,     {Potential dry matter increment based on actual transpiration}
 dmis,     {Potential dry matter increment based on intercepted radiation}
 dmi,      {Final dry matter increment}
 ldmi,     {Leaf dry matter increment}
 vdmi,     {Vegetative dry matter increment }
 hdmi,     {Head/fruit dry matter increment }
 fleaf,    {Fraction of ldmi partition to leaves}
 fr,       {Fraction of dmi partitioned to roots}
 Stagei
     : Real;
 TempSI  {Temporary variable for SI}
     : Real;

 Function CanopyLAI(gddi,ldmi,wsi: Real): Real;
 Var
  k,l,m: Integer;
  wsf,c,
  LDMCorrFact: Real;
 Begin
  Inc(Crop.DFE);
  Senesi        := 0;
  SenesDmDOY    := 0;
  TransTDMi     := 0;
  SenescTDMlossi := 0;
  c             := 0;
  wsf           := 1;
  LDMCorrFact   := 0;
  SeedlingStg := Crop.GDD < CropData.FIDD * EndSeedlDDFrac;
  {Seedling growth}
  if SeedlingStg then
   Begin
    Crop.DailyLAI[Crop.DFE] := Crop.LAI * (Exp(RGRleaf * gddi)-1)
   end
  else {Normal LAI growth of leaf area from ldmi}
   Crop.DailyLAI[Crop.DFE] := ldmi * CropData.SLA;

  if (not SeedlingStg) and (LDMCorrected = False) then {First day after end of seedling growth only}
   Begin
    GLDM       := Crop.LAI/CropData.SLA;
    TempFleaf := 1 / sqr(1 + CropData.part * Crop.TDM);{Fraction to leaves}
    Crop.SDM   := GLDM / TempFleaf; {Crop.SDM * LDMCorrFact;}
    Crop.TDM   := GLDM + Crop.SDM;
    LDMCorrected := True;
   end;

  {Increment leaf age}
  Crop.DailyLAIAge[Crop.DFE] := gddi;
  OldSLA := Cropdata.SLA;
  CurrentSLA := Cropdata.SLA;
  SenesRate := ShadeSenescCoef * Crop.FItransp;

  if (wsi < CropData.StressIndex) and (wsi > 0) then   {#}
   wsf := 1/wsi;
  if wsf > 2 then wsf := 2;
```

```
for k := 0 to Crop.DFE - 1 do {k = DAP counter for leaf aging and senescence}

  Begin
    Senesi := 0;
    Crop.DailyLAIAge[k]:= Crop.DailyLAIAge[k] + gddi {(wsf * gddi)};

    {Senescence and translocation}
    if Crop.DailyLAIAge[k] > CropData.MaxLeafAge then
      Begin
        {Senescence}
        Senesi := SenesRate * Crop.DailyLAI[k];
        SenescDOY := SenescDOY + Senesi;
        SenesDmDOY := SenesDmDOY + Senesi / CurrentSLA;
        Crop.DailyLAI[k] := Crop.DailyLAI[k] - Senesi;
        Crop.yLAI:= Crop.yLAI + Senesi;
        {Translocation of dry matter to fruits}
        SenescTDMlossi := SenescTDMlossi +
                        (1 - TransTDMFrac) * Senesi/CurrentSLA;
        TransTDMi := TransTDMi + TransTDMFrac * (Senesi/CurrentSLA);
       end; {if Crop.DailyLAIAge[k] > CropData.MaxLeafAge}

      {Modifies SLA to simulate storage of assimilates in leaves}
      OldSLA := CurrentSLA;
      {Decreases SLA}
      CurrentSLA := Cropdata.SLA + SLACoef * k; {Crop.DFE;}
      {Calculates new value of LAI with the modified SLA}
      Crop.DailyLAI[k] := Crop.DailyLAI[k] * CurrentSLA / OldSLA;

      c := c + Crop.DailyLAI[k];
  end; {For  k := 0 to Crop.DFE - 1}

 c := c + Crop.DailyLAI[Crop.DFE];
 TotSenesDmLoss := TotSenesDmLoss + SenesDmDOY;

 CanopyLAI := c;
end; {function CanopyLAI}

Begin {Procedure CropDayStep}
 StressDay := 0;                    {#}
 if Crop.CropPlanted then
  Begin    {CALCULATION OF GROWING DAY DEGREES (gddi)}
   if MeanTemp > CropData.Tbase then
    gddi :=  MeanTemp - CropData.TBase
   else
    gddi := 0;
   if gddi > CropData.Tcutoff then   {#}
    gddi := CropData.Tcutoff - CropData.TBase;
   Crop.GDD := Crop.GDD + gddi;
   DDi := gddi;
end;  {If CropPlanted}

 Crop.Mature   := Crop.GDD > CropData.MtDD; {#}
 Crop.Flowered := Crop.GDD > CropData.FlDD; {#}

 {EMERGENCE}
 if not Crop.Emerged and (Crop.GDD > CropData.EmDD) then
  Begin
   Crop.Emerged := True;
```

```
    Crop.LAI    := CropData.SLA * Crop.TDM * InitFleaf;
  end; {if}

If (Crop.GDD > RipeDD * 0.7) then
  KCmodified := CropData.KC * Crop.GDD / (RipeDD * 0.7)
else
  KCmodified := CropData.KC;
if KCmodified > MaxKC  then KCmodified := MaxKC;

{Calculates fractional interception of solar radiation}
{FI for transpiration based on green LAI only}
Crop.FItransp := 1 - Exp(-KCmodified * Crop.LAI);
{FI for evaporation based on green LAI plus yellow (dead) LAI}
Crop.FIevap   := 1 - Exp(-KCmodified * (Crop.LAI + Crop.yLAI));

if Crop.Emerged and not Crop.Mature then
  Begin
    ldmi := 0;

    {ASSIMILATE PRODUCTION}
    {Potential dry matter production based on actual transpiration}
    dmiw := Soil.ActualTrsp * CropData.DWR / WDayData.VPD;
                              {dmiw in kg/m2, ActualTrsp in mm}
    {Potential dry matter production based on intercepted radiation}
    {Temperature effect}
    if gddi >= (CropData.Tlo - CropData.Tbase) then
      tfact := 1
    else
      tfact := gddi / (CropData.Tlo - CropData.Tbase);
    {Seedling growth rate increased through higher radiation use
      efficiency}
    dmis := tfact * CropData.ConvEff * Crop.FItransp * WDayData.Solar;
    {Selects the most limiting of potential dmiw and potential dmis}
    if dmis < dmiw then
      dmi := dmis
    else
      dmi := dmiw;
    dmiDOY := dmi;
    {Calculates relative growth stage}
    RelGrwStg := Crop.GDD / CropData.MtDD;
    TempSI := Soil.SI;
    {Enhances end of leaf growth, maturity and ripening if stressed}
    If Soil.SI < CropData.StressIndex then
      Begin
        If Crop.GDD < RipeDD then
        Begin
          RipeDD := RipeDD - RipeSensStress {* stressdays = 1};
          CropData.MtDD := CropData.MtDD - MtSensStress {*stressdays = 1};
        end;
      end;

    {Respiration of HDM, Increased hdmRespRate after ripening, SolHDM?}
    if Crop.Flowered then
      Begin
        {Normal respiration before ripeness}
        hdmRespi := hdmRespRate * 0.5/RelGrwStg * crop.HDM
                      * Q10c * exp(0.01 * (MeanTemp - Tref));
        If Crop.GDD > RipeDD then   {Respiration at increasing rate after first ripeness}
```

```
   hdmRespi := hdmRespi + ClimRr
           * (Crop.GDD-(RipeDD))/(Cropdata.MtDD-(RipeDD))
                        {For increasing portion ripened fruits}
           * crop.HDM * Q10c * exp(0.01 * (MeanTemp - Tref));
  CumhdmResp := CumhdmResp + hdmRespi;
end; {If Crop.Flowered}

{PARTITIONING OF ASSIMILATES}
{Calculates portion of assimilates partitioned to fruits}
if Crop.Flowered then
  Begin
   Crop.gpf := (Crop.GDD - CropData.FlDD) / CropData.GpDD;  {#}
   if Crop.gpf > 1 then Crop.gpf := 1;
  end
else Crop.gpf := 0;
{Partitions dmi to HDM}
hdmi  := Crop.gpf * dmi;
hdmiDOY := hdmi;
{First priority in partitioning: subtract reproductive growth}
dmi  := dmi - hdmi;
{Stops root growth if max root depth is reached}
if Crop.RD < CropData.RDmax then fr := CropData.Froot else fr := 0;
{vdmi = Dry matter to leaves and stems}
vdmi := (1 - fr) * dmi;          {dmi not including hdmi any more}
Crop.RDM := Crop.RDM + fr * dmi;
Crop.TDM := Crop.TDM + vdmi; {At this stage TDM does not include fruits}

if Crop.SDM = 0 then
  Crop.SDM := (1-fleaf) * vdmi;

{Partitions more to roots if stressed}
if Soil.SI < CropData.StressIndex then
  Begin

   if fr > 0 then   {If roots is still growing}
    Begin
     Crop.RDM  := Crop.RDM + 0.5 * vdmi; {0.5*vdmi from TDM to RDM}
     Crop.TDM := Crop.TDM - 0.5 * vdmi;
     Crop.SDM := Crop.SDM + 0.5 * vdmi; {All to stems}
    end
   else      {If no root growth}
     Crop.SDM := Crop.SDM + vdmi; {All to stems}
   vdmi := 0;
   ldmi     := 0;
   StressDay := 1;                  {#}
  end
else  {No stress}
  Begin
   fleaf := 1 / sqr(1 + CropData.part * Crop.TDM); {Fraction to leaves}
   ldmi     := fleaf * vdmi;
   Crop.SDM  := Crop.SDM + (1 - fleaf) * vdmi; {Partitioning to stems}
  end; {If Soil.SI < CropData.StressIndex}

TempFleaf := fleaf;

{Root growth}
Crop.RD := InitRD + CropData.RGR * Sqrt(Crop.RDM);
```

```
if Crop.Flowered then
 Begin
  {FRUIT DEVELOPMENT}
  {Initial values for fruit components}
  if Crop.HDM = 0 then  {On day of start of flowering}
   Begin
    if HWC = 0 then HWC := InitialHWC;
    Crop.HDM  := Transl * Crop.SDM;          {Initiates fruit growth}
    FreshYield := Crop.HDM / ( 1 - HWC );        {kg/m2}
    SolHDM := FreshYield * InitialBrix / 100;    {kg/m2}
    SeedPeelHDM := (Crop.HDM - SolHDM) * InitialSeedPeelFrac;
    FixedHDM := FixedHDM - SeedPeelHDM;          {Fixes HDM only}
   end; {If Crop.HDM = 0,  On day of start of flowering}

  TempSI := Soil.SI;
  {Fruit water loss by if stressed}
  if TempSI < CropData.StressIndex then
   Begin
    if TempSI < 0.5 then Tempsi := 0.5;
    RelHwcLossRate := (MinHWC - HWC)*(MinHWC - HWC)
                 / (MaxHWC - MinHWC) / (MaxHWC - MinHWC);
    if RelHwcLossRate > 1 then RelHwcLossRate := 1;
    hwci := - PotHwcLoss
           * RelHwcLossRate
           * RelGrwStg
           / TempSI;
   end
  {Fruit water gain if not stressed}
  else
   Begin
    RelHwcGainRate := (MinHWC - HWC)*(MinHWC - HWC)
                 / (MaxHWC - MinHWC) / (MaxHWC - MinHWC);
    hwci := PotHwcGain
           * RelHwcGainRate
           * RelGrwStg;
   end; {If Soil.SI < CropData.StressIndex}

  {Adds fruit water increment (hwci) to fruit water}
  HWC := HWC + hwci;
  {Limitations to Fruit water}
  if HWC > MaxHWC then HWC := MaxHWC;
  if HWC < MinHWC then HWC := MinHWC;

  FixHdmFrac := FixedHDM / Crop.HDM;
  {Limitations to Fixed HDM fractions}
  if FixHdmFrac > MaxFixHdmFrac then FixHdmFrac := MaxFixHdmFrac;
  if FixHdmFrac < MinFixHdmFrac then FixHdmFrac := MinFixHdmFrac;

  {Adds translocated dmi from senesced leaves to FinHdmi
   and deducts respiration loss}
  NetHdmi  := hdmi + TransTDMi {prev day} - hdmRespi;

  {Fixes a portion of NetHdmi of the previous day}
  if NetHdmi > 0 then
   Begin
    hdmDissi := 0;
    hdmFixi:= hdmFixRate * NetHdmi;
    {Grows seeds and peels}
```

```
      hdmSeedPeeli := SeedPeelFrac * hdmFixi;
     end
    else {If FinHdmi of the previous day was negative}
     Begin
      hdmFixi := 0;
      hdmSeedPeeli := 0;
      {Dissolves FixedHDM}
      hdmDissi := hdmDissRate * FixedHDM;
    end; {If FinHdmi > 0}
    SolHDMi := NetHdmi - hdmFixi + hdmDissi;
    Crop.HDM := Crop.HDM + NetHdmi;
    SolHDM := SolHDM + SolHDMi;
    FixedHDM := FixedHDM + hdmFixi - hdmSeedPeeli - hdmDissi;
    SeedPeelHDM  := SeedPeelHDM + hdmSeedPeeli;
    HdmMassBalanceError := Crop.HDM -( SolHDM + FixedHDM + SeedPeelHDM);

    {Calculates FreshYield}
    FreshYield := Crop.HDM / ( 1 - HWC ); {kg/m2}
    FreshYield := FreshYield * 10000 / 1000;  {ton/ha}

    {Calculates percentage of soluble solids}
    If FreshYield > 0 then
     Begin
      Brix := SolHDM / (FreshYield*1000/10000) * 100;
      If Brix > MaxBrix then Brix := MaxBrix;
      If Brix < MinBrix then Brix := MinBrix;
     end;
  end;  {If Crop.Flowered}

{TDM now becomes Total top dry matter, including HDM, excluding RDM}
Crop.TDM :=  Crop.SDM + LDM + Crop.HDM;
         {Crop.TDM + hdmi - SenescTDMlossi - hdmRespi;}

Crop.LAI := CanopyLAI(GDDI,ldmi,Soil.SI);
if Crop.LAI > Crop.MaxLAI then  Crop.MaxLAI := Crop.LAI;
LDM := LDM + ldmi - SenesDmDOY;

{Calculates radiation use efficiency}
RadUsedDOY := Crop.Fltransp * WDayData.Solar;
TotalRadUsed := TotalRadUsed + RadUsedDOY;
TotalRad := TotalRad + WDayData.Solar;
FracRadUsed  := TotalRadUsed / TotalRad;
if TotalRadused > 0 then
RadUseEff := (Crop.TDM + Crop.RDM + CumhdmResp + TotSenesDmLoss)
                                / TotalRadUsed; {kg/MJ}
RadUseEff := RadUseEff;

{Calculates water use efficiency (DWRatio) from the equation:
  AvgDWRatio = Total dry matter produced * avg VPD/Transpiration,
  which is derived from:
            dmiw := Soil.ActualTrsp * CropData.DWR / WDayData.VPD}
TotalVPD := TotalVPD + WDayData.VPD;
if Crop.DFE > 0 then AvgVPD := TotalVPD / Crop.DFE;
TotalTrnsp := TotalTrnsp + Soil.ActualTrsp;
If (AvgVPD > 0) and (TotalTrnsp > 0) then
AvgDWRatio := (Crop.TDM + Crop.RDM + CumhdmResp + TotSenesDmLoss)
                                 * AvgVPD / TotalTrnsp;
{Indicates Stage
```

```
      1 = Emerged          1000.00001
      2 = Seedling         0100.00001
      3 = Flowered         0010.00001
      4 = Ripening         0001.00001
      5 = CanStructChanged 0000.10001
      6 = LeafGrowthStopped 0000.01001
      7 = Senescing        0000.00101
      8 = Mature           0000.00011}

    stage := 10000.00001;
    If Crop.GDD > CropData.EmDD then
      Begin
        Stagei := 1000.00001;
        Stage := Stage + Stagei;
      end;
    If Crop.GDD > EndSeedlDDfrac * CropData.FlDD then
      Begin
        Stagei := 100;
        Stage := Stage + Stagei;
      end;
    If Crop.GDD > CropData.FlDD then
      Begin
        Stagei := 10;
        Stage := Stage + Stagei;
      end;
    If Crop.GDD > RipeDD then
      Begin
        Stagei := 1;
        Stage := Stage + Stagei;
      end;
    If Crop.GDD > 0.7 * RipeDD then
      Begin
        Stagei := 0.1;
        Stage := Stage + Stagei;
      end;
    If Crop.GDD > CropData.GpDD then
      Begin
        Stagei := 0.01;
        Stage := Stage + Stagei;
      end;
    If Crop.GDD > CropData.MaxLeafAge then
      Begin
        Stagei := 0.001;
        Stage := Stage + Stagei;
      end;
    If Crop.GDD > CropData.MtDD then
      Begin
        Stagei := 0.0001;
        Stage := Stage + Stagei;
      end;
  end; {if Crop.Emerged and not Crop.Mature}

end; {procedure CropDayStep}

end. {unit _lCrop}
```