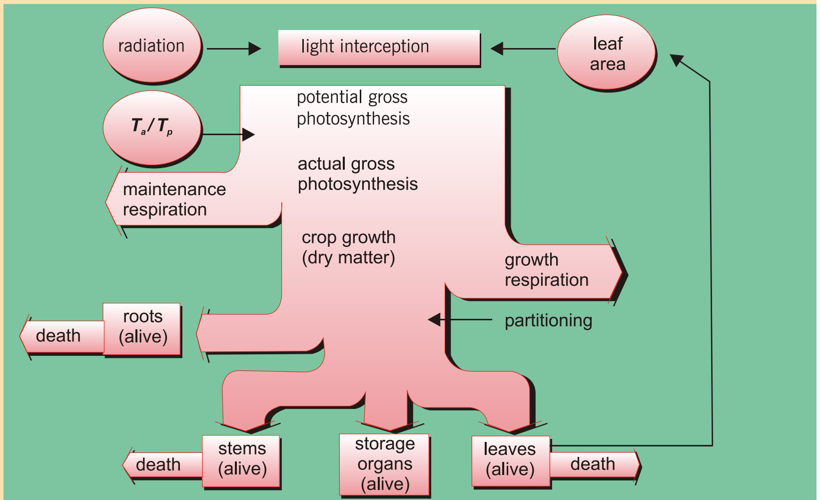
WORKING PAPER 22

Crop Growth and Soil Water Balance Modeling to Explore Water Management Options



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Amor Valeriano M. Ines, Peter Droogers, Ian W. Makin and Ashim Das Gupta

International Water Management Institute

FUTURE HARVEST
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Asian Institute of Technology Bangkok, Thailand

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Acronyms

General

AIT	-	Asian Institute of Technology
IREM	-	Irrigation Engineering and Management
CERES	-	Crop Environment Resource Synthesis
CROPGRO	-	Crop Growth
DSSAT	-	Decision Support System for Agrotechnology Transfer
NCSRC	-	National Corn Sorghum Research Center
SWAP	-	Soil Water Atmosphere Plant
USDA-SCS	-	United States Department of Agriculture-Soil Conservation Service
WOFOST	-	World Food Studies

Some Model Variables

C	-	Water capacity, dθ /dh, (cm^{-1})
c_{air}	-	Heat capacity of moist air ($J\ g^{-1}\ {}^oC^{-1}$)
CN2	-	Curve number (-)
D_{root}	-	Root layer thickness (cm)
DUL	-	Drained upper limit (cm)
DVS	-	Development stage (-)
e_{act}	-	Actual vapour pressure (kPa)
E_p	-	Potential soil evaporation ($mm\ d^{-1}$)
e_{sat}	-	Saturated vapour pressure (kPa)
ET_p	-	Potential Evapotranspiration rate ($cm\ d^{-1}$)
G	-	Soil heat flux ($J\ m^{-2}\ d^{-1}$)
h	-	Soil water pressure head (cm)
HOLD	-	Water holding capacity (cm)
K	-	Soil hydraulic conductivity ($cm\ d^{-1}$)
K_{sat}	-	Saturated hydraulic conductivity ($cm\ d^{-1}$)
LAI	-	Leaf area index ($m^2\ m^{-2}$)
LL	-	Drained lower limit (cm)
n	-	Dimensionless parameter (-)
N	-	Nitrogen
q	-	Soil water flux density ($cm\ d^{-1}$)

r_{air}	-	Aerodynamic resistance (s m^{-1})
r_{crop}	-	Crop resistance (s m^{-1})
R_n	-	Net radiation flux at the canopy surface (J m^{-2} d^{-1})
S	-	Soil water extraction rate of the plants (cm^3 cm^{-3} d^{-1})
S_a	-	Actual root water flux (d^{-1})
S_e	-	Relative saturation (-)
SALB	-	Soil albedo (-)
SC	-	Soil cover fraction (-)
S_p	-	Maximum possible root water extraction rate (d^{-1})
SWCON	-	Drainage constant (d^{-1})
t	-	Time dimension (d)
T_a	-	Actual transpiration (cm d^{-1})
T_p	-	Potential transpiration (cm d^{-1})
WR	-	Root weighting factor (-)
z	-	Vertical coordinate (cm)
α	-	Shape factor Mualem-Van Genuchten function (cm^{-1})
α_{rs}	-	Reduction coefficient, salt stress (-)
α_{rw}	-	Reduction coefficient, water stress (-)
Δ_v	-	Slope of the vapour pressure curve (kPa $^oC^{-1}$)
γ_{air}	-	Psychrometric constant (kPa $^oC^{-1}$)
γ_{sill}	-	Drainage resistance of surface runoff in SWAP (d^{-1})
λ	-	Shape factor Mualem-Van Genuchten equation (-)
λ_w	-	Latent heat of vaporization (J g^{-1})
θ	-	Volumetric water content (cm^3 cm^{-3})
θ_{res}	-	Residual water content (cm^3 cm^{-3})
θ_{sat}	-	Saturated water content (cm^3 cm^{-3})
ρ_{air}	-	Density of the air (g cm^{-3})

SUMMARY

The performance of the decision support system for agrotechnology transfer (DSSAT) and the soil water atmosphere plant (SWAP) was studied under an acid sulphate soil. The comparison of these models was done as a prerequisite to the selection of an appropriate model, which is capable of simulating water management scenarios, water balance and crop growth, to be coupled with an adaptive optimization algorithm that can be used to explore water management options.

As the models are basically different in structure, extra care was observed in setting up the simulations. Crop environment resource synthesis (CERES)-Maize in DSSAT and world food studies (WOFOST) in SWAP were used to simulate the growth and development of maize based on field experiment data. The soil water balance was also studied in the simulations.

The dates of the development stages could be properly simulated in DSSAT. The model correctly simulated these dates while SWAP performed well in its prediction. These are strongly influenced by the factors considered in the phenological development of the crop. In DSSAT, both temperature and day-length were considered while in SWAP only temperature was considered, because of the lack of data on the day-length response parameters.

DSSAT was able to predict with good accuracy the leaf area index (LAI) during silking stage; SWAP estimated the same fairly. However, in terms of yield, SWAP simulated the actual yield well. This is strongly influenced by the soil water balance model. The reduction of the potential biomass production has more physical basis in SWAP than in DSSAT. Likewise, the estimate of the potential evapotranspiration was observed to have a significant effect on the actual yield estimate. Along the growth process, DSSAT predicted that there was no water stress while SWAP simulated water and oxygen stress.

The soil water balance calculation in SWAP is more physically based than in DSSAT. SWAP solves the Richards' equation in the transport of soil water. Since the calculation of water flow is based on head differences, it thus allows situations like capillary flow at the bottom of the soil profile and soil water movement upward or downward from a soil layer. The latter used functional relationships in accounting the movement of soil water from layer to layer and assumes a free-draining column. The runoff calculation in both models has a strong empiricism as well. SWAP simulates the runoff by considering a maximum sill height and a resistance factor, while DSSAT uses the modified United States Department of Agriculture-Soil Conservation Service (USDA-SCS) method.

The big advantage of DSSAT over SWAP is its crop-nitrogen interaction. SWAP however, can simulate the movement and degradation of this element by assuming it as solute. DSSAT, on the other hand, does simulate N dynamics in the plant and soil but not for other solutes. The effect of salt stress in the water uptake is also not taken into account.

CROP GROWTH AND SOIL WATER BALANCE MODELING TO EXPLORE WATER MANAGEMENT OPTIONS

Amor Valeriano M. Ines
Peter Droogers
Ian W. Makin
and
Ashim Das Gupta

1. INTRODUCTION

Increasing competition in water use has spurred the concept of better use and management of water resources so that the needs of all stakeholders can be met properly. The need to study how water can be used efficiently is therefore necessary (Molden 1997). Agriculture, being considered the major user of water, is a potential avenue to study water use efficiency. A strategic point to start with is to answer the question of how much water is really needed to grow crops. But even this question is difficult to answer because of the interrelationship of factors in the soil-plant-atmosphere system. It is more difficult if the issue expands to how crops are using the applied water in the soil. Simulation models are strong in this regard; they can simulate the processes in the real system and predict the state variables at every stage in the simulation.

The role of simulation models in understanding the processes in the soil-plant-atmosphere system has increased significantly in recent years. This is attributed to increased computing capabilities available today. Mathematical models, be it physically or empirically based, have the promising potential to explore solutions to water management problems. Evaluation of water management scenarios can be easily done, thus facilitating better recommendations for improved water use (MacRobert and Savage 1998; Droogers and Kite 1999; Droogers and Bastianssen 2000; Droogers et al. 2000).

Comparing model results with field observations, or intercomparing models of different nature will provide information on the performance of the models and will reveal strong and weak points. This is essential in selecting appropriate models for practical applications in water resources analyses. A comparison of a physically based soil-plant-atmosphere model to a simpler one will give information on how the model fares in its performance compared with the other. If the simpler model can sufficiently simulate the processes, then this could be a good alternative to data-intensive complex simulation models. This makes sense from an economic point of view, because this will minimize the need for comprehensive data in the simulation. However, should this be the only criterion? Maybe not, a model has to be robust enough in most of the conditions prevailing in the system if one were to consider its relative capability.

SWAP (Van Dam et al. 1997) and DSSAT (Tsuji et al. 1994) are considered the standards of soil and crop models, respectively. However, each model has the capacity to simulate both soil and crop processes. The soil water dynamics in SWAP is physically based while in DSSAT, it is more empirical in nature. Recently, the generic crop model WOFOST has been linked with SWAP, thus enabling the model to simulate crop growth in more detail. DSSAT has a huge arsenal of detailed crop models, which includes the CERES and crop growth (CROPGRO) families and others. These are linked to one soil-water-balance model.

Simulation models are strong in understanding physical processes and scenario testing, but one cannot say if this combination of management alternatives can give the optimum return from scarce resources. Simulation and optimization make a strong tandem in water resources analysis, and, if used together, they could broaden the capacity to manage available resources. Combining a simulation model with an optimization algorithm is a promising tool for better water resources management.

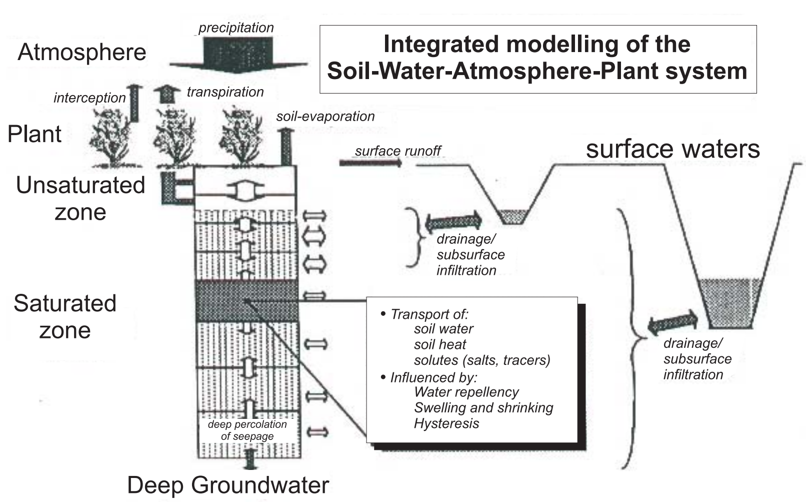
The main objective of this study is to compare the performance of SWAP and DSSAT in simulating the water balance and crop growth of maize (*Zea mayz*). This comparison is envisaged to give an idea on which of the two models is more robust in handling water management scenarios and water balance and crop growth simulation, and is highly promising to be coupled with an adaptive optimization algorithm. The data used in the simulation were collected from a corn experiment done at Irrigation Environment Resource Management (IREM) field experimental station of the Asian Institute of Technology (AIT), Bangkok, Thailand (Asadi 2000).

2. THE SWAP MODEL

General Description

The SWAP model is a physically based, detailed agro-hydrological model that simulates the relationships between soil, water, weather and plants (figure 2.1). The core of the model is the Richards' equation where the transport of soil water is modeled by combining Darcy's law and the law of continuity. SWAP models the soil water movement by considering the spatial differences of the soil water potentials in the soil profile. The governing equation is solved numerically,

Figure 2.1. A schematized overview of the modeled system in SWAP (Van Dam et al. 1997).



where the implicit scheme used (Belmans et al. 1983) can be effectively applied in saturated and unsaturated conditions.

The significant features of Richards' equation are that it allows the use of soil hydraulic databases and the simulation of all kinds of management scenarios. In SWAP, the soil hydraulic functions are described by the analytical functions of Van Genuchten (1980) and Mualem (1976) for soil water retention and hydraulic conductivity.

SWAP simulates not only the quantity of soil water but also the quality and considers the effect of heat on the fate of solutes. Hysteresis, water repellency, soil swelling and shrinkage can be also considered to affect soil water and solute transport.

The water balance is solved by considering two boundary conditions—the top and bottom boundaries. These boundaries can be either flux or head controlled. The Penman-Monteith equation is used in estimating evapotranspiration.

The model uses the leaf area index (LAI) or soil cover fraction (SC) to calculate the potential transpiration and evaporation of a partly covered soil. SWAP first separates the potential plant transpiration T_p and potential evaporation E_p and subsequently calculates the reduction of T_p in a more physically based approach (appendix figures C.1 and C.2). The effect of salt and water/oxygen stress on the actual transpiration is considered multiplicative.

The surface runoff is calculated by the ratio of the difference of ponding water and the maximum height of the sill or embankments, to the resistance of soil to surface runoff. The surface detention is accounted for by the resistance term.

Field drainage can be simulated using the Hooghoudt and Ernst equations in homogenous and heterogeneous soil profiles. The drainage can be modeled as single-level and multi-level systems. Bottom flux is calculated according to the boundary conditions adopted in the model.

A simple crop model, and detailed crop model WOFOST can simulate crop growth in SWAP. The simple crop model is based on the linear production function of Doorenbos and Kassam (1979). WOFOST (Supit et al. 1994) is a general crop model, which is capable of simulating the growth and development of most crops.

Several water management scenarios can be modeled in SWAP. Irrigation scheduling can be considered as fixed time or according to a number of criteria. Also, a combination of irrigation prescription and scheduling is possible. The scheduling criteria define the timing and depth of irrigation in the growth process (see appendix A for some of the model details).

Sensitivity and Limitations

Some conclusions based from Wesseling and Kroes (1998) on the global sensitivity of the model are as follows:

- Boundary conditions (both upper and lower) are of crucial importance when applying the model.

- For all soil-crop combinations, the soil evaporation and crop transpiration are strongly dependent on the function describing LAI.

- Drainage, simulated as lateral discharge, is very sensitive to surface water levels.

- High groundwater levels are strongly related to surface water levels; low groundwater levels depend on the combination of LAI, soil physical parameters and surface water levels;

the average groundwater level is mainly determined by the level of the primary drainage system.

- At low values for saturated hydraulic conductivity, the model did not succeed in finishing the simulations within one hour CPU-time; this occurred for peat at values below 0.1 cm d^{-1} and for clay at values below 0.06 cm d^{-1}. At these low values, the Richards' equation cannot be solved at the specified CPU-time.

Other limitations of SWAP are as follows (Kroes et al. 1998):

- No simulation of regional groundwater hydrology.
- No interaction between crop growth and nitrogen availability.
- No non-equilibrium sorption of pesticides and no simulation of metabolites.

3. THE DSSAT MODEL

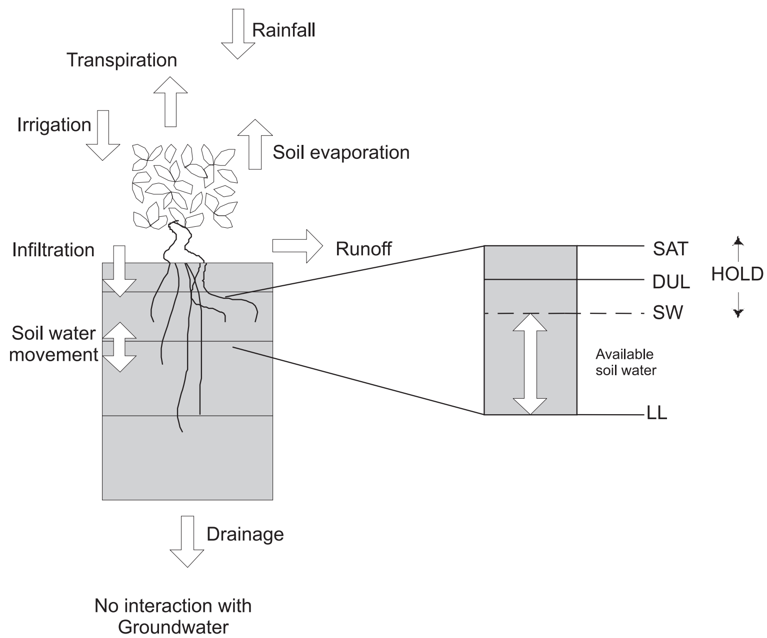
General Description

DSSAT (Tsuji et al. 1994) is composed of various crop models that are executed under one shell. The crop models available are: the CERES models for cereals (barley, maize, sorghum, millet, rice and wheat); the CROPGRO models for legumes (dry bean, soybean, peanut and chickpea); and models for root crops (cassava, potato) and other crops (sugarcane, tomato, sunflower and pasture). The crop model architecture differs from one model to another. See appendix B for some details.

Under this shell, simulation controls and management scenarios can be invoked in the system to simulate crop growth. The model can simulate seasonal, sequential cropping systems and a single cropping.

The soil water balance in DSSAT is based on Ritchie's model where the concept of drained upper limit (DUL) and drained lower limit (LL) of the soil is used as the basis of the available soil water (Ritchie1972; Ritchie 1981a; Ritchie 1981b). The approach is simple water accounting in each layer considered in the soil profile (Ritchie 1998). The water in the upper layer cascades to the lower layers mimicking the process of a series of linear reservoirs. Infiltration is calculated as the difference of the rainfall/irrigation and runoff. Drainage takes place if the infiltration and the soil water present in the layer exceed its water holding capacity (HOLD). The drainage at the bottom of the profile is the drainage flux of the bottom layer. Upward flow can be caused by root water uptake due to transpiration and soil evaporation. The potential root water extraction depends on the available soil water in the soil profile. The actual transpiration is calculated by accounting reduction factors as defined in appendix figure C.4. Runoff is calculated using the modified USDA-SCS curve number method (Williams 1991). The profile is assumed to be well drained and thus having no interaction with the groundwater (figure 2).

Figure 3.1. The soil water balance as simulated by DSSAT.



The nitrogen (N) balance in the soil is simulated using the CERES N model. The nitrogen model has two forms: for upland and lowland conditions (for rice). Basically, the nitrogen balance for other crops is derived from this model. Some functionalities like nitrogen fixing in the root nodules of legumes are introduced to this type of crops. Processes like mineralization, immobilization, nitrification, denitrification, nitrogen uptake by plants, distribution and remobilization within the plants are simulated (Godwin and Singh 1998).

Three levels of production can be modeled in DSSAT, i.e., potential, water and/or nutrient limited and reduced productions. The potential production can be modeled by modeling the growth under optimum conditions—only climate and crop characteristics are affecting crop growth. The water balance and nitrogen dynamics are disabled in DSSAT if this level of production is simulated. A limited level of production is modeled by enabling the water and nitrogen balance components, and the third level can be modeled by enabling the pest component (only for grain legume models at present) together with water and nitrogen. The compounded effect of water and N stress to the daily potential production of biomass is accounted as the minimum of the two.

Limitations

The main limitations of DSSAT relate to the included crop models (Jones et al., 1998). Models for only a few crops are included in the system and the models do not respond to all environment and management factors. Missing are the components to predict the effects of tillage, pests, intercropping, excess soil water and other factors on crop performance. These models are most useful in regions of the world where weather, water and nitrogen are the factors that affect crop performance. Their value to date has been for demonstrating the potential and in teaching (Jones et al. 1998). Performance of these models may not be good under severe environmental stress. The models currently simulate the potential, and water and nitrogen limited productions, but do not consider many factors that determine yield limitations in many agricultural fields, for example, Phosphorus availability.

The soil water balance model is limited to well-drained soils. Ritchie (1998) recommended the need for a better simulation of the water balance in very poorly drained conditions where oxygen stress will affect crop growth.

4. METHODOLOGY: SIMULATION OF WATER BALANCE AND CROP GROWTH

Experimental Area and Soil Data

The experimental field is located at IREM experimental station, AIT, Thailand; the soil is characterized as acid sulphate soil. Tables 4.1 and 4.2 show the soil physical and chemical properties of four layers of the soil profile sampled at every 15 cm each (Asadi 2000).

Table 4.1. Soil physical properties in the experimental field.

Depth	Particle size distribution(%)			Bulk density	FC[a]	PWP[b]	SAT[c]	Sat. hydraulic conductivity
cm	clay	silt	sand	g cm^{-3}	$cm^{-3}cm^{-3}$	cm^3cm^{-3}	cm^3cm^{-3}	cm d^{-1}
0-15	61	25	14	1.31	0.49	0.28	0.52	7.8
15-30	62	27	11	1.33	0.49	0.28	0.54	7.5
30-45	67	23	10	1.38	0.52	0.30	0.55	5.4
45-60	69	20	11	1.45	0.55	0.32	0.56	5.0

[a] Field capacity (@-333 cm suction head)
[b] Permanent wilting point (@-15000 cm suction head)
[c] Saturated water content

Table 4.2. Soil chemical properties in the experimental field.

Depth, cm	Organic C(%)	Total N(%)	pH	Cation exchange capacity, cmol kg^{-1}
0-15	5.2	0.11	5.4	33.3
15-30	3.8	0.09	5.0	32.0
30-45	5.0	0.07	4.6	27.3
45-60	2.9	0.05	4.5	27.4

In DSSAT, these data are needed to estimate other soil properties such as root weighting factor (WR), soil albedo (SALB), drainage constant (SWCON), curve number (CN2), etc., in the simulation, SWCON = 0.05 d^{-1}, SALB = 0.13 and CN2 = 76. The parameters of the analytical functions of Mualem (Mualem 1976) and Van Genuchten (Van Genuchten 1980) in SWAP are estimated using pedo-transfer functions (Wösten et al. 1998; Droogers 1999).

To provide a better comparison of the models in estimating the runoff, a minimal bund height (2.54 cm) is applied in SWAP. DSSAT does not account this parameter under upland condition. Slope to both is considered flat. The default value of the drainage resistance of surface runoff in SWAP (γ_{sill} = 0.1 d^{-1}) is used in the simulation.

Weather Data

The simulation was conducted from January 6 to April 5, 2000. Weather variables considered in DSSAT are only solar radiation, minimum and maximum temperature and rainfall. In SWAP, wind and actual vapor pressure are needed in addition to the minimum weather requirements of DSSAT. Weather data were gathered from the adjacent weather station in the experimental area.

Figures 4.1 and 4.2 show the weather during simulation period. The average solar radiation was about 19 MJ m^{-2} d^{-1}; average maximum and minimum temperature were 34 °C and 22 °C, respectively. Total rainfall was 84 mm (see figure 5.4) and the average actual vapour pressure and wind speed were 2.6 kPa and 0.9 m s^{-1}, respectively. The modified Priestley-Taylor equation was used in estimating evapotranspiration in DSSAT while the Penman-Monteith equation was used in SWAP.

Figure 4.1. Solar radiation, maximum and minimum temperature during simulation.

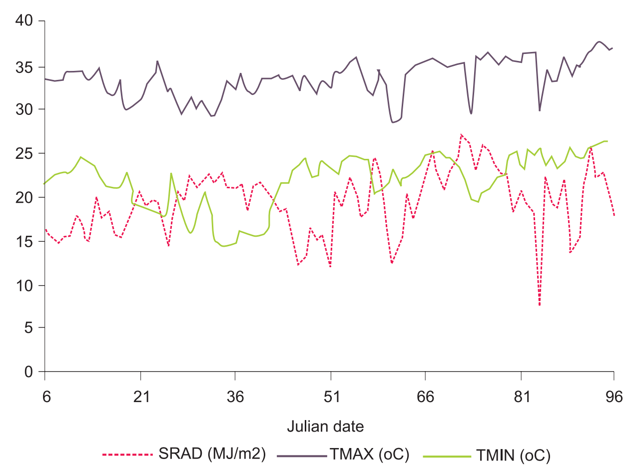
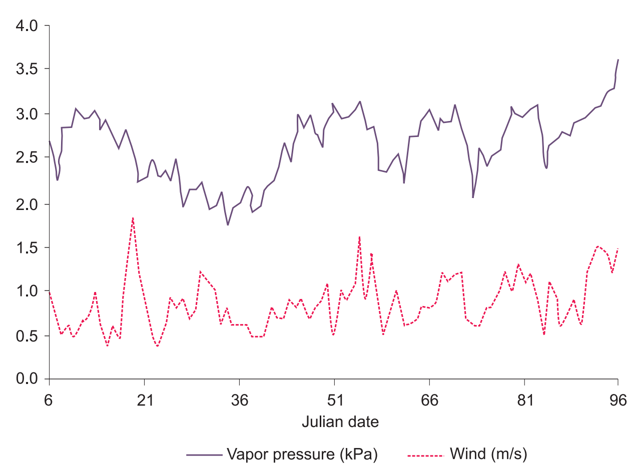


Figure 4.2. Vapour pressure and wind speed during simulation.



Crop Data

SUWAN 3851, a corn variety for animal feeds, was used in the simulation. In DSSAT, the cultivar-specific parameters were taken from the calibrated data of Asadi (2000) derived from the experimental study.

The data for SWAP was taken from the parameterized data of maize for WOFOST published by Van Diepen et al. (1988) as cited in Van Heemst 1988. The data was calibrated and used in the SysNet project in the South and Southeast Asian region in 1996-1997 in exploring future land use options. To develop a hypothetical SUWAN 3851 in SWAP, some parameters in the crop data were calibrated using the experimental data and the data of the National Corn and Sorghum Research Center (NCSRC), Thailand.

Initial and Boundary Conditions

The soil water in DSSAT was initialized according to the mineral nitrogen in the soil during sampling and the soil water index (SW), which was set to 1. The soil water contents in each layer were set almost to their drained upper limits under this condition.

With SWAP, the soil water was initialized according to the depth of the water table during the start of simulation. An equilibrium condition in all layers was established with this water table depth. This permitted a better basis on the comparison of soil water simulation in the soil profile because the water table is shallow during the start of the season.

The soil profile in DSSAT was divided into four soil layers at 15 cm intervals each. However, the model divided the upper layer into two, with an interval of 5 cm and 10 cm, respectively. All in all, there were five soil layers used in the simulation.

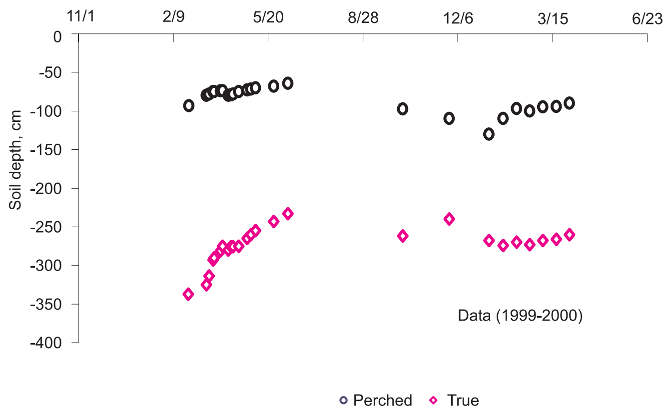
In SWAP, however, the maximum number of soil layers allowed is ten (with the present setting) but each layer can be divided into smaller compartments to ensure stability in the numerical computations. In the simulation, there were five layers considered—the measured four layers in the first 60 cm depth of the soil profile and an additional layer of 190 cm depth. The first layer was divided into 12 compartments; the second, third and fourth layers were divided into three compartments, respectively, and the fifth layer was divided into 13 parts. The soil physical and hydraulic properties of the fifth layer were assumed to be the same as the fourth layer. This was added to ensure that the water table depth was within the limits of the soil profile.

The soil water balance computation in DSSAT does not need any bottom boundary condition, as it assumes a well-drained soil. In SWAP, however, the chosen boundary condition was a flux determined by the groundwater level. A time series of water table was defined in the bottom boundary condition, which was used by SWAP to interpolate groundwater levels. In the field, there exists a perched water table throughout the growing period. Since it is believed that this perched water table significantly affected the soil water transport, this was used as the bottom boundary. The true water table was also shallow throughout the growing period. Figure 4.3 shows the levels of perched and true water table in the field from February 1999 to March 2000.

Although SWAP is capable of handling lateral drainage computation and the interaction with surface water levels, this aspect was not simulated in both models; to date DSSAT is not capable of handling this situation.

Moreover, as restricted by the soil (based from observation), the roots were limited to a growth of 40 cm length only in SWAP. This was adopted in DSSAT by varying the estimated root-weighting factor (WR) and forcing a minimum value within the vicinity of 40 cm soil depth. This allowed the roots to grow up to 45 cm in the simulation.

Figure 4.3. Water table in the experimental farm from February 1999 to March 2000 (Asadi 2000).



The root length density in SWAP was assumed as triangular, from the soil surface to the bottom of the roots. In DSSAT, the flow rate of root water absorption is calculated under the assumption that the root length density in uniformly distributed in each soil layer.

Water and Crop Management

Irrigation was done at frequent intervals after sowing and with lesser frequency during the later part of the growing period using overhead sprinklers (Table 4.3); the total irrigation applied was 423 mm. Likewise, the total N applied was 200 kg ha^{-1} during the whole period. From the sets of fertilizer levels in the experiment, this was chosen to allow a better comparison of the performance of SWAP and DSSAT in the simulation of crop growth because SWAP does not simulate the interaction of N and crops. The simulation of growth in SWAP is assumed as an N unlimited scenario.

Table 4.3. Irrigation and nitrogen application during the growing period (Asadi 2000).

Date	Irrigation depth, mm	Date	Application rate of N, kg ha^{-1}	Remarks
Jan 6				Sowing
Jan 7	23	Jan 13	60	
Jan 8	23	Feb 5	60	
Jan 9	23	Feb 29	80	
Jan 11	23			Emergence
Jan 13	32			
Jan 18	35			
Jan 29	30			
Feb 5	34			
Feb 15	50			
Feb 29	50			
Mar 10	50			
Mar 18	50			
Apr 5				Harvesting

5. RESULTS AND DISCUSSION

Crop Growth Simulation

Table 5.1 shows the results of the simulation of yield. According to NCSRC (1997), the potential yield of SUWAN 3581 in the corn belt of Thailand is in the order of 6,757–7,677 kg ha^{-1}. The data used for SWAP yielded a potential production of 7275 kg ha^{-1} while the DSSAT simulation resulted in 6010 kg ha^{-1}. The calibrated data for SWAP simulation was considered to be quite appropriate.

Table 5.1 Comparison of simulated and measured yields.

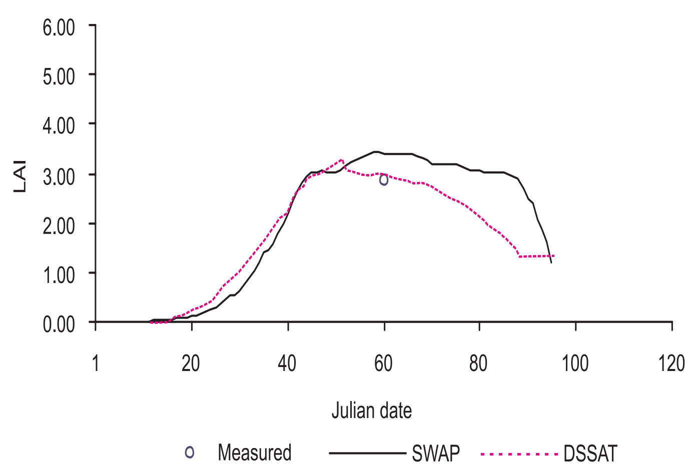
Model/Source	Actual yield, kg ha^{-1}	Potential yield, kg ha^{-1}
DSSAT	5,993	6,010
SWAP	5,338	7,275
NCSRC (1997)	-	6,757 – 7,677
Asadi (2000)	5,312	-

DSSAT simulated correctly (based on the observed dates) the emergence, floral initiation and start of grain filling dates (based on the date of silking observed), i.e., January 11, February 25 and February 29, respectively. The crop matured 85 days after sowing. According to NCSRC (1997), the maturity of this cultivar is 110–120 days. In DSSAT, both temperature and photoperiods are considered in simulating the length of a specific growth stage.

SWAP, on the other hand, simulated the flowering date February 22; the emergence date is an input data in the model. The crop matured 84 days after emergence, meaning 90 days after the date of sowing. The grain also started to fill at anthesis. The discrepancies of these dates to the observed ones are attributed to the chosen driving force of phenological development in the model, i.e., only temperature. When this cumulative heat unit is achieved, then it is the start of a new crop stage and end of the previous stage (morphological development). Day-length can also be used as a factor that would affect the length of the development stage—it is user specified. But due to lack of data this was not considered in the simulation.

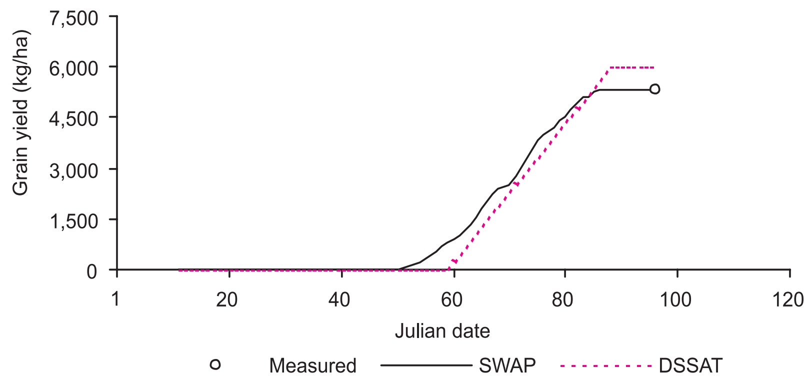
There was only one data of the leaf area index (LAI), which was taken on February 29. Figure 5.1 shows the result of the simulation of LAI with DSSAT and SWAP. DSSAT simulated 2.93 while SWAP simulated 3.3; the LAI taken manually was measured at 2.85.

Figure 5.1. Simulated leaf area index.



Furthermore, SWAP simulated the yield almost similar to the measured data (figure 5.2 and table 5.1). The measured yield was 5,312 kg ha^{-1} and SWAP predicted it to be 5,338 kg ha^{-1}, while DSSAT predicted the yield as 5,993 kg ha^{-1}. The figure shows clearly why the yield from SWAP was reduced significantly compared to DSSAT. The trend of grain filling in SWAP was non-linear because of the effect of stresses; DSSAT on the other hand was perfectly linear. The results of the soil water balance simulation explains these trends.

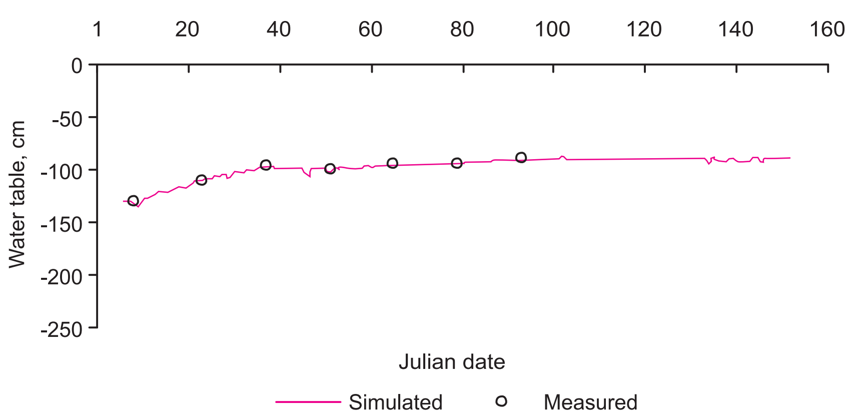
Figure 5.2. Simulated yield with DSSAT and SWAP.



Soil Water Balance

The SWAP model simulated the perched water table within the range of the measured values (figure 5.3). As the growing season progressed the water table rose as a result of irrigation, rainfall and poor lateral drainage—the latter was not considered in the simulation.

Figure 5.3. Simulated water table in the growing period by SWAP.



Figures 5.4 and 5.5 show the results of simulation of the water balance components in SWAP and DSSAT. SWAP fairs well with DSSAT in the runoff calculation. There was considerable runoff from the field when excessive rainfall occurred on February 2.

The water fluxes at the depth of 60 cm in SWAP were extracted and plotted with time to better compare vertical drainage simulated by the models. The results showed that during the

Figure 5.4. Water balance simulated by SWAP.

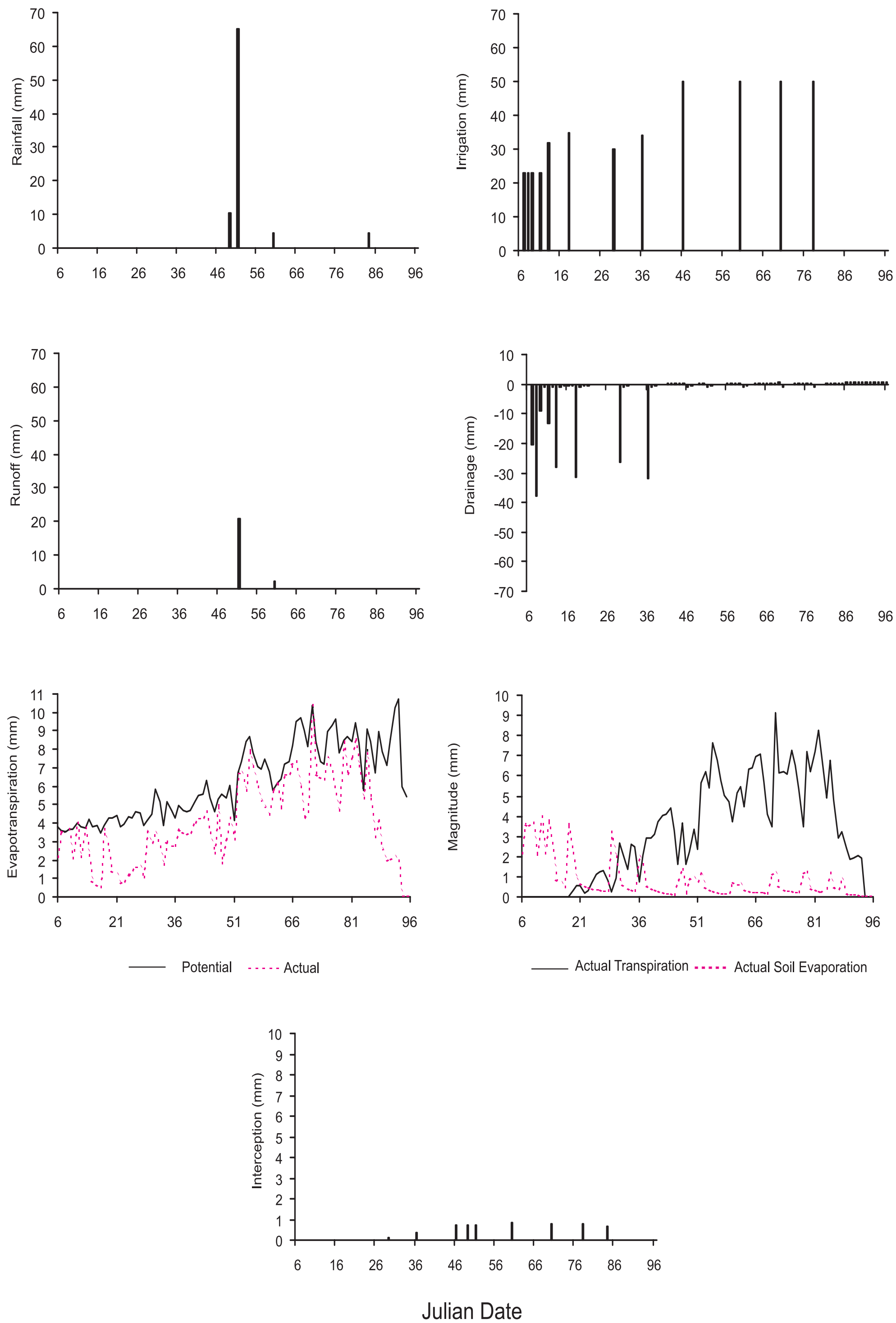
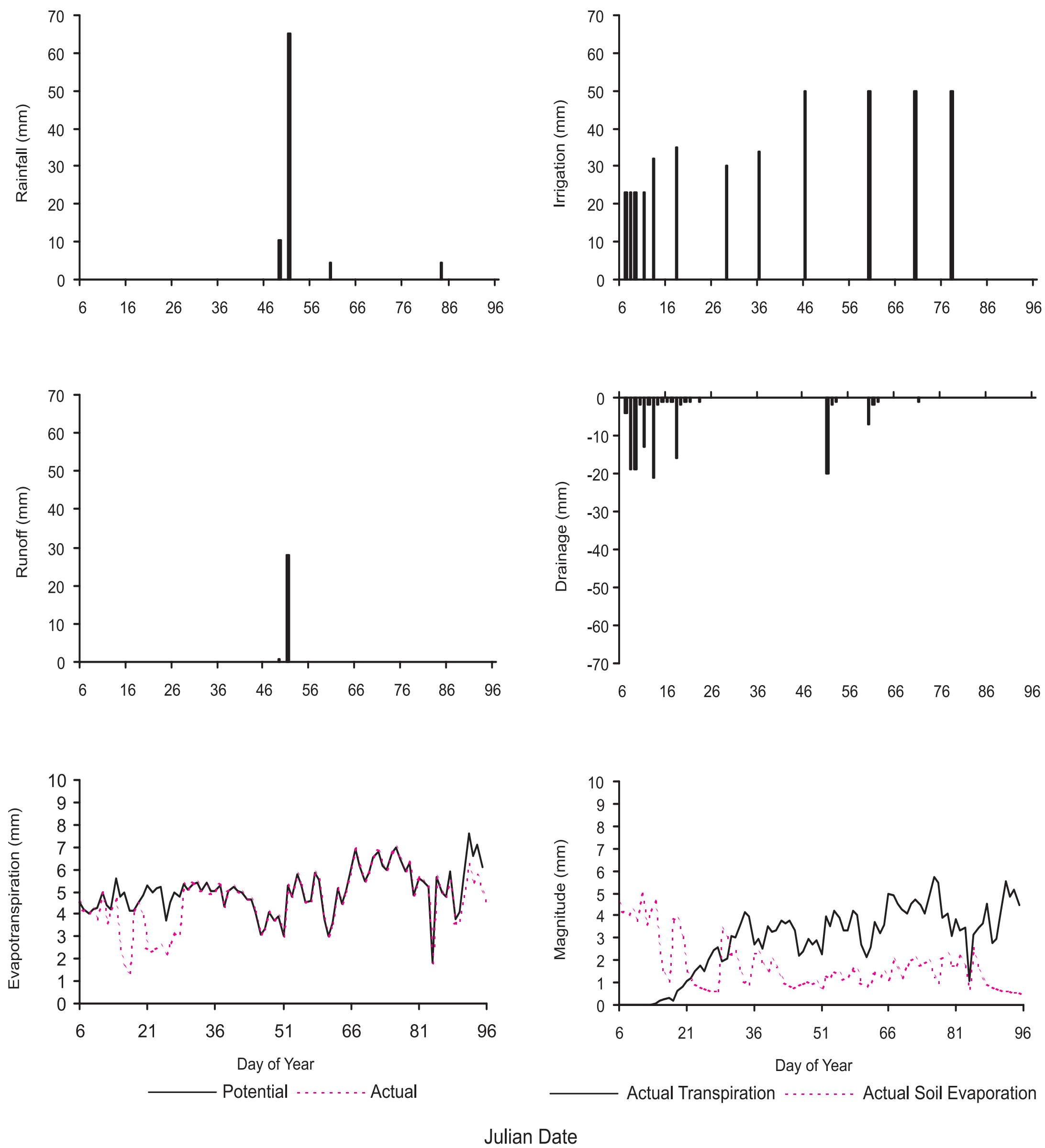


Figure 5.5. Water balance simulated by DSSAT.



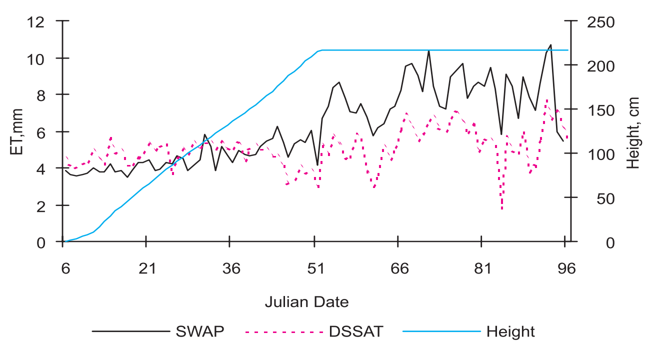
first 15 days after sowing (first to the sixth irrigation application), there were significant downward movements of soil water as a result of frequent irrigation. This was also predicted by DSSAT but at lesser quantity compared to SWAP. During the seventh and eighth irrigations, SWAP simulated downward flows, but for the last four applications there were non-significant downward fluxes at 60 cm depth. For DSSAT, however, drainage was realized on the ninth, tenth and eleventh applications.

SWAP determines if the soil water flux is directed upwards or downwards. Upward water fluxes imply suction, which can be caused by the extraction of water by the roots or of drier upper layers. SWAP can then model capillary rise at the bottom of the soil profile. In DSSAT, this phenomenon is not simulated. Moreover, in SWAP, rainfall and irrigation (sprinkler) is intercepted first by the canopy before reaching the soil.

There is a big difference in the calculation of the evapotranspiration between SWAP and DSSAT. The reason why the crops in DSSAT did not suffer water stress is that the calculated evapotranspiration is lesser than in SWAP. Also, the model cannot consider oxygen stress that crops can experience when the soil is saturated. The only stress that caused the reduction of yield in DSSAT is N but it was only minimal in the simulation.

Taking Penman-Monteith as a reference, the Priestley-Taylor in DSSAT underestimated the evapotranspiration during the peak of growth when the canopy covers most of the soil. As a result of full grown height of the crops, the aerodynamic resistance is small thus increasing the flow of water in the canopy-atmosphere interface. Likewise, it overestimated the evapotranspiration when the crops are small, because the aerodynamic resistance was underestimated in the approach. This is the disadvantage of considering the aerodynamic factor as multiplicative over crop growth. Figure 5.6 shows the comparison of SWAP and DSSAT in their simulated potential evapotranspiration.

Figure 5.6. Comparison of potential ET in SWAP and DSSAT.



Soil Water

The soil water status in the soil profile determines the performance of the crops. Figure 5.7 shows the soil water content in the soil column as a function of time in SWAP. During the early stage of crop growth, the wetness of the soil is high as a result of high frequency of irrigation. There were 12 irrigations during the growing period and six were given at the first 15 days of the crops. As simulated by SWAP, the seventh and eighth irrigations caused an oxygen stress to the crops. Before the ninth irrigation, the crops suffered considerable stress and the applied water was not able to restore their full water uptake potential. The two rainfall events before the tenth irrigation restored the soil water and hence the water uptake. Before the tenth, eleventh and twelfth irrigations, the crops suffered an average maximum stress of 0.55. These periods were sensitive to the crops as they were at the peak of grain/kernel filling. This resulted in a lower yield at the end of the growing period.

Figure 5.8 also shows the situation in DSSAT. The indicator of water stress used in the figure is the ratio of the actual and potential evapotranspiration (ET) because the potential transpiration could not be located in the output file. Nevertheless, the representation is sufficient. There was significant difference between the actual and potential ET during the early stage of growth particularly before the sixth and seventh irrigation, but figure 5.5 shows that this difference is mostly due to decreased soil evaporation. During the mid and late season of crop growth, DSSAT simulated that there was no water stress experienced by the crops. The difference of the simulated yield and potential production is due to the N stress that occurred in the process. Notice that even though the N stresses were very small (because N applied was almost sufficient) they reduced the actual yield to 99.7 percent of the potential.

Figure 5.9 shows the measured soil water at every 15 cm from the soil surface. The sampling coincided with the DSSAT requirement as the experiment was intended for this model. Measurement was carried out every seven days. A depression from the thirtieth to fortieth day is prominent in the figure as well as from the seventieth to the last day of growth.

Furthermore, in figures 5.10 and 5.11 they show how the models simulated the soil water at 0-15 and 45-60 cm depths of soil. It appears that in the upper layer, DSSAT did not simulate the measured soil water as well as SWAP. During the whole period of crop growth, DSSAT underestimated the soil water while SWAP did better predictions. Apparently, SWAP overestimated the soil water during the first 1.5 months of growth but improved significantly thereafter. These discrepancies in SWAP could be attributed to the initial and bottom boundary conditions used in the simulation—likewise, with the estimate of the Van Genuchten and Mualem parameters. However, as the situation in the soil came into equilibrium, the SWAP simulation improved in comparison to DSSAT. Both models, on the other hand, overestimated the soil water at the lower layer. This can be improved in SWAP by adopting the proper bottom boundary condition prevailing in the field and considering lateral drainage in the simulation. For DSSAT however, there is no way to adjust the bottom boundary condition.

Figure 5.7. Soil water content in the soil profile simulated by SWAP (cm^3 cm^{-3}).

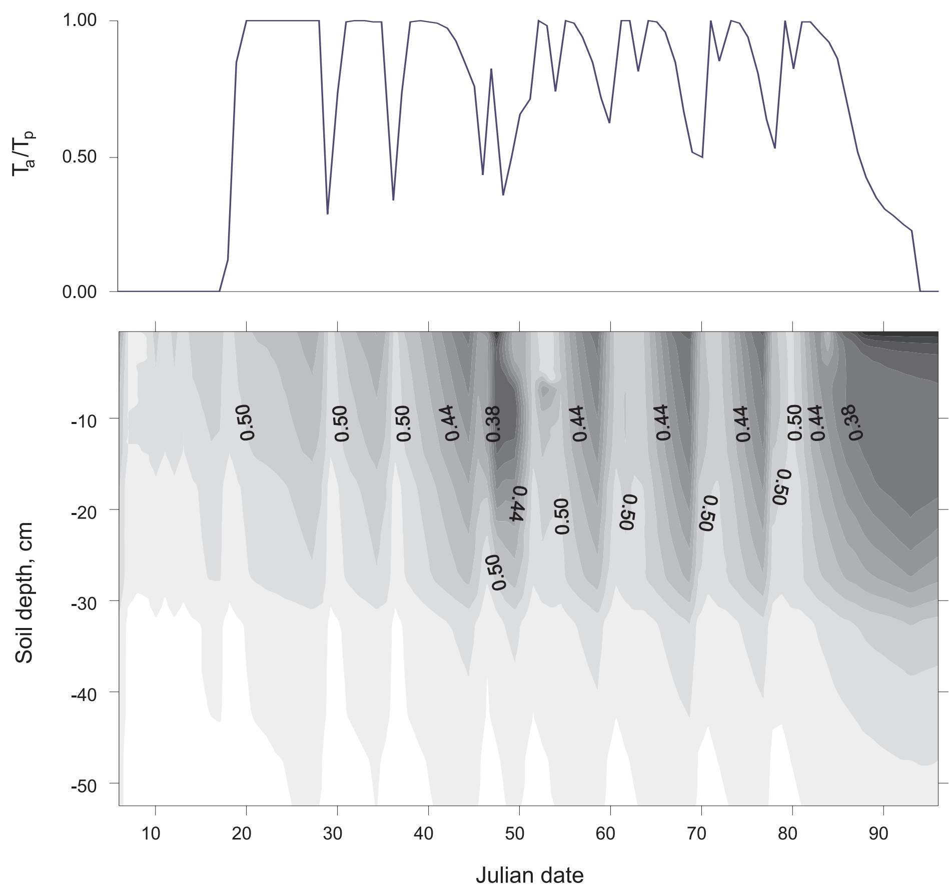


Figure 5.8. Soil water content in the soil profile simulated by DSSAT ($cm^3\ cm^{-3}$).

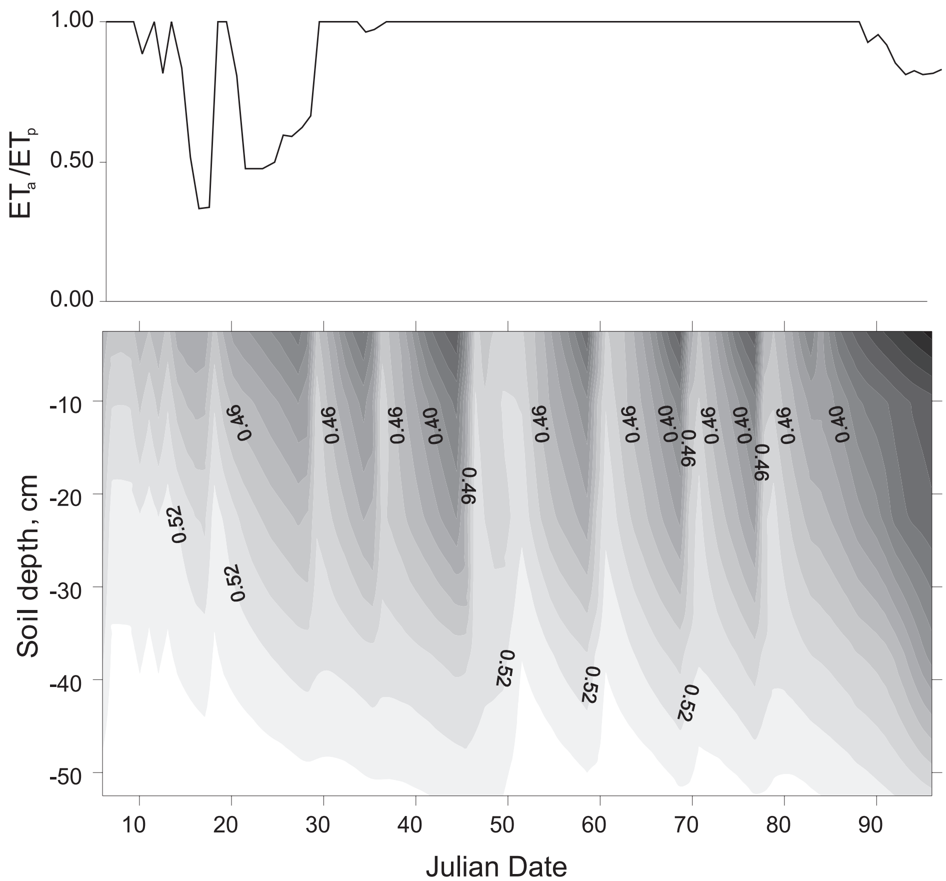


Figure 5.9. Measured soil water in the soil profile averaged at every 15 cm ($cm^3\ cm^{-3}$).

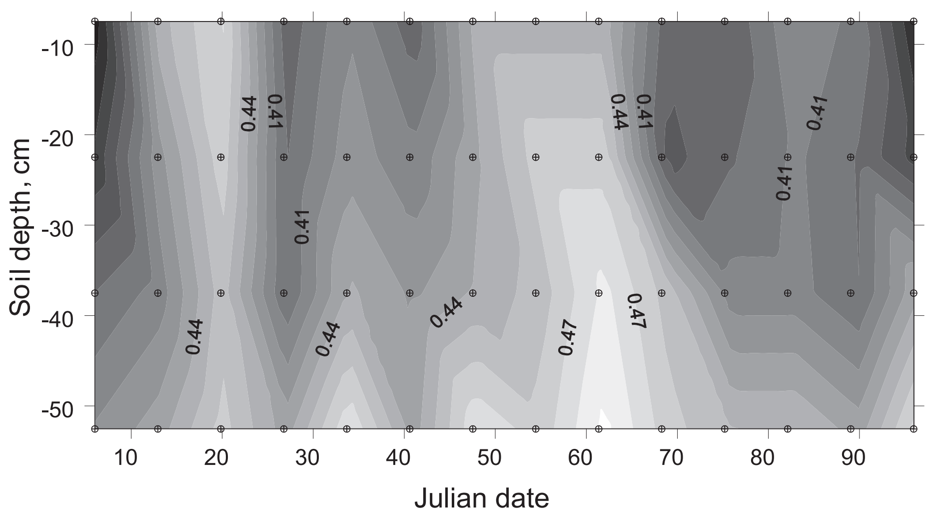


Figure 5.10. Soil water at 0-15 cm depth of the soil profile.

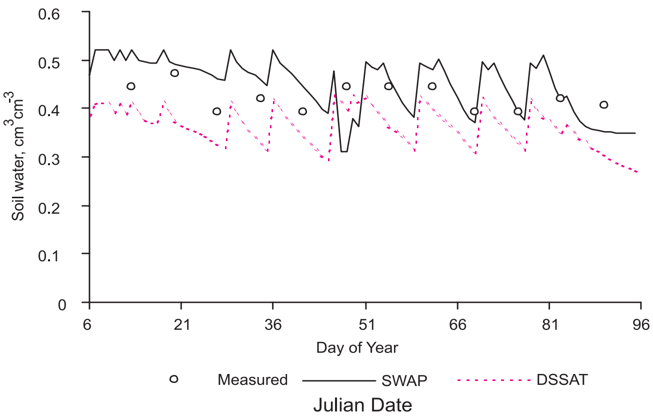
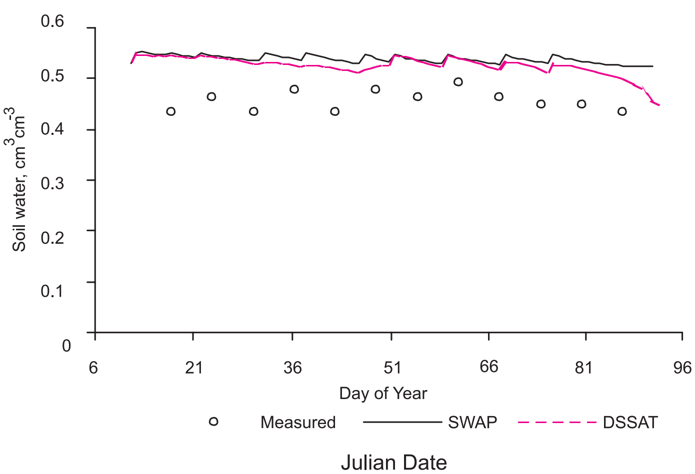


Figure 5.11. Soil water at 45-60 cm depth of the soil profile.



6. CONCLUSIONS AND RECOMMENDATIONS

The conclusions from this specific study are summarized in tables 6.1 and 6.2. The study showed that SWAP, although it is broadly considered as the standard in soil process models, can also perform well in crop growth simulation along with the popular crop models available today, like DSSAT. The physical basis of the soil water transport in SWAP allows a better simulation of the crop processes when a crop model is linked with it. Both models have their own strengths and limitations and these should be the basis in answering the question of which model is appropriate for a specific task. SWAP, although it is more physically based, falls short on the crop-nitrogen interaction compared to DSSAT. DSSAT on the other hand has more empiricism in simulating the soil water balance and is therefore not generally applicable when soil moisture is an important parameter.

When considering detailed crop growth studies, for instance when studying detailed phenological stages, DSSAT is more appropriate than SWAP. This is because the phenological stages in SWAP are only determined with emergence, anthesis and maturity whereas in DSSAT, seven stages are being considered. When studies on crop and N-fertilizer are the major variables, DSSAT is more preferable. But in studies where water, oxygen and salt stress are important, SWAP is more preferable because DSSAT does not respond properly under extreme environmental stress. Besides, the effects of oxygen and salt stress to water uptake are not simulated by the model. In terms of general applicability in water management and crop growth, SWAP has an edge. Thus, when the relationships of crop growth and soil water are being considered, the physical basis of SWAP elevates its performance compared to DSSAT.

In terms of data requirements, DSSAT requires a lesser volume of input data on soil, crop and weather because the principle of minimum dataset was adopted during its development. This is the reason why most of the functional relationships governing the processes in the model were simple functions derived from decades of research outputs. Compared to SWAP, in DSSAT a lesser volume of data is needed in the simulation of crop growth and soil water balance. Moreover, DSSAT has a graphical user interface, which enables the user to input data, run the crop models and graphically view the results of the simulation. To date, SWAP does not have this capability.

Conclusions from this study are the following recommendations for the improvement of the models. For SWAP, a robust update in the future is the inclusion of crop-nitrogen interaction and a graphical user interface where the end users can easily input data, calibrate the model and analyze model results. For DSSAT, the interaction of the soil water balance model with groundwater should be considered. Likewise, proper definition of water, oxygen and salt stress should be done in a more generic way. The inclusion of lateral drainage routines where drainage studies can be explored should be also considered.

Since SWAP is more preferable in water management studies and its promising capability in crop growth simulation, the model was chosen for the optimization algorithm. The integrated model will be used in the future in studies exploring improved water management options.

Table 6.1 Performance of SWAP and DSSAT in this specific study.

Predicted	DSSAT	SWAP
Yield	+	++
DVS	++	+
Soil moisture	+	++
ET	—	++
LAI	++	++

Note: ++ Satisfactory, + Good, — Fair, - Not applicable

Table 6.2. Overall comparison of SWAP and DSSAT models.

Properties	DSSAT	SWAP
Data requirements [a]		
Soil	+	++
Meteorological	+	++
Crop	+	++
Interface	++	-
Performance	+	++
Scenarios		
Water management	—	++
Irrigation	+	++
Drainage	-	++
Crop production	++	+
Fertilizer management	++	+
Crop	++	-
Environment	++	++

Note a: less or more volume

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APPENDIX

A. SWAP Model

A.1 Darcy's Law

$$q \qquad K \; h \; \frac{h \quad z}{z}$$

A.2 Continuity Equation

$$\frac{\quad}{t} \qquad \frac{q}{z} \quad S \; h$$

A.3 Richards' Equation

$$\frac{\quad}{t} \quad C \; h \; \frac{h}{t} \quad \frac{K \; h \; \frac{h}{z} \quad 1}{z} \quad S \; h$$

A.4 Van Genuchten and Mualem Equations:

$$\theta(h) = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{\left[1 + |\alpha h|^{n}\right]^{m}}$$

$$K(h) = K_{sat} S_e^{\lambda} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^{m} \right]^{2}$$

$$S_e = \frac{\theta - \theta_{res}}{\theta_{sat} - \theta_{res}} \; ; \; m = 1 - \frac{1}{n}$$

A.5 Penman-Monteith Equation

$$\lambda_w ET_p = \frac{10^{-4} \Delta_v (R_n - G) + 8.64 \times 10^{-6} \rho_{air} c_{air} \frac{(e_{sat} - e_{act})}{r_{air}}}{\Delta_v + \gamma_{air} \left(1 + \frac{r_{crop}}{r_{air}} \right)}$$

A.6 Actual Root Water Flux

$$S_a(z) \qquad {}_{rw} \quad {}_{rs} S_p(z)$$

A.7 Potential Root Water Flux

$$S_p \;\; z \qquad \frac{T_p}{D_{root}} \text{ for uniform root density}$$

A.7 Crop Growth

Brief Description

The source of energy for the growth and development of plants is the sun. The canopy receives the incoming solar radiation and converts it into carbohydrates (CH_2O) through the process of photosynthesis. The potential gross photosynthesis is calculated by taking into account the photosynthetic leaf characteristics and absorbed energy. Due to water and/or salinity stress, the potential gross photosynthesis is reduced to actual gross photosynthesis.

A portion of the produced carbohydrates is used to provide energy for maintenance respiration. The remaining carbohydrates are converted into structural matter. In this process some of the weight is lost as growth respiration. The dry matter produced is partitioned among roots, leaves, stems and storage organs by using partitioning factors that are a function of the phenological development stage of the crop. The fraction partitioned to the leaves determines the leaf area development and hence the dynamics of light interception. The dry weights of the plant organs are obtained by integrating their growth rates over time. During development of the crop, part of the living biomass dies due to senescence. Only stems, leaves and roots are allowed to die. The death rate of the storage organ during the growth process is zero.

Some crop growth processes are influenced by temperature, for instance, the maximum rate of photosynthesis and the maintenance respiration. Others, like partitioning of assimilates or decay of crop tissue, are influenced by the phenological development stage (Spitters et al. 1989; Van Dam et al., 1997). See appendix figure C.3 for a schematic diagram of crop growth in WOFOST.

A.8 Water Management Capabilities

Five irrigation timing criteria in SWAP

Allowable daily stress. In this criterion, irrigation is applied whenever the actual transpiration rate T_a drops below a predetermined fraction of the potential transpiration T_p. This option is relevant for sub-optimal irrigation when the water supply is limited.

Allowable depletion of readily available water in the root zone. Irrigation is applied whenever the water depletion in the root zone is greater than the predetermined fraction of the readily available water. For deficit irrigation purposes, stress can be allowed by specifying the fraction greater than 1.

Allowable depletion of total available water in the root zone. Here, irrigation is applied whenever the depletion is greater than the predetermined fraction of the total available water; between field capacity and permanent wilting point.

Allowable depletion amount of water in the root zone. Here irrigation is applied whenever a predetermined water content is extracted below field capacity. This option is useful in the case of high frequency irrigation systems like trickle irrigation.

Critical pressure head or moisture content at sensor depth. Under this criterion, irrigation is applied whenever moisture content or pressure head at a certain depth in the root zone drops below a prescribed threshold value.

Application depth criteria in SWAP

Back to field capacity. SWAP calculates the amount of irrigation water to bring the pressure heads in the root zone to field capacity. An over and under irrigation amount can be specified depending on the development stage of the crop for leaching salts or when rainfall is expected.

Fixed irrigation depth. This is generally used in gravity irrigation systems that allow a little variation in irrigation depths. A specified amount of water is applied.

B. DSSAT Model

Crop Growth Models

CERES Models

CERES crop simulation models can predict the duration of growth, the average growth rates and the amount of assimilate partitioned to the economic yield components of the plants. The cereal crops included in DSSAT are rice, corn, millet, wheat, barley and sorghum. A feature of each model is its capability to include cultivar specific information that makes possible prediction of the cultivar variation with each interaction with weather. CERES computes phasic and morphological development using temperature, day-length and cultivar characteristics. Biomass growth is calculated using the radiation use efficiency approach; biomass produced is partitioned between leaves, stems, roots, ears and grains. The proportion partitioned to each growing organ is determined by the stage of development and general growing conditions. The partitioning principles are based on the sink-source concept and are modified whenever deficiencies of water and nutrient supplies take place. Crop yields in CERES models are determined as a product of the grain numbers per plant times the average kernel weight at physiological maturity. The grain numbers are determined from the above ground biomass growth during a critical stage in the plant growth cycle for a fixed thermal time before anthesis. The grain weight is calculated as a function of the cultivar specific optimum growth rate multiplied by the duration of grain filling. Moreover, grain filling is reduced below the optimum value when there is an insufficient supply of assimilates either by daily biomass production or from the stored mobile biomass in the stem (Ritchie et al. 1998).

CROPGRO Model

The CROPGRO model is a generic model based on the SOYGRO, PNUTGRO and BEANGRO models. It computes canopy photosynthesis in an hourly time steps using leaf-level photosynthesis parameters and hedge-row light interception calculations.

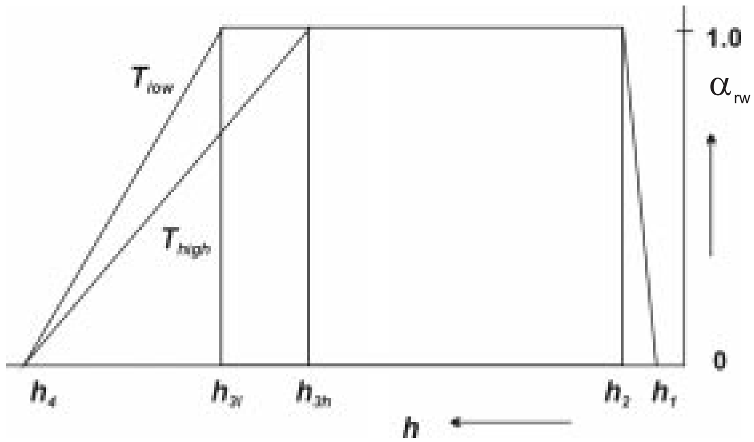
The CROPGRO is a process-oriented model and considers crop carbon balance, crop and N soil balance and soil water balance. The state variables in this approach are the amounts, masses and numbers of tissues, whereas the rate variables are the rate of inputs, transformations and losses from the state variable pools. For example, the carbon balance includes the daily inputs from photosynthesis, conversion and condensation of C into crop tissues, C losses due to abscised parts and C losses due to growth and maintenance respiration. The carbon balance processes also include leaf area expansion, pod addition, seed addition, shell growth rate, seed growth rate, nodule growth rate, senescence and carbohydrate mobilization. Addition of pods and seeds and their growth rates are actually determined by the partitioning during seed filling phase. Before the seed growth phase, the growth rates of leaves, stems and roots are determined by the current partitioning to respective tissue types multiplied by the rate of total growth. Important ancillary processes include rate of leaf appearance, rate of reproductive development, rate of height and width increase and the rate of root depth increase. The crop N balance processes include daily N uptake, N_2-fixation, mobilization from vegetative tissues, rate of N use from new tissue growth and rate of N loss in abscised parts. Soil water balance processes include infiltration of rainfall and irrigation, soil evaporation, distribution of root water uptake, drainage of water through the root zone and crop transpiration. Evapotranspiration can be calculated by either Priestley-Taylor or FAO-Penman equations (Boote et al. 1998; Jones et al. 1998).

Other Crop Models and Capabilities

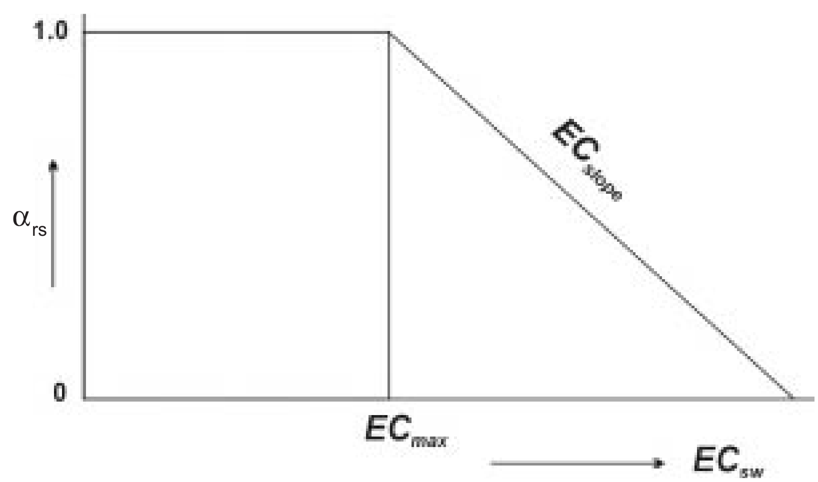
The detailed processes of other crop models, including DSSAT, can be found in Tsuji et al. 1994 and Tsuji et al. 1998. There are other capabilities of DSSAT, since it is a decision support system per se, utility tools that can help modelers to manage weather, soil and cultivar data are incorporated in the system. Weather predictors are built in DSSAT to allow the user model the long-term effects of climate to crop production. Graphical utility is also built in where the outputs can be presented in charts. This also allows easier calibration of the crop models.

C.

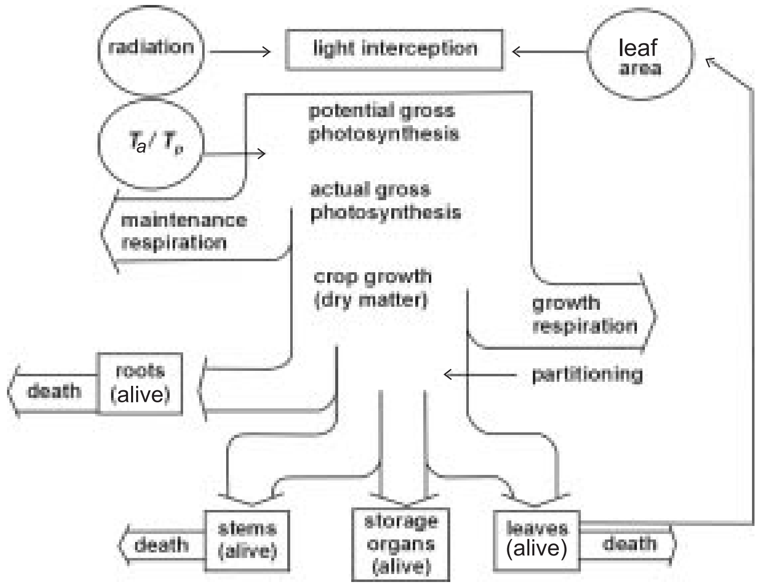
Appendix Figure C.1. Reduction coefficient of root water uptake as a function of soil water pressure head and potential transpiration rate (after Feddes et al. 1978).



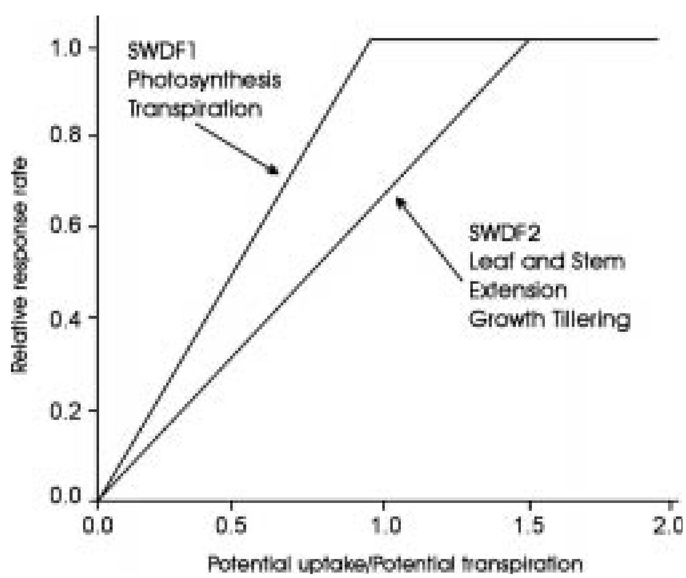
Appendix Figure C.2. Reduction coefficient of root water uptake as function of soil water electrical conductivity (after Maas and Hoffman 1977)



Appendix Figure C.3. Crop growth process as simulated by WOFOST (after de Koning et al. 1993).



Appendix Figure C.4. Relationship used to calculate soil water factors, SWDF1 and SWDF2 to incorporate water stress in CERES models (after Ritchie 1998).



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