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# 5. Analysis of crop growth

**J.J.E. Bessembinder, A.S. Dhindwal, P.A. Leffelaar, T. Ponsioen and Sher Singh**

## Summary

SWAP/WOFOST was used for a balanced estimation of yield and *ET*, and to include interactions between soil-water and solute transport and crop development. This way *WP*, defined as yield divided by *T* or *ET*, can be estimated accurately for a wide range of field conditions and management options. The model was calibrated for wheat, rice and cotton in Sirsa. In 2002 the simulated water-limited productions for rice and cotton are close to the actual productions at the farmer fields. However, for wheat the yield gap was considerable. Part of the yield gap could be explained with a statistical analysis. With better nutrient, pest and disease management the yield gap of wheat can be bridged, which will lead to higher water productivity. Transpiration and assimilation are affected proportionally by water stress. Consequently, in general deficit irrigation will have a minor effect on $WP_T$ and $WP_{ET}$. However, the timing of water stress does affect the ratio between grain yield and T, and the $WP_T$. Considerable differences in *WP*'s between years can be observed, due to differences in evaporative demand between years. Soil type does not affect $WP_T$, but it does affect the optimum timing of irrigations and the total *E* during the growing season. With early sowing of wheat higher *WP*'s can be obtained, because higher grain yields can be obtained. The water need does not decrease with earlier sowing, it increases slightly. The large differences in $WP_T$ and $WP_{ET}$ between crops are due to the contribution of *E* to *ET*, the harvest index and the chemical composition.

## 5.1 Introduction

### 5.1.1 Water productivity and simulation models

Often used definitions for water productivity (*WP*) are the yield divided by the (evapo)transpiration (*E*)*T* or irrigation. Irrigation amounts are based on crop needs for *ET*. In order to derive options for improvement of *WP*, simultaneously good estimates of crop production and (*E*)*T*, and their interactions are needed. Simulation models can be of great help in estimating crop production and *ET* in a wide range of situations.

WOFOST is a dynamic, explanatory model for crop growth with descriptive elements, but with a relatively simple soil module ('tipping bucket'*; Boogaard et al.*, 1998*; Supit et al.,* 1994). Early versions of SWAP, a dynamic explanatory model with descriptive elements, only had forcing functions to describe soil cover, and rooting depth ("simple crop module"). There was no interaction between water availability and e.g. leaf development (*van Dam et al.*, 1997*; Kroes et al.*, 1999). The combination of SWAP with WOFOST in SWAP version 2.0, hereafter called SWAP/WOFOST, gives a more balanced description and quantification of the various physical and physiological processes underlying crop growth, soil moisture flow and solute transport and their interactions (*van Ittersum et al.*, 2003).

In this chapter SWAP/WOFOST will be used to study the effect of various management practices and changes in environmental factors. It may enhance awareness of the effect of different management practices and help in decision making at field scale.

### 5.1.2 Research objectives

This chapter will explore the options to improve water productivity at field scale by focusing on the following objectives:

1. Further development of crop growth models for conditions in Sirsa Irrigation Circle (SIC);
2. Quantifying the maximum increase in water productivity by changes in crop management.

The crop growth analysis performed for this chapter consists of 3 steps:

1. Analysis of crop data from experiments and farmer fields and calibration of SWAP/WOFOST for wheat, cotton and rice;
2. Comparison of actual and simulated crop production and *ET* at farmer fields;
3. Analysis of some management options and their effect on water productivity.

## 5.2 Calibration of SWAP/WOFOST for wheat, rice and cotton

### 5.2.1 The detailed crop module in SWAP

SWAP 2.0 contains three crop growth routines: a simple module, a detailed module, and the detailed module attuned to simulate grass growth. Independent of external stress factors, the simple model prescribes the length of the crop growth phases, leaf area, rooting depth and height development. The detailed crop module is based on WOFOST 6.0 (*Supit et al.,* 1994; *Spitters et al.,* 1989).

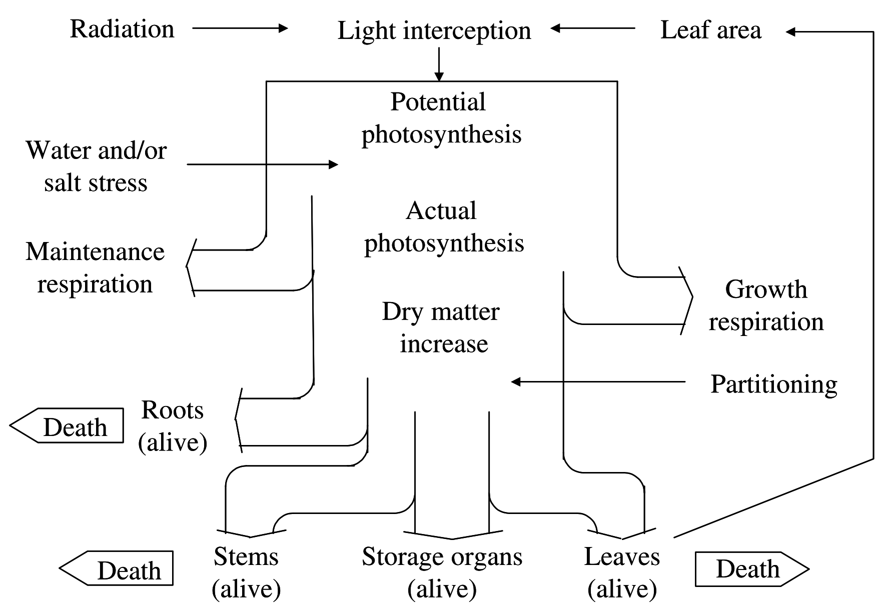


**Figure 5.1** Overview of the main crop growth processes and interactions as included in WOFOST.

Figure 5.1 shows the main processes and relations included in the detailed crop module. The intercepted radiation energy is a function of the incoming radiation and the leaf area index (*LAI*). WOFOST computes at three selected moments of the day incoming photosynthetically active radiation just above the canopy. Using this radiation and the photosynthetic characteristics of the crop, the potential gross assimilation is computed at three selected depths in the canopy (*Spitters et al.,* 1989). Gaussian integration of these values results in the daily rate of potential gross $CO_2$ assimilation (kg $CO_2.ha^{-1}.d^{-1}$). This potential can be reduced due to water and/or salinity stress. The ratio of actual *T* and potential *T*, $T_a/T_p$, is used as reduction coefficient.

Part of the assimilates produced are used to provide energy for the maintenance, depending on the amount of dry matter (*DM*) in the various living plant organs, the relative maintenance rate per organ and the temperature. The remaining assimilates are partitioned among roots, leaves, stems and storage organs (*SO*), depending on the phenological development stage (*DVS*) of the crop (*Spitters et al.,* 1989). Than conversion into structural *DM* takes place, and part of the assimilates is lost as growth respiration.

The net increase in leaf structural *DM* and the specific leaf area ($ha.kg^{-1}$) determine leaf area development, and hence the dynamics of light interception, except for the initial stage when the rate of leaf appearance and final leaf size are constrained by temperature, rather than by the supply of assimilates. The dry weights of the plant organs are obtained by integrating their growth and death rates over time. The death rate of stems and roots is considered to be a function of *DVS*. Leaf senescence occurs due to water stress, shading (high *LAI*), and also due to life span exceedance.

Some simulated crop growth processes are influenced by temperature, such as the maximum rate of photosynthesis and the maintenance respiration. Other processes, such as the partitioning of assimilates or decay of crop tissue, are steered by the *DVS*. Development rates before anthesis are controlled by day length and/or temperature. After anthesis only temperature will affect development rate. The ratio of the accumulated daily effective temperatures, a function of daily average temperature, after emergence (or transplanting in rice) divided by the temperature sum (*TSUM*) from emergence to anthesis, determines the phenological development stage. A similar approach is used for the reproductive growth stage (*van Dam et al.,* 1997).

Water uptake of the crop is determined by the rooting depth, root density distribution, soil water pressure head, and critical pressure heads for wet and dry conditions (Fig. 4.2). When the soil water electrical conductivity becomes higher than the crop specific critical salinity levels, *T* is reduced as illustrated in Fig. 4.3.

### 5.2.2 Methodology

To calibrate SWAP/WOFOST for wheat, cotton and rice, data are needed from experiments where potential and/or water-limited production levels are obtained (Chapter 3). Potential production is the production level defined by $CO_2$-concentration in the air, radiation, temperature and intrinsic plant characteristics. Water-limited production is the production level when the growth rate is limited only by water shortage during at least a part of the growing season. Before calibrating the crop module in SWAP/WOFOST, the best soil and water parameters were determined in a calibration procedure using SWAP with the simple crop module (prescribing crop characteristics, based on field measurements; see Chapter 4).

A crop data file for a similar cultivar and similar climatic conditions is used as a "start" file. Part of the crop parameters can be adjusted and determined on the basis of the experimental data or literature. For the parameters that cannot be fixed, a range of realistic values is determined, based on experimental data and literature. During the calibration the latter parameters are adjusted by running the model with various combinations of values within these realistic ranges (Table 5.1). With the help of automated calibration (PEST*; Doherty et al.,* 1995) the smallest possible deviation from the observed data was obtained. As observed data the leaf *DM*, storage organs *DM*, total above ground *DM* (*TDM*) and *LAI* were used. In this project a good simulation of the *LAI*, and consequently of the *ET*, is very important. Therefore, the sum of squared differences for the *LAI* had a relatively higher weight than for *DM*. This had hardly any effect on the simulation of *DM* (<0.5% difference).

**Table 5.1** Overview of crop parameters that were based on measurements, and those adjusted, within realistic values, during calibration. Parameters not mentioned are based on literature.

| **Parameters based on measurements** | **Parameters adjusted during calibration** |
|---|---|
| Initial *DM*, *LAI* and growth rate *LAI* | Initial *DM* and growth rate *LAI*(1) |
| Specific leaf area | Life span leaves(1), (2) |
| Life span leaves | Specific leaf area(1) |
| Effect temperature on assimilation | Effect temperature on assimilation(1) |
| *DM*-partitioning | *DM*-partitioning(1), (2) |
| Conversion coefficients | Extinction coefficient diffuse light(2) |
| Rooting depth increase | Initial light use efficiency(2) |
| Maximum rooting depth | Maximum assimilation rate(2) |
| Crop height | Death rate leaves due to water stress |
| Length growth phases | Critical pressure heads for water uptake |
| Day length sensitivity | Root density distribution(2) |
| | Critical salt level and reduction factor |
| | Relative root distribution |

(1) Only small changes of values, based on measurements, within possible measurement errors; for *DM*-partitioning also some adjustments due to absence of reallocation in model;
(2) Most important crop parameters adjusted during calibration.

After calibration, SWAP/WOFOST was validated. A completely independent validation was not possible, since for the determination of crop parameters some data from the other treatments in the experiments were used (mainly specific leaf area and *DM*-partitioning) and also some data from the farmer fields (to determine daylength sensitivity). However, comparison of the simulated crop growth with the measured crop growth for the treatments or farmer fields that were not used as reference for calibration (but without nutrient stress and with good control of pests and diseases) gives an indication of the validity of the crop files.

### 5.2.3 Calibration for wheat

For the calibration, data from the moisture experiment with wheat cultivar PBW-343 were used. Treatments "0.7" and "0.5" (irrigation water/$ET_p$=0.7 or 0.5 after crown root initiation were used as reference (Chapter 3). In Figures 5.2-5.3 measured *DM* and *LAI* is compared with the fitted *DM* and *LAI*, obtained with SWAP/WOFOST. The estimation of the *TDM* and the final yield is good (Fig. 5.2 and 5.3). The *LAI* is estimated reasonably, although in the beginning of the growing season it is underestimated and at the end overestimated. Comparison of the estimated *ET* obtained with SWAP/WOFOST and the simple crop module (using measured *LAI*) shows that the difference in total *ET* from emergence to maturity is only 1.5% higher with the measured *LAI*. In the simple crop module linear interpolation between measured *LAI*'s takes place. This results in some overestimation of *LAI*, and thus of transpiration in the beginning of the growing season.

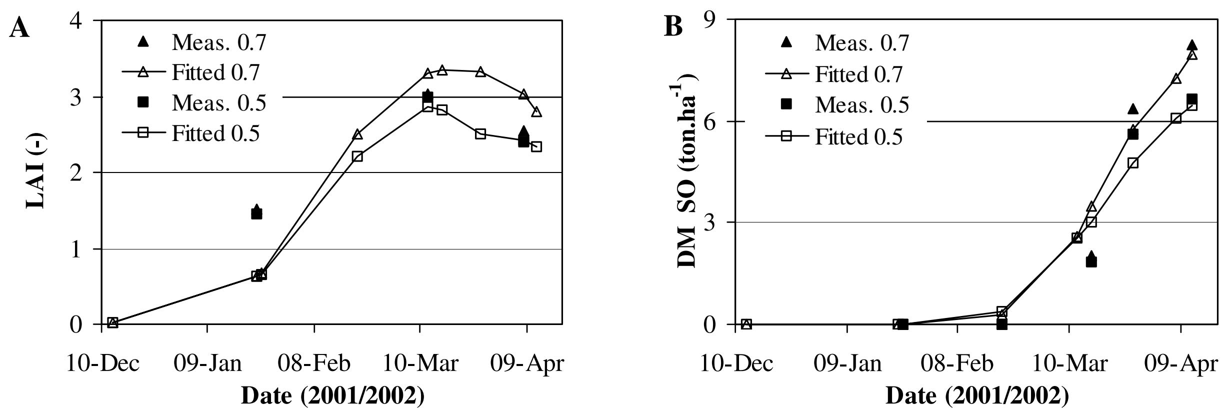


**Figure 5.2** Measured and fitted *LAI* (A) and *DM* in storage organs (B) for wheat cultivar PBW-343 (moisture experiment Sirsa; "0.7" means irrigation water/$ET_p$ = 0.7 after crown root initiation; calibrated model with measured plant height, length growth phases and rooting depth; 80% grain in storage organs).

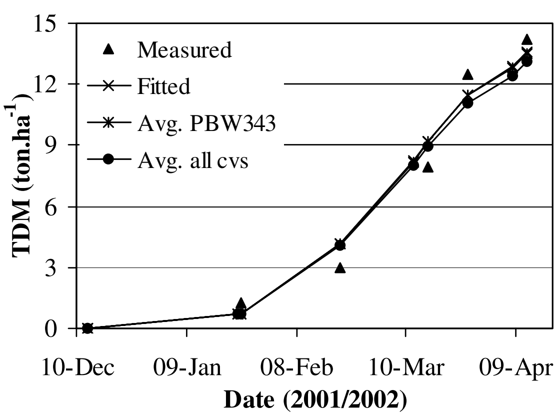


**Figure 5.3** Measured and fitted total above ground *DM* for wheat cultivar PBW-343 (Sirsa 2001-02; "0.7" means irrigation water/$ET_p$ = 0.7 after crown root initiation; calibrated model; "avg." is with average length growth phases, plant height and rooting depth).

The wheat cultivars used in the experiments and at the farmer fields appeared to be sensitive to daylength during the vegetative and generative stage. Since this cannot be included in SWAP/WOFOST (Par. 5.2.1), four crop files for different sowing dates were prepared (different lengths of growth phases, represented by the *TSUM*s). The difference between wheat cultivar PBW-343 and the other cultivars seems small. There is no clear difference in *DM* partitioning in relation to development stage between cultivars and between sowing dates. The length of the growing season for PBW-343 is almost the same as the length of the growing season of the other cultivars. Only the relative length of the vegetative phase is slightly longer for PBW-343. Therefore, the calibrated crop module for PBW-343 was used also for other cultivars, with the exception of the length of the growth phases.

A sensitivity analysis was performed where all crop parameters were increased or decreased with 10%. The model is considered relatively sensitive when a change of 10% results in more than 10% change in e.g. *DM* or *ET* (Table 5.2). The analysis showed that, for mild and severe water stress, SWAP/WOFOST is relatively sensitive to the specific leaf area, the conversion coefficients for assimilates to structural biomass, the length of the vegetative growth phase, and the maximum daily increase in rooting depth. Under mild water stress the model is also relatively sensitive to changes in the maximum assimilation rate and the initial light use efficiency. When there is clear water stress the model becomes relatively sensitive to the extinction coefficient. Correct estimation of these parameters is essential. Most of the above mentioned parameters are based directly on the measurements in the experiments, and therefore contain limited uncertainty. The maximum assimilation rate and initial light use efficiency are estimated indirectly during calibration. Similar results were obtained for cotton and rice.

Table 5.2 Overview(1) of SWAP/WOFOST sensitivity to changes in parameters under mild water stress (irrigation schedule "0.7") and severe water stress (no irrigation) (soil experimental station Sirsa, initial conditions of wheat moisture experiment).

| | | Mild water stress | | | Severe water stress | | |
|---|---|---|---|---|---|---|---|
| | Change | *DM* Storage Organs | Total above ground *DM* | Trans-piration | *DM* Storage Organs | Total above ground *DM* | Trans-Piration |
| Specific leaf area | +10% | 109 | 114 | 110 | 89 | 107 | 102 |
| | -10% | 84 | 81 | 87 | 110 | 90 | 98 |
| Temperature sum vegetative phase | +10% | 95 | 107 | 111 | 70 | 102 | 103 |
| | -10% | 93 | 87 | 83 | 134 | 95 | 94 |
| Max. assimilation rate | +10% | 109 | 110 | 104 | 100 | 107 | 101 |
| | -10% | 89 | 88 | 95 | 99 | 91 | 99 |
| Extinction coef-ficient diffuse light | +10% | 98 | 100 | 104 | 90 | 97 | 101 |
| | -10% | 102 | 100 | 95 | 113 | 104 | 99 |
| Initial light use efficiency | +10% | 110 | 112 | 105 | 101 | 108 | 101 |
| | -10% | 88 | 87 | 95 | 99 | 91 | 99 |
| Conversion coefficients | +10% | 113 | 118 | 108 | 95 | 113 | 101 |
| | -10% | 83 | 80 | 90 | 103 | 86 | 98 |

(1) Results of 10% change in parameter values that did not result in more than 10% change in *SO*, *TDM*, *T* are not shown; relative change shown: 100=same as reference situation without change of crop parameters.

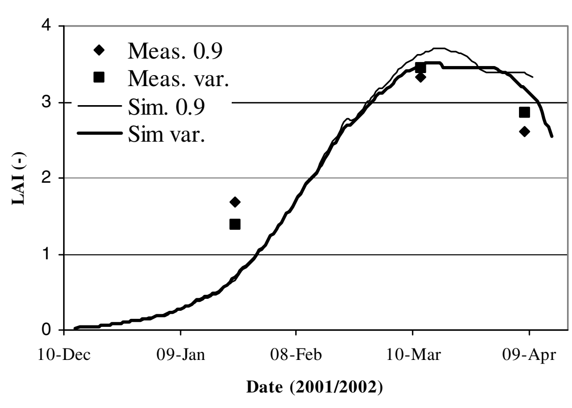


**Figure 5.4** Measured and simulated *LAI* for wheat cultivar PBW-343 (wheat experiments; "0.9" means irrigation water/$ET_p$ = 0.9 after crown root initiation; "var." is variety experiment; simulated with average length growth phases, plant height and rooting depth for PBW-343).

Validation was performed with treatment "0.9" from the moisture experiment and for cultivar PBW343 in the variety experiment (Chapter 3). Simulation of *DM* development and *LAI* was good during the main part of the growing period. Figure 5.4 shows the *LAI* development for both treatments. Some underestimation of the *LAI* in the first part of the growing season is observed.

### 5.2.4 Calibration for rice

For rice, fields 6 and 2 with cultivar PR-106 were used for calibration of SWAP/WOFOST, since calibration of the soil-water module in SWAP for the rice experiment in Karnal could not be performed due to missing data. The yield in field 6 was that high, that we assumed that hardly any (water) stress occurred. For field 2 we assumed that the lower yield was due to only water stress. Rice growth is simulated from transplanting to maturity. Figures 5.5 and 5.6 show some results for field 6. *LAI* development in the early season could be fitted well, but later on in the growing season *LAI* is overestimated. This overestimation takes place in the period with almost complete soil cover, and therefore, it hardly results in overestimation of the *T* (< 0.5% lower *T* compared with the simulation with measured *LAI* for field 6).

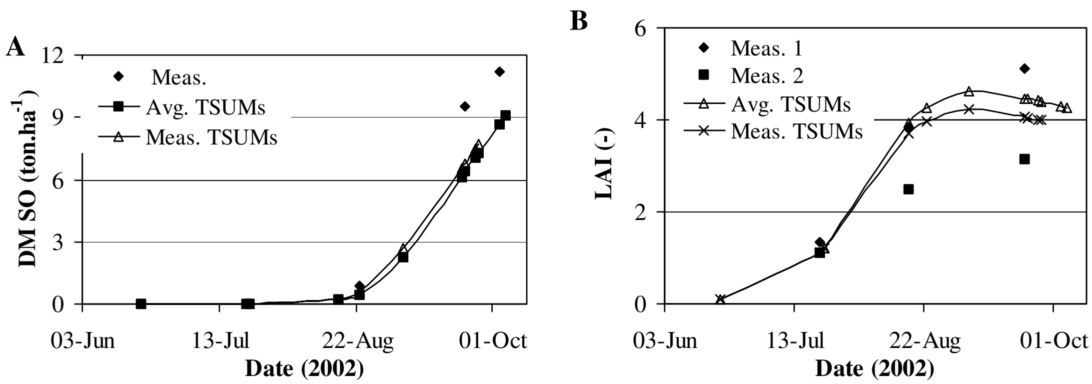


**Figure 5.5** Measured and fitted *DM* in storage organs (A; 81% grain) and LAI (B) for rice cultivar PR-106 in field 6 (Meas. 1 = measured with PAR-meter; Meas. 2 = measured with leaf area meter; meas./avg. TSUMs = measured/average length growth phases).

The *DM* in the *SO* (Fig. 5.5A) and the *TDM* is somewhat underestimated. However, higher crop productions could not be obtained with realistic values for the crop parameters. Besides, the samples taken at harvest (larger samples and 5 replicates) give a lower estimate of final yield than the samples taken for *DM*-partitioning (shown in figures; 3 replicates; 81% of *SO* is grain; see also Par. 5.3). With average *TSUM*s, the final *DM* in *SO* at maturity is clearly higher than with the observed *TSUM*s ($9.1 \cdot 10^3$ kg *DM*.$ha^{-1}$ compared with $7.7 \cdot 10^3$ kg *DM*.$ha^{-1}$). However, this amount of biomass is reached 8 days later. The longer simulated growing season results in higher *T* (532 mm compared with 491 mm).

In all farmer fields cultivar PR-106 was used. The farmers transplant the rice from 28 to 58 days after emergence (avg. 38 days; June 12 to July 1). The length of the growth phases between transplanting and maturity, measured in °C·d, was almost constant, independent of the transplanting date (transplanting to anthesis: 81 ± 4 days; anthesis to maturity: 26 ± 4 days).

Validation of the crop files was performed with the other farmer fields (fields 1, 4 and 5; production close to potential; Par. 5.3). The largest deviation found was 17% when average lengths of the growth phases were used.

### 5.2.5 Calibration for cotton

For cotton the data from the moisture experiment with cultivars LHH-144 and H-1098 were used to determine the best crop parameters (Chapter 3). Figures 5.6 and 5.7 show some results. *LAI* development in the early season is overestimated, but later on it is underestimated. This underestimation takes place in the period with almost complete soil cover, and fitted *LAI* remains mostly above 3. Therefore, it hardly results in underestimation of *T* (<0.5% difference with measured *LAI*).

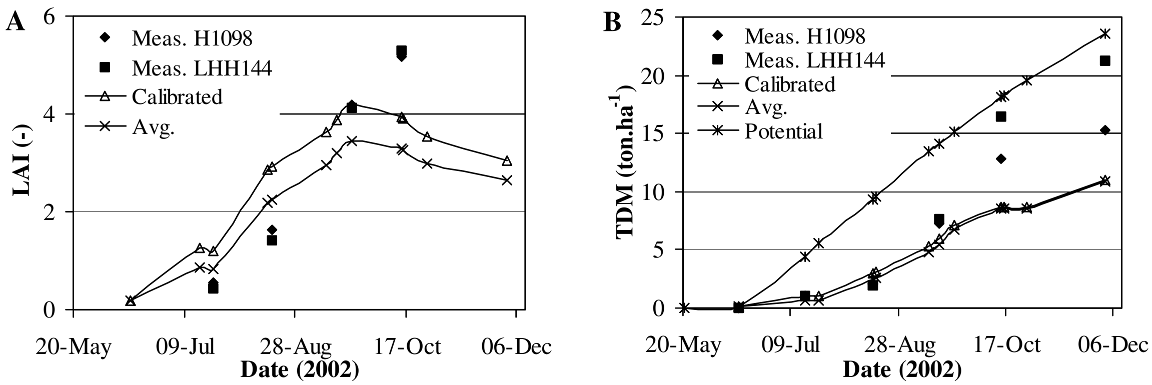


**Figure 5.6** Measured and fitted *LAI* (A) and total above ground *DM* (B) for cotton cultivars H-1098 and LHH-144 with "optimum" moisture (moisture experiment; Fitted/avg. = measured/average length growth phases and rooting depth).

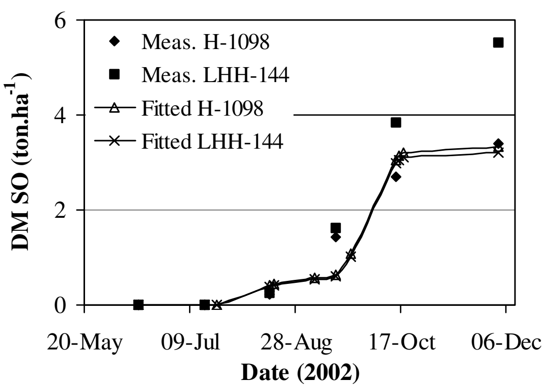


**Figure 5.7.** Measured and fitted *DM* in storage organs (44% seed cotton) for cotton cultivars H-1098 and LHH-144 with "low" moisture (moisture experiment; length growth phases and rooting depth as measured).

Most obvious in Figure 5.6 is the underestimation of water-limited *DM* production. However, the calculated final potential *DM*-production is only slightly higher than the measured *TDM* for LHH-144, indicating that the calculated moisture stress is the main reason for the underestimation of the water-limited production. Water-limited *DM* production in the first part of the growing season could be fitted well. During this period on purpose light to medium water-stress was created to avoid excessive vegetative growth. From the second part of September on severe water stress is simulated, whereas in practice apparently hardly any stress occurred. The calculated amount of soil water from 30-120 cm depth is severely underestimated. The soil-water module of SWAP was calibrated using data from the *rabi* season. Maybe these soil water parameters do not represent accurately the situation in the *kharif* season. The calculated *E* (avg. 0.5 $mm.day^{-1}$) and percolation (13 mm) were not the reason for this underestimation. The calculated $T_p$ of about 800 mm in 196 days in the *kharif* season seems realistic. The amount of water applied (with irrigation and rain about 460 mm) is very low compared to the calculated $T_p$. With the values for the crop parameters within realistic ranges, it was impossible to come close to the measured productions under "optimum" moisture. The reason for the large differences between the measured and calculated *DM*-productions is not clear. Possibly the rooting depth was underestimated (88 cm measured), or there might have been some upward movement of water from soil layers below 120 cm. There is some uncertainty about the value for the canopy resistance (70 $s.m^{-1}$), but the range of uncertainty (60-80 $s.m^{-1}$) can not explain more than 10% of the difference between measured and calculated *TDM*. For the maximum assimilation rate and the initial light use efficiency the maximum values found in literature were used. Maybe the maintenance respiration has to be lowered. However, no data are available to do this, except for *SO*.

For "low" moisture availability the fitted *DM* production was close to the measured production for H1098, but *DM* production for LHH-144 was still clearly underestimated (Figure 5.7). The water content in the soil layers up to 120 cm depth was estimated better than for "optimum moisture". No clear underestimation of soil water content was observed.

The cultivars used in the experiment were not cultivated on the selected farmer fields, although these two cultivars are cultivated in the region. The cotton cultivars used at the farmer fields appeared to be sensitive to daylength during the vegetative and generative stage. Since this cannot be included in SWAP/WOFOST (Par. 5.2.1), three crop files for different sowing dates were prepared. The *DM* partitioning in relation to *DVS* did not differ clearly between early and late sowing.

The year 2002 was a relatively dry year. Water was probably the most limiting element during the growing season. Therefore, the comparison between the measured and simulated productions at the farmer fields could serve as a kind of validation. The results in Par. 5.3 show that the average level of production was simulated reasonably. However, for 5 out of the 10 fields large differences between the simulated water-limited yield and the actual yields were obtained.

## 5.3 Comparison of actual and simulated crop production and evapotranspiration

### 5.3.1 Methodology

With SWAP/WOFOST potential and water-limited production can be simulated (Par. 5.2.2). By definition, water-limited production can only be reached when the crop is amply supplied with nutrients and when it is free of weeds, pests and diseases (for potential production also ample supply of water is needed). In the farmer fields, generally, further reduction of the water-limited production takes place by effects of nutrient shortage, weeds, pests, diseases and/or pollutants, which lead to the so-called actual production. This means that a translation of simulated water-limited to actual production and ($E$)$T$ is needed. For this purpose a "management" factor might be used which reduces the simulated yield. However next a better approach is described.

*DM-production*
In order to translate the simulated water-limited production to the actual production, the measured actual yields and the simulated water-limited productions were compared for each farmer field. Measured productions at harvest (5 replicates) were used for the comparison, and not with those for *DM*-partitioning (3 replicates), since the latter are considered less accurate (fewer and smaller replicates). For rice and cotton too few comparisons were available to analyse the difference statistically. For wheat 17 comparisons could be made. For the remaining 7 fields no calibration of the soil-water module was possible. The simulation model includes already most aspects of crop production, such as sowing date, amount, timing and quality of water supply. However, some aspects are not included, e.g. nutrient stress, competition with weeds, or unfavourable pH. Besides this, calibration was performed for PBW-343 and for emergence date December 13. Simulation for other cultivars and emergence dates may be less accurate. With the help of the available information from the farmer fields, the explaining value of several variables for the yield gap between actual and simulated water-limited production was studied.

*Evapotranspiration*
Also translation of simulated water-limited *ET* (hereafter called $ET_{wl}$) obtained with SWAP/WOFOST to actual *ET* (hereafter called $ET_a$) is needed. $ET_a$ was not measured, however with the help of the simple crop module (and using measured *LAI* values) reasonable estimates of $ET_a$ can be made. Several researchers established relations between yield and T, *ET* or vapour deficit (*Tanner & Sinclair*, 1983). The constants in the relations are often not given for the 3 crops and conditions in our study. However, in our case we have limited data available to determine the constants ourselves. *Doorenbos & Kassam* (1979) presented the relation:

$$\left(1-\frac{Y_a}{Y_p}\right)=K_y\left(1-\frac{ET_a}{ET_p}\right) \tag{5.1}$$

where $Y_a$ is the actual yield component (e.g. total above ground biomass or grain), $Y_p$ is the potential yield, $ET_a$ is cumulative actual evapotranspiration, $ET_p$ is the cumulative potential evapotranspiration and $K_y$ is a constant dependent on yield component and plant species. The relation was assumed valid for water deficits up to 50%. The $K_y$ values given by *Doorenbos & Kassam* (1979) are based on an analysis of experimental data covering a wide range of growing conditions and represent high-producing crop varieties, well-adapted to the growing environment and grown under a high level of crop management.

### 5.3.2 Comparison for wheat

**Dry matter production**

As expected the water-limited yields are higher than the actual yields at the farmer fields, since SWAP/WOFOST does not include the effects of nutrient stress and pests and diseases. Only for fields 22 and 24 the water-limited yields were lower than the actual yields. This can be due to several things: the cultivars on these fields can be less sensitive to salt stress, salt transport is not simulated well, or water content is underestimated. Simulation with a less sensitive cultivar (20% higher critical salt level) resulted in an increase of 53% of the yield in field 24 and less in field 22, but the simulated yields still remained clearly below the measured yield. Some fields have very high water-limited productions, e.g. fields 1 and 2.

These productions were all simulated with early sowing and are higher than the potentials mentioned by *Aggarwal et al.* (2000). On the other hand, these simulated yields are close to the highest measured yields with late sowing in the variety experiment (Chapter 3).

The relation found between the measured actual and simulated water-limited wheat yields is weak ($R^2$: 0.25-0.33 for *TDM*), but positive. Simulation with average *TSUM*s for all cultivars (Table 5.3) gives more or less the same relation as simulation with measured *TSUM*s (similar $R^2$). The average water-limited *TDM* is 41-43% higher than the measured *TDM* (5 replicates; Table 5.3). The average water-limited grain yield (kg *FM*.ha$^{-1}$; assuming 80% grain in *SO*, 14 % moisture (fresh material)) is 87-89% higher than the measured actual grain yield (5 replicates). When using the final *DM* estimates based on the samples for *DM*-partitioning (3 replicates; Chapter 3) the water-limited *TDM* is only 2% higher than the measured actual *TDM*, and water-limited grain yield is 30-31% higher than the measured actual grain yield. Apparently, it was difficult to get representative samples. The measurements with 3 replicates are considered less accurate due to the lower number of replicates and the smaller sample size.

For simulation at regional scale and over several years no measured *TSUM*s can be used, because they are not available at these scales. In the case of wheat the difference between measured and average *TSUM*s never resulted in differences larger than 0.7 ton fresh grain per ha and 2.3 ton total above ground fresh biomass per ha.

**Table 5.3** Measured actual and simulated water-limited wheat production ($10^3$ kg.ha$^{-1}$) at farmer fields (various cultivars; calibration of soil-water module per field).

| | Measured (5 replicates) | | Simulated (meas. TSUMs) | | Simulated (avg. TSUMs all cultivars) | | Simulated (avg. TSUMs PBW-343) | |
|---|---|---|---|---|---|---|---|---|
| Field | Grain *FM*(1) | Total *FM*(1) | *FM* grain | Total *FM* | *FM* grain | Total *FM* | *FM* grain | Total *FM* |
| 1 | 7.0 | 16.1 | 11.6 | 20.5 | 10.9 | 18.2 | - | - |
| 2 | 4.7 | 9.5 | 10.6 | 17.5 | 11.1 | 18.9 | - | - |
| 4 | 6.4 | 14.7 | 9.9 | 16.9 | 9.9 | 16.9 | - | - |
| 5 | 5.9 | 15.4 | 9.9 | 16.6 | 10.4 | 17.8 | - | - |
| 6 | 6.1 | 14.0 | 10.2 | 17.1 | 10.7 | 18.6 | - | - |
| 7 | 5.2 | 14.3 | 8.9 | 14.7 | 9.6 | 16.4 | - | - |
| 9 | 2.5 | 6.2 | 5.1 | 11.1 | 5.1 | 11.0 | 5.0 | 11.3 |
| 10 | 4.4 | 10.3 | 9.6 | 18.4 | 9.7 | 17.5 | 9.7 | 18.2 |
| 11 | 4.4 | 11.3 | 9.4 | 18.3 | 9.6 | 17.6 | 9.5 | 18.1 |
| 13 | 4.3 | 10.7 | 6.5 | 11.9 | 5.9 | 10.3 | 5.9 | 10.3 |
| 15 | 5.0 | 12.1 | 10.4 | 19.1 | 10.2 | 18.4 | 10.3 | 19.2 |
| 16 | 5.2 | 11.4 | 9.1 | 18.5 | 9.5 | 17.7 | 9.4 | 18.2 |
| 18 | 3.3 | 8.0 | 9.3 | 17.2 | 9.2 | 17.3 | - | - |
| 19 | 2.3 | 5.7 | 7.9 | 16.6 | 8.2 | 15.7 | 8.2 | 15.7 |
| 20 | 4.3 | 9.2 | 9.9 | 17.9 | 9.9 | 17.9 | - | - |
| 22(2) | 3.0 | 7.9 | 0.0 | 0.0 | 0.0 | 0.0 | - | - |
| 24(2) | 1.8 | 4.2 | 1.0 | 2.0 | 1.2 | 2.4 | - | - |
| Avg. | 4.6 | 11.0 | 8.6 | 15.8 | 8.8 | 15.6 | 8.3 | 15.8 |

(1) 14% and 12% moisture in grain and straw (fresh material, *FM*), 0.8 grain in *SO* (avg. farmer fields+experiments)

(2) salt stress simulated, see text

Multiple linear regression has been applied to analyse the difference between the water-limited *TDM* production and the actual *TDM* production. The following variables were taken into account:

- Cultivar (for calibration PBW-343 used);
- Emergence date (for calibration emergence at Dec. 13 used, potential production increases with earlier sowing);
- Time between maturity and harvest (measured *DM* was determined during harvest, whereas the simulated *DM* is at maturity);
- Use of herbicides (competition with weeds may result in yield reduction);
- pH in top 30 cm (pH influences the availability of nutrients);
- Available Zn in top 30 cm (Zn deficiency occurs regularly in the region);
- N applied (as a measure of N availability);
- P applied (as a measure of P availability);
- Rotation (rotation with rice may have effects on soil properties not included in the model);
- Discharge (irrigation times were not provided on a very exact basis. The higher the discharge, the higher the possible error in irrigation amounts used in the simulations).

This list of variables was based on the information available at the farmer fields. Since the aim is to "translate" the simulated water-limited productions to actual productions at regional level, the selection of variables was also based on available information at village or regional level (*Aggarwal et al.,* 2001). Fields 22 and 24 were left out the comparison, due to doubt about the simulated water-limited yields, and because these two fields change the significance of certain variables dramatically. After determining the explaining value of each individual variable, variables were added until the best explaining model (highest $R_{adj}^2$ and/or highest significance) was obtained. This procedure was repeated for the difference between the simulated water-limited and actual *SO* production.

**Table 5.4** Best models obtained with the statistical analysis of the difference between the simulated water-limited (WL) production and the measured actual (A) production (5 replicates) for wheat on the farmer fields (see text for explanation).

| | | Simulated with measured *TSUM*s | | Simulated with avg. *TSUM*s (all cultivars) | |
|---|---|---|---|---|---|
| Explaining variables | | $TDM_{WL}$-$TDM_A$ | $SO_{WL}$-$SO_A$ | $TDM_{WL}$-$TDM_A$ | $SO_{WL}$-$SO_A$ |
| Cultivar | PBW-343=0, other =1 | 4748 | 2336 | 4259 | 1553 |
| Maturity to harvest | d | 458 | 274 | - | - |
| Herbicide use | Yes=1, no=0 | -1752 | - | - | - |
| Avail. Zn 0-30 cm | $kg.ha^{-1}$ | -1591 | - | -1751 | - |
| N applied | $kg.ha^{-1}$ | 44.4 | - | 48.8 | - |
| Rotation with | Rice=1, cotton=0 | -10195 | -1874 | -8460 | -1269 |
| Constant | | -1178 | 2659 | -687 | 4618 |
| $R_{adj}^2$ | | 0.54 | 0.20 | 0.34 | -0.005 |
| Significance | | 0.045 | 0.148 | 0.087 | 0.408 |

(1) *SO* = *DM* storage organs, *TDM* = total above ground *DM*; assumed: 80% grain in *SO*, 14% moisture in air-dried grains, 12% moisture in air-dried straw.

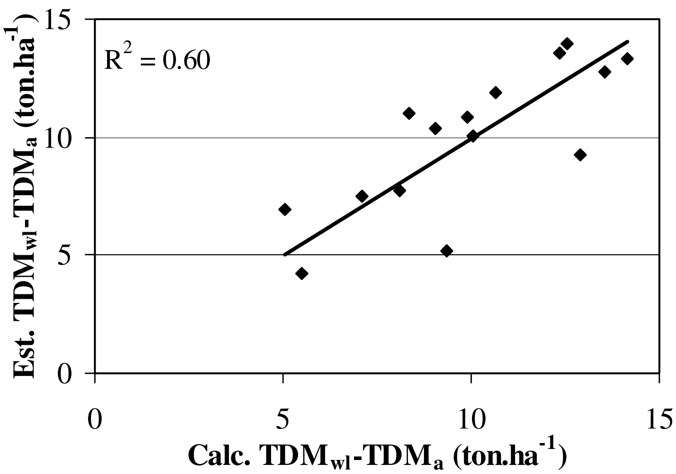


**Figure 5.8** Relation between calculated and estimated water-limited and actual *TDM* (water-limited production of wheat simulated with average *TSUM*s; estimated difference calculated with statistical model from Table 5.4).

The statistical analysis shows that the difference between the simulated water-limited production and the measured production most often can be explained partly by the cultivar used and the rotation. At maximum 54% of the difference is explained with the included variables. When using average *TSUM*s during the simulation, as will be done during the regional analysis, a much lower percentage of the difference between the water-limited production and the actual yield is explained and the significance of the models decreases. Fig. 5.8 shows how well the statistical model for *TDM* (avg. *TSUM*s) reproduces the difference between the water-limited and actual *TDM*. The models for *SO* are never significant at the 0.10 probability level, but the harvest index (HI) for grain (on *DM* basis) as observed in the farmer fields does not show a trend with *TDM* production level and is rather stable (average 0.42, std. 0.03). This value can be used to estimate the grain yield from the *TDM* production.

The statistical models are based on data from one year and a limited number of farmer fields, that were not distributed evenly over the region. For reliable "translation" of the water-limited yields to actual yields more data and especially data from more years are needed, since the effect of e.g. pests and diseases can differ considerably between years.

**Evapotranspiration**

*Doorenbos & Kassam* (1979) mention a range of *ET* for wheat of 450-650 mm, assuming a growing period of 180-250 days for winter wheat. *Bastiaanssen et al.* (1996) mention a lower range of 400 mm for crop water requirements. The simulated $ET_p$ for the farmer fields is in the range of 419-607 mm (avg. 526 mm), but the estimated $ET_a$ is 224-440 mm (avg. 353 mm) and the simulated $ET_{wl}$ is 139-393 mm (avg. 316 mm). This is very similar to the $ET_a$ values from Bastiaanssen et al. (1996). However, the growing season in the farmer fields is on average 138 days. Figure 5.9 shows the relation between the relative *TDM* and *SO* production and the relative *ET*. The $K_y$ value from literature is 1.0 for winter wheat and 1.15 for spring wheat (*Doorenbos & Kassam*, 1979). Here higher values are obtained (1.24 for *TDM*, 1.64 for *SO*). However, the data used are limited and contain some uncertainty. The $ET_a$ is estimated using linear interpolation between the measured *LAI*'s, resulting in a slight overestimation of the *LAI* and transpiration in the beginning of the growing season. Thus, in reality ($1-ET_a/ET_p$) might have been higher. If $TDM_p$ is overestimated, than ($1-TDM_a/TDM_p$) is overestimated as well. Besides, water was not the only limiting factor for actual production as can be seen in Table 5.3. The $K_y$ of *Doorenbos & Kassam* (1979) was established for high management levels, suggesting that water was the main limiting factor.

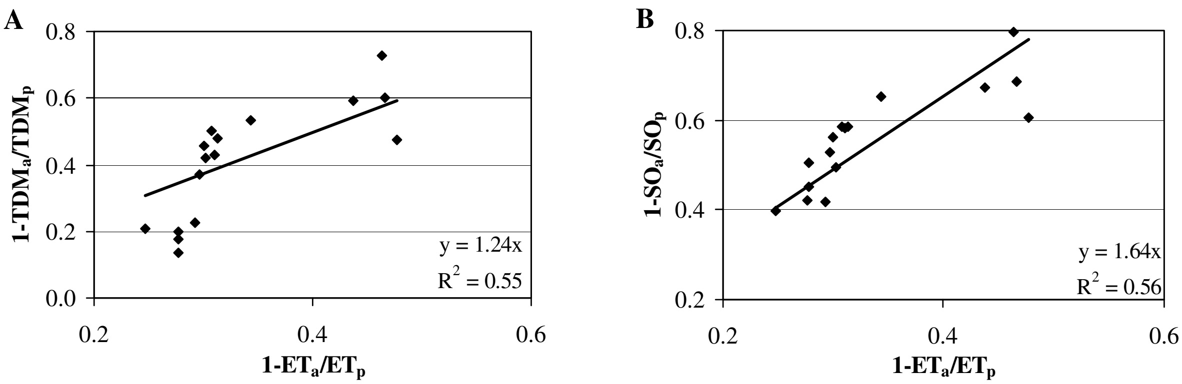


**Figure 5.9** Relation between the ratio of actual *TDM* to simulated potential *TDM* (A) or the ratio of the actual *SO* to the simulated potential *SO* (B) and the ratio of estimated actual *ET* and simulated potential *ET* for farmer fields with wheat (Sirsa 2001/02; average lengths of growth phases).

### 5.3.3 Comparison for rice

#### Dry matter production

The relation found between the measured actual and simulated water-limited rice yields is weak ($R^2 < 0.35$; only 5 fields) and slightly negative. However, the average simulated *TDM* of rice is only 1-3% higher than the average measured *TDM* (Table 5.5). The average simulated grain yield is less than 4% higher than the average measured grain yield. All yields were close to the simulated potential yield. Apparently, the actual yield was hardly limited or reduced by nutrients, water and/or pests and diseases. *Aggarwal et al.* (2000) mention potential rice productions of 10.8 $10^3$ $kg.ha^{-1}$ for Sirsa. However, 2002 was a year with relatively high temperatures and a shorter growing season, resulting in relatively low productions.

**Table 5.5**. Measured actual and simulated water-limited rice production ($10^3$ $kg.ha^{-1}$) at farmer fields (cultivar PR-106; calibration of soil-water module per field).

| | Measured (5 replicates) | | Simulated (measured *TSUM*s) | | Simulated (avg. *TSUM*s) | |
|---|---|---|---|---|---|---|
| Field | grain *FM* (1) | total biomass *FM* (1) | grain *FM* (1) | total biomass *FM* (1) | grain *FM* (1) | Total biomass *FM* (1) |
| 1 | 8.1 | 18.0 | 7.5 | 15.6 | 8.8 | 19.4 |
| 2 | 7.4 | 16.0 | 8.8 | 20.3 | 8.2 | 17.6 |
| 4 | 8.0 | 18.7 | 8.9 | 20.2 | 8.7 | 19.1 |
| 5 | 9.0 | 19.0 | 8.0 | 16.3 | 7.5 | 15.7 |
| 6 | 8.0 | 16.5 | 7.2 | 16.6 | 8.8 | 19.3 |
| Avg. | 8.1 | 17.6 | 8.1 | 17.8 | 8.4 | 18.2 |

(1) air dry samples (fresh material, *FM*) about 16% moisture; 0.81 grain in *SO* (avg. farmer fields);

#### Evapotranspiration

*Doorenbos & Kassam* (1979) mention a range of *ET* for rice of 450-700 mm. *Tuong* (1999) mentions an *ET* for rice in Punjab of 770-530 mm for transplanting dates ranging from May 1 to July 16, respectively. *Bastiaanssen et al.* (1996) mention water requirements up to 1500 mm. The simulated $ET_p$ for the farmer fields is in the range of 816-943 mm (avg. 888 mm), estimated $ET_a$ is 796-920 mm (avg. 872 mm) and the simulated $ET_{wl}$ is 795-928 mm (avg. 873 mm). In the *Kharif* season temperatures are high and vapour pressure was low in 2002. Consequently, evaporative demand was high. 50-56% of *ET* is T.

The $K_y$ value from literature is >1.15 (*Doorenbos & Kassam*, 1979). For rice only 5 comparisons for actual and potential *DM* and *ET* and a very narrow range of relative *TDM* and *ET* are available. This is not sufficient to determine a $K_y$. In this case we will have to use the $K_y$ value from literature to estimated *ET* for production levels below potential.

### 5.3.4 Comparison for cotton

**Dry matter production**

The relation between the measured actual and simulated water-limited cotton yields is weak ($R^2$: 0.08-0.38), but positive. The average water-limited *TDM* is 4-6% lower than the average actual *TDM* (5 replicates; 15% moisture in air-dry seed cotton, 18% in straw). The average simulated seed cotton yield (kg $FM.ha^{-1}$; assuming 44% seed cotton in *SO*, and same moisture contents) is 27-32% higher than the average actual seed cotton yield.

**Table 5.6** Measured actual and simulated water-limited cotton production ($10^3$ $kg.ha^{-1}$) at farmer fields (various cultivars; calibration of soil-water module per field).

| | Measured (5 replicates) | | Simulated (measured *TSUMs*) | | Simulated (average *TSUMs*) | |
|---|---|---|---|---|---|---|
| Field | Seed cotton *FM* (1) | Total *FM* (1) | Seed cotton *FM* (1) | Total *FM* (1) | Seed cotton *FM* (1) | Total *FM* (1) |
| 10 | 1.8 | 7.3 | 3.7 | 17.0 | 4.4 | 18.2 |
| 11 | 0.4 | 1.3 | 1.0 | 6.2 | 1.4 | 7.3 |
| 13 | 2.2 | 16.8 | 3.2 | 12.3 | 3.3 | 12.9 |
| 15 | 1.9 | 9.0 | 2.0 | 10.2 | 1.9 | 9.9 |
| 16 | 2.3 | 12.9 | 3.8 | 17.3 | 3.6 | 17.4 |
| 18 | 3.6 | 22.8 | 3.4 | 14.2 | 3.0 | 12.6 |
| 19 | 2.8 | 14.2 | 3.2 | 14.7 | 3.1 | 14.4 |
| 20 | 2.3 | 14.1 | 4.0 | 17.1 | 4.2 | 17.6 |
| 22 | 0.0 | 0.2 | 0.4 | 2.9 | 0.5 | 2.9 |
| 24 | 3.3 | 29.2 | 1.6 | 8.8 | 1.9 | 9.0 |
| Average | 2.1 | 12.8 | 2.6 | 12.1 | 2.7 | 12.2 |

(1) 15% and 18% moisture in seed cotton and straw (fresh material, *FM*); 0.44 seed cotton in *SO* (avg. farmer fields+experiments).

**Evapotranspiration**

*Doorenbos & Kassam* (1979) mention an $ET_a$ range for cotton of 700-1300 mm for a growing season of 150-180 days. The simulated $ET_p$ for the farmer fields is in the range of 1340-1675 mm (avg. 1527 mm), but for an average growing season of 192 days. The estimated $ET_a$ is 263-777 mm (avg. 553 mm) and the simulated $ET_{wl}$ is 274-795 mm (avg. 559 mm). The high $ET_p$ is probably due to the climate in Sirsa with high temperatures and low vapour pressure. The simulated $ET_a$ is lower due to the water stress that is simulated in all fields. Transpiration composes 62-84% of the *ET*.

The $K_y$ value from literature for cotton is 0.85 (*Doorenbos & Kassam*, 1979). This value could not be reproduced in our study. However, the simulated water stress was in all cases more than 50% ($ET_a/ET_p$<0.5). The $K_y$ value is assumed valid for water stress of less than 50%. The number of comparisons between actual and potential yield and *ET* is not sufficient for determining a $K_y$ value, especially not when taking into account the uncertainty in $ET_a$ estimates and simulated productions (Par. 5.3.2). Using only the averages of all fields, a $K_y$ of 0.86 is obtained for seed cotton, and a $K_y$ of 0.84 for *TDM*. This is very close to the value mentioned above.

## 5.4 Management options and water productivity

### 5.4.1 Definitions of water productivity

As will be discussed in Chapters 8 and 9 the relevant definition of water productivity (*WP*) can change with the spatial and temporal scale one is working on. In this paragraph we will discuss the effect of some management options and climate on yield and *WP* at field scale. Only transpired water is used in a productive way. This means that definitions such as kg *TDM* or economic yield per unit transpiration are logical to use. Evaporation, water used for field preparation, leaching of salts, etc. does not directly result in crop production, although some water is needed for e.g. field preparation, and evaporation cannot be avoided completely. The water need of a crop depends also on management practices. When a rice field is prepared long before transplanting, more water will be lost due to evaporation, compared with preparation and ponding shortly before transplanting. In literature *WP* is often given (implicitly) as yield per unit water supplied through e.g. irrigation. This water use is, however, not the same as the water need of a crop on a certain field, since over- or under irrigation may occur. For a fair comparison between fields, one should focus on water needs, and management practices should be kept the same, or minimum amounts of water needed for these practices should be defined. To avoid arbitrary choices, we will focus on *T* and *ET* from emergence to maturity. To understand where and when water can be saved, distinction between water needs for T, E, leaching of salts, etc. is needed. In this chapter we focus mainly on water needs for *T* and E. Some data on production per unit water supplied by irrigation will be presented for the farmer fields. The effect of management options and climate is demonstrated mainly for wheat, but for rice and cotton similar effects are observed.

### 5.4.2 Levels of water productivity

In Table 5.7 the simulated *WP* for different irrigation schedules is presented. Various definitions are used to give an idea of the effect of the definition on the level of *WP*.

**Wheat**

*Open Universiteit* (1992) and *Lövenstein et al*. (2000) mention as indicative values for wheat 1.5-2.5 kg grain *DM*.$m^{-3}$ *T*. With a harvest index *HI* of 0.40-0.50 this results in a *WP* of 3-6.25 kg *TDM*.$m^{-3}$ *T*. In Table 5.7 a maximum *DM* production of 5.8 kg.$m^{-3}$ *T* is presented and a grain yield of 2.56-2.76 kg *DM*.$m^{-3}$ *T*. This is close to or within the range presented above. From this we can conclude that the simulated $T_{wl}$ is in the correct order of magnitude. In *Doorenbos & Kassam* (1979) a *WP* of 0.8-1.0 kg grain.$m^{-3}$ *ET* for wheat is mentioned (12-15% moisture in grain; yield level 4-6 ton grain.$ha^{-1}$). *Tuong* (1999) mentions in his overview of some literature a range of 0.65-1.5 kg fresh grain.$m^{-3}$ *ET*. *Hussian et al.* (2003) give *WP*'s of 1.25-1.38 kg.m$^{-3}$ water consumed in India, and an average of 1.27-1.71 kg.m$^{-3}$ water diverted. The difference between the $WP_{ET}$ in Table 5.7 and the values from literature is mainly due to the yield level, and to the time before emergence and after maturity taken into account in the other studies (here *ET* from emergence to maturity). The estimated *WP*'s in the farmer fields (Table 5.8; lower yields) are lower than those in Table 5.7, but close to the values from literature and the *WP*'s obtained with remote sensing (Chapter 6). The $WP_T$ and $WP_{ET}$ in Table 5.7 can be considered the maximum that could be obtained in 2001/02 with emergence at Dec. 13.

**Table 5.7** Simulated *WP*'s of wheat, rice and cotton (kg.m$^{-3}$) for season 2001/02, Sirsa.

| Definition *WP*(2) | Wheat: irrigation schedule(1) | | Rice: farmer fields | | Cotton: irrigation schedule(1) | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 2 | 6 | O | L |
| Yield $DM/T_{wl}$ | 2.76 | 2.56 | 1.29 | 1.27 | 0.60 | 0.44 |
| Yield $DM/ET_{wl}$ | 2.22 | 2.10 | 0.80 | 0.75 | 0.49 | 0.35 |
| Yield $DM/I$ | 1.64 | 1.78 | 0.49 | 0.41 | 0.90 | 0.87 |
| Yield $FM/T_{wl}$ | 3.21 | 2.97 | 1.47 | 1.44 | 0.70 | 0.51 |
| Yield $FM/ET_{wl}$ | 2.58 | 2.44 | 0.91 | 0.85 | 0.58 | 0.41 |
| Yield $FM/I$ | 1.91 | 2.06 | 0.56 | 0.46 | 1.06 | 1.02 |
| $TDM/T_{wl}$ | 5.76 | 5.65 | 2.99 | 2.89 | 2.55 | 1.94 |
| $TDM/ET_{wl}$ | 4.63 | 4.64 | 1.85 | 1.70 | 2.10 | 1.56 |
| $TDM/I$ | 3.43 | 3.92 | 1.14 | 0.92 | 3.83 | 3.86 |
| Yield(2) *DM* ($10^3$ kg.ha$^{-1}$) | 6378 | 5526 | 7369 | 6247 | 2539 | 1432 |
| *TDM* ($10^3$ kg.ha$^{-1}$) | 13300 | 12218 | 17027 | 14186 | 10851 | 6377 |
| *T* (mm) | 231 | 216 | 569 | 491 | 426 | 328 |
| *ET* (mm) | 287 | 263 | 928 | 833 | 517 | 409 |
| *I* (mm) | 388 | 311 | 1489 | 1537 | 283 | 165 |

(1) wheat: schedule 1 and 2 are "0.7" and "0.5" in moisture experiment; Cotton: Schedule O and L are "optimum moisture" and "low moisture" in moisture experiment (Chapter 3); Rice: irrigation water from transplanting to maturity.

(2) wheat: 80% grain in *SO*, 14% moisture in grain; rice: 81% grain in *SO*, 12% moisture in grain: cotton: 44% seed cotton in *SO*, 15% moisture in seed cotton; $T_{wl}$/ $ET_{wl}$: from emergence/transplanting to maturity.

## Rice

In *Doorenbos & Kassam* (1979) a productivity of 0.7-1.1 kg grain.m$^{-3}$ *ET* is mentioned (15-20% moisture in grain; yield level 4-8 ton grain.ha$^{-1}$). *Tuong* (1999) found a range of 0.40-1.61 kg fresh grain.m$^{-3}$ *ET*. The $WP_{ET}$ in the farmer fields is mostly within this range. The average $WP_{ET}$ obtained with remote sensing (Chapter 6) is slightly lower than the average for the farmer fields. *Bouman & Tuong* (2000) give $WP_I$ of 0.2-0.4 kg grain.m$^{-3}$ in India. *Aslam & Prathapar* (2001) mention $WP_I$ of up to 1.0 kg wheat grain.m$^{-3}$ in Pakistan. Our data are within this range. *Lu et al.* (2002) mention a $WP_I$ of up to 16 kg grain.m$^{-3}$, but in these cases rainfall covers a much larger fraction of water needs. The low $WP_I$ of rice compared with wheat and cotton is due to the high percolation and seepage losses. *Bouman & Tuong* (2000) mention percolation losses of up to 50-80%. Theoretically, 150-250 mm of water is needed to saturate the top soil and establish a water layer, but in practice water evaporates, recharges groundwater and there is flow out of the field during field preparation (*Tuong,* 1999). The same author mentions a range of 350-1500 mm needed for land preparation. In pot experiments, without seepage and percolation, *WP*'s of up to 1.9 kg grain.$m^{-3}$ water inputs could be reached (*Bouman & Tuong*, 2000).

**Table 5.8** Estimated *WP* values of wheat, rice and cotton (kg.$m^{-3}$) on the farmer fields (2001/02, Sirsa).

| Definition WP[2] | Wheat | | Rice | | Cotton | |
|---|---|---|---|---|---|---|
| | Avg. | Range | Avg. | Range | Avg. | Range |
| yield $FM^{(1)}/T_a$ | 1.73 | 0.80-2.06 | 1.87 | 1.56-2.65 | 0.41 | 0.02-0.71 |
| yield $FM^{(1)}/ET_a$ | 1.28 | 0.26-1.60 | 1.13 | 0.82-2.10 | 0.33 | 0.01-0.58 |
| yield *FM*/irr | 1.32 | 0.35-2.93 | 0.63 | 0.50-0.84 | 0.59 | 0.05-1.65 |
| $TDM/T_a$ | 3.61 | 1.75-4.28 | 3.40 | 2.83-4.72 | 2.13 | 0.11-3.71 |
| $TDM/ET_a$ | 2.66 | 1.37-3.29 | 2.09 | 1.66-3.75 | 2.08 | 0.08-3.66 |
| *TDM*/irr | 2.73 | 0.77-5.85 | 1.15 | 0.90-1.51 | 3.02 | 0.32-6.86 |

(1) Wheat: 14% moisture in grain, rice: 16% moisture in grain; cotton: 15% moisture in seed cotton;
(2) Grain *FM* = measured grain fresh material (*FM*); *TDM* = measured total above ground dry matter; $T_a/ET_a$: from emergence/transplanting to maturity with measured *LAI*.

## Cotton

For cotton little information is available, but *Doorenbos & Kassam* (1979) mention a seed cotton production of 0.4 to 0.6 kg.$m^{-3}$ *ET* (10% moisture in seed cotton; yield level 3-4.6 ton seed cotton.$ha^{-1}$). *Droogers & Kite* (2001) mention *WP*'s of 0.21 to 0.54 kg seed cotton.$m^{-3}$ *T* for basin to field level, and of 0.16 to 0.39 kg seed cotton.$m^{-3}$ *ET*, also for basin to field level. The *WP*'s in Table 5.7 are somewhat above or in this range, but on the farmer fields lower *WP*'s are obtained. The average $WP_{ET}$ obtained with remote sensing (Chapter 6) is very similar to the average $WP_{ET}$ form the farmer fields in Table 5.8. The yield levels in SIC are clearly lower than the productions used by *Doorenbos & Kassam* (1979). There is a strong relation between the *WP* obtained and the *TDM* on the farmer fields ($R^2$=0.9).

The differences in $WP_T$ between the three crops are due to the differences in chemical composition and harvest index (*Tanner & Sinclair*, 1983). For $WP_{ET}$ also the fraction of *E* in *ET* is important. In the cases shown in Table 5.7 the fraction *E* in *ET* was about 0.20 for wheat and cotton, however, for rice it was around 0.40. In the farmer fields the fraction *E* in *ET* ranges from 0.22-0.34 for wheat, 0.43-0.49 for rice, and 0.16-0.38 for cotton. Irrigation need is strongly related to the *ET* of a crop. In SIC the rainfall is low, therefore a large part of the *ET* should be covered by irrigation. Extra water may also be needed for soil preparation. For wheat the farmers used 45-224 mm to prepare the field before sowing (average 116 mm). For rice the farmers used 104-157 mm to submerge the field shortly before transplanting.

The *WP* values in Table 5.7 are in most cases higher than the *WP* values found in literature. This is partly due to the fact that only $T_{wl}$ or $ET_{wl}$ from emergence/transplanting to maturity were used in the calculations in this chapter. To give an idea of the effect of a longer period, the $ET_{wl}$ from sowing to harvest for wheat was calculated, assuming that sowing took place a week before emergence, and harvest took place a week after maturity. This resulted in 2.31 kg wheat grain *FM*.$m^{-3}$ $ET_{wl}$ for irrigation schedules 1 and 2 in Table 5.8 (compare with 2.44-2.58). Especially the transpiration after maturity caused this decrease in *WP*. Secondly, the simulated potential and water-limited *WP*'s will normally be higher than the *WP*'s obtained on farmer fields, since the farmers experience yield reductions due to pests and diseases, nutrient limitations, etc. The effect of pests and diseases can vary enormously. A pest or disease that reduces leaf area from the beginning of de growing season, will reduce transpiration and final grain yield proportionally. In that case the $WP_T$ may still be close to the maximum. However, a pest or disease that reduces grain yield, but not the leaf area (thus *T*), will result in clearly lower yield per unit *T*. According to *Tanner & Sinclair* (1983) and *Van Keulen & Wolf* (1986) there are no strong indications for large differences in the *T* to assimilation ratio under different nutritional conditions. However, *Ritchie* (1983) and *Tuong* (1999) presents results that show an increased yield per unit *ET* with increased nitrate availability. These seemingly contradictory results may be due to the different definitions used: the first per unit *DM* produced, and the second per unit grain. The timing of nutrient shortage is important: nutrient shortage during grain filling results in lower assimilation rates and lower grain production, whereas the production of leaves and stems may not be affected much. *Ritchie* (1983) argues that the maximum *ET* is reached at a lower *LAI* than the maximum *DM* production. Thus, any nutrient application that increases *LAI* above the *LAI* for maximum *ET* up to the *LAI* for maximum *DM* production, will result in increased *WP*.

### 5.4.3 Deficit irrigation

When water supply is not sufficient to keep the actual or water-limited *T* ($T_a$ or $T_{wl}$) of a crop equal to $T_p$, the stomata in the leaves will partially close and *DM* production will decrease. When using "deficit" irrigation, not enough irrigation water is applied to keep $T_a$ equal to $T_p$. Generally, in SIC the available canal irrigation water is insufficient to cover crop needs completely.

Table 5.9 shows *WP* values for irrigation schedules varying in the level of deficit and the timing of the deficit. The $WP_T$ and $WP_{ET}$ remain more or less stable, irrespective of the irrigation schedule, as expected (except for "opt.-20% beginning season" and $T_{wl}/T_p$=0.8). The small differences are due to differences in *HI* (0.47-0.49). It appears that assimilation and *T* are affected approximately to the same extent (*Tanner & Sinclair*, 1983; *Van Keulen & Wolf*, 1986; *Penning de Vries et al.,* 1989). Consequently, the amount of *DM* produced per unit *T* remains more or less constant. The fraction *E* is relatively small and rather stable (0.18-0.21 of $ET_{wl}$), therefore, $WP_{ET}$ also hardly changes.

**Table 5.9** Simulated *WP* of wheat (kg.m$^{-3}$) and grain yield (10$^3$ kg.ha$^{-1}$) for 2 irrigation schedules (2001/02, soil experimental station Sirsa, emergence date 13/12).

| | Grain $FM/T_{wl}$ (2) | | Grain $FM/ET_{wl}$ (2) | | Grain $FM/I$ | | Grain kg *FM* | |
|---|---|---|---|---|---|---|---|---|
| Irrigation schedule | $T_{wl}/T_p$ >0.95 (1) | $T_{wl}/T_p$ >0.8 | $T_{wl}/T_p$ >0.95 | $T_{wl}/T_p$ >0.8 | $T_{wl}/T_p$ >0.95 | $T_{wl}/T_p$ >0.8 | $T_{wl}/T_p$ >0.95 | $T_{wl}/T_p$ >0.8 |
| optimum schedule | 3.22 | 3.18 | 2.54 | 2.62 | 2.62 | 2.87 | 7.9 | 6.9 |
| opt. -20% all irr | 3.13 | 3.09 | 2.46 | 2.53 | 3.00 | 3.31 | 7.2 | 6.3 |
| opt. -20% beginning season | 3.14 | 2.62 | 2.49 | 2.07 | 2.81 | 2.46 | 6.8 | 4.8 (3) |
| opt. -20% end season | 3.22 | 3.17 | 2.54 | 2.61 | 3.28 | 3.55 | 7.9 | 6.9 |

(1) irrigation back to field capacity when $T_{wl}/T_p$ = 0.95 or 0.80;

(2) 80% grain in *SO*, 14% moisture in grain; $T_{wl}$ / $ET_{wl}$: from emergence to maturity;

(3) *HI* = 0.42, compared with 0.48 for other treatments.

The yield level, however, does change with the irrigation schedule and the timing of water stress. *Hussain et al.* (2003) also observed this. Consequently, the $WP_I$ does change with the irrigation schedule. When less irrigation water is applied, the rainfall covers a larger fraction of the $(E)T$. Consequently, $WP_I$ increases with decreasing irrigation amounts. How much $WP_I$ increases depends on the timing of the water stress. Light water stress at the end of the growing season results in less yield depression, compared with a constant mild water stress during the whole growing season. Many crops are less sensitive to water stress during the ripening stage. The low *WP* values for the runs with water stress at the beginning of the growing season are due to the poor *LAI* development and, consequently, lower yield.

### 5.4.4 Variation between years

For the same crop and cultivar, different *WP*'s can be obtained in different years and environments. This is mainly due to the difference in water vapour concentration between the atmosphere and inside the stomata. When the relative humidity of the atmosphere is lower, and the leaf temperature is higher, more water will be lost (*Tanner & Sinclair*, 1983), and *WP* will be lower.

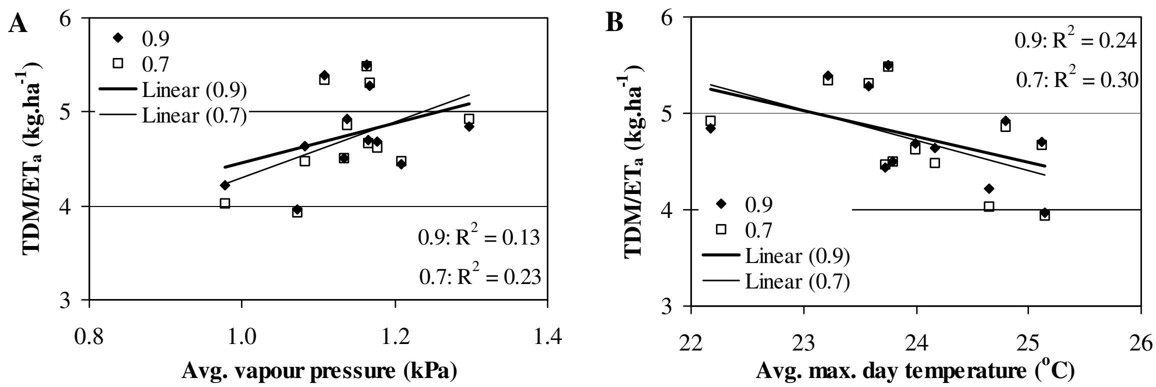


**Figure 5.10** Relation between $WP_{ET}$ and the average vapour pressure (A) or average maximum day temperature (B) during the growing season (emergence date 17/11, "optimum" irrigation schedule for $T_{wl}/T_p > 0.9$ or 0.7).

Table 5.10 shows the *WP* values for 2 irrigation schedules. The difference within years is small (Par. 5.4.2). However, there is considerable variation in *WP* values between years. No clear relations were found between the individual climatic input data and the *WP* values. However, some weak relations exist between the *WP* and the average vapour pressure and average maximum day temperature during the growing season (Fig. 5.10). When the average maximum day temperature is higher, the *WP* is generally lower. When the average vapour pressure is higher, higher *WP*'s can be obtained. Low vapour pressure often coincided with low rainfall ($R^2$=0.24) and especially with high avg. maximum day temperatures ($R^2$=0.72). Consequently, in the years with the lowest rainfall, the evaporative demand is highest.

**Table 5.10** Simulated water productivity of wheat ($kg.m^{-3}$) and grain yield ($10^3$ $kg.ha^{-1}$) for 2 irrigation schedules and several years (soil experimental station Sirsa, emergence date 17/11).

| Year | Grain $FM/T_{wl}$ (2) | | Grain $FM/ET_{wl}$ (2) | | Grain $FM/I$ | | Grain $FM$ | |
|---|---|---|---|---|---|---|---|---|
| | $T_{wl}/T_p$ >0.9 (1) | $T_{wl}/T_p$ >0.7 | $T_{wl}/T_p$ >0.9 | $T_{wl}/T_p$ >0.7 | $T_{wl}/T_p$ >0.9 | $T_{wl}/T_p$ >0.7 | $T_{wl}/T_p$ >0.9 | $T_{wl}/T_p$ >0.7 |
| 1991 | 4.31 | 4.26 | 3.32 | 3.26 | 5.16 | 3.89 | 11.6 | 10.4 |
| 1992 | 3.81 | 3.59 | 2.95 | 2.83 | 3.62 | 4.63 | 10.5 | 8.5 |
| 1993 | 3.63 | 3.36 | 2.83 | 2.67 | 3.07 | 3.17 | 10.3 | 8.3 |
| 1994 | 3.30 | 3.15 | 2.60 | 2.52 | 3.07 | 3.08 | 9.3 | 8.2 |
| 1995 | 4.80 | 4.69 | 3.59 | 3.51 | 5.00 | 5.36 | 11.3 | 10.5 |
| 1996 | 3.88 | 3.73 | 2.98 | 2.90 | 4.37 | 5.02 | 10.4 | 9.2 |
| 1997 | 3.97 | 3.93 | 3.11 | 3.13 | 4.10 | 6.10 | 11.7 | 10.7 |
| 1998 | 3.99 | 3.96 | 3.02 | 3.04 | 4.55 | 5.75 | 10.7 | 9.9 |
| 1999 | 3.42 | 3.34 | 2.68 | 2.63 | 3.00 | 3.13 | 9.9 | 9.1 |
| 2000 | 3.65 | 3.52 | 2.87 | 2.82 | 3.56 | 3.17 | 10.5 | 9.1 |
| 2001 | 3.41 | 3.29 | 2.79 | 2.70 | 3.61 | 3.46 | 10.6 | 9.3 |
| 2002 | 3.74 | 3.66 | 2.95 | 2.91 | 3.29 | 3.22 | 9.4 | 8.2 |
| Average | 3.83 | 3.71 | 2.98 | 2.91 | 3.87 | 4.17 | 10.5 | 9.3 |

(1) irrigation back to field capacity when $T_{wl} / T_p$ = 0.90 or 0.70;

(2) 80% grain in *SO*, 14% moisture in grain; $T_{wl} / ET_{wl}$: from emergence to maturity.

In years with a lower average day temperature, the growing season was a little longer (crop development is determined by temperature, *TSUM*s). This longer growing season resulted in a higher *DM* production. As a result of climate change temperatures are expected to increase (Chapter 9). From the above analysis, we can conclude that this will probably result in lower maximum $WP_T$ and $WP_{ET}$ (when the vapour pressure remains the same).

### 5.4.5 Sowing date

**Table 5.11** Simulated *WP* of wheat ($kg.m^{-3}$) for different sowing dates (2001/02, soil of experimental station Sirsa; optimum schedule with $T_{wl} / T_p > 0.9$ (1)).

| Definition *WP* | Sowing date (2001) | | | |
|---|---|---|---|---|
| | Nov. 10 | Nov. 20 | Nov. 30 | Dec. 10 |
| Grain $FM/T_{wl}$ (2) | 3.75 | 3.55 | 3.36 | 3.12 |
| Grain $FM/ET_{wl}$ (2) | 2.95 | 2.79 | 2.64 | 2.45 |
| Grain $FM/I$ (1) | 3.35 | 3.21 | 3.05 | 2.78 |
| $TDM/T_{wl}$ | 5.96 | 5.82 | 5.75 | 5.49 |
| $TDM/ET_{wl}$ | 4.69 | 4.57 | 4.53 | 4.31 |
| $TDM/I$ | 5.33 | 5.26 | 5.22 | 4.89 |
| Grain *FM* ($10^3$ $kg.ha^{-1}$) | 9.4 | 9.0 | 8.3 | 7.4 |
| *TDM* ($10^3$ $kg.ha^{-1}$) | 15.0 | 14.7 | 14.3 | 13.0 |
| *T* (mm) | 251 | 253 | 248 | 237 |
| *ET* (mm) | 319 | 322 | 315 | 302 |
| *I* (mm) | 281 | 280 | 273 | 266 |
| Days E-M | 142 | 135 | 126 | 118 |

(1) irrigation back to field capacity when $T_{wl} / T_p$ = 0.90; *I* = opt. irrigation amount calculated by SWAP;

(2) 80% grain in *SO*, 14% moisture in grain; $T_{wl} / ET_{wl}$: from emergence to maturity.

Sowing date can have an effect on *WP*, since the conditions during the growing season may change with the sowing date (Table 5.11). With later sowing the yield decreases. *Aggarwal et* *al.* (2000) and *Hussain et al.* (2003) also mentioned that early sowing results in higher yields. Also *WP* decreases when wheat is sown later. The decrease in grain *FM* per unit water consumed or applied is partly due to the relatively shorter period between flowering and maturity with later sowing. This results in lower harvest indices with late sowing (54% grain for Nov. 10; 49% grain for Dec. 10), and consequently lower grain production per unit (*E*)*T*. Besides this, the yield decreases relatively faster than the (*E*)*T* or the irrigation need. When the same level of water stress is applied, early sowing results in higher *WP* and higher yields, but also in higher absolute amounts of irrigation water applied.

### 5.4.6 Soil type

Table 5.12 shows some results of a comparison of *WP*'s for two soils. As initial conditions complete saturation 10 days before emergence was used.

**Table 5.12** Simulated *WP* of wheat (kg.m$^{-3}$) on 2 soils. Simulated with emergence on November 23, 2001, and with completely saturated soil 10 days before emergence.

| | Field 5 | | Field 16 | |
|---|---|---|---|---|
| | $T_{wl}/T_p$ >0.9[(1)] | $T_{wl}/T_p$ >0.7 | $T_{wl}/T_p$ >0.9 | $T_{wl}/T_p$ >0.7 |
| Grain $FM/T_{wl}$[(2)] | 3.72 | 3.68 | 3.69 | 3.58 |
| Grain $FM/ET_{wl}$[(2)] | 3.15 | 3.18 | 2.90 | 2.84 |
| Grain $FM/I$[(1)] | 4.10 | | 3.93 | 4.92 |
| Grain *FM* ([(1)]$10^3$ kg.ha$^{-1}$) | 9.5 | 9.5 | 9.5 | 8.7 |
| *TDM* ([(1)]$10^3$ kg.ha$^{-1}$) | 15.3 | 15.4 | 15.1 | 14.0 |
| T (mm) | 254 | 259 | 257 | 242 |
| *ET* (mm) | 300 | 300 | 327 | 305 |
| *I* (mm) | 231 | 0 | 241 | 176 |
| Texture | Loam-Clay loam | | Sandy loam-Loamy sand | |
| *AWC*[(3)] 0-30 cm | 0.33 | | 0.18 | |
| *AWC* 30-120 cm | 0.49 | | 0.14 | |
| $\theta_{sat}$ 0-30 cm | 0.50 | | 0.31 | |
| $\theta_{sat}$ 30-120 cm | 0.58 | | 0.32 | |
| $K_{sat}$ 0-30 cm (cm.d-1) | 2.63 | | 101.7 | |
| $K_{sat}$ 30-120 cm (cm.d-1) | 1.87 | | 120.9 | |

(1) irrigation back to field capacity when $T_{wl}/T_p$ = 0.90 or 0.70; *I*=opt. irrigation amount calculated by SWAP;
(2) 80% grain in *SO*, 14% moisture in fresh grain; $T_{wl}$ / $ET_{wl}$: from emergence to maturity;
(3) *AWC* defined as the fraction water between pF2.0 and pF4.2.

As expected, the soil type has no or hardly any effect on the $WP_T$ (Par. 5.4.2). However, soil type may affect E, since in some soils the top soil dries out faster than in others. In the simulations in Table 5.12, the fraction *E* of $ET_{wl}$ was lower for field 5 (0.15) than for field 16 (0.21). The soil in field 5 has a much higher water holding capacity. Therefore, less frequent irrigations are needed, affecting the number of days with wet soil surface. *Gupta et al.* (2002) observed some variation in the percentage *ET* of total water requirements. It was lowest for a sandy loam (33%) and highest for (sandy) clay loam (44%). When infiltration rates are high (as in field 16), irrigation water does not remain long on the soil surface. However, when overirrigating takes place, the extra amount percolates fast. In field 16 more frequent and smaller irrigations are needed than in field 5. Under these conditions it may be more difficult to avoid underirrigation or overirrigation. Not included here are the possible differences in minimum amounts of water needed for soil preparation.

### 5.4.7 Irrigation water quality

The equation of Maas and Hoffman to express the tolerance of crops to salt, as used in SWAP/WOFOST, assumes that crops respond primarily to the osmotic potential of the soil solution. Other chemical effects of the presence of salts, such as nutritional disorders and toxic effects, are generally secondary in importance (*Tanji,* 1990) and not considered here. The hypothesis that seems to fit observations best asserts that excess salt reduces plant growth, primarily because it increases the energy that the plant must expend to acquire water from the soil and make the biochemical adjustments necessary to survive (*Tanji,* 1990; *Penning de Vries,* 1975; *Yeo,* 1983). The response to salinity varies with many factors, including climate, soil conditions, agronomic practices, irrigation management, crop variety, stage of growth, and salt composition (*Tanji,* 1990).

Long term simulations were performed with different irrigation water qualities (not shown here). As expected $WP_T$ and $WP_{ET}$ are hardly affected by the salt levels in the irrigation water, since the effect of salt is the same as that of water stress.

## 5.5 Discussion and conclusions

### 5.5.1 Methodology and recommendations for further research

WOFOST includes many aspects of crop growth, however some are not included such as redistribution of carbohydrates, nutrient stress and pest and disease effects. The combination of SWAP/WOFOST has a clear advantage over the simple crop growth module that may also be used in SWAP, since the interactions between soil water and solute transport and crop development and feedback through *LAI* and *ET* are included. Once calibrated, the crop files can be used for varying levels of water and salt stress, sowing dates, etc. Hence, SWAP/WOFOST is a useful tool to study the effect of various conditions and management options on water productivity. This is not possible with the simple crop module. A disadvantage is the larger volume of data needed for calibration. However, after calibration and validation it can be used in a wide range of situations.

A translation of the water/salt-limited productions simulated with SWAP/WOFOST is needed to get estimates of actual productions, due to nutrient stress and/or yield reductions by pests and diseases. A statistical analysis as used here can be useful to analyse the yield gap, but more data from more years are needed. The selected farmers fields were not distributed homogeneously over the whole region and the number of comparisons (farmer fields) was too limited to derive relations that are valid for entire SIC and for several years. Apparently it was difficult the include the variation in the fields during the field measurements (see difference between *DM*-partitioning samples (3-replicates) and final sampling (5 replicates). This further complicated the comparison between the water-limited yields and the actual yields of the farmer fields.

Although a large amount of data was collected, calibration of the crop files was regularly complicated by limited information. Insufficient information was available to calibrate for salt stress, although salt stress is a potential problem in a large part of the region. Since the crop cultivars were not known to be very sensitive or insensitive to salt stress, general data were used to simulate salt stress. Correct estimation of *T* and *E* is essential to get reliable *WP* estimates. However, no reliable A-pan measurements or lysimeter data are available to check the estimates of $ET_a$ obtained with the simulation model and remote sensing. The $ET_a$ values are in the correct order of magnitude, but there might be some over- or under-estimation.

### 5.5.2 Management options, water productivity and yield level

The level of deficit irrigation hardly affects the $WP_T$ and $WP_{ET}$, but it does affect yield level. Depending on the timing of irrigations and thus water stress, with the same amount of irrigation water available, a considerable variation in water-limited yield can be obtained. As a consequence, $WP_{Irr}$ can vary, and investments in measures that allow adjusting the timing of irrigations may be profitable. Many farmers in the region have access to groundwater. If this groundwater is of sufficient quality it gives the farmers the possibility to irrigate when needed. This access to groundwater also increases the reliability of water supply, and may reduce overirrigation.

*WP* values can vary considerably over the years. In years with below average rainfall often the evaporative demand is above average. Hence, the demand for irrigation in these years is increased due to the low rainfall, but also due to the higher crop needs. The *WP*'s in these years are relatively low. For good management of the crop and to avoid severe water stress in the most sensitive crop stages, the farmers need good estimates of the potential *ET*. In other words, reliable and local weather data are needed on the short term, e.g. on a weekly basis. The weather data from the experimental station in Sirsa contained a lot of missing data and some data were unreliable. It is not possible to provide one fixed irrigation scheme that is valid for all years. For optimum use of water, constant adjustment to the climatic conditions at that moment is needed.

Early sowing results in higher potential wheat yields and *WP* values. However, the absolute amounts of water needed also increase with earlier sowing. With earlier sowing only less water per unit production is needed.

The soil type does not affect the $WP_T$, but it does affect the level of $WP_{ET}$ and $WP_I$. On coarser soils generally lower $WP_{ET}$ and $WP_I$ will be obtained due to the higher fraction of *E* in *ET*, the higher risk of percolation, and the higher number of irrigations needed.

There are large differences in *WP* values between crops due to the contribution of *E* to *ET*, the harvest index and the chemical composition. The maximum $WP_T$ for rice and wheat does not differ too much (similar chemical composition and HI), but the maximum $WP_{ET}$ for irrigated rice will always be much lower than for wheat, due to the large *E* losses from the ponding water in rice.

Management options, such as earlier sowing, and good nutrient and pest and disease management can increase water productivities, especially in wheat. These management options will increase production, but will not decrease water use. Only irrigation scheduling based on more detailed information about evaporative demand may result in some reduction of water use, as compared to the current situation.

At present, there is still a yield gap between the actual yields obtained by the farmers and the water/salt-limited yield. This gap may be bridged by better nutrient management and better control of pests and diseases (*Dhindwal et al*., 2002). As a result the $WP_T$ and $WP_{ET}$ may increase. However, when the actual yields are close to the water-limited yields, as was observed for rice and cotton in the farmer fields, increased productions (up to potential productions) can only be obtained with the same or higher absolute amounts of water, and $WP_T$ and $WP_{ET}$ will not increase further. This was concluded also by *Bouman et al.* (2002). In this last case, making more water available for nature, industry and domestic users will result in lower agricultural production, and a choice has to be made between the need for more food production and the amount of water available for other than agricultural uses.