Calibration and Validation of the STICS Crop Model for Managing Wheat Irrigation in the Semi-Arid Marrakech/Al Haouz Plain

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CALIBRATION AND VALIDATION OF THE STICS CROP MODEL FOR MANAGING WHEAT IRRIGATION IN THE SEMI-ARID MARRAKECH/AL HAOUZ PLAIN

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الخلاصـة

يتناول الجزء الأول من البحث معايرة نموذج STICS، وبيان صلاحية مراحل نموّ محصول القمح (الحبوب والتبن) في تلك المعايرة تحت الظروف المناخية للمملكة الغربية. ولتحقيق ذلك استعملت مدخلات النمو لمحصول القمح تحت الري في منطقة الحوز ذات المناخ شبه الجاف بمراكش.

وقد اعتمدت المعايرة على المدة الحرارية للمراحل الأربع التي تتحكم في مساحة الأوراق، وكذلك المدة الحرارية بين الإنبات وبداية امتلاء الحب. وقد تمّت المعايرة باستعمال بيانات من ثلاثة حقول قمح زُرعت خلال موسم ٢٠٠٢-٢٠٠٣ م. كما تم التحقّق من صلاحية النموذج باستعمال بيانات من ستـة حقول زُرعت خلال موسم ٢٠٠٣-٢٠٠٤ م.

وبيّنت النتائج ملاءَمة عالية للنموذج STICS عند استخدام تلك المدخلات كما بيّنت النتائج أن النباتات قد تأثرت سلباً نتيجة لنقص النيتروجين.

وبيّن الجزءالثاني من البحث إمكانية استعمال النموذج STICS في حقول جدولة الري عند افتراض عدم محدودية النيتروجين، آخذاً بالاعتبار الحد الحرج للعطش. كما أظهرت النتائج علاقة بدرجة مقبولة بين المحصول من جهة وكمية ماء الري وبرمجة الري من جهة أخرى. وتبيّن أن محصول عام ٢٠٠٣-٢٠٠٤ يمكن الحصول عليه بترشيد الري الحسب النموذج، وذلك بكمية من ماء الري تقل بمقدار ٧٠ ملم و ٤٠ ملم علي التوالي عند الحرث المبكر والمتأخر.

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ABSTRACT

In the first part of this work, the shoot growth module and grain yield of the STICS crop model were calibrated and validated by using field data which was collected from irrigated winter wheat fields in the Haouz plain near Marrakech. The calibration was performed on the thermal units between the four phenological stages that control the dynamics of leaf area index and the thermal unit between emergence and the beginning of grain filling. The plant phenology was calibrated for three fields monitored during the 2002/03 season. Evaluation of the grain yields and the temporal evolution of leaf area index were done for six validation fields during 2003/04. The results showed the significant accuracy of the model in simulating these variables, and also indicated that the plants mainly suffered from lack of nitrogen.

The results in the second part show the potential of crop modeling to schedule irrigation water, on the assumption that the plants were growing under optimal conditions of fertilization. In this case, the model was used to manage the time of irrigation according to a threshold for water deficit. Various simulations displayed logical trends in the relationship between the grain yield and both the amount and timing of irrigation water. These results were finally compared with those obtained from real irrigation practices. For the particular climate of 2003/04, the comparison showed that 70 mm and 40 mm of water could be saved in case of early and late sowing, respectively.

Key words: STICS crop model, calibration, validation, wheat, grain yield, semi-arid, irrigation water

CALIBRATION AND VALIDATION OF THE STICS CROP MODEL FOR MANAGING WHEAT IRRIGATION IN THE SEMI-ARID MARRAKECH/AL HAOUZ PLAIN

1. INTRODUCTION

In Morocco, agriculture and agro-industry are the principal activities of the majority of the population. Cereals are dominant and covered 59% of the cultivated area during 1990–2000. A significant part of this area is located in the semi arid zones like the Haouz plain that surrounds the city of Marrakech (centre of Morocco) [1]. In these areas, particular attention should be paid to managing irrigation water to ensure sustainable development.

In the Haouz plain, wheat is one of the dominant crops, along with olive and orange orchards. Water supplies are scarce and the availability of water is one of the main factors that control plant growth and grain yield. Indeed, the reference evapotranspiration is around 1600 mm per year, according to FAO estimates [2]. This value is very large as compared with prevailing average rainfall, which is about 240 mm. It is known that wheat is very sensitive to water stress. Thus, it needs frequent irrigation to attain its potential growth and grain yield [3, 4].

Because of the shortage of rainfall and its irregular distribution during the wheat growing season in the Haouz plain, farmers practice irrigation as the ultimate way to avoid water stress in case of droughts. On several irrigated areas, the ORMVAH regional public agency (*Office Régional de Mise en Valeur Agricole du Haouz*) is in charge of dam water distribution, in collaboration with farmers associations. Generally, they distribute the water according to a predetermined schedule during the growing season, with the same quantity in each irrigation. The number of irrigations and the total amount of applied water depend on the dams' water level. The irrigation schedule is predetermined at the beginning of the growing season regardless of the actual climate and agricultural practices. Therefore, improper quantities of water are usually delivered; thus, there is an urgent need to improve the management of irrigation water for cereal crops. In this context, crop modeling can help to save water.

Crop models have the capability to predict crop development and grain yield as influenced by the climatic conditions, soil characteristics, and agricultural practices. Modeling is becoming more and more efficient tools in the management of water resources [5]. Models could provide quantitative estimates of grain yield under different environmental conditions, as well as simulation of water and nutrients balance. They may also be used to test the crop response to environmental stresses, *e.g.* droughts, in complement with field practices [5, 6].

There are many crop models in the literature. Some are designed for particular crops, *e.g.* for wheat, ARCWHEAT [7] and CERES-Wheat [8], while others are generic models, *e.g.* EPIC [9], DAISY [10], STICS [11, 12, 13]. Amongst them, the STICS (*Simulateur mulTIdisciplinaire pour les Cultures Standard*) crop model was developed at the National Agronomic Research Institute (INRA, France) to simulate the processes associated with plant growth and senescence at the field scale and on a daily basis. The validation of STICS was commenced in several studies for different climates: under temperate conditions in France [12], under semi-arid conditions in Mexico [14, 15] and Morocco [16]. These previous works have shown that the model simulates accurately the water balance when the leaf area index (LAI) is correctly estimated.

In this work, the STICS model was used as a simulation tool in an attempt to explain grain yield losses caused by lack of irrigation and fertilization practices in the test sites of the Haouz plain. The main objectives were: (1) to calibrate and validate the shoot growth module of STICS against data collected in the Haouz plain; and (2) to evaluate how the STICS model can be used in scheduling irrigation water in semi-arid region of Morocco.

2. MATERIALS

2.1. Region of Interest

The experimental site is located in the Haouz semi arid region in the center of Morocco, 40 km East of Marrakech city. It is an irrigated area managed by the ORMVAH since the year 1999. The area covers 2800 ha and is almost flat. The dominant crops are cereals, mainly durum and bread wheats. The wheat is generally sown between mid November and mid January, depending on climatic conditions and the start of the rainfall season.

In this irrigated area, ORMVAH manages the distribution of water starting from December through May. Frequency and amount of water of each irrigation are predetermined depending on the dam water level. Flood irrigation technique is mostly used. Soil types are rather homogeneous, poor in organic matter (<2%), with a fine texture (dominated by clay).

2.2. Field experiments

Field experiments were conducted in 2002/03 and 2003/04 seasons. Locations of the experimental sites are indicated in Figure 1. The first set of data was collected during the first season from the three fields referred to as C1, C2, and C3. It was used to calibrate the shoot growth module and grain yield of the STICS model. During the second season, a second set of data was collected from six fields referred to as V1 to V6 to validate the model. All fields were cropped with durum wheat variety (*Karim*), which has relatively short life cycle. This variety is suitable for semi-arid conditions and commonly used in the Marrakech–Haouz plain (ORMVAH technical documentation, [1]).
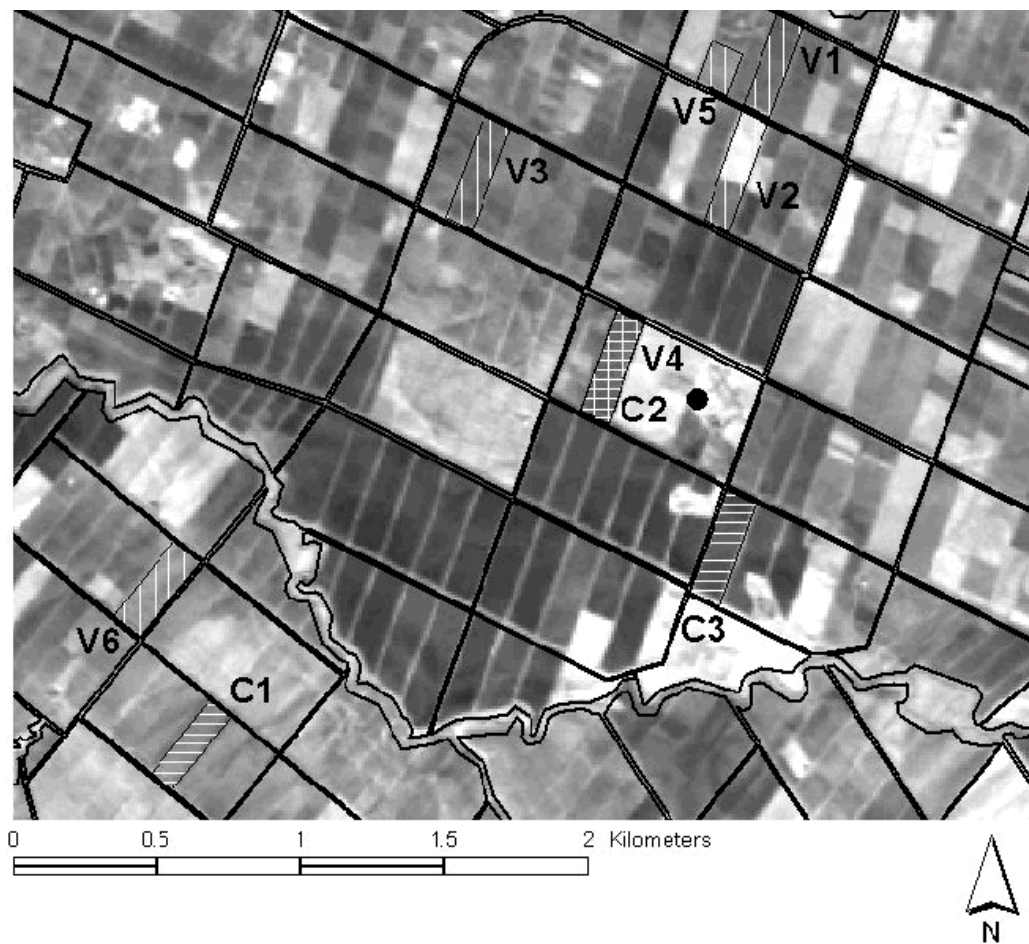

Figure 1. Location of the wheat fields under study during 2002/2003 and 2003/2004 season in the Haouz plain, Marrakech, Morocco. The calibration fields (2002/2003) are referred to as C1, C2, and C3 and the validation fields (2003/2004) are referred to as V1 to V6. The dot shows the location of the meteorological station.

The studied fields were irrigated by using concrete canals that carry water from the main canal to the regularly irrigated units, which include six fields of 4 ha each (see Figure 1). Table 1 summarizes the sowing and the irrigation dates of the studied fields. The fields were irrigated three times during both seasons, except C3 which was irrigated six times. According to the ORMVAH irrigation water scheduling, the applied amount of water was about 30 mm and 60 mm each time during the 2002/03 and 2003/04 winter wheat seasons, respectively.

The validation fields varied in their cultivation practices in terms of fertilization and seeding rate (Table 2), depending essentially on the farmers' choices. Fertilization depends on the economical capability of the owner, the experience of the manager and environmental conditions. In particular, the fields are more probably fertilized in case of good rainfall. The fertilizer NPK (14-28-14) was used in the studied fields. Nitrogen supply was either null (V1, V3, V5 fields) or low (50 or 100 kg/ha) at sowing time on the V2, V4, and V6 fields. Seeding rate ranged from 100 to 150 kg/ha. For the calibration fields, the seeding rate was always 150 kg/ha and no nitrogen fertilizer was added, except on the C3 field where 100 kg/ha of nitrogen was applied on April 8, 2003 which coincided with the start of the grain filling stage, although it might be more proper if nitrogen were applied at the stage of tillering. Since the cultivation practices affect the development, growth and grain yield, each field had its appropriate set of data, describing these practices, that will be used in calibration and validation.

The leaf area index (LAI) and grain yield were measured as described in [17] and [18], mainly for the 2002/03 season. The LAI was measured on a weekly basis. It was derived from reflectance measurements [19, 20] for the 2002/03 season, and retrieved through hemispherical digital photography [21, 22] for the 2003/04 season.

At the end of May for both seasons, grain maturity was reached and final grain yield was visually estimated by the ORMVAH specialist technicians (with an error of less than 0.5 t/ha). This technique is used by ORMVAH to get cereal grain yields in the whole Haouz plain (ORMVAH technical documentation, [1]). During 2003/04 season, an additional protocol allowing measurement of this variable as described by [23] was used. In each of the six validation fields, the plant and ear densities were recorded in four quadrates (*i.e.* area of $0.25m^2 = 0.5\ m \times 0.5\ m$) selected randomly. From each quadrate, subsamples were used to measure the number and weight of grains per ears of 25 plants selected randomly. This allowed to estimate the average and standard deviation of grain yield of the validation fields.

Table 1. Dates of Sowing and Irrigation Events of Both Calibration and Validation Fields

	Field	Sowing date	Irrigation dates					
			1st irrig.	2nd irrig.	3rd irrig.	4th irrig.	5th irrig.	6th irrig.
Calibration fields	C1	Dec-17-02	Jan-29-03	Feb-21-03	Apr-14-03			
	C2	Dec-23-02	Jan-23-03	Feb-22-03	Mar-20-03			
	C3	Jan-11-03	Feb-1-03	Feb-21-03	Mar-14-03	Mar-24-03	Apr-7-03	Apr-24-03
Validation fields	V1	Nov-21-03	Jan-16-04	Feb-17-04	Mar-28-04			
	V2	Nov-21-03	Jan-20-04	Feb-23-04	Apr-1-04			
	V3	Dec-15-03	Jan-20-04	Feb-15-04	Mar-17-04			
	V4	Dec-19-03	Jan-18-04	Feb-24-04	Apr-21-04			
	V5	Dec-20-03	Jan-16-04	Feb-16-04	Mar-26-04			
	V6	Dec-24-03	Jan-26-04	Feb-21-04	Mar-27-04			

Table 2. Date of Fertilization, Quantity of Fertilizer and the Seeding Rate of Validation Fields

Field	Nitrogen fertilizer[*]		Seeding rate
	Date	Quantity (kg/ha)	(kg/ha)
V1	-	-	100
V2	21/11/2003	50	150
V3	-	-	150
V4	18/12/2003	100	100
V5	-	-	100
V6	24/12/2003	50	140

[*] NPK (14-28-14) was the fertilizer type used

2.3. Climate

Climatic data were measured by a meteorological station installed in the studied zone. Figure 2 shows the daily temporal evolution of average air temperature, solar radiation, and precipitation. It also shows the reference evapotranspiration, calculated for well-watered grass, according to the FAO–Penman–Monteith equation [24] during the two seasons of study. The climate is basically of the semi-arid continental type. It is characterized by: (1) low temperature at the beginning of the cropping season with an average of 5°C for January and February; (2) high temperature in spring, during the grain filling, *e.g.* an average of 33°C between May 10 and 27; (3) low and irregular rainfall, with an accumulative amount around 200 mm between December and May for both seasons; (4) high water demand, with an accumulated reference evapotranspiration value around 600 mm between December 17, 2002 and May 27, 2003, and 530 mm in the same period during 2003/04.
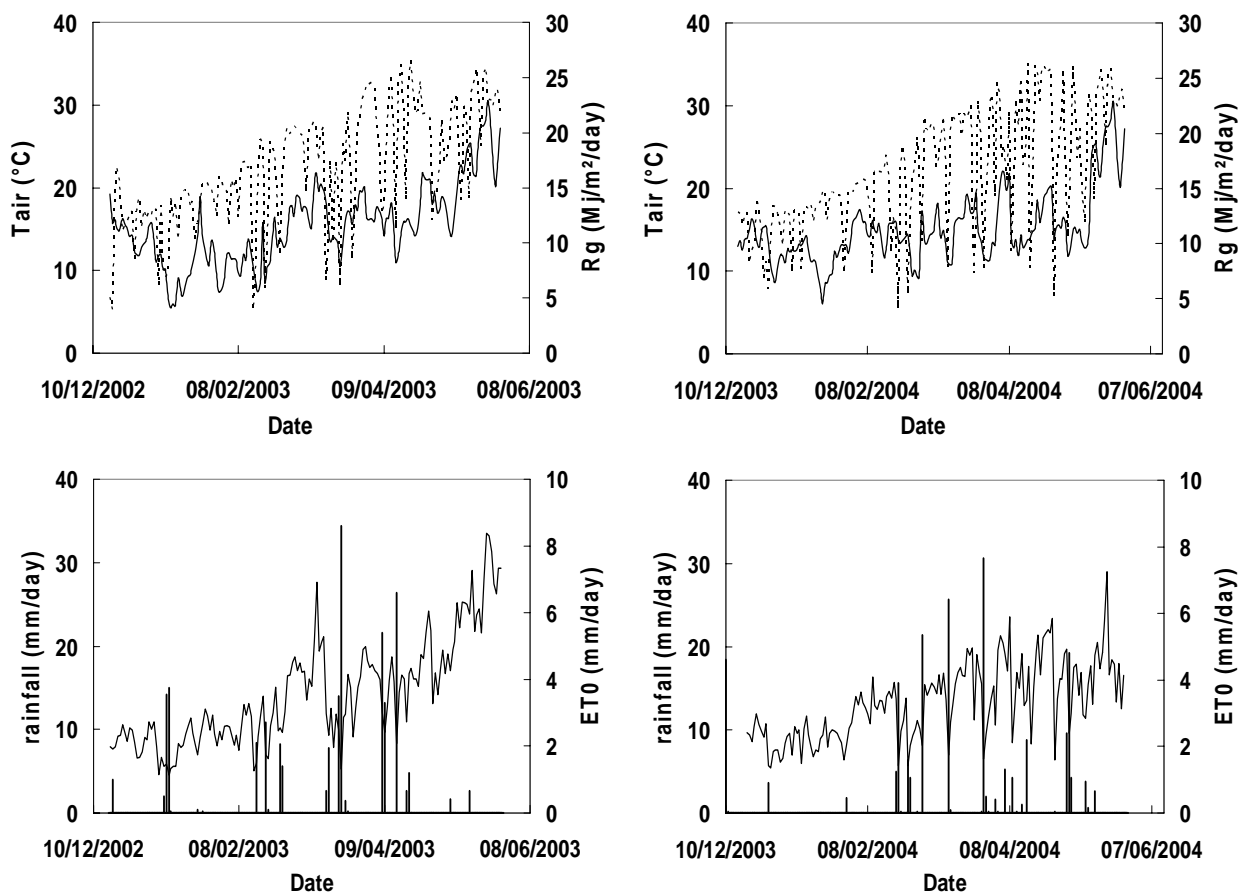

Figure 2. Climatic variations during the 2002/03 and 2003/04 experiments. In the top Figures, the dotted lines represent the solar radiation and the solid lines show the daily average air temperature. In the lower Figures, the vertical bars represent the daily accumulated value of rainfall and the solid lines show the calculated potential evapotranspiration.

3. CALIBRATION AND VALIDATION OF THE STICS CROP MODEL

The theory and parameterization of the STICS model have been described in [11, 12], and its sensitivity analysis has been performed by [25]. The latest version (version 5.0) used here was presented in [13]. After the determination of the parameters common to all studied fields, a specific analysis was done for both the calibration (C1 to C3, 2002/03 season) and the validation (V1 to V6, 2003/04 season) fields.

3.1. STICS Basic Parameters

The input parameters of STICS are grouped into four classes: crop management, climate, soil, and plant characteristics. All parameters of the model were kept at their standard values, which were furnished by the 5.0 version of the software [13] with the exception of some main parameters. These parameters were pertinent to the studied fields, those include the sowing dates, and amount and time of irrigation and fertilizer.

In addition, the STICS model requires daily values of the following climatic variables: solar radiation; maximum and minimum air temperature; wind speed; and precipitation. These data were derived from the values recorded half-hourly at the meteorological station installed in the vicinity of the studied fields.

Three soil-layers (0−15 cm, 15−45 cm, and 45−95 cm) with the same permanent hydrodynamic parameters (water content at field capacity, water content at wilting point, and bulk density) were considered. Water content at field capacity and at wilting point (around 0.33 m^3/m^3 and 0.17 m^3/m^3, respectively) was deduced from soil textural analysis using the model proposed by [26]. These values are in accordance with those proposed by [27] and [2] for clay loamy soil. They were also checked against the extreme values observed on gravimetric measurements. The bulk density, around 1.4 g/cm^3, was measured at the field.

All plant parameters were kept at their standard values for wheat, except: (1) the maximum grain number and the maximum weight of 1000 grains that were fixed to 20000 grains/m² and 40g, respectively, as given in SONACOS (*Société Nationale de commercialisation de Semences*) documentations for the *Karim* variety [28]; (2) a set of parameters that control the LAI temporal evolution; and (3) the thermal units between emergence and the beginning of the grain filling stage. The last two parameters are discussed in Sections 3.2 and 3.3, respectively.

3.2. Leaf Area Index

To characterize the wheat variety sown in the Haouz plain, five key phenological stages that control the LAI evolution were calibrated [11] from the data collected during the 2002/03 season. The Simplex method [29], which is available in the STICS software, was used to optimize the thermal units that separate the following phenological phases: from seedling emergence (LEV) to the beginning of the stem elongation (AMF); from AMF to the date of maximum LAI (LAX); from LAX to the beginning of plants senescence (SEN); and finally from SEN to the end of foliage senescence (LAN).
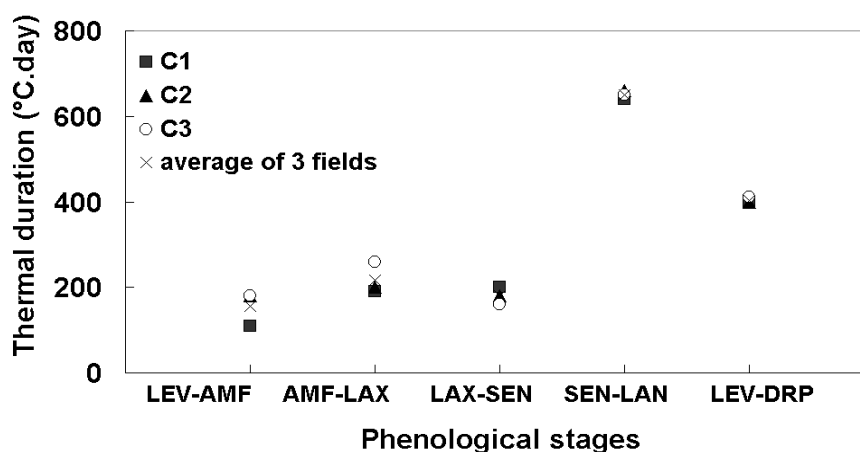

Figure 3. Thermal units between the four phenological stages that control the LAI,
obtained from C1, C2, and C3 calibration fields.
LEV, emergence; AMF, the beginning of stems elongation; LAX, the maximum LAI; SEN, the beginning of plant senescence;
LAN, the end of foliage senescence; LEV–DRP thermal units between emergence and the beginning of the grain filling.

The obtained values of the thermal units of wheat phenological stages, corresponding to the three calibration fields, are presented in Figure 3. The later emphasizes slight differences between the values of the three fields, especially for the LAX–SEN and the SEN–LAN phases. These thermal units were inferior by around 10% to those given by [12] for temperate wheat varieties. This was due to the fact that the fields were cropped with a short life cycle variety which is adapted to the semi-arid conditions of the Haouz plain.

Since the thermal units between the phenological stages obtained for the three calibration fields were comparable (Figure 3), their average values were used as input parameters to test the STICS model against the data collected for the validation fields. At this stage, only the parameter that controls the rate of foliage production was fitted against observed LAI for each field.

Observed and simulated LAI were compared using the correlation coefficient (R^2) of the regression line and the Root Mean Square Error (*RMSE*):

$$R^2 = \frac{\left(\sum_{i=1}^{n} (y_i - Y)(x_i - X) \right)^2}{\left[\sum_{i=1}^{n} (y_i - Y)^2 \right]\left[\sum_{i=1}^{n} (x_i - X)^2 \right]}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \ .$$

Where y_i is the predicted value, x_i is the observed value, Y is the predicted mean, X is the measured mean, and n is the number of observation.

Figure 4 highlights examples of the temporal evolution of simulated LAI for one calibration (C2) and one validation (V2) field. These fields were chosen because they correspond to intermediate accuracy of the STICS model. There is a close agreement between the observations and the simulations; however, a slight deviation can be noticed for the validation field. These qualitative findings are confirmed by the statistics displayed in Table 3. For the calibration, the slopes and intercepts of linear regressions between simulated and observed LAI are close to 1 and 0 respectively. In the worst case, the R^2 is larger than 0.9, and *RMSE* is 0.6 m²/m² (*i.e.* 14 % of the maximum value of LAI which is about 4.1 m²/m²). For the validation, the slopes and intercepts of linear regressions between simulated and observed LAI temporal evolutions are always higher than 0.77 and near to 0 respectively. The *RMSE* ranges between 0.4 m²/m² and 1 m²/m² and R^2 between 0.75 and 0.93, respectively. According to these results, the calibration of wheat phenology appears acceptable to correctly simulate the temporal evolution of LAI. This is an important step to provide accurate simulations in terms of water balance [14–16, 18].

Table 3. Statistics between Observed and Simulated LAI for Calibration and Validation Fields

	Calibration fields			Validation fields					
	C1	C2	C3	V1	V2	V3	V4	V5	V6
n	16	13	14	18	19	17	19	18	14
RMSE (m²/m²)	0.6	0.3	0.2	0.6	0.6	1.0	0.5	0.4	1.0
Slope	1.00	0.92	0.97	0.86	0.77	0.77	0.85	0.81	0.81
Intercept	0.12	0.14	0.04	−0.04	0.37	−0.20	0.08	−0.06	−0.18
R^2	0.91	0.96	0.98	0.88	0.75	0.93	0.87	0.88	

n is the number of observations, *RMSE* is the Root Mean Square Error, and R^2 is the correlation coefficient of the regression line
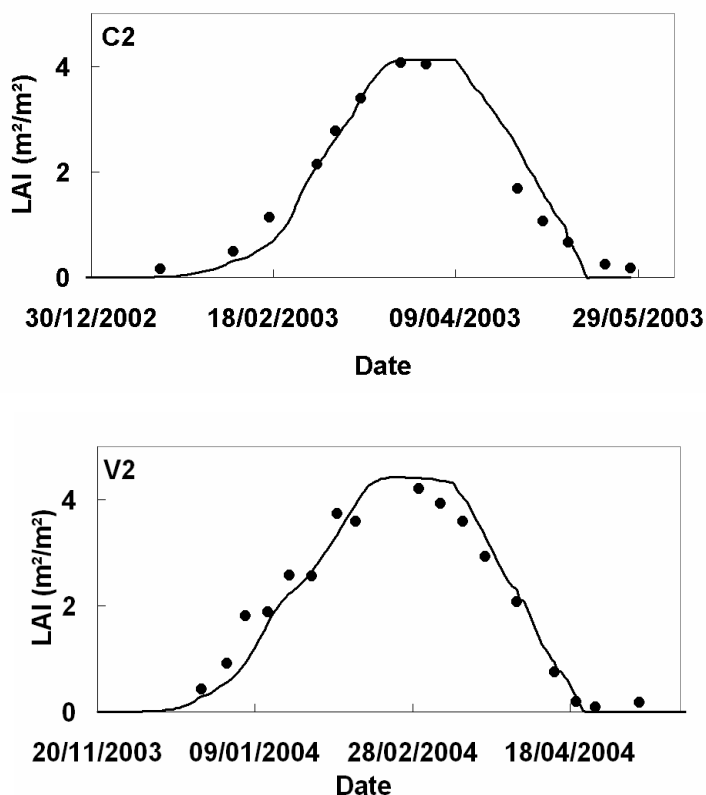
Figure 4. Examples of LAI temporal evolution for one calibration field (C2) and one of validation field (V2). Lines and dots (●) are simulated and measured LAI, respectively.

3.3. Grain Yield

For grain yield, the calibration was performed on the thermal units between plant emergence and the beginning of the grain filling stage (DRP). As for LAI, the LEV–DRP thermal units parameter was optimized on the three calibration fields (see Figure 3), then the average value was used for the validation fields.

Table 4 and Figure 5 give a comparison between observed and simulated grain yields for both the calibration and the validation fields. The calibration provides grain yield values, which are in the range of those observed by the ORMVAH technicians. The same result is obtained for the six fields of validation, but the model has slightly overestimated the grain yield values, especially for fields V5 and V6. This may be due to the fact that the agricultural conditions were more favorable for the validation than for the calibration fields. Indeed, half of the validation fields were fertilized at sowing (see Table 2). Furthermore, there is more irrigation water (180 mm instead of 90 mm) and less evaporation (reference evapotranspiration of 530 instead of 600 mm) for the 2003/04 season than for the 2002/03 season. These differences also show that the grain yield is larger for the 2003/04 season than for the 2002/03 season, even when the fields that have not been supplied with fertilizers at sowing were compared (C1 to C3; V1, V3, and V5). Despite this slight overestimation, the model has accurately reproduced the grain yield. This was noticed especially when considering the grain yield values obtained from direct measurements. It is concluded from Figure 5 that the variations of grain yield from one field to another were generally well simulated.

Figure 5 shows that the grain yields of the validation fields were firstly increased with the supply of nitrogen (Table 2). Thus, three groups of fields can be marked out corresponding to (V4), (V2 and V6), and (V1, V3, and V5) supplied by 100, 50, and 0 kg/ha of nitrogen respectively. The diagnosis of nitrogen stresses are investigated by running the STICS model in the same agricultural and environmental conditions as the 2003/04 season but without the effect of nitrogen stress. These results are presented in Table 5. The grain yield values are consistent with those obtained under optimal

conditions in the agricultural experiment stations in Morocco [1, 30]. The grain yield values are generally close to the maximum value (8 t/ha) which was simulated according to the characteristics of the grain density and the weight of 1000 grains that have been considered (20000 grains/m² and 40 g, respectively). This was evident for the favorable rainfall and irrigation conditions of the 2002/03 and 2003/04 seasons. Consequently, the increase of grain yield between fertilized and non-fertilized conditions was substantive (Table 5); it was always more than 99% of the maximum grain yield, predominantly for the fields that do not suffer from water stress (C3, V4, and V6) and for the fields that have not been supplied with nitrogen (C1 to C2, V1, V3, and V5).
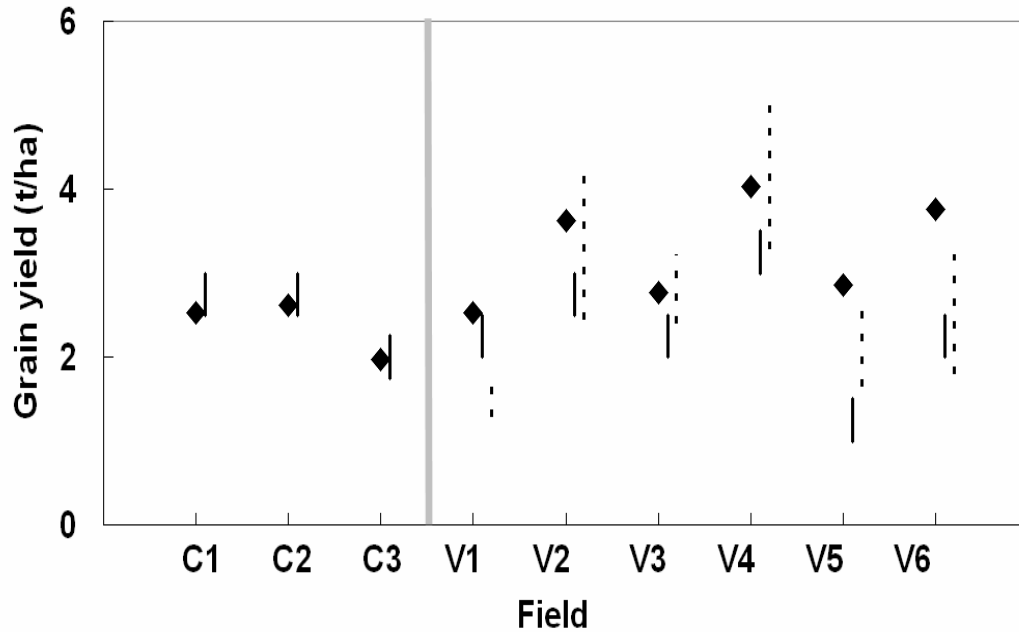

Figure 5. Estimated and observed grain yield for both calibration (C1 to C3, at left) and validation (V1 to V6, at right) fields. Symbols (♦) correspond to simulated grain yield. Solid bars correspond to minimum and maximum values of visual estimates by ORMVAH technicians. Dotted bars display twice the standard deviation centred on the average measured values at field.

Table 4. Estimated and Observed Grain Yield for Both Calibration and Validation Fields

	Field	Grain yield (t/ha)	
		Observed	Simulated
Calibration fields	C1	2.5−3.0[*]	2.5
	C2	2.5−3.0	2.6
	C3	1.8−2.2	1.9
Validation fields	V1	2.0−2.5 (1.6±0.4)[**]	2.5
	V2	2.5−3.0 (3.4±1.7)	3.6
	V3	2.0−2.5 (2.8±0.8)	2.8
	V4	3.0−3.5 (4.3±1.8)	4.0
	V5	1.0−1.5 (2.2±0.9)	2.9
	V6	2.0−2.5 (2.5±1.4)	3.8

[*] Minimum and maximum of grain yield based on visual estimates

[**] Field grain yield measurements and its standard deviation as described in II-2

Table 5. Differences between Simulated Grain Yield with and without Nitrogen Stress

		Simulated grain yield (t/ha)		
		With N stress	Without N stress	Gain % [*]
Calibration fields	C1	2.5	6.7	166
	C2	2.6	7.6	189
	C3	2.0	8.0	306
Validation fields	V1	2.5	7.7	204
	V2	3.6	7.6	110
	V3	2.8	7.1	156
	V4	4.0	8.0	99
	V5	2.9	7.9	176
	V6	3.8	8.0	113

[*] Gain = 100 × (grain yield without N stress – grain yield with N stress) / grain yield with N stress

According to these results, it appeared that the effect of nitrogen stress was dominant, and the grain yield loss due to water stress appeared to be limited at a maximum of 20% (1.3 t/ha on C3 fields, by comparing the value without nitrogen effect to the maximum, *i.e.* from 6.7 to 8 t/ha in Table 5).

To quantify the effect of water stress and to examine how STICS can be used to schedule irrigation, it was thus necessary to maintain optimal conditions of fertilization. The results provided in the next section were obtained under this assumption.

4. APPLICATION: USE OF THE STICS MODEL TO MANAGE IRRIGATION

The main objective of this application is to investigate the possibility offered by STICS to manage the irrigation water. The model can schedule the irrigation by fixing a threshold of one water stress index, TURFAC, that affects growth during the whole cycle. The TURFAC is defined in the model as the ratio between actual and maximum crop evapotranspiration. In this option, the model automatically applies an irrigation of 20 mm after sowing to ensure the grain germination. After sowing, the TURFAC variable may decrease as the soil becomes dryer. The model then calculates the amount of irrigation water needed in the days when the stress index becomes lower than a given threshold (RATIOL). If the threshold is close to 1, the model applies irrigation as soon as the plants are stressed. If this threshold is close to 0, the plants may suffer from severe water stress, depending on the distribution and amount of rainfall. The maximum water quantity allowed by the irrigation system is fixed beforehand by the user (30 mm in this case study).

To investigate the effect of the water deficit in the Haouz plain, a series of simulations were performed for eight values of RATIOL ranging from 0.3 to 1. This effect was illustrated under the 2003/04 season climatic conditions on two fields that differ by their sowing dates; V2 and V3, which were sown on November 21 and on December 15, 2003, respectively. These two fields were characterized as the common practices of early and late sowing around Marrakech [30].

Figure 6 depicts the biomass and grain yield simulations obtained for the V2 and the V3 fields, as a function of RATIOL. The values of the biomass ranged from 15 to 25 t/ha, while the values of the grain yield were always larger than 6.2 t/ha. The grain yield values were generally close to the maximum value (8 t/ha). This is consistent with the results discussed in Table 5. As expected, the seasonal amount of irrigation water increased with RATIOL. It has displayed a minimum value of 20 mm for V2 with severe water stress since the model only applies the first irrigation after sowing. It has reached a maximum value of 230 mm for V3 with no water stress as the model applies eight irrigations, regularly distributed, during the season. In parallel, the biomass and the grain yield have increased with RATIOL up to their optimal values.
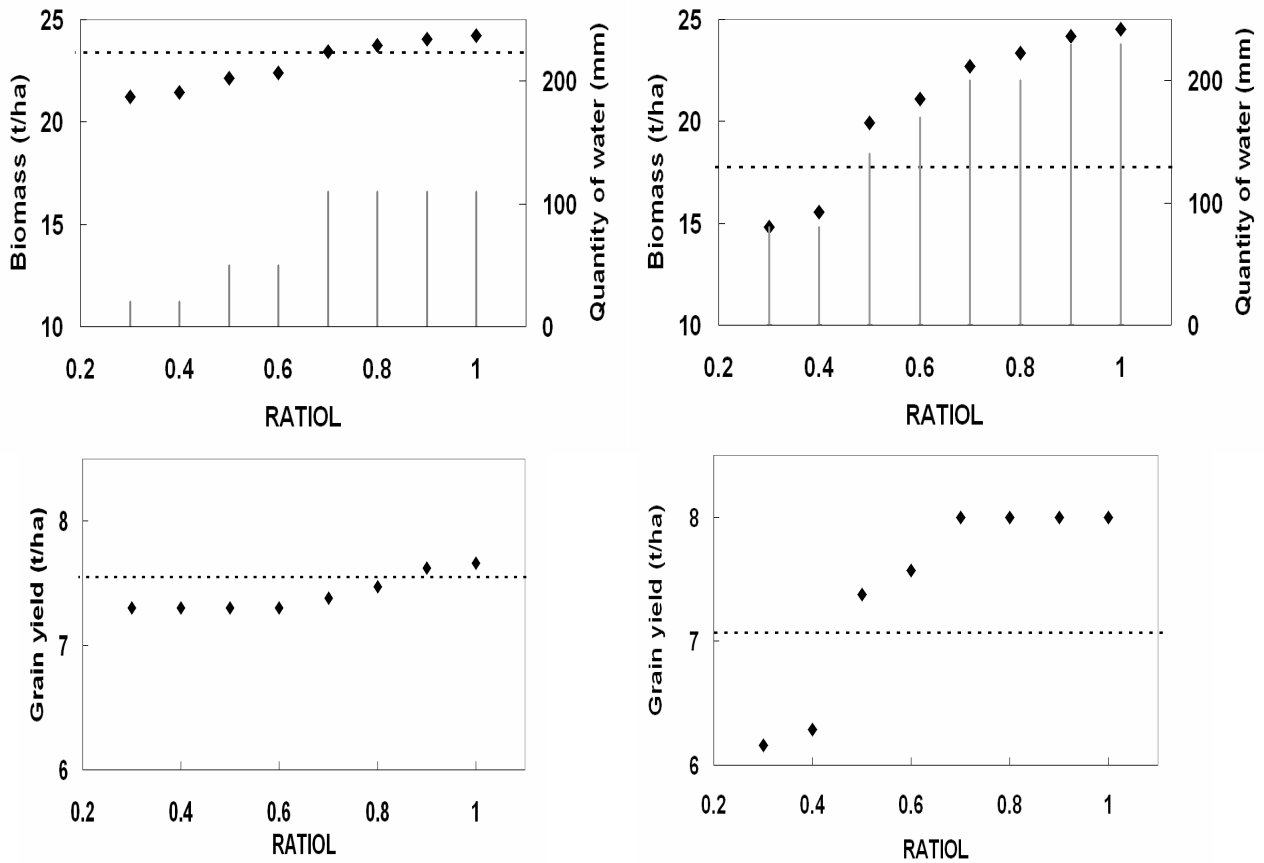
Figure 6. Estimates of biomass and grain yield of V2 (left) and V3 (right) as a function of RATIOL, along with the seasonal quantity of irrigation water supplied by STICS (vertical bars in the top Figures). The horizontal lines represent the values of biomass and grain yield estimated by the model when using actual irrigations and no nitrogen stress.

The relationship between water supplied and RATIOL has a staircase form. For the early sowing (field V2), three groups can be clearly marked out according to the RATIOL values: (0.3 and 0.4), (0.5 and 0. 6), and (0.7 to 1). These groups corresponded to a supply of 20, 50, and 110 mm of water irrigation, respectively. In these groups, high variation has occurred between the biomass and grain yield because of variation in the quantity of irrigation water. Within each group, these outputs had slightly varied according to the differences in the irrigation schedule. To illustrate this, four examples of the irrigation schedules (Figure 7), corresponding to the values of RATIOL between 0.7 to 1, were presented. The irrigations occurred earlier when RATIOL increases, especially for the first irrigations. When RATIOL is equal to 1, the model applies an irrigation as soon as the plants are stressed, while the irrigations were more and more delayed when the level of stress that can be simulated increased (RATIOL decreasing from 0.9 to 0.7). For the late sowing (field V3), this relationship was less evident (except for the groups of RATIOL: 07−0.8 and 0.9−1) because of a high variation in number of irrigations.

The simulations allow to point out large differences between early and late sowing (V2 and V3 fields, respectively). The variation in biomass and grain yield, due to water conditions, was threefold larger for V3 than that of V2. In conjunction, the quantity of irrigation water was always higher for V3 than for V2, by an average of 100 mm. It was for example 110 mm for V2 and 230 mm for V3 under non-stressed condition (RATIOL equal to 1). Figure 8 represents the temporal evolutions of LAI of the two fields (V2 and V3) along with the rainfall. The V2 field has responded to the early effective rainfall at the beginning of the season, while irrigation was necessary just after sowing to prevent the V3 field from water stress. In addition, the evapotranspiration was much higher at the end of the season (see Figure 2), where the evapotranspiration rate from V3 fields was higher than that from V2 fields because of the late sowing. As a

result, there was a difference of about 110 % of water consumption between these two fields due to the differences of the sowing dates.

These simulations also allow to quantify the saving that could be realized in irrigation water when using the STICS model. Figure 6 presents the particular values of biomass and grain yield that correspond to the simulations performed with the prevailing cultivation practices and environmental conditions. These conditions observed for V2 and V3 were under an amount of 180 mm of irrigation water during the 2003/04 season. The values of biomass and grain yield were also retrieved using RATIOL value of 0.8 and 0.5 for a seasonal irrigation water of 110 mm and 140 mm for V2 and V3, respectively. Comparing these values with those used to obtain the reference biomasses and grain yields (180 mm), it could be concluded that 70 mm and 40 mm could be saved for early and late sowing, respectively.

Finally, Figure 6 also allows the prediction of the gain in biomass and grain yield if there is no restriction on irrigation water, by comparing the simulations performed under severe water stress (RATIOL equal to 0.3) and those performed
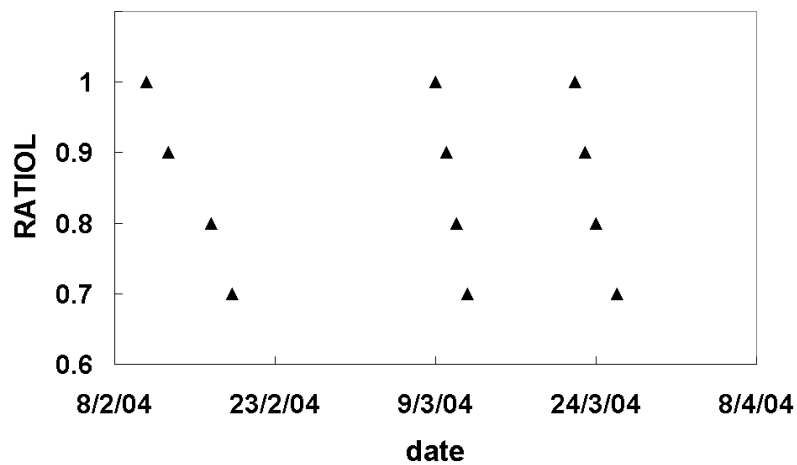

*Figure 7. Irrigation schedule corresponding to the simulations performed for the V2 field
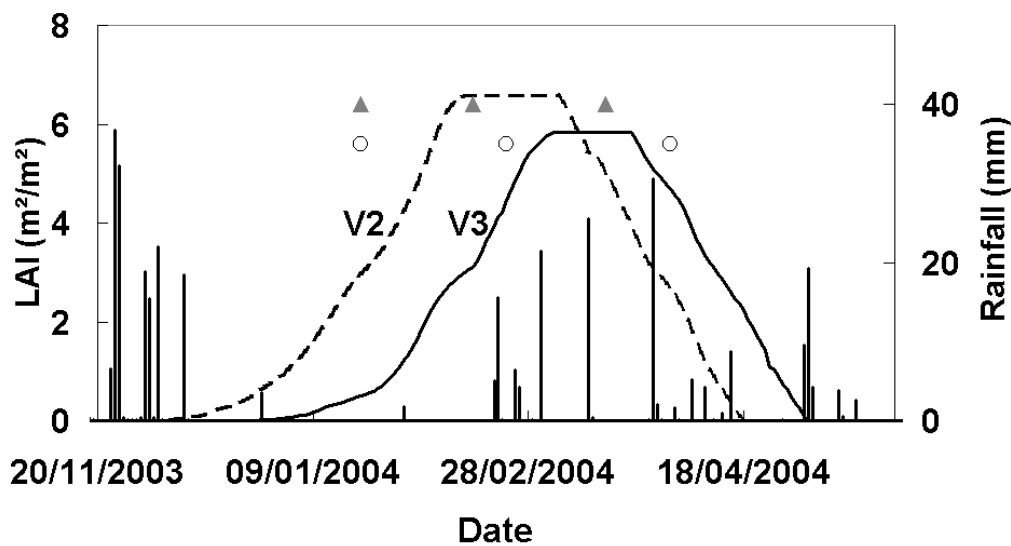for different values of RATIOL (from 0.7 to 1)*

*Figure 8. Simulations of LAI when using actual irrigations and no nitrogen stress for the V2 and V3 fields. Vertical bars show the
rainfall and symbols, ▲ for V2 and ○ for V3, highlight irrigation dates.*

with no water stress (RATIOL equal to 1). It was evident that for the V2 field, all the simulated production was close to the optimal 25 t/ha and 8 t/ha for the biomass and grain yield values, respectively. Under these conditions, the supply of only 90 mm (3 irrigations) allowed a low increase of the biomass and grain yield, by around 13% and 4% respectively. The need for irrigation was more obvious for V3, where the biomass and grain yield increased by about 65% and 30%, respectively, when 150 mm (5 irrigation events) was additionally supplied.

It is important to note that this application is only based on simulations, with the assumption that the plants do not suffer from nitrogen stress. Further validation work would be necessary to confirm these conclusions. Despite this limitation, this application showed the potential use of a crop model to manage the irrigation water. For the particular case of the 2003/04 season in Haouz/Marrakech plain, a first conclusion is that early sowing is more appropriate than late sowing in saving water and obtaining adequate grain yields. This elucidates the capacity of the model to improve the cultivation practices. The model also offers the possibility to schedule the irrigations in order to reduce the water stress. In this respect, this application indicates that up to 70 mm can be saved without grain yield loss in the case of late sowing. This value represents 75% and 40% of the quantity of the water available for irrigation in the experiment site during the 2002/03 season and 2003/04 season, respectively.

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