Crop Monitoring as an
E-agricultural tool in
Developing Countries

EVALUATION REPORT ON WHEAT SIMULATION AT FIELD LEVEL

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report presents the results of the evaluation at field level of the model WOFOST for soft and durum wheat growth and development in Morocco. For calibration and validation purposes, the observations datasets were split in two parts, taking into account potential and water limited conditions. Evaluation metrics showed discrete performances for the model, although some unexpected results will be further discussed with the researchers in charge for collecting the data.

NOTE:
The deliverable corresponding to this report (D34.3) is scheduled for month 30. This version of the report contains the results of the calibration/validation performed using the data from the field experiments carried out during the first year of project. This report will be integrated in the next months with data coming from the new field experiments, and with the results obtained with the CropSyst model.
This strategy – i.e., submitting partial versions of the deliverable, each integrating the previous one – is due to an explicit request form the Project Reviewers, to avoid an accumulation of too many reports to be reviewed in the last months of the Project.

1. Materials and methods

1.1. Field level calibration and validation of the WOFOST model for wheat simulation in Morocco

1.1.1. The observation datasets

The data used for the calibration and validation of the WOFOST model were collected in two sites selected during the year 2011 (Sidi-el-Aydi and Khemis-Zemamra; see the D31.1 report). Six varieties were used in the field experiments, three of durum wheat (Marzak, Tarek and Karim) and three of soft wheat (Achtar, Amal and Arrihanne). Two independent parameter sets were developed for durum and soft wheat. The details about the available experiments and varieties are provided in Table 1.
The calibration of phenology was performed with data coming from the two sites (Table 1) whereas the calibration of potential aboveground biomass was carried out in one site (Sidi-el-Aydi) and the evaluation of the model performances in the other site (Khemis-Zemamra).
The only experiment carried out in rainfed condition (Sidi-el-Aydi site) was used to calibrate the WOFOST model coupled with an hydrological model to simulate water stressed conditions. Figure 1 shows the distribution of the selected sites.

Figure 1 Distribution of calibration and validation datasets in the study region

Table 1 Available Moroccan datasets selected for calibration (cal) and evaluation (eva). Asterisks indicate if the experiment was used to calibrate phenology.

ID	Wheat variety	Site	Wheat type	Growing condition	Use
SEA_D_A	Marzak	Sidi El Aydi	Durum	Potential	cal
SEA_D_B	Tarek	Sidi El Aydi	Durum	Potential	cal*
SEA_D_C	Karim	Sidi El Aydi	Durum	Potential	cal
SEA_D_D	Achtar	Sidi El Aydi	Soft	Potential	cal*
SEA_D_E	Amal	Sidi El Aydi	Soft	Potential	cal
SEA_D_F	Arrihanne	Sidi El Aydi	Soft	Potential	cal*
SEA_W_A	Marzak	Sidi El Aydi	Durum	Water limited	cal/eva
SEA_W_B	Tarek	Sidi El Aydi	Durum	Water limited	cal/eva
SEA_W_C	Karim	Sidi El Aydi	Durum	Water limited	cal/eva
SEA_W_D	Achtar	Sidi El Aydi	Soft	Water limited	cal/eva
SEA_W_E	Amal	Sidi El Aydi	Soft	Water limited	cal/eva
SEA_W_F	Arrihanne	Sidi El Aydi	Soft	Water limited	cal/eva
KHZ_D_A	Marzak	Khemis-Zemamra	Durum	Potential	eva*
KHZ_D_B	Tarek	Khemis-Zemamra	Durum	Potential	eva
KHZ_D_C	Karim	Khemis-Zemamra	Durum	Potential	eva*
KHZ_D_D	Achtar	Khemis-Zemamra	Soft	Potential	eva
KHZ_D_E	Amal	Khemis-Zemamra	Soft	Potential	eva*
KHZ_D_F	Arrihanne	Khemis-Zemamra	Soft	Potential	eva

Before the model calibration, an analisys of wheat aboveground biomass and leaf area index observations was performed.

Some datasets showed unexpected behaviours related to very high values of biomass in the second to last available measurement followed by a decided decrease in the last one. Figure 2 presents an example of this for SEA_D_A, SEA_D_B and SEA_D_C experiments.

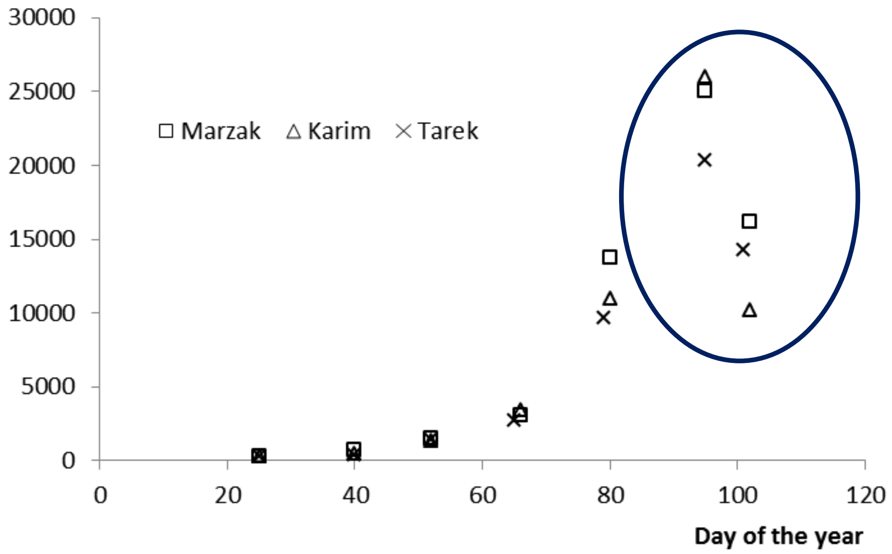

Figure 2 Total aboveground biomass observed at SD3

Another criticality is related to the leaf area index values (LAI) measured in the fields. These values are approximately in the range 1-3.7 m^2 m^{-2} in all the experiments, and the corresponding yields are in some cases very high (5700-7000 Kg ha^{-1} in Sidi-El-Aydi and 4250-5950 Kg ha^{-1} in Khemis-Zemamra experimental sites). This could suggest that LAI measures are too low compared to the aboveground biomass values collected in the field experiments. A literature search to investigate this issue was performed and LAI values decidedly higher for wheat grown were found in ISI papers about wheat grown in Morocco, associated with yields in line with the measured data (LAI>6 Duchemin et al., 2006[1]; LAI 4-5 Corbeels et al., 1998[2]; LAI 2.8-5.8 Hadria et al., 2010[3]; LAI 3-6 in Algeria Bouthiba et al., 2008[4]). This problem could be due to the methodology adopted to derive LAI measurements because it is well known that the specific method adopted could

[1] Duchemin, B., Hadria, R., Er-Raki, S., Boulet, G., Maisongrande, P., Chehbouni, A., Escadafal, R., Ezzahar, J., Hoedjes, J., Karroui, H., Khabba, S., Mougenot, B., Olioso, A., Rodriguez, J.C., Simonneaux, V. Monitoring wheat phenology and irrigation in Central Morocco: on the use of relationship between evapotranspiration, crops coefficients, leaf area index and remotely-sensed vegetation indices. Agric. Water Manage., 79 (2006), pp. 1-27.

[2] Corbeels, M., Hofman, G., Van Cleemput, O. Analysis of water use by wheat grown on a cracking clay soil in a semi-arid Mediterranean environment: weather and nitrogen effect. Agric. Water Manage., 38 (1998), pp. 147-167.

[3] Hadria, R., Duchemin, B., Jarlan, L., Dedieu, G., Baup, F., Khabba, S., Olioso, A., Le Toan, T. Potentiality of optical and radar satellite data at high spatio-temporal resolutions for the monitoring of irrigated wheat crops in Morocco. Int. J. Appl. Earth Obs., 12 (2010) 32-37.

[4] Bouthiba, A., Debaeke, P., Hamoudi, S.A. Varietal differences in the response of durum wheat (Triticum turgidum L. var. durum) to irrigation strategies in a semi-arid region of Algeria. Irrig. Sci., 26 (2008) pp. 239-251

strongly affect the obtained values. For these reasons, it was decided – for this first calibration step and before carefully discussing data with Moroccan partners – to avoid using LAI data to calibrate the model, in order to avoid to assign inconsistent values to the model parameters, probably depriving them of their biological meaning. Since the availability of LAI data usually greatly improve the reliability of the calibrations, before using the second year measurements to calibrate the model this criticality and the unexpected pattern of biomass will be discussed during the Rabat meeting (19-22 March 2013) with the people who carried out the field observations.

1.1.2. The meteorological datasets

The meteorological datasets used to calibrate the models were derived from the MARS database[5], at a spatial resolution of 25×25 Km. Figure 3 shows the comparison between the air temperature data observed at the Sidi-El-Aydi site and Khemis-Zemamra one. Figure 4 presents the comparison between global solar radiation data collected in the two experimental sites.

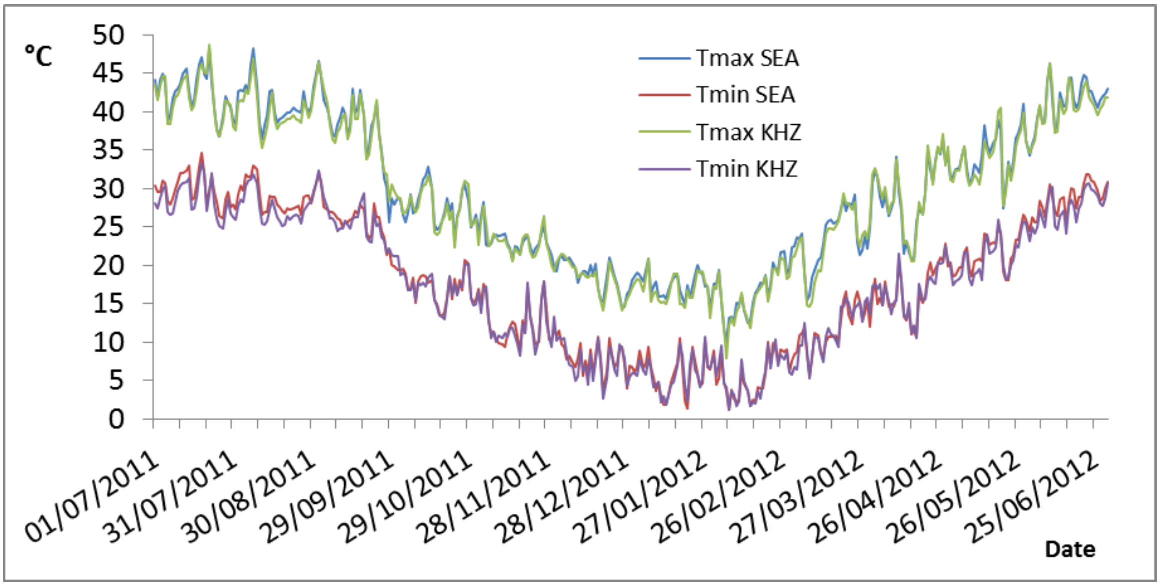

Figure 3 Comparison of daily maximum and minimum air temperature derived from the MARS database for the Sidi-El-Aydi (SEA) and Khemis-Zemamra (KHZ) datasets.

5 Micale F, Genovese G (2004) Methodology of the MARS Crop Yield Forecasting System. Vol. 1. Meteorological data collection, processing and analysis. Publications Office: European Communities, Italy, 100 pp.

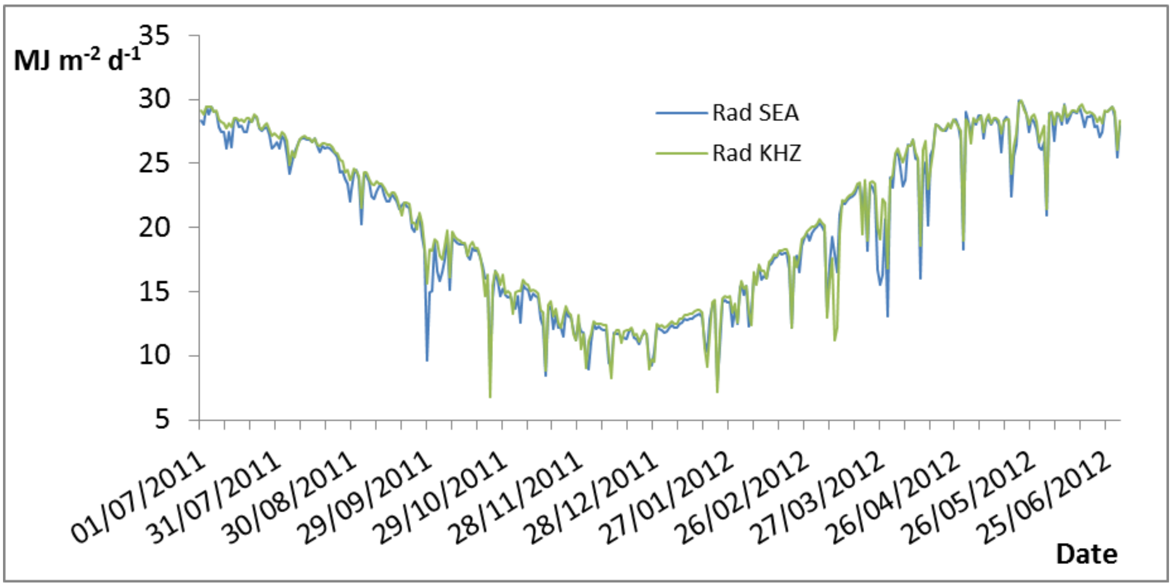

Figure 4 Comparison of daily global solar radiation derived from the MARS database for the Sidi-El-Aydi (SEA) and Khemis-Zemamra (KHZ) datasets

Given the proximity of the two sites (135 Km), the meteorological data used for preliminary calibration and validation activities are very similar. We will try to explore more heterogenous meteorological conditions during the refining of the calibration procedure which will be performed with the second year of field measurements, possibly by adding one more experimental site.

2. Results and Discussion

2.1. Calibration and validation of the model WOFOST for wheat simulation in Morocco – Potential production level

The complete list of the calibrated parameter values of WOFOST for soft wheat and durum wheat is detailed in Appendix A. Results discussion is separated according to soft and durum wheat.

2.1.1. Results obtained with soft wheat

The first parameters calibrated are those affecting plant development. The only available measurements are related to flowering stage, therefore only the parameters related to the first part of crop cycle were calibrated. The parameters related to the flowering-maturity phase were determined in order to reach maturity around the mid of April, which is in line with Moroccan harvest date. The parameter values chosen for the three models led to a discrete performance of flowering simulation, determining an average difference of eight days between the observed and simulated values. Only in one case (ID KHZ_D_D), it can be observed a larger difference in the simulated flowering date (17 days). The validation confirmed the good results obtaining with parameters used during the calibration. Table 2 reports all the simulated and observed values for the potential datasets tested for soft wheat.

Table 2 Observed and simulated values of flowering day of year in the potential datasets tested (soft wheat).

ID	Observed	Simulated
SEA_D_D	131	124
SEA_D_E	133	124
SEA_D_F	118	124
KHZ_D_D	143	126
KHZ_D_E	123	126
KHZ_D_F	120	126

Once crop development was calibrated, the parameters involved in wheat growth were considered. A particular effort was put in the calibration of those parameter that showed a

maximum influence on output variation, according to the sensitivity analysis results (see report D32.1 and Confalonieri et al., 2012[6]).
Since the observation sites chosen for calibration are located at similar latitudes and there were no relevant differences in meteorological data, the simulated aboveground biomass (AGB) trends are very similar.
The AGB trends simulated by the WOFOST model in the Sidi-El-Aydi site (calibration) are shown in Figure 5, where they are compared with data collected at different stages of wheat growth. The results of the simulations performed in the Khemis-Zemamra dataset (evaluation) are presented in Figure 6. Since it was not performed a specific calibration for each variety, for each measurement date the values belonging to the three cultivars tested are reported.

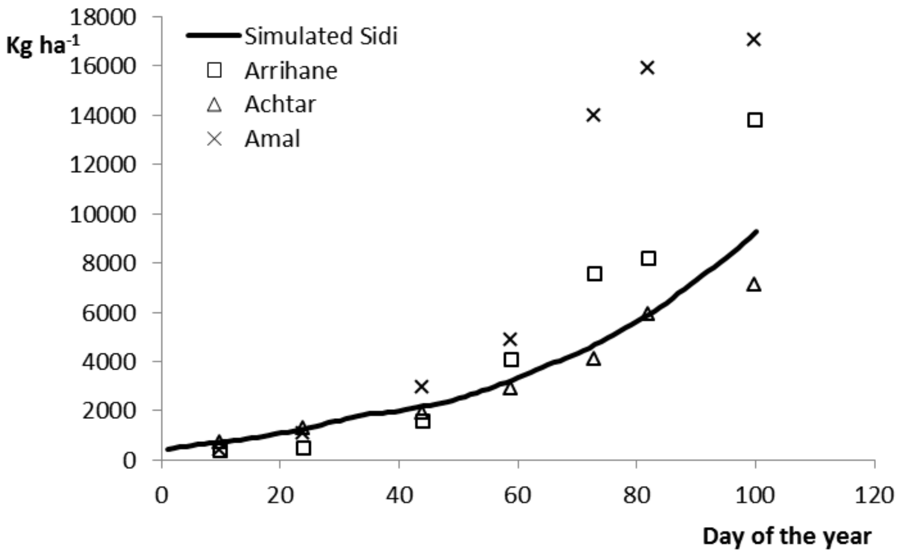

Figure 5 Comparison between simulated and measured aboveground biomass in Sidi-El-Aydi experimental site for soft wheat, used for calibration.

[6] Confalonieri, R., Bregaglio, S., Cappelli, G., Francone, C., Carpani, M., Acutis, M., El Aydam, M., Niemeyer, S., Balaghi, R., Dong, Q., 2013. Wheat modelling in Morocco unexpectedly reveals predominance of photosynthesis versus leaf area expansion plant traits. Agronomy for Sustainable Development, 33, 393-403.

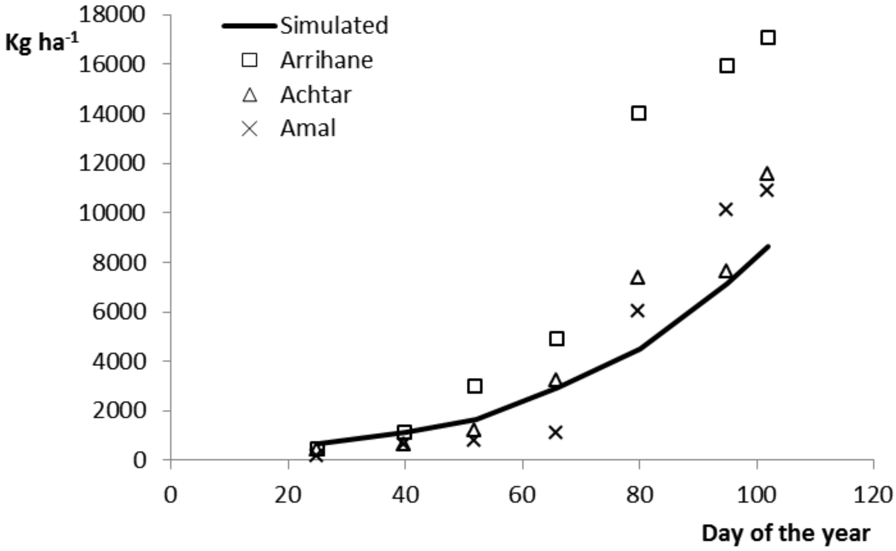

Figure 6 Comparison between simulated and measured aboveground biomass in Khemis-Zemamra experimental site for soft wheat, used for evaluation.

The overall measured trends were reproduced by WOFOST with a sufficient degree of accuracy, for both the calibration and validation datasets. In the calibration dataset, it can be observed the unexpected trend already discussed in paragraph 1.1.1. In general, the aboveground biomass values are very high, and there are marked differences among the three cultivar tested. It can be observed an overall underestimation of the model of the measured aboveground biomass values.

In order to evaluate the accuracy of the WOFOST model, in Table 3 the values of some fitting indices are presented, quantifying the agreement between measured and simulated data. These indices are (i) the mean absolute error (MAE, 0÷∞); (ii) .the relative root mean squared error (RRMSE, minimum and optimum = 0%; maximum = + ∞), (iii) the modelling efficiency (EF, - ∞ ÷ 1, optimum =1, if positive, indicates that the model is a better predictor than the average of measured values), (iv) the coefficient of residual mass (CRM, 0÷1, optimum = 0, if positive indicates model underestimation), (v) the coefficient of determination (CD, 0÷∞). See also report D32.3 for the description of the evaluation procedure.

Table 3 Indices of agreement between measured and simulated AGB values referred to the soft wheat datasets

	Indices							
Condition	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
Calibration	1474.12	45.86	0.77	0.12	2.28	1.44	-1.1	0.87
Validation	2313.44	65.05	0.55	0.32	2.62	1.71	-0.91	0.80

These values confirmed the sufficient performance of WOFOST in reproducing the measures collected both in calibration and validation datasets. The overall RRMSE referred to aboveground biomass showed a value of 46% in calibration and of 65% in validation dataset. This indicates a worsening of the model performance when applied to dataset independent from the calibration one. This trend is also confirmed by the values of the other indices; WOFOST obtained a satisfactory value for EF during calibration (0.77) and a worse one in validation (0.55). The CRM obtained by the model is always above 0, which indicates a clear model underestimation.
The performance of the model is confirmed by the values of regression parameters (i.e., slope, intercept and coefficient of determination) listed in **Error! Reference source not found.**. The coefficient of determination of the regression had values ranging from 0.87 (calibration) and 0.80 (validation), the values of intercept of regression line was around -1 and slope is above 1.
The index of robustness (I_R) was not applied in these datasets because of the high similarities between the meteorological data coming from the available datasets (see paragraph 1.1.2).

2.1.2. Results obtained with durum wheat

The calibration of parameters involved with development led to results similar to those obtained for soft wheat (paragraph 2.1.1). The application of these parameters in the validation datasets confirmed the model performances which can be considered satisfactory. The considerations about the difficulty encountered when calibrating phenology only disposing of flowering dates (paragraph 2.1.1) are still valid also for durum wheat.
Table 4 reports all the simulated and observed values for the potential datasets tested for durum wheat.

Table 4 Observed and simulated values of flowering day of year in the potential datasets tested (durum wheat).

ID	Observed	Simulated
SEA_D_D	119	110
SEA_D_E	121	110
SEA_D_F	121	110
KHZ_D_D	111	112
KHZ_D_E	114	112
KHZ_D_F	108	112

The same procedure adopted for soft wheat was then applied, so the following step was the calibration of the parameters involved in durum wheat growth. As already observed for soft wheat, since the observation sites chosen for calibration are located at similar latitudes and there were no significant differences in meteorological data, the simulated aboveground biomass (AGB) trends are very similar.
The AGB trends simulated by the WOFOST model in the Sidi-El-Aydi site (calibration) are shown in Figure 5, where they are compared with data collected at different stages of durum wheat growth. The results of the simulations performed in the Khemis-Zemamra dataset (evaluation) are presented in Figure 8. Since it was not performed a specific calibration for each variety, for each measurement date the values belonging to the three cultivars tested are reported.

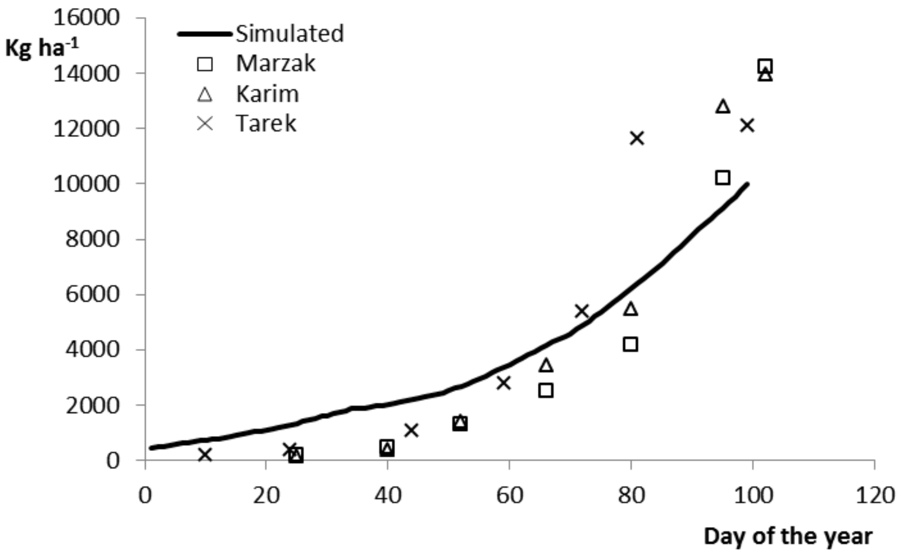

Figure 7 Comparison between simulated and measured aboveground biomass in Sidi-El-Aydi experimental site for durum wheat, used for calibration.

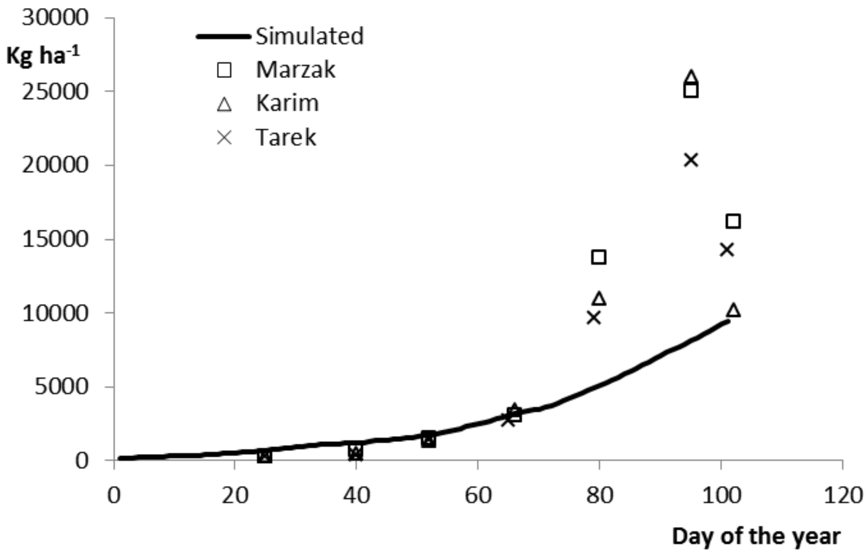

Figure 8 Comparison between simulated and measured aboveground biomass in Sidi-El-Aydi experimental site for durum wheat, used for calibration.

The results obtained for durum wheat are very similar to the ones discussed for soft wheat. The overall measured trends were sufficiently reproduced by WOFOST both in calibration and validation dataset. In the validation dataset (Khemis-Zemamra) it can be observed the unexpected trend already discussed in paragraph 1.1.1. In general, the aboveground biomass values are lower than the ones observed for soft wheat, and there are low differences among the three cultivar tested. It can be observed a good performance of the model in the calibration vadaset and a slight underestimation in the validation one.
The same indices of model evaluation computed for soft wheat are presented in Table 4.

Table 5 Indices of agreement between measured and simulated AGB values referred to the durum wheat datasets

	Indices							
Condition	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
Calibration	1718.38	49.72	0.76	0.17	2.59	1.60	-1.6	0.92
Validation	2038.34	67.10	0.62	0.30	2.69	1.68	-0.8	0.84

These values confirmed the sufficient performance of WOFOST in reproducing the measures collected in calibration dataset (RRMSE=49.72%; EF=0.76) and the decide worse performance of the model in the validation one (RRMSE=67.10%; EF=0.62). This can be

partly due to the unexpected pattern of the data in the validation dataset, already discussed in this paragraph. This trend is also confirmed by the values of the other indices; The CRM obtained by the model is always above 0, which indicates a clear model underestimation.
The heterogeneous performance of the model is confirmed by the values of regression parameters (i.e., slope, intercept and coefficient of determination) listed in **Error! Reference source not found.**. The coefficient of determination of the regression had values ranging from 0.92 (calibration) and 0.84 (validation), the values of intercept of regression line was lower in the validation (-0.8) than in the calibration dataset (-1.6) and slope of the regression curve is in both cases is above 1.
As for soft wheat, the index of robustness (I_R) was not applied in these datasets because of the high similarities between the meteorological data coming from the available datasets (see paragraph 1.1.2).

2.2. Evaluation of the model WOFOST for wheat simulation in Morocco – Water limited production level

The same parameter sets developed for the simulation of potential production level for soft and durum wheat were then applied in the Sidi-El-Aydi datasets SEA_W_A, SEA_W_B, SEA_W_C, SEA_W_D, SEA_W_E and SEA_W_F, which were grown under water limited conditions (see Table 1). Detailed measures of soil properties were available for this site and are reported in Table 6. The WOFOST model was coupled with the UNIMI.SoilW component (http://agsys.cra-cin.it/tools/soilw/help/), implementing several approaches to simulate water dynamics into soil. Aiming at applying the modelling solution (WOFOST+hydrological model) in large areas to run spatialized simulations, a cascading approach simulating the movement of water along the soil profile was chosen. This approach (also known as 'tipping bucket') is one of the most simplified and assumes that water can move only downward through the soil profile, filling up the layers until field capacity is reached, with the fraction of water exceeding this threshold moving to the deeper layer (Jones and Ritchie, 1990[7]; Ritchie 1998[8]). It is very suitable to be used in large area simulations because it requires as input easily obtainable parameters, i.e., soil water

[7] Jones, J.W., Ritchie, J.T., 1990. Crop growth models, in: Hoffman, G.J., Howell, T.A., Solomon, K.H. (Eds.), Management of Farm Irrigation Systems. ASAE, St. Joseph, MI, pp. 63-89.

[8] Ritchie, J.T., 1998. Soil water balance and plant water stress, in: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, pp. 41-54.

content at field capacity and soil water content at wilting point. When these values are absent, they can be estimated via pedotransfer functions.

Table 6 Soil properties of the Sidi-El-Aydi experimental site.

Depth	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})	Water retention (by weight)	
					0.33 bar	15 bar
0-10	25	53	22	1.1	27	15
10-20	28	53	19	1.18	26	16
20-30	33	48	19	1.25	27	15
30-40	39	45	16	1.33	30	14
40-50	42	39	19	1.35	27	15
50-60	55	34	11	1.42	31	18
60-70	67	22	11	1.55	31	18
70-80	67	22	11	1.65	30	15
80-90	67	19	14	1.7	30	14
90-100	67	19	14	1.7	30	15

Figure 9 and 10 present the results obtained by the WOFOST model run under water limited conditions compared to the observations collected for soft and durum wheat, respectively.

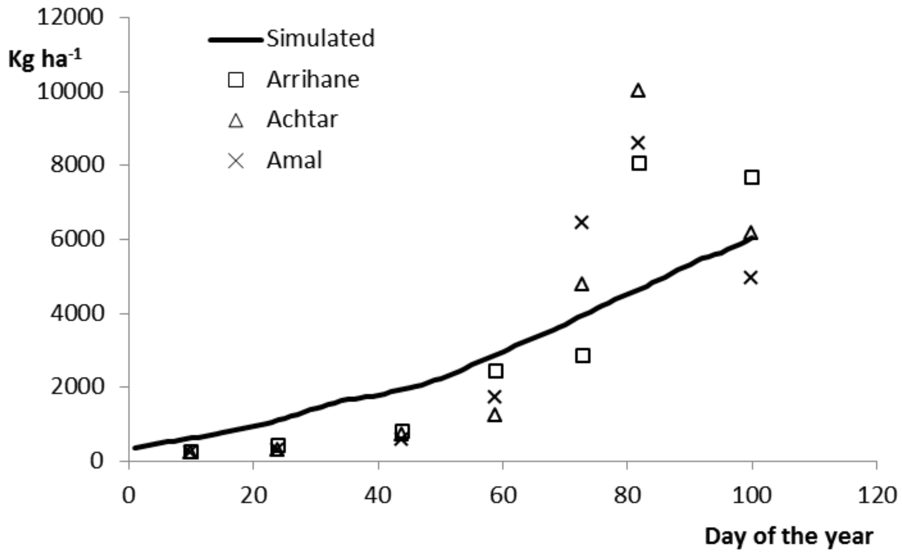

Figure 9 Comparison between simulated and measured aboveground biomass in Sidi-El-Aydi experimental site for soft wheat, water limited conditions.

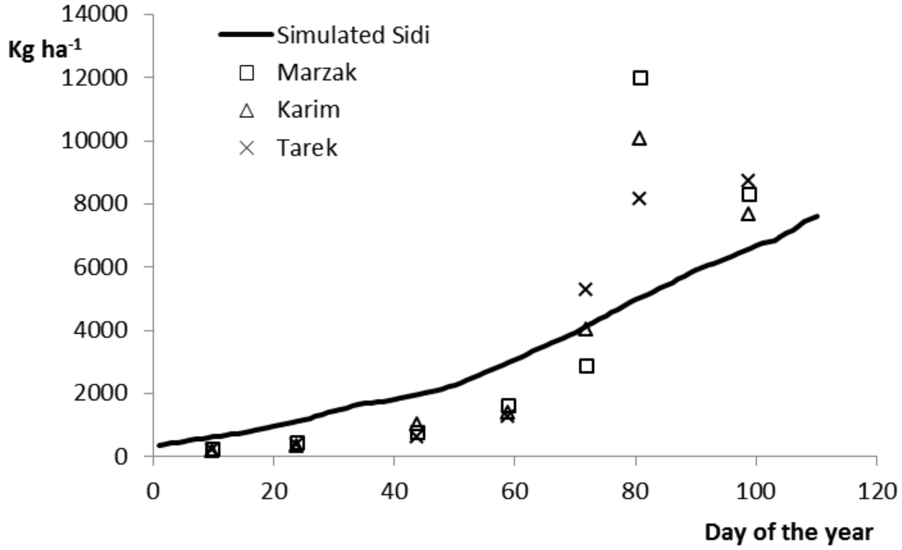

Figure 10 Comparison between simulated and measured aboveground biomass in Sidi-El-Aydi experimental site for durum wheat, water limited conditions.

The overall measured trends of aboveground biomass were sufficiently reproduced by WOFOST both for durum and soft wheat, even better than in potential conditions. In both these datasets it can be observed the unexpected trend already discussed in paragraph 1.1.1. In general, the aboveground biomass values are decidedly lower than the ones collected in potential conditions, with few differences among the three cultivar tested.
The same indices of model evaluation computed for potential conditions were computed for durum and soft wheat simulations and are presented in Table 7.

Table 7 *Indices of agreement between measured and simulated AGB values referred to soft and durum wheat grown under water limited conditions*

	Indices							
Wheat type	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
Soft	1000.70	49.53	0.78	-0.19	1.69	1.23	-1.1	0.84
Durum	1066.93	47.30	0.83	-0.16	1.98	1.38	-1.5	0.92

These values confirmed the better performance of WOFOST in reproducing the measures collected under water limited conditions with respect to potential ones (average RRMSE=48.4%; average EF=0.805). This can be partly due to the lower aboveground

biomass values and by the detailed information provided to parameterize soil properties. This trend is also confirmed by the values of the other indices; the CRM obtained by the model is always below 0, which indicates a model overestimation which can be observed in the first part of the crop cycle, whereas in the last part the WOFOST model tends to underestimate the measured data.
The good performance of the model is confirmed by the values of regression parameters (i.e., slope, intercept and coefficient of determination) listed in **Error! Reference source not found.**. The coefficient of determination of the regression had values ranging from 0.92 (durum wheat) and 0.84 (soft wheat), the values of intercept of regression line were very similar (-1.1÷-1.5) and slope of the regression curve is in both cases is above 1.
As for potential conditions, the index of robustness (I_R) was not applied in these datasets because of the high similarities between the meteorological data coming from the available datasets (see paragraph 1.1.2).
A further analysis was performed to analyze the accuracy of the cascading model coupled with WOFOST in reproducing the measuremnetas of volumetric soil water content at different depths. The results obtained for soft and durum wheat are shown in Figures 11 and 12, respectively.

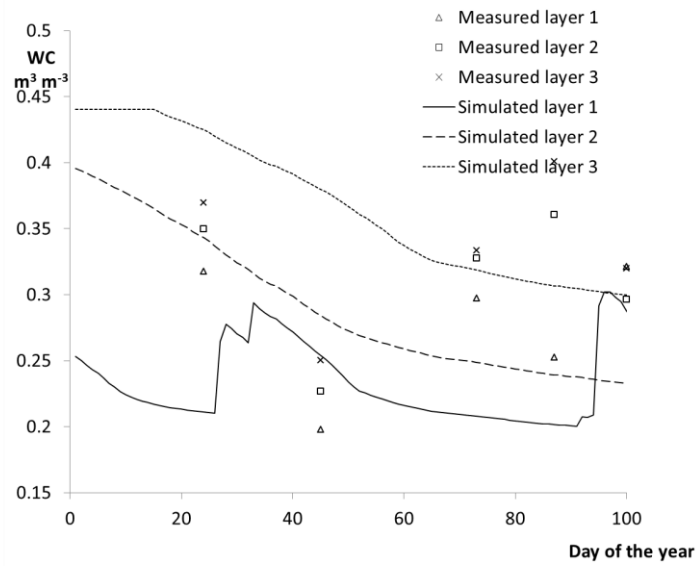

Figure 11 Comparison between simulated and measured volumetric soil water content at three different depths (0-20; 20-40; 40-60 cm) in Sidi-El-Aydi experimental site for soft wheat, water limited conditions.

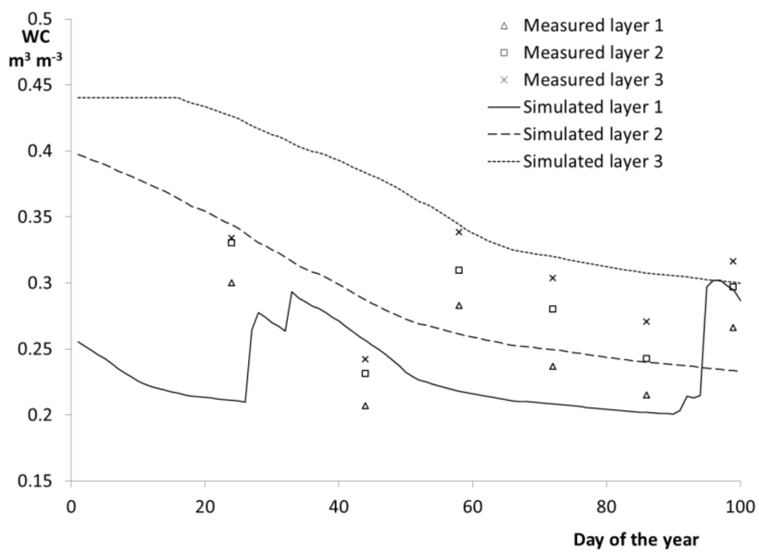

Figure 12 Comparison between simulated and measured volumetric soil water content at three different depths (0-20; 20-40; 40-60 cm) in Sidi-El-Aydi experimental site for durum wheat, water limited conditions.

The results obtained for volumetric soil water content indicate an overall good performance of the models in reproducing the soil water movements along the profile for both durum and soft wheat situations. The overall measured trends were sufficiently reproduced by WOFOST, in particular for the top layer soil (0-20 cm).

3. Conclusions

The evaluation of the WOFOST model in simulating durum and soft wheat development and growth In the Moroccan country was carried out into two steps. The two observations sites available for potential conditions for each crop (durum and soft wheat) were then splitted in two parts, the first used for calibration (Sidi-El-Aydi) and the second for validation purposes (Khemis-Zemamra). The only dataset available for water limited conditions (i.e., the one in which the soil properties were available) was used to evaluate the model performance.

The calibration allowed to sufficiently reproduce the validation datasets for both soft and durum wheat experiments. The quantitative evaluation by means of the fitting indices indicate that in order to achieve a better model performance, more datasets are needed and some criticalities and unexpected patterns in the measured data should be clarified (see paragraph 1.1.1). Since the datasets were located in a restricted area and the meteorological inputs are retrieved from the ECMWF archive, the variability explored in this first phase of calibration should be expanded via the inclusion of different dasets different from the ones used to determine the parameter sets. All these issue will be discussed in the Rabat meeting which will be held on 19-21 March 2013.

Appendix A. Parameter values (S: soft, D: durum) and determination (C: calibrated parameters; L: literature; D: default) relative to WOFOST model.

Parameter	Unit	Value S	Value D*	Det.
Development				
Base temperature for emergence (TBASEM)	°C	0	0	C
Maximum temperature for emergence (TEFFMX)	°C	30	30	C
Temperature sum emergence (TSUMEM)	°C-d	70	80	C
Temperature sum from emergence to anthesis (TSUM1)	°C-d	1320	950	C
Temperature sum from anthesis to maturity (TSUM2)	°C-d	450	450	C
Daily increase in temperature sum (DTSMTB)	°C; °C-d	0; 0	0;0	C
Daily increase in temperature sum (DTSMTB)	°C; °C-d	25.5; 25.5	21;21	C
Daily increase in temperature sum (DTSMTB)	°C; °C-d	34; 0	34;0	L
PhotoInhibition (DLC)	°C; °C-d	9.8	9.8	C
PhotoInsensitivity (DLO)	°C; °C-d	12.3	12.3	C
Growth				
Leaf area index at emergence (LAIEM)	$m^2\ m^{-2}$	0.3	0.1	C
Relative leaf area growth rate (RGRLAI)	$°C\ d^{-1}$	0.00817	0.00817	C
Specific leaf area at DVS[a] = 0 (SLATB00)	$ha\ kg^{-1}$	0.0035	0.0035	C
Specific leaf area at DVS[a] = 35 (SLATB35)	$ha\ kg^{-1}$	0.0025	0.0035	C
Specific leaf area at DVS[a] = 200 (SLATB200)	$ha\ kg^{-1}$	0.0025	0.0035	C
Life span of leaves growing at 35°C (SPAN)	d	32	32	C
Base temperature for leaves aging (Tbase)	°C	0	0	C
Extinction coefficient for diffuse visible light at DVS = 0 (KDIF000)	-	0.6	0.6	D
Extinction coefficient for diffuse visible light at DVS = 65 (KDIF65)	-	0.6	0.6	D
Extinction coefficient for diffuse visible light at DVS = 100 (KDIF100)	-	0.6	0.6	D
Extinction coefficient for diffuse visible light at DVS =200 (KDIF200)	-	0.6	0.6	D
Light use efficiency at Tavg[b] = 0°C (EFFTB0)	$kg\ ha^{-1}\ h^{-1}\ J^{-1}$	0.45	0.36	C
Light use efficiency at Tavg = 40°C (EFFTB40)	$kg\ ha^{-1}\ h^{-1}\ J^{-1}$	0.45	0.45	C
Maximum CO_2 assimilation rate at DVS = 000 (AMAXTB000)	$kg\ ha^{-1}\ h^{-1}$	18	20	C
Maximum CO_2 assimilation rate at DVS = 035 (AMAXTB035)	$kg\ ha^{-1}\ h^{-1}$	-	30	C
Maximum CO_2 assimilation rate at DVS = 090 (AMAXTB090)	$kg\ ha^{-1}\ h^{-1}$	40	40	C
Maximum CO_2 assimilation rate at DVS = 200 (AMAX200)	$kg\ ha^{-1}\ h^{-1}$	40	40	C
AMAX reduction factor at Tavg = 0°C (TMPFTB0)	°C	0	0	C
AMAX reduction factor at Tavg = 10°C (TMPFTB10)	°C	0.2	0.2	C
AMAX reduction factor at Tavg = 16°C (TMPFTB16)	°C	1	1	C
AMAX reduction factor at Tavg = 34°C (TMPFTB34)	°C	1	1	C
Correction factor for transpiration rate (CFET)	-	1	1	D
Efficiency of conversion into leaves (CVL)	$kg\ kg^{-1}$	0.754	0.754	D
Efficiency of conversion into storage organs (CVO)	$kg\ kg^{-1}$	0.8	0.8	D
Efficiency of conversion into roots (CVR)	$kg\ kg^{-1}$	0.694	0.694	D
Efficiency of conversion into stems (CVS)	$kg\ kg^{-1}$	0.754	0.754	C
Relative increase in respiration rate per 10°C of temperature increase (Q10)	-	1.8	1.8	C
Relative maintenance respiration rate for leaves (RML)	$kg\ CH_2O\ kg^{-1}\ d^{-1}$	0.03	0.03	C
Relative maintenance respiration rate for storage organs (RMO)	$kg\ CH_2O\ kg^{-1}\ d^{-1}$	0.001	0.01	C
Relative maintenance respiration rate for roots (RMR)	$kg\ CH_2O\ kg^{-1}\ d^{-1}$	0.015	0.015	D
Relative maintenance respiration rate for stems (RMS)	$kg\ CH_2O\ kg^{-1}\ d^{-1}$	0.015	0.015	D
Fraction of total biomass to roots at DVS = 0 (FRTB000)	$kg\ kg^{-1}$	0.5	0.5	D
Fraction of total biomass to roots at DVS = 10 (FRTB10)	$kg\ kg^{-1}$	0.25	0.25	D

Fraction of total biomass to roots at DVS = 100 (FRTB100)	kg kg^{-1}	0	0	D
Fraction of total biomass to roots at DVS = 200 (FRTB200)	kg kg^{-1}	0	0	D
Fraction of aboveground dry matter to leaves at DVS = 0 (FLTB000)	kg kg^{-1}	0.65	0.65	C
Fraction of aboveground dry matter to leaves at DVS = 10 (FLTB010)	kg kg^{-1}	0.65	0.65	C
Fraction of aboveground dry matter to leaves at DVS = 25 (FLTB025)	kg kg^{-1}	0.7	0.7	C
Fraction of aboveground dry matter to leaves at DVS = 60 (FLTB060)	kg kg^{-1}	0.5	0.5	C
Fraction of aboveground dry matter to leaves at DVS = 90 (FLTB090)	kg kg^{-1}	0.0	0.0	C
Fraction of aboveground dry matter to leaves at DVS = 200 (FLTB200)	kg kg^{-1}	0.0	0.0	C
Fraction of aboveground dry matter to storage organs at DVS = 0 (FOTB000)	kg kg^{-1}	0	0	C
Fraction of aboveground dry matter to storage organs at DVS = 90 (FOTB090)	kg kg^{-1}	0	0	C
Fraction of aboveground dry matter to storage organs at DVS = 100 (FOTB100)	kg kg^{-1}	1	1	C
Fraction of aboveground dry matter to storage organs at DVS = 200 (FOTB200)	kg kg^{-1}	1	1	C
Fraction of aboveground dry matter to stems at DVS = 0 (FSTB000)	kg kg^{-1}	0.35	0.35	C
Fraction of aboveground dry matter to stems at DVS = 10 (FSTB010)	kg kg^{-1}	0.35	0.35	C
Fraction of aboveground dry matter to stems at DVS = 25 (FSTB025)	kg kg^{-1}	0.3	0.3	C
Fraction of aboveground dry matter to stems at DVS = 50 (FSTB050)	kg kg^{-1}	0.5	0.5	C
Fraction of aboveground dry matter to stems at DVS = 64.6 (FSTB0646)	kg kg^{-1}	0.7	0.7	C
Fraction of aboveground dry matter to stems at DVS = 95 (FSTB095)	kg kg^{-1}	1	1	C
Fraction of aboveground dry matter to stems at DVS = 100 (FSTB100)	kg kg^{-1}	0	0	C
Fraction of aboveground dry matter to stems at DVS = 200 (FSTB200)	kg kg^{-1}	0.0	0.0	C
Specific stem area at DVS = 0 (SSA000)	ha kg^{-1}	0.0	0.0	D
Specific stem area at DVS = 90 (SSA090)	ha kg^{-1}	0.0	0.0	D
Specific stem area at DVS = 200 (SSA200)	ha kg^{-1}	0.0	0.0	D
Initial total crop dry weight (TDWI)	kg ha^{-1}	210	210	C

[a] Development stage code (unitless; 0: emergence, 100: flowering, 200: physiological maturity)

[b] Average air daily temperature (°C)