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 models WOFOST and CropSyst for soft and durum wheat growth and development in Morocco. For calibration and validation purposes, observations datasets were split in two datasets, taking into account potential and water limited conditions. Three independent sets of parameters were developed (durum wheat, soft wheat – high potential, soft wheat – low potential) for each model. This was decided in agreement with INRA-Morocco partners after the discussions held on 19-22 March 2013 during the Rabat meeting. The accuracy of the two models in reproducing wheat growth under potential conditions is decidedly high and very similar. The simulation of water limited datasets highlighted the higher accuracy of the WOFOST model with respect to CropSyst, especially in the Marchouch experimental site, which presented very low values of aboveground biomass in 2011-2012 cropping season. The two models achieved good performances for water limited datasets, even with a higher correlation with respect to the potential ones. This is crucial for the project objectives because most of the Moroccan wheat area is rainfed, thus an accurate simulation of the impact of water stress on aboveground biomass accumulation is essential to provide effective forecasts about crop productivity under the explored conditions.

NOTE:
This deliverable (D34.3) contains the results of the calibration/validation performed using the data from the field experiments carried out during the first and the second year of the project. This report integrates the partial version of the deliverable which was submitted in month 24, to address the request from the Project Reviewers, in order 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 and CropSyst models were collected in four experimental stations of INRA-Morocco selected during the year 2011 (Sidi-El-Aydi, Khemis-Zemamra, Marchouch and Jemaa Shaim). Table 1 reports the coordinates, the vocation and the major biotic and abiotic stresses of wheat in these four experimental sites.

Table 1. Location and vocation of the experimental stations of INRA-Morocco.

INRA Experimental Station	Coordinates		Agroecological zone	Major stresses	Growing Season
	Lat.	Long.			
Jemaa-Shaim	32.350	-8.850	Semi arid	Drought, Hessian fly, Leaf rust	2012-2013
Khemiss Zmamra	32.633	-8.700	Semi arid	Drought, Hessian fly, Leaf rust	2011-2012 2012-2013
Marchouch	33.987	-6.496	Favourable	Rusts, septoria, Hessian fly, drought	2011-2012
Sidi El Aydi	33.167	-7.400	Intermediate	Drought, Hessian fly, rusts	2011-2012 2012-2013

Figure 1 reports the geographical distribution of the four experimental stations.

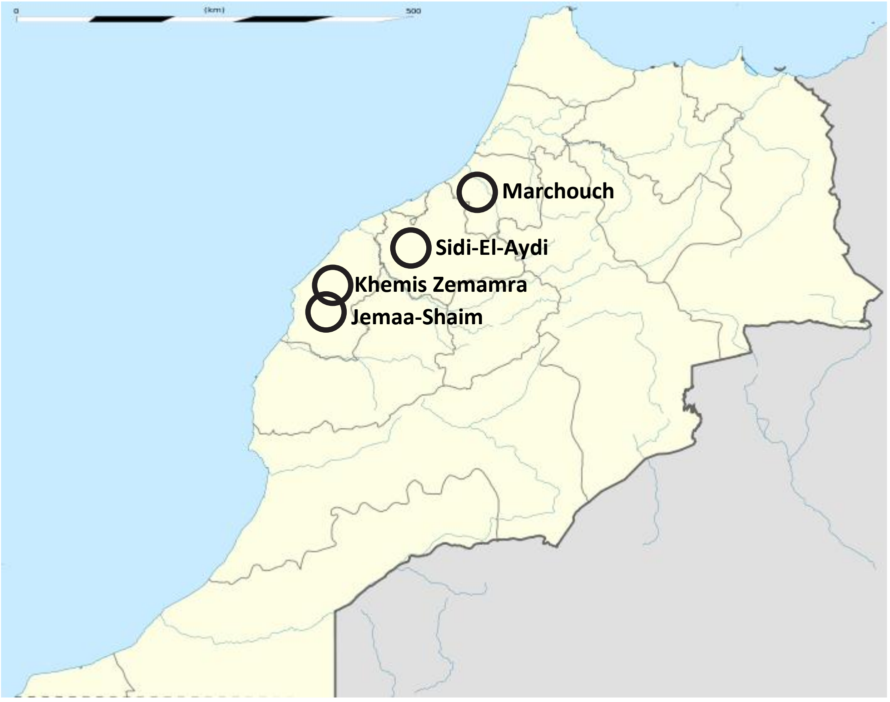

Figure 1. Distribution of the INRA-Morocco experimental sites in the study region.

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). After the discussions held during the Rabat Meeting, UNIMI and INRA-Morocco agreed to develop three independent parameter sets for each model, one for durum wheat (cv. Marzak, Tarek and Karim), one for soft wheat – low productivity (cv. Achtar and Amal) and one for soft wheat – high productivity (cv. Arrihanne). The details about the datasets and years used for calibration and evaluation of models performances are reported in Table 2, 3, 4 and 5 for durum wheat, soft wheat – low productivity, soft wheat – high productivity and water limited conditions, respectively. The dataset related to potential production were used to calibrate phenological development of the three wheat types.

Table 2. Moroccan datasets selected for calibration and evaluation of durum wheat. In the dataset identifier (ID), P stands for potential conditions.

		Calibration		
ID	**Wheat variety**	**Site**	**Year**	**Growing condition**
SEA_11_P_A	Marzak	Sidi El Aydi	2011-2012	Potential Production
SEA_11_P_C	Karim	Sidi El Aydi	2011-2012	Potential Production
KHZ_11_P_B	Tarek	Khemis-Zemamra	2011-2012	Potential Production
SEA_12_P_B	Tarek	Sidi El Aydi	2012-2013	Potential Production
KHZ_12_P_A	Marzak	Khemis-Zemamra	2012-2013	Potential Production
KHZ_12_P_C	Karim	Khemis-Zemamra	2012-2013	Potential Production
		Evaluation		
ID	**Wheat variety**	**Site**	**Data**	**Growing condition**
SEA_11_P_B	Tarek	Sidi El Aydi	2011-2012	Potential Production
KHZ_11_P_A	Marzak	Khemis-Zemamra	2011-2012	Potential Production
KHZ_11_P_C	Karim	Khemis-Zemamra	2011-2012	Potential Production
SEA_12_P_A	Marzak	Sidi El Aydi	2012-2013	Potential Production
SEA_12_P_C	Karim	Sidi El Aydi	2012-2013	Potential Production
KHZ_12_P_B	Tarek	Khemis-Zemamra	20 j12-2013	Potential Production

Table 3. Moroccan datasets selected for calibration and evaluation of soft wheat – low productivity. In the dataset identifier (ID), P stands for potential conditions.

		Calibration		
ID	**Wheat variety**	**Site**	**Year**	**Growing condition**
SEA_11_P_D	Achtar	Sidi El Aydi	2011-2012	Potential Production
KHZ_11_P_E	Amal	Khemis-Zemamra	2011-2012	Potential Production
SEA_12_P_E	Amal	Sidi El Aydi	2012-2013	Potential Production
KHZ_12_P_D	Achtar	Khemis-Zemamra	2012-2013	Potential Production
		Evaluation		
ID	**Wheat variety**	**Site**	**Data**	**Growing condition**
SEA_11_P_E	Amal	Sidi El Aydi	2011-2012	Potential Production
KHZ_11_P_D	Achtar	Khemis-Zemamra	2011-2012	Potential Production
SEA_12_P_D	Achtar	Sidi El Aydi	2012-2013	Potential Production
KHZ_12_P_E	Amal	Khemis-Zemamra	2012-2013	Potential Production

Table 4. Moroccan datasets selected for calibration and evaluation for soft wheat – high productivity. In the dataset identifier (ID), P stands for potential conditions.

Calibration				
ID	**Wheat variety**	**Site**	**Year**	**Growing condition**
SEA_11_P_F	Arrihanne	Sidi El Aydi	2011-2012	Potential Production
KHZ_12_P_F	Arrihanne	Khemis-Zemamra	2012-2013	Potential Production
Evaluation				
ID	**Wheat variety**	**Site**	**Data**	**Growing condition**
KHZ_11_P_F	Arrihanne	Khemis-Zemamra	2011-2012	Potential Production
SEA_12_P_F	Arrihanne	Sidi El Aydi	2012-2013	Potential Production

Table 5. Moroccan datasets selected for model evaluation for durum wheat, soft wheat – high productivity and soft wheat – low productivity under water limited conditions. In the dataset identifier (ID), WL stands for water limited conditions.

Evaluation					
ID	**Wheat variety**	**Wheat type**	**Site**	**Year**	**Growing condition**
SEA_11_WL_A	Marzak	Durum	Sidi El Aydi	2011-2012	Water Limited
SEA_11_WL_B	Tarek	Durum	Sidi El Aydi	2011-2012	Water Limited
SEA_11_WL_C	Karim	Durum	Sidi El Aydi	2011-2012	Water Limited
SEA_11_WL_D	Achtar	Soft-low	Sidi El Aydi	2011-2012	Water Limited
SEA_11_WL_E	Amal	Soft-low	Sidi El Aydi	2011-2012	Water Limited
SEA_11_WL_F	Arrihanne	Soft-high	Sidi El Aydi	2011-2012	Water Limited
MAR_11_WL_A	Marzak	Durum	Marchouch	2011-2012	Water Limited
MAR_11_WL_B	Tarek	Durum	Marchouch	2011-2012	Water Limited
MAR_11_WL_C	Karim	Durum	Marchouch	2011-2012	Water Limited
MAR_11_WL_D	Achtar	Soft-low	Marchouch	2011-2012	Water Limited
MAR_11_WL_E	Amal	Soft-low	Marchouch	2011-2012	Water Limited
MAR_11_WL_F	Arrihanne	Soft-high	Marchouch	2011-2012	Water Limited
SEA_12_WL_A	Marzak	Durum	Sidi El Aydi	2012-2013	Water Limited
SEA_12_WL_B	Tarek	Durum	Sidi El Aydi	2012-2013	Water Limited
SEA_12_WL_C	Karim	Durum	Sidi El Aydi	2012-2013	Water Limited
SEA_12_WL_D	Achtar	Soft-low	Sidi El Aydi	2012-2013	Water Limited
SEA_12_WL_E	Amal	Soft-low	Sidi El Aydi	2012-2013	Water Limited
SEA_12_WL_F	Arrihanne	Soft-high	Sidi El Aydi	2012-2013	Water Limited

Before the calibration of the two crop models, an analisys of wheat aerial biomass and leaf area index measurements was performed. Some datasets showed unexpected patterns related to very high values of biomass in the penultimate available measurement followed by a decided decrease in the last one. Figure 2 presents an example in the KHZ_D_A, KHZ_D_B and KHZ_D_C datasets.

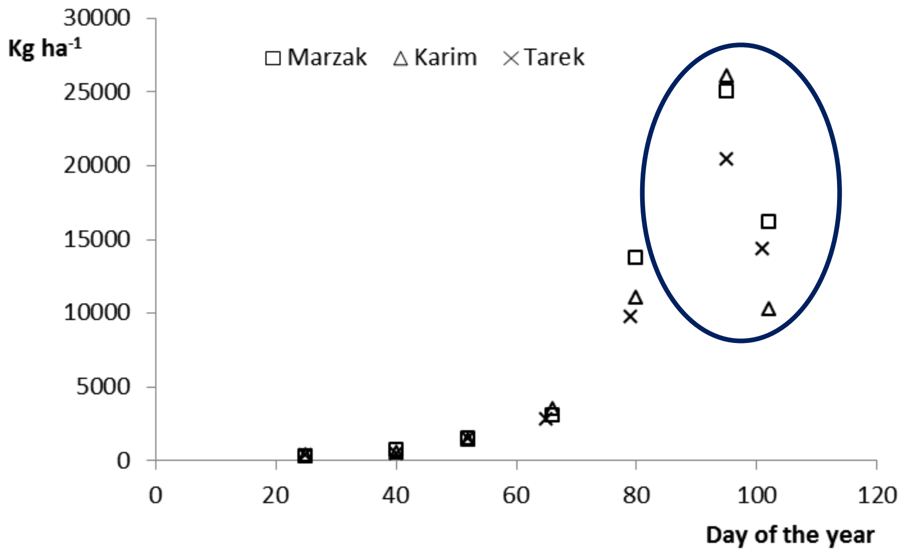

Figure 2. Total aboveground biomass measured at Khemis Zemamra site in 2012.

The reason of this pattern was clarified during the Rabat meeting: an heavy attack of Hessian fly during the 2011-2012 cropping season caused a rapid decline of aboveground biomass in the whole wheat Moroccan area. For this reason, since both CropSyst and WOFOST models did not include the simulation of pest damages to production, the last sampling was excluded from the calibration and evaluation activities.
When INRA-Morocco partners delivered the data related to the 2012-2013 cropping season, they provided metadata about the field experiments in order to explain the unexpected pattern of aboveground biomass in their field experiments. In this report we report their observations related to the Khemis-Zemamra experimental site:

- Late sowing
- Heavy attack of Hessian Fly
- Diseases attack even with treatments

These evidences forced us to calibrate the CropSyst and WOFOST models aiming at reproducing the highest measured biomass value in all the experiments, thus assuming that the observed decline is reasonably due to pest and disease impact on wheat crop.
An analogue behaviour, even more pronounced, can be observed in the 2012-2013 growing season in Jemaa-Shaim experimental site, in which wheat was grown under water stressed conditions (Figure 3, data from the three available cultivars of durum wheat). For this dataset the soil profile data were unavailable. In this site, the measured aboveground biomass is decidedly below the values of the other stations (maximum value around 6000 kg ha^{-1} against 12000 kg ha^{-1} of Sidi-El-Aydi) and the values of measured biomass start to

decline after February, 12th. It can be supposed that even in this situation Hessian fly or other biotic stresses (e.g., leaf rusts, septoria) contributed to damage wheat crop, thus rendering these data unsuitable for calibration and/or evaluation purposes. For this reason, these data were not used in the evaluation of the CropSyst and WOFOST models.

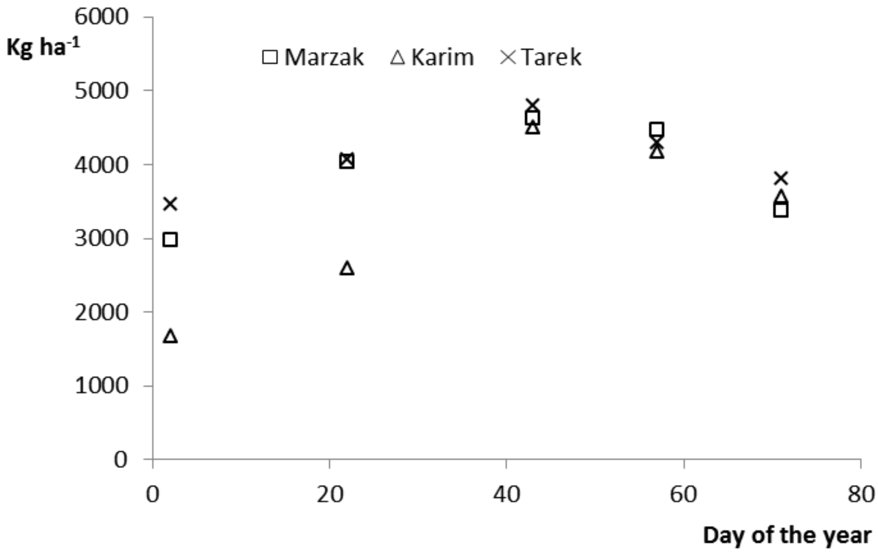

Figure 3. Total aboveground biomass measured at Jemaa-Shaim experimental site in 2013

Another criticality is related to the leaf area index data (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 suggests that LAI measures are therefore too low compared to the aboveground biomass values collected in the field experiments. A literature search was performed aiming at investigating this issue and LAI values decidedly higher for wheat grown were found in ISI papers about wheat grown in the Moroccan environment, 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-

[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.

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 instrumentation adopted strongly affects the accuracy of the measurements. For these reasons it was decided not to use 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.

During the Rabat meeting it emerged that irrigation system in 2011 at Sidi-El-Aydi experimental site encountered some problems, and Moroccan partners suggested that this could be the main reason explaining the low values of LAI. However, they confirmed that their wheat varieties show a high resistance to water stress, thus justifying high production levels with low LAI values.

1.1.2. The meteorological datasets

The meteorological datasets to calibrate the models were recorded in meteorological stations placed near the fields. This is a clear step forward with respect to the preliminary calibration activities (see the partial version of this report), in which the meteorological data derived from the MARS database[5] were used to calibrate and evaluate the WOFOST model. An analysis of the meteorological data coming from the four experimental sites was performed, and the results are reported in the paragraph below.

1.1.2.1. Air temperature

Figures 4 and 5 show the average monthly air maximum temperature recorded in the weather stations of Marchouch (only 2012 available), Khemis-Zemamra and Sidi-El-Aydi in 2011-2012 and 2012-2013 cropping seasons.

[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

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.

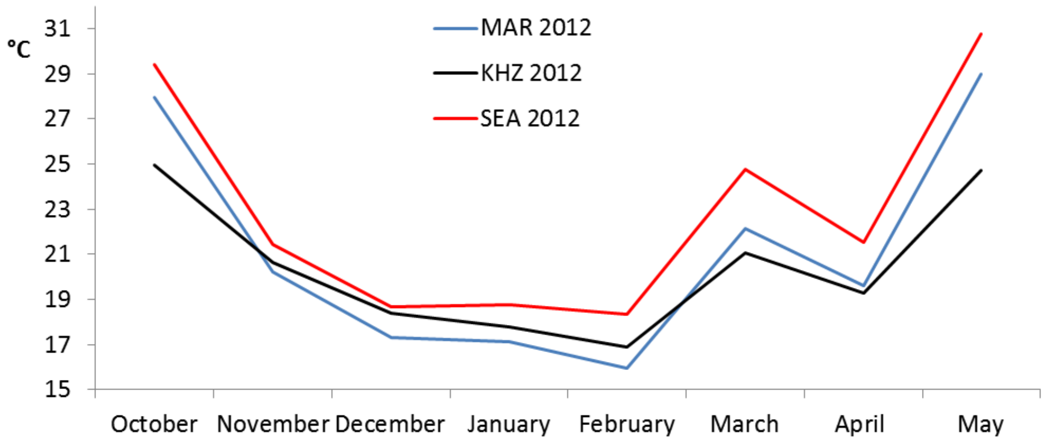

Figure 4. Comparison of average maximum air temperature measured in the weather stations of Marchouch (MAR), Khemis-Zemamra (KHZ) and Sidi-El-Aydi (SEA) in the wheat growing period in 2011-2012.

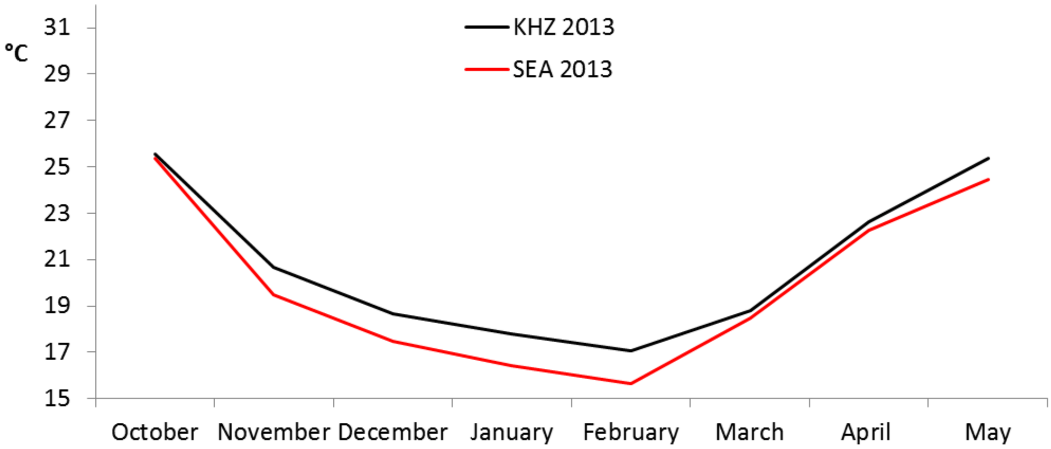

Figure 5. Comparison of average maximum air temperature measured in the weather stations of Khemis-Zemamra (KHZ) and Sidi-El-Aydi (SEA) in the wheat growing period in 2012-2013.

In the 2011-2012 cropping season, the average maximum temperature for the available experimental sites was higher in Sidi-El-Aydi during the whole wheat growing period. In this experimental station and in the Marchouch one, there were very high values in October and May (around 30°C). During the winter period, average maximum temperature remained at high levels, always above 15°C in the three experimental sites.

In the 2012-2013 cropping season, the average maximum air temperature was decidedly lower (maximum average air temperature around 26°C in both experimental sites) than in 2011-2012, and the highest values were recorded in Khemis-Zemamra.
Figures 5 and 6 report the average monthly air minimum temperature recorded in the weather stations of Marchouch (only 2012 available), Khemis-Zemamra and Sidi-El-Aydi in 2011-2012 and 2012-2013 cropping seasons.

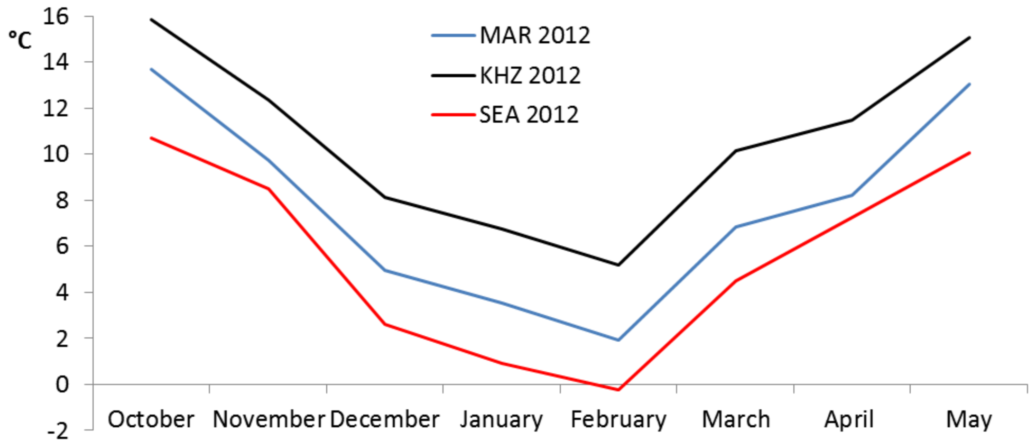

Figure 6. Comparison of average minimum air temperature measured in the weather stations of Khemis-Zemamra (KHZ) and Sidi-El-Aydi (SEA) in the wheat growing period in 2011-2012.

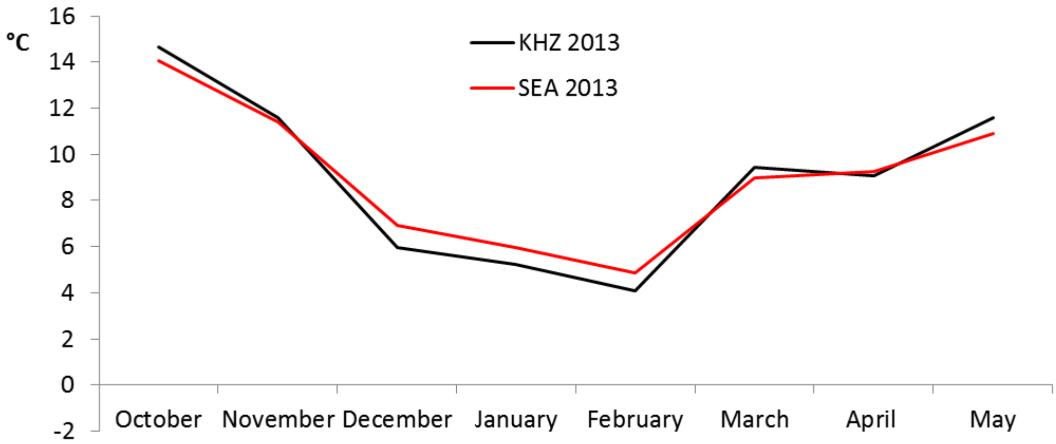

Figure 7. Comparison of average minimum air temperature measured in the weather stations of Khemis-Zemamra (KHZ) and Sidi-El-Aydi (SEA) in the wheat growing period in 2012-2013.

During the 2011-2012 cropping season, average minimum temperature in Khemis-Zemamra experimental site was higher than in the other two sites, with the lowest value in February (5.17 °C). This determine, in conjunction with average maximum air temperature values, very suitable thermal conditions for wheat growth, characterized by sub-optimal or optimal temperatures in the whole cropping season. Average minimum air temperatures in Sidi-El-Aydi were colder, with lowest value below 0°C in February. This experimental site is thus characterized by the highest average thermal excursion among the available ones. In 2012-2013 cropping season, average minimum temperatures are higher than in 2012-2013 and very similar in Khemis-Zemamra and Sidi-El-Aydi, with values in the range from 4°C (February) to 15°C (October).

1.1.2.2. Global solar radiation

Figures 8 and 9 show the average global solar radiation measured in the weather stations of Marchouch (only 2012 available), Khemis-Zemamra and Sidi-El-Aydi in 2011-2012 and 2012-2013 cropping seasons.

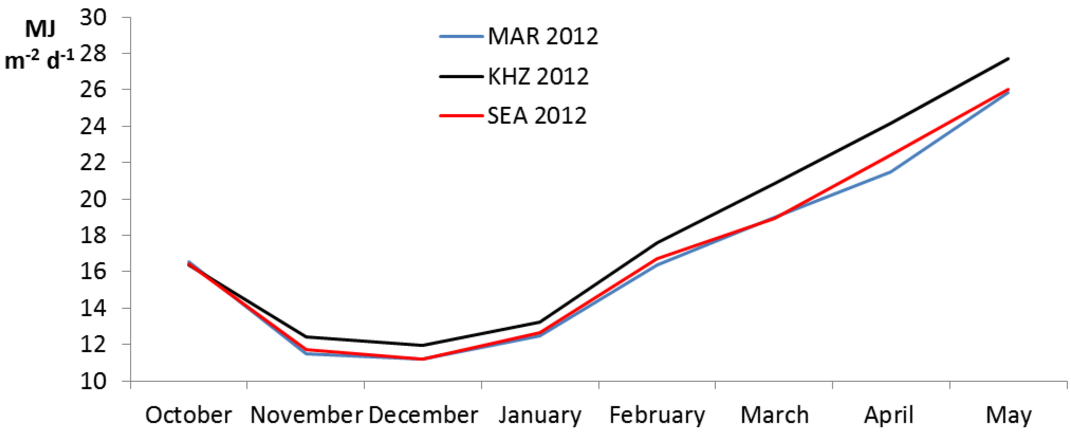

Figure 8. Comparison of average global solar radiation measured in the weather stations of Khemis-Zemamra (KHZ) and Sidi-El-Aydi (SEA) in the wheat growing period in 2011-2012

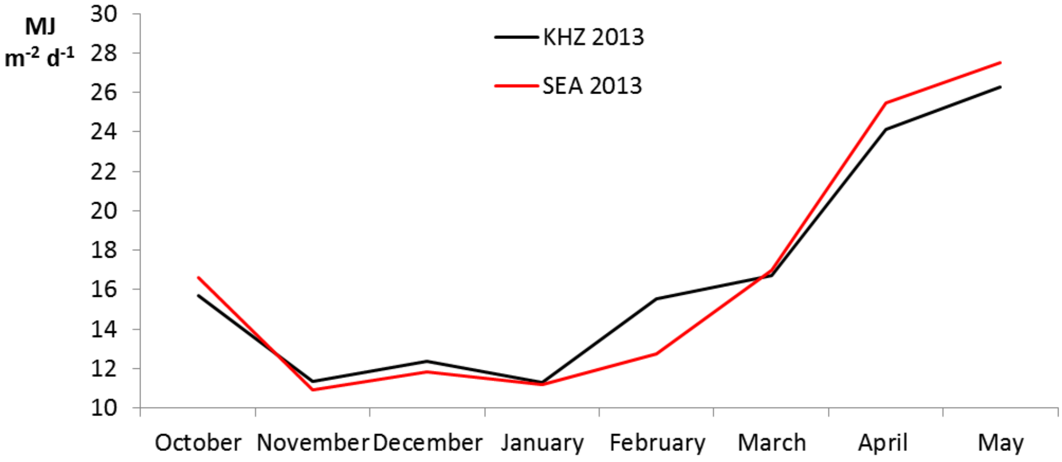

Figure 9. Comparison of average global solar radiation measured in the weather stations of Khemis-Zemamra (KHZ) and Sidi-El-Aydi (SEA) in the wheat growing period in 2012-2013.

Average global solar radiation values in cropping season 2011-2012 measured in the three weather stations are very similar, ranging from 11 MJ m^{-2} d^{-1} in November and December to 28 MJ m^{-2} d^{-1} in May. The pattern of radiation in 2012-2013 cropping season is different in the two experimental sites available, with higher values in February in Khemis-Zemamra than in Sidi-El-Aydi whereas in May this situation is inverted.

1.1.2.3. Precipitation

Figures 10 and 11 show the sum of precipitations recorded in the weather stations of Marchouch (only 2012 available), Khemis-Zemamra and Sidi-El-Aydi in 2011-2012 and 2012-2013 cropping seasons.

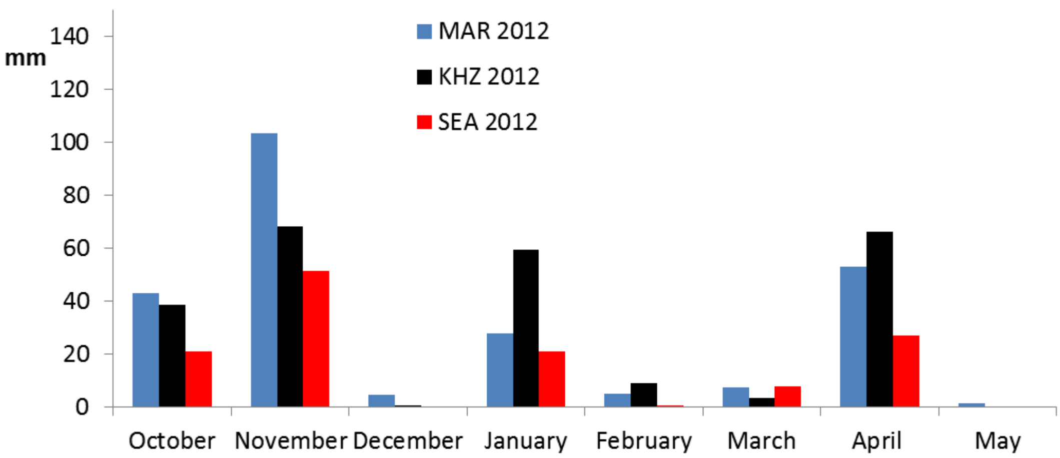

Figure 10. Comparison of the sum of precipitations recorded in the weather stations of Khemis-Zemamra (KHZ) and Sidi-El-Aydi (SEA) in the wheat growing period in 2011-2012.

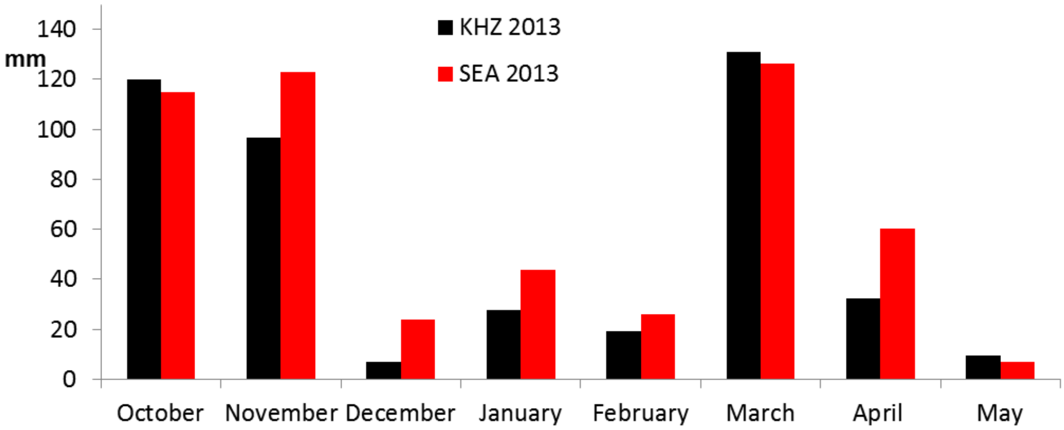

Figure 11. Comparison of the sum of precipitations recorded in the weather stations of Khemis-Zemamra (KHZ) and Sidi-El-Aydi (SEA) in the wheat growing period in 2011-2012.

Precipitation regime in the 2011-2012 cropping season was quite similar in the three experimental sites. November and April resulted the months with the highest cumulated rain, whereas the most arid conditions occurred in December, February and March (below 20 mm).

Cropping season 2012-2013 was characterized by decidedly higher precipitation along the whole wheat growing period. Very high values were recorded in March, November and October (above 100 mm in the two experimental sites of Khemis-Zemamra and Sidi-El-Aydi). Also in the winter period (December, January and February), precipitations were higher than 2011-2012, thus suggesting more favourable conditions for rainfed wheat crop.

2. Results and Discussion

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

The complete list of the calibrated parameter values for the WOFOST model are reported in the Appendix A for durum wheat and Appendix B for soft wheat – low productivity and high productivity. The parameter values for the CropSyst model are reported in Appendix C for durum wheat and Appendix D for soft wheat – low productivity and high productivity. The discussion about the results of the calibration of phenology is separated from the one of aboveground biomass. Both for phenology and biomass accumulation, the results of the simulations carried out with durum wheat, soft wheat – low productivity and soft wheat – high productivity are separated.

2.1.1. Simulation of phenology

When calibrating a crop model, the first parameters to adjust are those affecting plant development. In the Moroccan field experiments, the available measurements are related to emergence, flowering and maturity dates, therefore for each crop cycle the parameters related to these three phases were calibrated.

2.1.1.1. Durum wheat

Table 6 reports all the simulated and observed values for the potential datasets tested for durum wheat.

Table 6. Observed and simulated values of phenological dates in the potential datasets (durum wheat).

ID	Phase	Measured	WOFOST	CropSyst
SEA_11_P_A	emergence	341	342	342
SEA_11_P_A	flowering	88	104	104
SEA_11_P_A	maturity	131	137	138
SEA_12_P_A	emergence	328	327	327
SEA_12_P_A	flowering	65	97	96
SEA_12_P_A	maturity	110	129	127
SEA_11_P_C	emergence	341	342	342
SEA_11_P_C	flowering	90	104	104
SEA_11_P_C	maturity	133	137	138
SEA_12_P_C	emergence	328	327	327
SEA_12_P_C	flowering	66	97	96
SEA_12_P_C	maturity	114	129	127
SEA_11_P_B	emergence	341	342	342
SEA_11_P_B	flowering	90	104	104
SEA_11_P_B	maturity	133	137	138
SEA_12_P_B	emergence	328	327	327
SEA_12_P_B	flowering	60	97	96
SEA_12_P_B	maturity	116	129	127
KHZ_11_P_A	emergence	27	350	350
KHZ_11_P_A	flowering	141	98	98
KHZ_11_P_A	maturity	165	132	130
KHZ_12_P_A	emergence	341	338	338
KHZ_12_P_A	flowering	100	99	99
KHZ_12_P_A	maturity	128	130	129
KHZ_11_P_C	emergence	24	350	350
KHZ_11_P_C	flowering	137	98	98
KHZ_11_P_C	maturity	158	132	130
KHZ_12_P_C	emergence	347	338	338
KHZ_12_P_C	flowering	91	99	99
KHZ_12_P_C	maturity	135	130	129
KHZ_11_P_B	emergence	29	350	350
KHZ_11_P_B	flowering	145	98	98
KHZ_11_P_B	maturity	169	132	130
KHZ_12_P_B	emergence	344	338	338
KHZ_12_P_B	flowering	86	99	99
KHZ_12_P_B	maturity	122	130	129

The parameter values chosen for the two models led to an overall satisfactory simulation of phenology. Figure 12 reports the scatter plot of measured and simulated values for CropSyst and WOFOST.

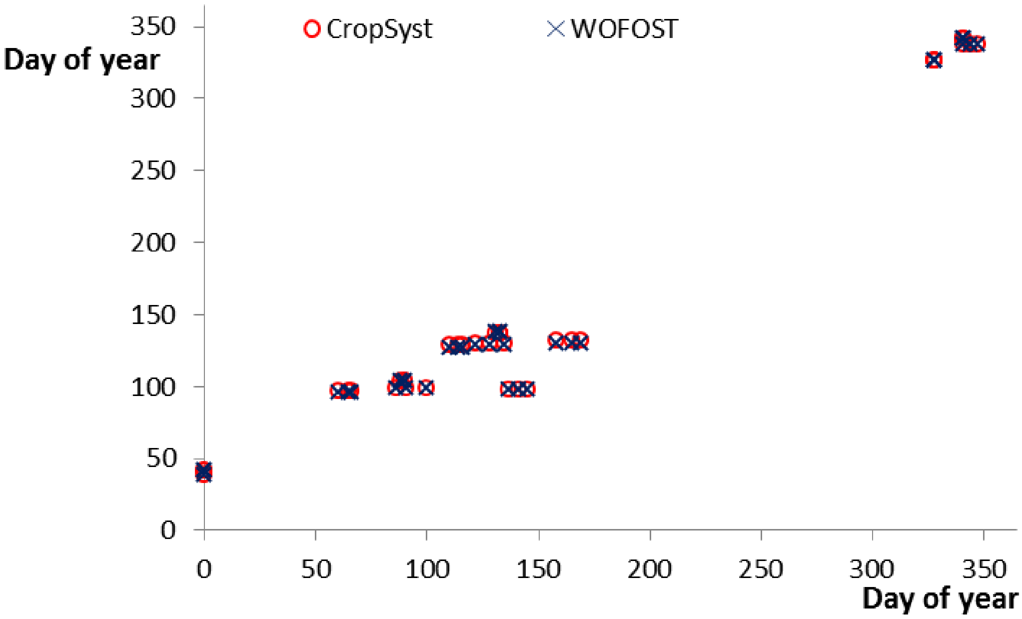

Figure 12. Scatter plot showing the correlation between the simulated and the observed day of year related to the phenological phases of emergence, flowering and maturity of durum wheat for WOFOST and CropSyst model

The simulation of phenology of durum wheat carried out with the two models is decidedly similar, with a very high correlation for both CropSyst (R^2=0.97) and WOFOST (R^2=0.96). Table 12 reports the values of some of the mostly used fitting indices, 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 as formulated by Loague and Green (1991)[6] (CD, 0÷∞), other than regression indices (Slope, Intercept and Squared R). The same indices presented here will be used throughout this document also for the evaluation of aboveground biomass.

[6] Loague, K., and R.E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. J. Contam. Hydrol., 7:51-73.

Table 7. Indices of agreement between measured and simulated phenological dates referred to the durum wheat datasets

	Indices							
Model	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (days)**	**R^2**
CropSyst	13.64	12.21	0.97	0.00	1.06	1.01	-1.36	0.97
WOFOST	14.85	11.71	0.96	0.00	1.06	1.01	-0.96	0.96

The average absolute error of the two models is very similar (13.64 days for CropSyst and 14.85 days for WOFOST), as the RRMSE values (around 12 for both the models), and they highlight the very good performance of the two models.

2.1.1.2. Soft wheat – low productivity

Table 8 reports all the simulated and observed values for the potential datasets tested for soft wheat – low productivity.

Table 8. Observed and simulated values of phenological dates in the potential datasets (soft wheat – low productivity).

ID	Phase	Measured	WOFOST	CropSyst
SEA_11_P_D	emergence	341	345	345
SEA_11_P_D	flowering	100	101	101
SEA_11_P_D	maturity	132	140	138
SEA_12_P_D	emergence	328	329	329
SEA_12_P_D	flowering	73	95	95
SEA_12_P_D	maturity	116	131	132
SEA_11_P_E	emergence	341	345	345
SEA_11_P_E	flowering	102	101	95
SEA_11_P_E	maturity	134	140	138
SEA_12_P_E	emergence	328	329	329
SEA_12_P_E	flowering	79	95	99
SEA_12_P_E	maturity	118	131	132
SEA_11_P_D	emergence	362	352	352
SEA_11_P_D	flowering	121	96	95
SEA_11_P_D	maturity	141	133	134
SEA_12_P_D	emergence	343	342	341
SEA_12_P_D	flowering	111	97	96
SEA_12_P_D	maturity	150	132	132
KHZ_11_P_E	emergence	364	352	352
KHZ_11_P_E	flowering	101	96	95
KHZ_11_P_E	maturity	145	133	134
KHZ_12_P_E	emergence	345	342	341
KHZ_12_P_E	flowering	105	97	96
KHZ_12_P_E	maturity	140	132	132

The parameter values chosen for the two models led to a very good performance of the simulation of phenology of soft wheat – low productivity. Figure 13 reports the scatter plot of measured and simulated values for CropSyst and WOFOST

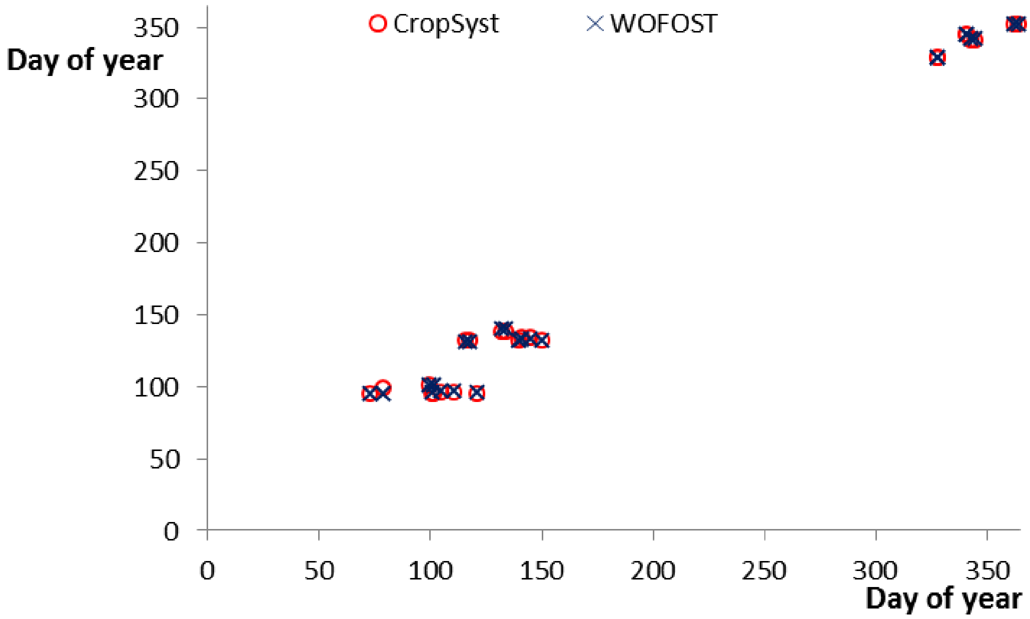

Figure 13. Scatter plot showing the correlation between the simulated and the observed day of year related to the phenological phases of emergence, flowering and maturity of soft wheat – low productivity for WOFOST and CropSyst model

As observed for durum wheat, the simulation of phenology of soft wheat – low productivity carried out with the two models is decidedly similar, with a very good correlation for both CropSyst and WOFOST (R^2=0.99 for both the models).
Table 9 reports the values of some fitting indices, quantifying the agreement between measured and simulated data.

Table 9. Indices of agreement between measured and simulated phenological dates referred to the soft wheat – low productivity datasets

	Indices							
Model	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (days)**	**R^2**
CropSyst	9.50	6.10	0.99	0.01	1.02	1.00	1.27	0.99
WOFOST	9.00	5.84	0.99	0.01	1.02	1.00	0.69	0.99

The simulations are characterized by a very high value of modelling efficiencies and by very good values of MAE (9.5 days for CropSyst and 9 days for WOFOST) and RRMSE (6.10 for

CropSyst and 5.84 for WOFOST)for both the models. In general the performances of CropSyst and WOFOST for the soft wheat – low productivity phenological simulation are slightly better than the ones obtained for durum wheat.

2.1.1.3. Soft wheat – high productivity

Table 10 reports all the simulated and observed values for the potential datasets tested for soft wheat – high productivity.

Table 10. Observed and simulated values of phenological dates in the potential datasets (soft wheat – high productivity).

ID	Phase	Measured	WOFOST	CropSyst
SEA_11_P_F	emergence	341	345	345
SEA_11_P_F	flowering	87	87	100
SEA_11_P_F	maturity	120	126	134
SEA_12_P_F	emergence	341	329	329
SEA_12_P_F	flowering	110	91	93
SEA_12_P_F	maturity	130	131	127
KHZ_11_P_F	emergence	360	352	352
KHZ_11_P_F	flowering	98	83	94
KHZ_11_P_F	maturity	131	118	129
KHZ_12_P_F	emergence	341	342	342
KHZ_12_P_F	flowering	110	94	94
KHZ_12_P_F	maturity	130	132	127

As discussed for the other two wheat types, also in this case the parameter values chosen for the two models led to a very good performance of the simulation of phenology, but with some differences between the two models, in particular in the flowering dates (e.g., thirteen days of difference in SEA_11_P_F, eleven days of difference in KHZ_11_P_F). Figure 14 reports the scatter plot of measured and simulated values for CropSyst and WOFOST.

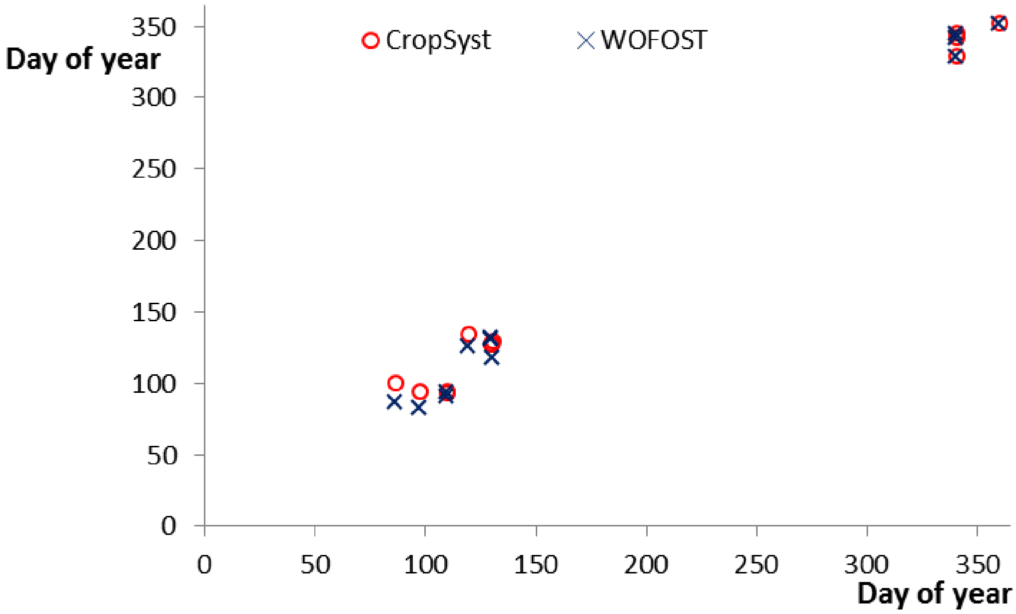

Figure 14. Scatter plot showing the correlation between the simulated and the observed day of year related to the phenological phases of emergence, flowering and maturity of soft wheat – high productivity for WOFOST and CropSyst model

The simulation of phenology of soft wheat – high productivity carried out with the two models is similar, with a very good correlation for both CropSyst and WOFOST (R^2=0.99 for both the models).

Table 11 reports the values of some fitting indices, quantifying the agreement between measured and simulated data.

Table 11. Indices of agreement between measured and simulated phenological dates referred to the soft wheat – high productivity datasets

	Indices							
Model	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (days)**	**R^2**
CropSyst	8.08	5.16	0.99	0.01	1.01	1.00	2.60	0.99
WOFOST	8.08	5.38	0.99	0.03	0.96	0.98	9.37	0.99

The simulations of phenological development of soft wheat – high productivity are characterized by a very high value of modelling efficiencies (0.99 fpor both models) and by very good values of MAE and RRMSE for both the models (around 5%). In general the performances of CropSyst and WOFOST for the soft wheat – high productivity phenological simulation are in line with the ones obtained for the low productivity wheat types.

2.1.2. Simulation of aboveground biomass

Once crop development was calibrated, the parameters involved in wheat growing were considered. A particular effort was put in the calibration of those parameters that showed a maximum influence on output variation, according to the sensitivity analysis results (see report D3.2.1 and Confalonieri et al., 2012[7]).

2.1.2.1. Durum wheat

The AGB trends simulated by the CropSyst model in the calibration and evaluation datasets of durum wheat are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 16 (Khemis-Zemamra experimental site), compared with data collected at different stages of wheat growth. The AGB trends simulated by the WOFOST model in the calibration and evaluation datasets of durum wheat are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 18 (Khemis-Zemamra experimental site), compared with data collected at different stages of wheat growth.

[7] 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.

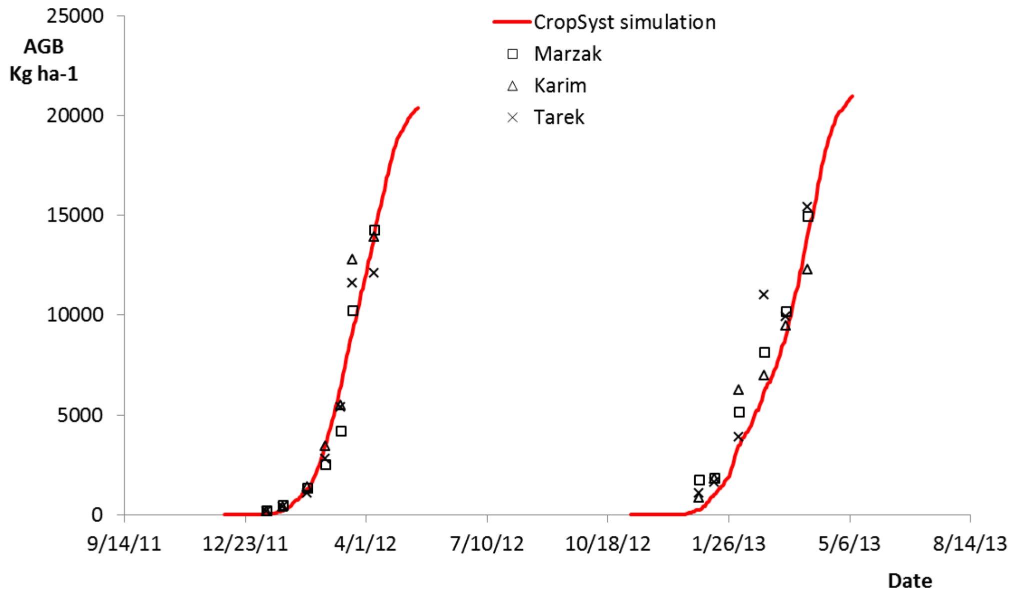

Figure 15. Comparison between measured (squares, triangles and crosses identify the different cultivars) and simulated (red line) aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, CropSyst model

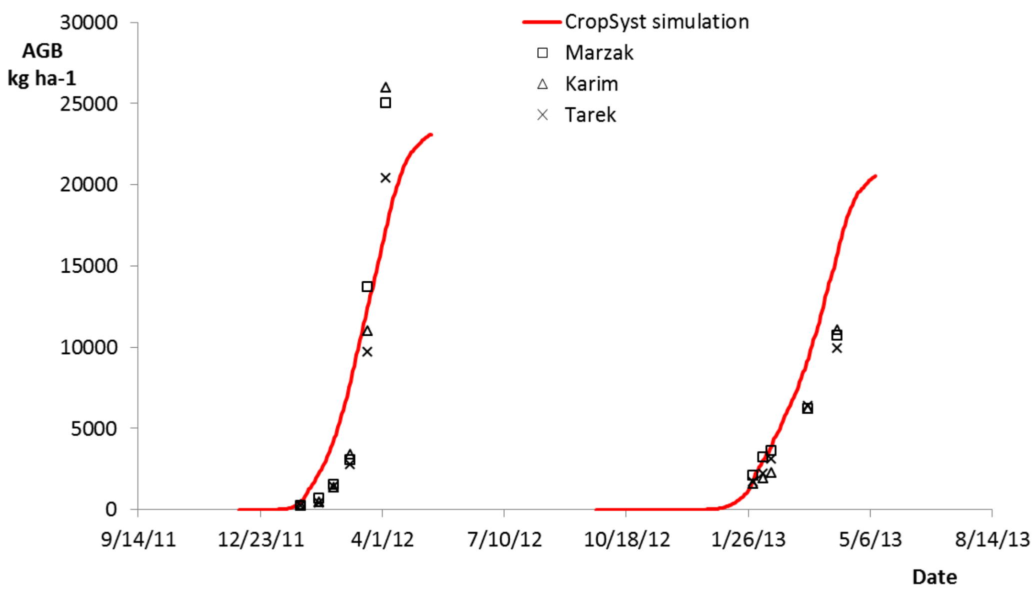

Figure 16. Comparison between measured (squares, triangles and crosses identify the different cultivars) and simulated (red line) aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Khemis-Zemamra, CropSyst model

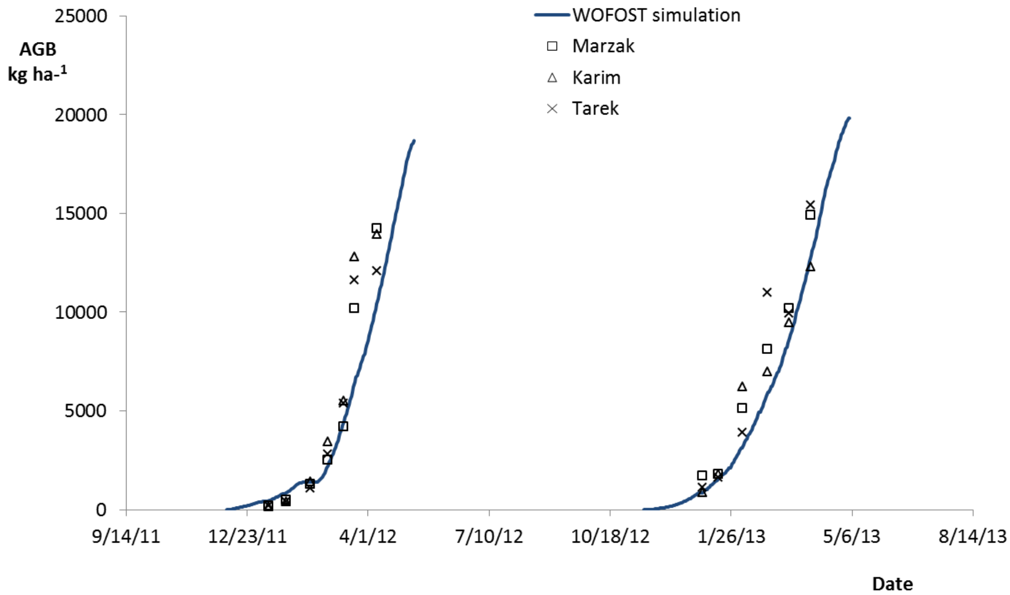

Figure 17. Comparison between measured (squares, triangles and crosses identify the different cultivars) and simulated (blue line) aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, WOFOST model

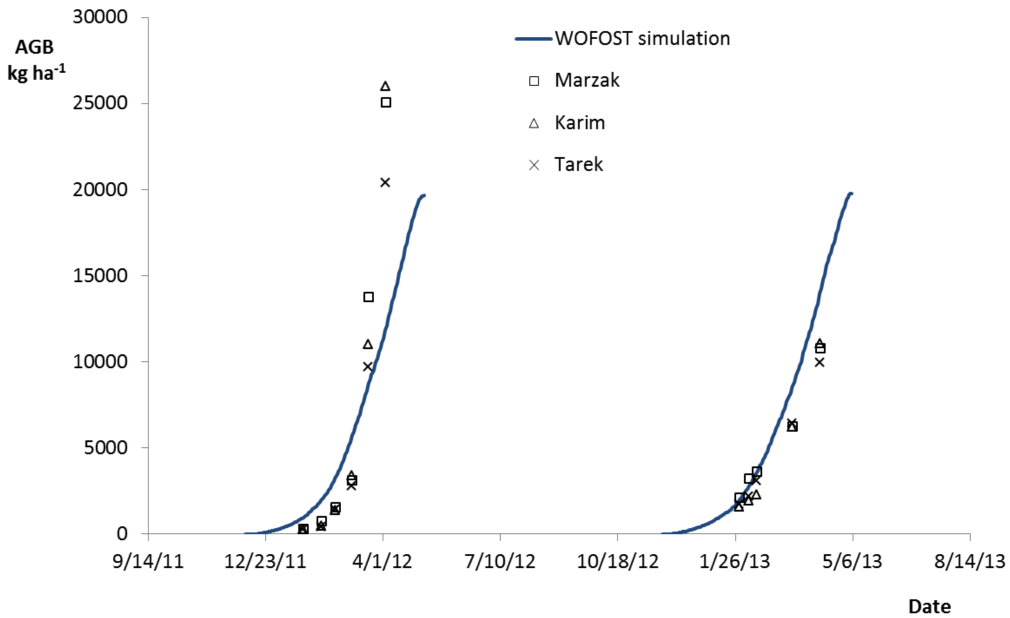

Figure 18. Comparison between measured (squares, triangles and crosses identify the different cultivars) and simulated (blue line) aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Khemis-Zemamra, WOFOST model

The overall measured trends were accurately reproduced by both CropSyst and WOFOST in calibration and validation dataset. It can be observed a slight better performance of the two models in the Sidi-El-Aydi experimental site with respect to the Khemis-Zemamra one. This can also be due to the unexpected pattern of aboveground biomass in this site, as already discussed in paragraph 1.1.1. In general, the aboveground biomass values are very high, and there are some differences among the three cultivar tested, in particular in the late part of the growing seasons.
In order to evaluate the accuracy of the models, in Table 12 and Table 13 the values of some fitting indices are presented for the CropSyst and WOFOST models, respectively, quantifying the agreement between measured and simulated data. The indices are the same of the ones used for the evaluation of the simulation of phenology. See also report D3.2.3 for the description of the evaluation procedure.

Table 12. Indices of agreement between measured and simulated AGB values referred to the durum wheat datasets for the CropSyst model

				Calibration				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_P_A	732.84	23.74	0.95	-0.07	1.05	1.00	-350.10	0.95
SEA_11_P_C	1020.45	27.58	0.92	-0.06	0.95	0.94	38.73	0.93
KHZ_11_P_B	2633.92	51.82	0.83	-0.27	1.42	1.17	-2822.18	0.89
SEA_12_P_B	1178.08	23.51	0.86	0.08	0.67	0.80	1676.71	0.94
KHZ_12_P_A	1782.07	51.48	0.26	-0.31	0.32	0.59	1141.10	0.99
KHZ_12_P_C	2180.71	58.68	0.45	-0.47	0.42	0.70	-138.31	0.99
AVERAGE	***1588.01***	***39.47***	***0.71***	***-0.18***	***0.81***	***0.87***	***-75.68***	***0.95***
				Evaluation				
SEA_11_P_B	779.71	26.19	0.93	0.06	1.19	1.06	25.71	0.94
KHZ_11_P_A	3042.50	53.75	0.81	0.00	2.40	1.47	-3550.18	0.90
KHZ_11_P_C	3243.64	60.40	0.78	-0.05	2.44	1.46	-3764.91	0.87
SEA_12_P_A	1191.91	18.30	0.93	0.17	0.87	0.96	1434.20	0.99
SEA_12_P_C	1178.08	23.51	0.86	0.08	0.67	0.80	1676.67	0.94
KHZ_12_P_B	2107.39	63.67	0.08	-0.45	0.31	0.60	620.35	1.00
AVERAGE	***1923.87***	***40.97***	***0.73***	***-0.03***	***1.31***	***1.06***	***-593.03***	***0.94***

Table 13. Indices of agreement between measured and simulated AGB values referred to the durum wheat datasets for the WOFOST model

ID	MAE	RRMSE	EF	CRM	CD	Slope	Intercept (t/ha)	R^2
Calibration								
SEA_11_P_A	1089.91	35.69	0.89	0.16	1.87	1.38	-793.18	0.98
SEA_11_P_C	1606.94	44.45	0.80	0.26	1.92	1.46	-432.60	0.96
KHZ_11_P_B	2738.86	64.68	0.73	0.06	3.43	1.77	-3878.93	0.90
SEA_12_P_B	1661.60	33.41	0.80	0.23	1.36	1.20	555.21	0.92
KHZ_12_P_A	1288.33	36.95	0.62	-0.21	0.43	0.67	988.20	0.99
KHZ_12_P_C	1666.62	42.42	0.71	-0.36	0.55	0.79	-330.10	1.00
AVERAGE	***1675.38***	***42.93***	***0.76***	***0.02***	***1.59***	***1.21***	***-648.57***	***0.96***
Evaluation								
SEA_11_P_B	1101.65	34.70	0.88	0.17	1.67	1.30	-370.38	0.96
KHZ_11_P_A	4062.44	78.96	0.59	0.26	4.42	2.23	-4879.42	0.91
KHZ_11_P_C	3781.91	83.59	0.59	0.22	4.77	2.22	-5098.05	0.88
SEA_12_P_A	1472.76	23.40	0.88	0.21	1.10	1.10	906.50	0.99
SEA_12_P_C	964.62	22.25	0.88	0.12	0.87	0.91	1267.03	0.92
KHZ_12_P_B	1593.30	47.12	0.50	-0.34	0.40	0.67	456.97	1.00
AVERAGE	***2162.78***	***48.34***	***0.72***	***0.11***	***2.21***	***1.41***	***-1286.23***	***0.94***

Both the models obtained good results in all the evaluation metrics considered, and their performance in calibration and validation datasets are very similar. CropSyst model obtained better results for what concerns the RRMSE metric (39.47 in calibration and 40.97 in validation) than WOFOST (42.93 in calibration and 48.34 in validation). In general CropSyst model tends to slightly overestimate the measured AGB (negative values of CRM both in calibration and validation) whereas WOFOST simulations are characterized by a general underestimation of the measurements (positive values of CRM in both calibration and validation). Modelling efficiencies is higher for WOFOST in calibration datasets (0.76 versus 0.71 of CropSyst) whereas is better for CropSyst in the evaluation datasets (0.73 versus 0.72).

These values confirmed the reliability of WOFOST and CropSyst in reproducing the measures collected both in calibration and validation datasets. This trend is also confirmed by the values of the other indices; The performance of the models is confirmed by the values of regression parameters (i.e., slope, intercept and coefficient of determination). The coefficient of determination of the regression for the two models had values ranging from 0.95 (CropSyst, calibration) and 0.94 (both the models in evaluation datasets).

2.1.2.2. Soft wheat – low productivity

The AGB trends simulated by the CropSyst model in the calibration and evaluation datasets of soft wheat – low productivity are shown in Figure 19 (Sidi-El-Aydi experimental site) and Figure 20 (Khemis-Zemamra experimental site), compared with data collected at different stages of wheat growth. The AGB trends simulated by the WOFOST model in the calibration and evaluation datasets of soft wheat – low productivity are shown in Figure 21 (Sidi-El-Aydi experimental site) and Figure 22 (Khemis-Zemamra experimental site), compared with data collected at different stages of wheat growth.

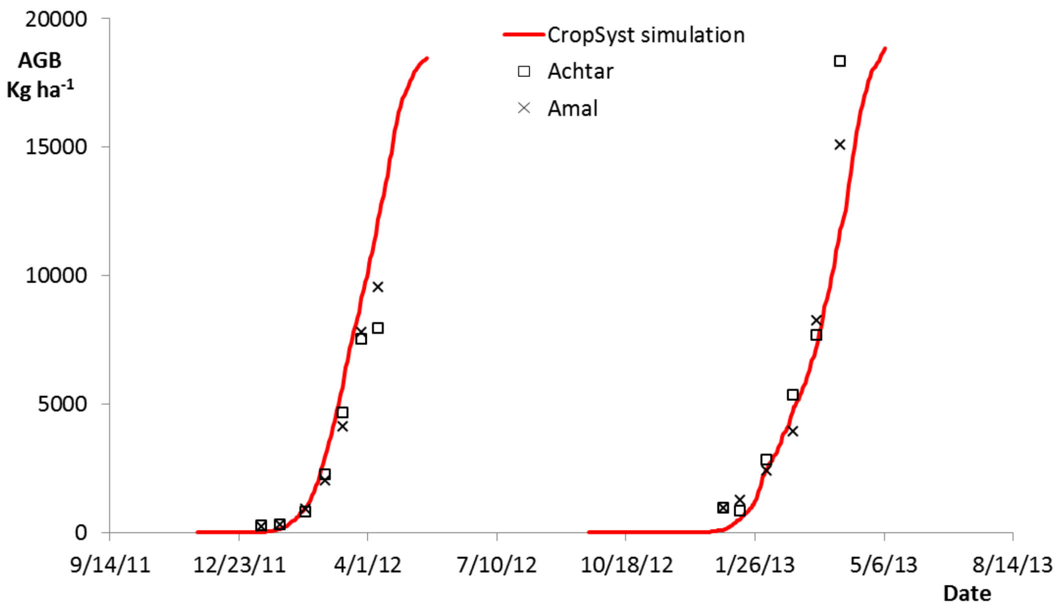

Figure 19. Comparison between measured (squares and crosses identify the different cultivars) and simulated (red line) aboveground biomass of soft wheat – low productivity in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, CropSyst model

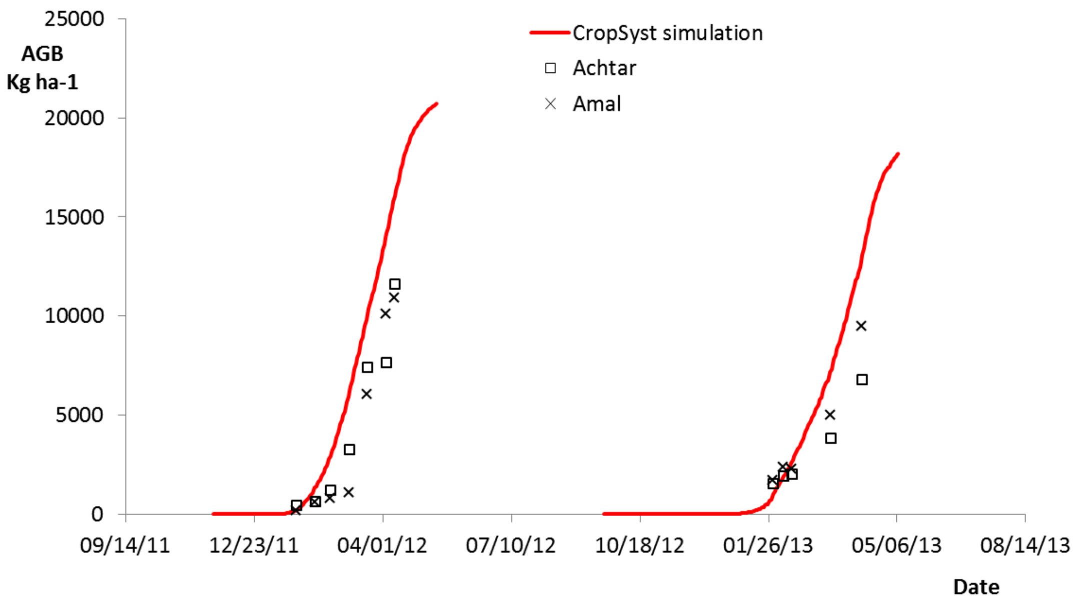

Figure 20. Comparison between measured (squares and crosses identify the different cultivars) and simulated (red line) aboveground biomass of soft wheat – low productivity in 2011-2012 and 2012-2013 cropping seasons. Khemis-Zemamra, CropSyst model

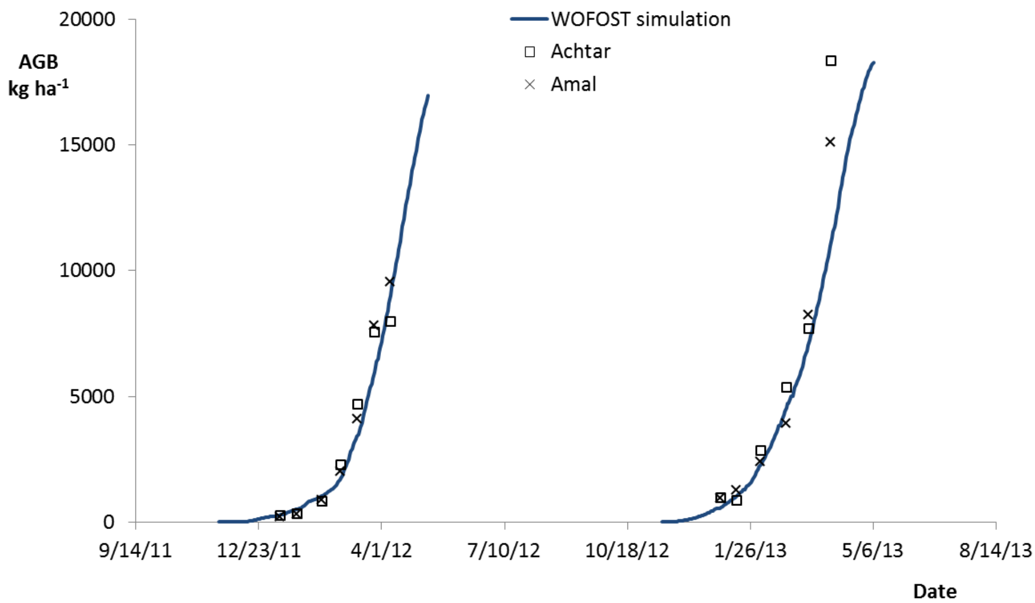

Figure 21. Comparison between measured (squares and crosses identify the different cultivars) and simulated (blue line) aboveground biomass of soft wheat – low productivity in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, WOFOST model

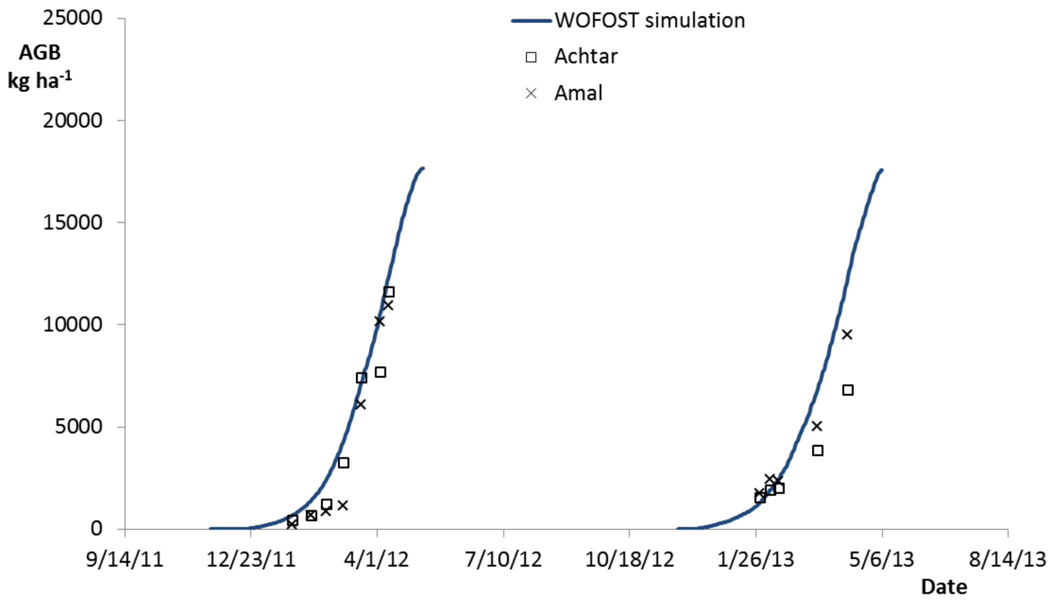

Figure 22. Comparison between measured (squares and crosses identify the different cultivars) and simulated (blue line) aboveground biomass of soft wheat – low productivity in 2011-2012 and 2012-2013 cropping seasons. Khemis-Zemamra, WOFOST model

The simulations carried out for soft wheat – low productivity show a similar pattern for the two models. As discussed for durum wheat, the overall measured trends were sufficiently reproduced by both CropSyst and WOFOST in calibration and validation datasets. The measured biomass in Sidi-El-Aydi and in Khemis-Zemamra in 2011 is decidedly lower than in 2012, and it could be due to the problems encountered by the irrigation systems or by the attacks of Assian fly which is a major costraint to production in the whole Moroccan wheat area. Measured values in 2012 are higher, and it could be explained by the high volumes of precipitation of the first months of 2013. As observed for durum wheat, in general model performances are better in the Sidi-El-Aydi experimental site than in Khemis Zemamra. In this case, there are few differences in the measured aboveground biomass of the two cultivars tested. Table 12 and Table 15 report the values of the evaluation indices for the CropSyst and WOFOST model, respectively, quantifying the agreement between measured and simulated data.

Table 14. Indices of agreement between measured and simulated AGB values referred to the soft wheat – low productivity datasets for the CropSyst model

				Calibration				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_P_D	1194.63	53.22	0.66	-0.32	0.46	0.69	298.13	0.98
KHZ_11_P_E	3112.85	86.24	0.29	-0.73	0.43	0.72	-1073.32	0.94
SEA_12_P_E	1020.37	38.31	0.85	-0.26	0.60	0.79	30.67	0.99
KHZ_12_P_D	2222.94	101.38	-1.78	-0.63	0.16	0.43	946.67	0.99
AVERAGE	***1887.70***	***69.79***	***0.00***	***-0.49***	***0.41***	***0.66***	***50.54***	***0.98***
				Evaluation				
SEA_11_P_E	1020.37	38.31	0.85	-0.26	0.60	0.79	30.67	0.99
KHZ_11_P_D	2837.56	76.34	0.24	-0.61	0.38	0.67	-345.58	0.95
SEA_12_P_D	1480.21	45.34	0.80	0.25	1.92	1.43	-452.12	0.94
KHZ_12_P_E	1504.40	47.10	0.53	-0.25	0.39	0.64	846.39	0.99
AVERAGE	***1710.64***	***51.77***	***0.61***	***-0.22***	***0.82***	***0.88***	***19.84***	***0.97***

Table 15. Indices of agreement between measured and simulated AGB values referred to the soft wheat – low productivity datasets for the WOFOST model

				Calibration				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_P_D	693.29	25.74	0.92	0.05	0.98	0.95	326.71	0.93
KHZ_11_P_E	1106.85	31.34	0.87	-0.24	0.80	0.90	-557.94	0.96
SEA_12_P_E	1047.68	30.98	0.89	0.15	1.68	1.30	-578.04	0.97
KHZ_12_P_D	1134.50	36.87	0.71	-0.20	0.46	0.69	710.07	0.99
AVERAGE	***995.58***	***31.23***	***0.85***	***-0.06***	***0.98***	***0.96***	***-24.80***	***0.96***
				Evaluation				
SEA_11_P_E	463.54	19.23	0.96	0.09	1.24	1.11	-12.40	0.98
KHZ_11_P_D	1426.88	39.76	0.85	-0.34	0.92	0.99	-1343.91	0.96
SEA_12_P_D	1533.05	48.41	0.77	0.24	2.20	1.55	-1019.24	0.94
KHZ_12_P_E	1864.25	88.47	-1.11	-0.56	0.19	0.47	855.63	1.00
AVERAGE	***1321.93***	***48.97***	***0.37***	***-0.14***	***1.14***	***1.03***	***-379.98***	***0.97***

The agreement indices highlight a very different situation with respect to durum wheat simulations. In fact CropSyst model showed very poor performances in the Khemis Zemamra experimental site in 2012 for the Achtar cultivar (EF=-1.78, RRMSE=101.38), thus

lowering the overall accuracy of this model in the calibration datasets. This model obtained decidedly better performances in the evaluation datasets (EF=0.61, RRMSE=51.77). On the contrary, WOFOST model obtained very good values of agreement indices in the calibration datasets (average EF=0.85, average RRMSE=31.23) but its performances are worse than the CropSyst ones in the evaluation datasets (EF=0.37, RRMSE=48.97). It can be observed a general overestimation of the measured AGB values for both models (CRM always negative), but high values of coefficient of determination (R^2 values ranging from 0.96 to 0.98), thus indicating a very good correlation between measured and simulated aboveground biomass.
In general the performances of the two models in reproducing the potential growth of soft wheat – low productivity in the explored conditions are satisfactory, even if worse than the ones obtained for durum wheat.

2.1.2.3. Soft wheat – high productivity

The AGB trends simulated by the CropSyst model in the calibration and evaluation datasets of soft wheat – high productivity are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 24 (Khemis-Zemamra experimental site), compared with data collected at different stages of wheat growth. The AGB trends simulated by the WOFOST model in the calibration and evaluation datasets of soft wheat – high productivity are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 26 (Khemis-Zemamra experimental site), compared with data collected at different stages of wheat growth.

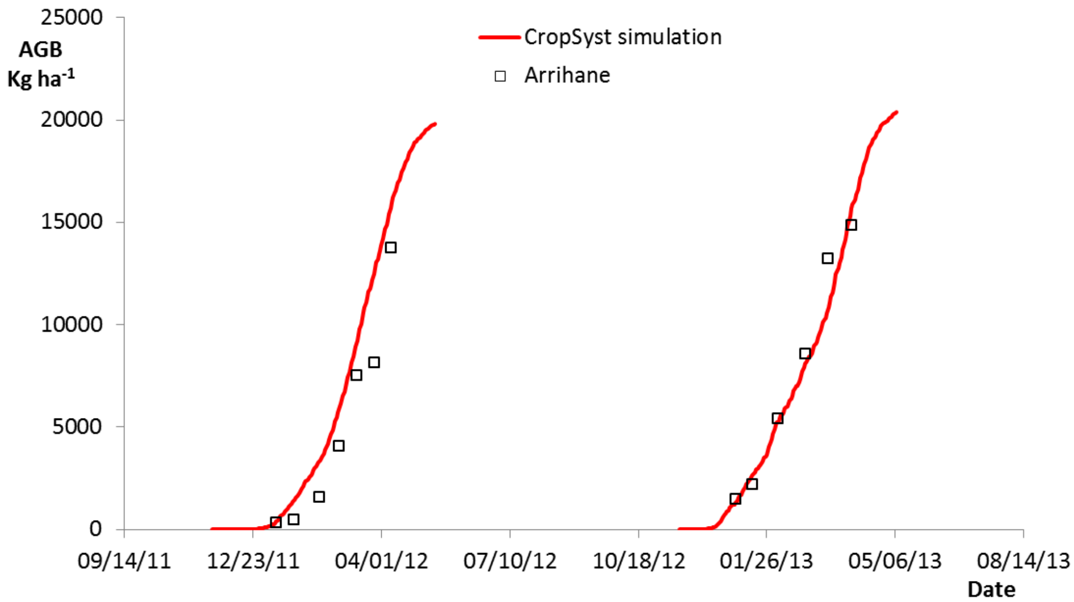

Figure 23. Comparison between measured (squares identify the Arrihanne cultivar) and simulated (red line) aboveground biomass of soft wheat – high productivity in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, CropSyst model

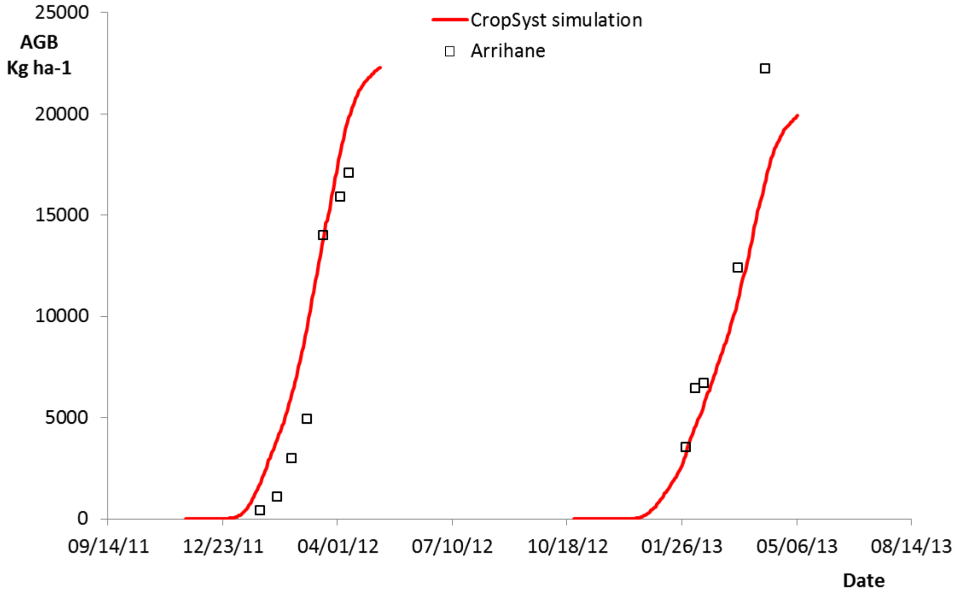

Figure 24. Comparison between measured (squares identify the Arrihanne cultivar) and simulated (red line) aboveground biomass of soft wheat – high productivity in 2011-2012 and 2012-2013 cropping seasons. Khemis-Zemamra, CropSyst model

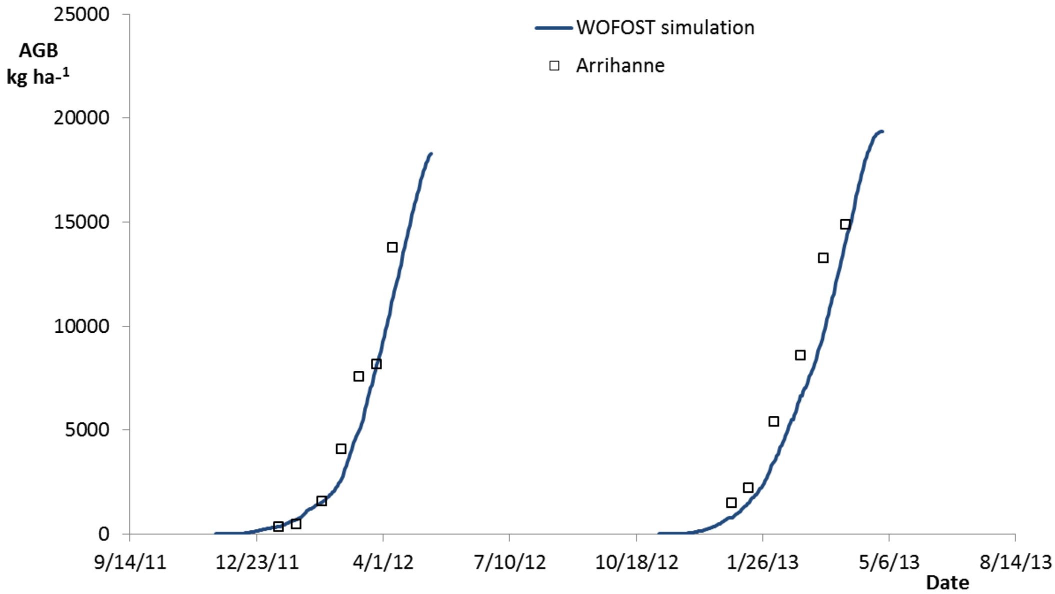

Figure 25. Comparison between measured (squares identify the Arrihanne cultivar) and simulated (blueline) aboveground biomass of soft wheat – high productivity in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, WOFOST model

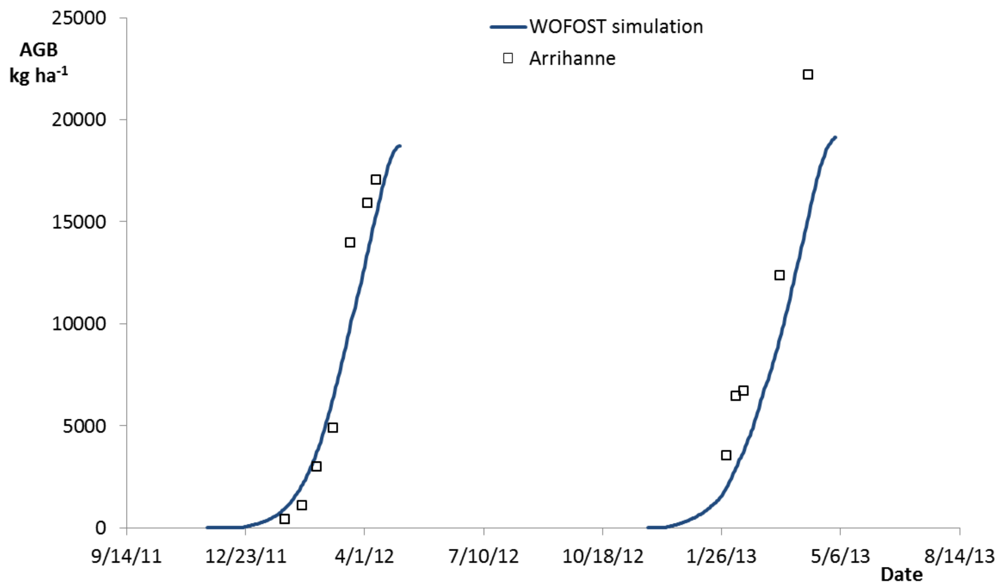

Figure 26. Comparison between measured (squares identify the Arrihanne cultivar) and simulated (blue line) aboveground biomass of soft wheat – high productivity in 2011-2012 and 2012-2013 cropping seasons. Khemis-Zemamra, WOFOST model

The simulations of the CropSyst and WOFOST model were compared with the measurements of aboveground biomass of the Arrihanne cultivar, which is the most productive among the soft wheat varieties tested. The pattern of aboveground biomass were accurately reproduced by both CropSyst and WOFOST in calibration and validation datasets. It emerged from the figures that the models do not succeed in reproducing the highest measured value of AGB (around 22000 kg ha^{-1}) reached by Arrihanne cultivar in 2012-2013 cropping season in Khemis Zemamra. As for the other two wheat types, it can be observed a slight better performance of the two models in the Sidi-El-Aydi experimental site respect to Khemis-Zemamra. Table 16 and Table 17 report the values of the fitting indices for CropSyst and WOFOST model, respectively.

Table 16. Indices of agreement between measured and simulated AGB values referred to the soft wheat – high productivity datasets for the CropSyst model

				Calibration				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_P_F	1879.29	44.64	0.75	-0.37	0.64	0.83	-672.93	0.96
KHZ_12_P_F	2039.61	26.57	0.83	0.20	1.53	1.33	-650.92	0.99
AVERAGE	***1959.45***	***35.61***	***0.79***	***-0.09***	***1.09***	***1.08***	***-661.93***	***0.98***
				Evaluation				
SEA_12_P_F	730.07	13.89	0.96	0.04	1.07	1.02	184.95	0.96
KHZ_11_P_F	2477.16	35.07	0.83	-0.31	0.94	1.02	-2627.16	0.96
AVERAGE	***1603.62***	***24.48***	***0.90***	***-0.14***	***1.01***	***1.02***	***-1221.11***	***0.96***

Table 17. Indices of agreement between measured and simulated AGB values referred to the soft wheat – high productivity datasets for the WOFOST model

				Calibration				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_P_F	946.87	27.87	0.90	0.17	1.35	1.17	169.84	0.96
KHZ_12_P_F	3618.00	39.31	0.63	0.35	1.16	1.32	1506.74	0.99
AVERAGE	***2282.44***	***33.59***	***0.77***	***0.26***	***1.26***	***1.25***	***838.29***	***0.98***
				Evaluation				
SEA_12_P_F	1591.30	25.07	0.86	0.21	1.05	1.06	1227.26	0.96
KHZ_11_P_F	1698.64	25.38	0.91	0.08	1.64	1.26	-1338.57	0.96
AVERAGE	***1644.97***	***25.23***	***0.89***	***0.15***	***1.35***	***1.16***	***-55.66***	***0.96***

The performances of the two models in reproducing potential aerial biomass of soft wheat – high productivity are decidedly better with respect to the other soft wheat type, and in line with the ones obtained for durum wheat. Both the models showed a better behaviour in the evaluation datasets compared to the calibration ones. CropSyst model is characterized by a slight overestimation of AGB values (CRM=-0.09 in calibration and CRM=-0.14 in evaluation) whereas WOFOST by a general underestimation of measurements (CRM=0.26 and 0.15 in calibration and evaluation, respectively). RRMSE values are very good for the models, and in both cases are better in evaluation datasets (CropSyst 24.48 and WOFOST 25.23) than in calibration ones (CropSyst 35.61 and WOFOST 33.59). Both models are characterized by very similar and high values of modelling efficiency, both in calibration and in evaluation datasets.

In general the performances of the two models in reproducing the potential growth of soft wheat – high productivity in the explored conditions are very good.

2.2. Evaluation of the models WOFOST and CropSyst for wheat simulation in Morocco – water limited production level

After the calibration of the two models for potential growth conditions, the parameter sets developed for durum wheat, soft wheat – high productivity and soft wheat – low productivity were applied in the datasets grown under water limitation (see Table 5 for details). Soil properties for the two experimental sites of Sidi-El-Aydi and Marchouch were delivered by INRA-Morocco and are reported in Table 18 and Table 19

Table 18. 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

Table 19. Soil properties of the Marchouch experimental site.

Depth	Clay (%)	Silt (%)	Sand (%)	Bulk density ($g\ cm^{-3}$)	Water retention (by weight)	
					0.33 bar	15 bar
0-20	50,0	37,3	12,7	1,41	39	17
20-40	51,3	38,2	10,5	1,47	41	18
40-90	52,5	35,1	12,4	1,54	40	17,5

The WOFOST and the CropSyst models were 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 (i.e., crop model+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[8]; Ritchie 1998[9]). It is very suitable to be used in large area simulations because it requires as input easily obtainable parameters, i.e., soil water content at field capacity and soil water content at wilting point. When these values are absent, they can be estimated via pedotransfer functions.

2.2.1. Simulation of phenology

2.2.1.1. Durum wheat

No impact of water stress on phenological development was implemented in both the models. The same parameter sets developed for potential conditions were then applied in the water limited datasets in order to verify the reliability of the calibration activity.
Table 20 reports all the simulated and observed values for the water limited datasets tested for durum wheat.

[8] 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.

[9] 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.

Table 20. Observed and simulated values of phenological dates in the water limited datasets (durum wheat).

ID	Phase	Measured	WOFOST	CropSyst
SEA_11_WL_A	emergence	341	342	342
SEA_11_WL_A	flowering	84	104	104
SEA_11_WL_A	maturity	150	137	138
SEA_11_WL_B	emergence	341	342	342
SEA_11_WL_B	flowering	84	104	104
SEA_11_WL_B	maturity	150	137	138
SEA_11_WL_C	emergence	341	342	342
SEA_11_WL_C	flowering	88	104	104
SEA_11_WL_C	maturity	150	137	138
MAR_11_WL_A	emergence	359	354	354
MAR_11_WL_A	flowering	93	109	109
MAR_11_WL_A	maturity	157	143	140
MAR_11_WL_B	emergence	359	354	354
MAR_11_WL_B	flowering	93	109	109
MAR_11_WL_B	maturity	157	143	140
MAR_11_WL_C	emergence	359	354	354
MAR_11_WL_C	flowering	93	109	109
MAR_11_WL_C	maturity	157	143	140
SEA_12_WL_A	emergence	328	327	327
SEA_12_WL_A	flowering	66	97	97
SEA_12_WL_A	maturity	115	129	129
SEA_12_WL_B	emergence	328	327	327
SEA_12_WL_B	flowering	66	97	97
SEA_12_WL_B	maturity	115	129	129
SEA_12_WL_C	emergence	328	327	327
SEA_12_WL_C	flowering	71	97	97
SEA_12_WL_C	maturity	120	129	129

The parameter values calibrated in potential conditions led to a good performance of the models in the simulation of phenology in the water limited datasets. Figure 12 reports the scatter plot of measured and simulated values for CropSyst and WOFOST.

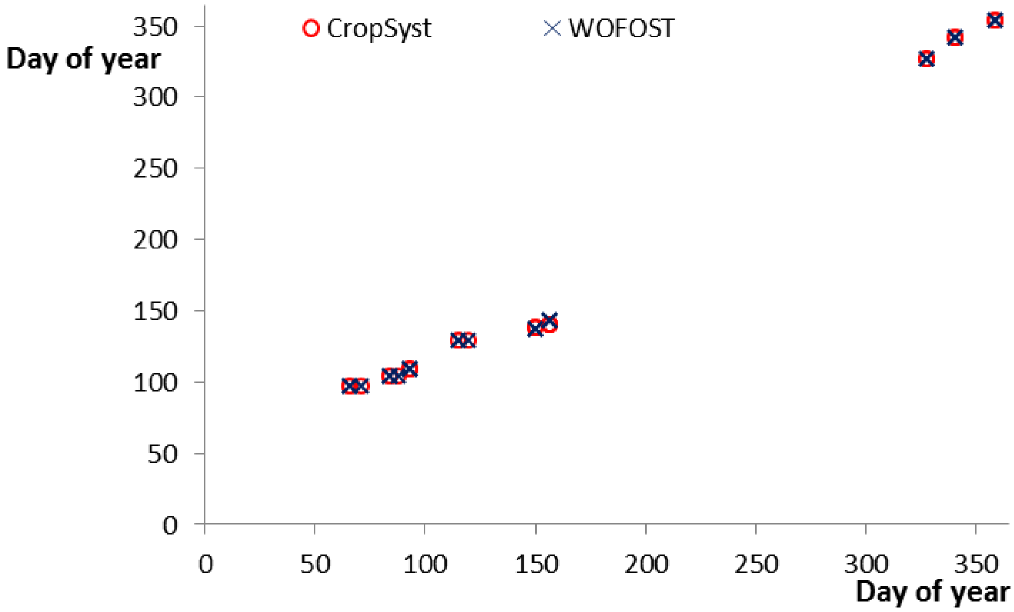

Figure 27. Scatter plot showing the correlation between the simulated and the observed day of year related to the phenological phases of emergence, flowering and maturity of durum wheat for WOFOST and CropSyst model

As observed for the simulation of phenology in potential conditions (see paragraph 2.1.1.1), the reproduction of phenology of durum wheat carried out with the two models is decidedly similar, with a very high correlation for both CropSyst and WOFOST (R^2=0.99 for the two models). Table 12 reports the values of the agreement indices.

Table 21. Indices of agreement between measured and simulated phenological dates referred to the durum wheat datasets

	Indices							
Model	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (days)**	**R^2**
CropSyst	12.48	8.08	0.98	-0.02	1.13	1.06	-16.00	0.99
WOFOST	12.26	7.95	0.98	-0.03	1.14	1.06	-16.53	0.99

The average mean absolute error of the two models is very similar (12.48 days for CropSyst and 12.26 days for WOFOST), as the RRMSE values (8.08 for CropSyst and 7.95 for WOFOST). The models showed a good accuracy in the reproduction of phenology of durum wheat grown under water limited conditions.

2.2.1.2. Soft wheat – low productivity

Table 22 reports all the simulated and observed values for the water limited datasets tested for soft wheat – low productivity.

Table 22. Observed and simulated values of phenological dates in the water limited datasets (soft wheat – low productivity).

ID	Phase	Measured	WOFOST	CropSyst
SEA_11_WL_D	emergence	341	345	345
SEA_11_WL_D	flowering	97	101	95
SEA_11_WL_D	maturity	150	140	134
SEA_11_WL_E	emergence	341	345	345
SEA_11_WL_E	flowering	68	101	95
SEA_11_WL_E	maturity	150	140	134
MAR_11_WL_D	emergence	359	357	357
MAR_11_WL_D	flowering	93	105	100
MAR_11_WL_D	maturity	157	145	138
MAR_11_WL_E	emergence	359	357	357
MAR_11_WL_E	flowering	93	105	100
MAR_11_WL_E	maturity	157	145	138
SEA_12_WL_D	emergence	328	329	329
SEA_12_WL_D	flowering	75	95	92
SEA_12_WL_D	maturity	119	131	130
SEA_12_WL_E	emergence	328	329	329
SEA_12_WL_E	flowering	80	95	92
SEA_12_WL_E	maturity	121	131	130

As discussed for durum wheat, the parameter values calibrated in potential conditions led to a good performance of the models in the simulation of phenology in the water limited datasets. In this case models performances are slightly better than for durum wheat. Figure 12 reports the scatter plot of measured and simulated values for CropSyst and WOFOST.

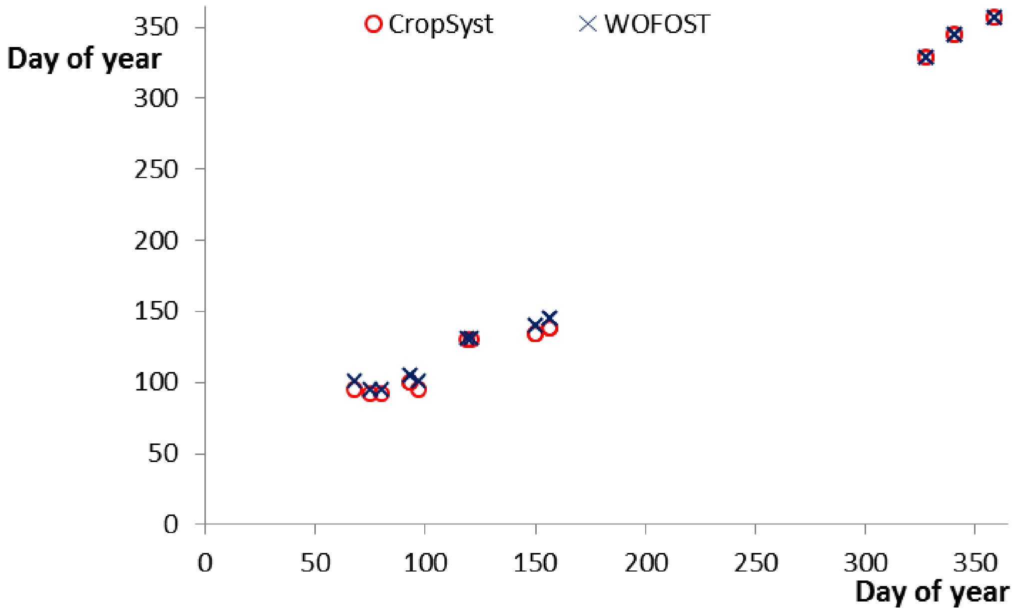

Figure 28. Scatter plot showing the correlation between the simulated and the observed day of year related to the phenological phases of emergence, flowering and maturity of durum wheat grown under water limited conditions for WOFOST and CropSyst model

Table 23 reports the evaluation indices of CropSyst and WOFOST concerning their performances in the reproduction of phenology of sofw wheat – low productivity.

Table 23. Indices of agreement between measured and simulated phenological dates referred to the durum wheat datasets

	Indices							
Model	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (days)**	**R^2**
CropSyst	9.78	6.50	0.99	-0.01	1.04	1.01	-4.08	0.99
WOFOST	9.78	6.56	0.99	-0.02	1.08	1.04	-11.37	0.99

The mean average absolute error of the two models is the same (9.78 days), and the RRMSE values are very similar (around 6.5). On the whole, the performances of the CropSyst and WOFOST models in reproducing phenological development of soft wheat – low productivity are very good.

2.2.1.3. Soft wheat – high productivity

Table 24 reports all the simulated and observed values for the water limited datasets tested for soft wheat – high productivity.

Table 24. Observed and simulated values of phenological dates in the water limited datasets (soft wheat – high productivity).

ID	Phase	Measured	WOFOST	CropSyst
SEA_11_WL_F	emergence	341	345	345
SEA_11_WL_F	flowering	84	87	92
SEA_11_WL_F	maturity	157	126	129
SEA_12_WL_F	emergence	328	329	329
SEA_12_WL_F	flowering	63	91	90
SEA_12_WL_F	maturity	112	131	125
MAR_11_WL_F	emergence	359	357	357
MAR_11_WL_F	flowering	93	90	103
MAR_11_WL_F	maturity	157	162	137

Figure 29 presents the scatterplot of observed and simulated dates of phenological development of soft wheat – high productivity grown under water limited conditions for the two models.

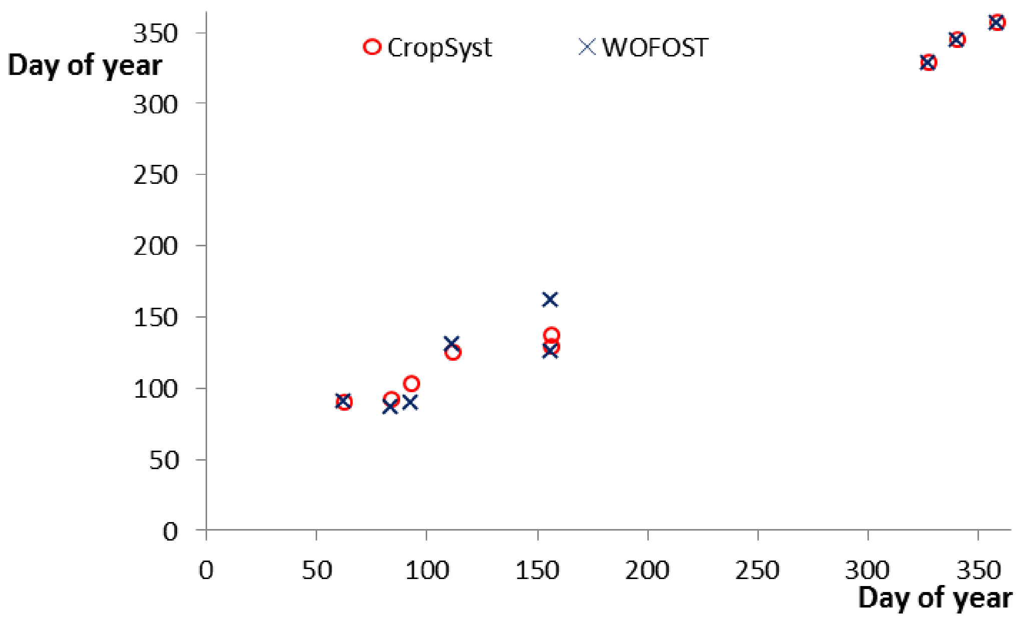

Figure 29. Scatter plot showing the correlation between the simulated and the observed day of year related to the phenological phases of emergence, flowering and maturity of durum wheat grown under water limited conditions for WOFOST and CropSyst model.

The simulation of phenology of the soft wheat –high productivity variety Arrihanne led to the greatest differences among the two models. Table 25 presents the values of the agreement indices.

Table 25. Indices of agreement between measured and simulated phenological dates referred to the durum wheat datasets

	Indices							
Model	MAE	RRMSE	EF	CRM	CD	Slope	Intercept (days)	R^2
CropSyst	12.56	8.43	0.98	-0.01	1.06	1.02	-4.92	0.98
WOFOST	10.67	8.25	0.98	-0.01	1.05	1.02	-5.54	0.98

The mean average absolute error of the two models is higher than the one obtained in the simulation of the other soft wheat type (12.56 days for CropSyst and 10.67 days for WOFOST). As discussed for the other wheat types, CropSyst and WOFOST performances are very similar (e.g., RRMSE=8.43 for CropSyst and RRMSE=8.25 for WOFOST), thus highlighting a good performance of the two models in the reproduction of phenological development of the cultivar Arrihanne grown under water limited conditions.

2.2.2. Simulation of aboveground biomass

2.2.2.1. Durum wheat

The AGB trends simulated by the CropSyst model in the calibration and evaluation datasets of durum wheat grown under water limited conditions are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 31 (Marchouch experimental site, only 2011-2012 cropping season available), compared with data collected at different stages of wheat growth. The AGB trends simulated by the WOFOST model in the calibration and evaluation datasets of durum wheat grown under water limited conditions are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 33 (Marchouch experimental site), compared with data collected at different stages of wheat growth.

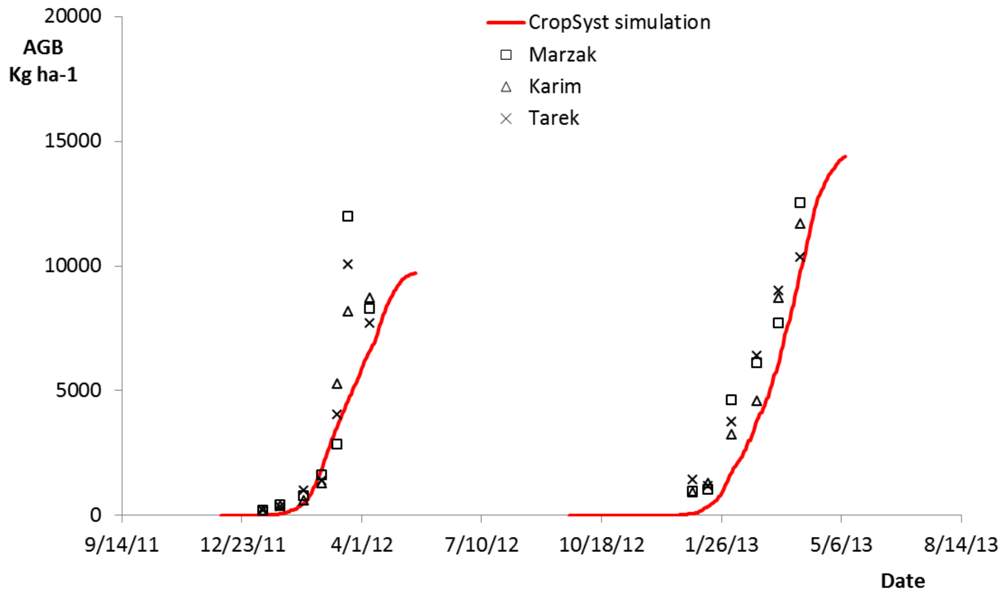

Figure 30. Comparison between measured (squares, triangles and crosses identify the different cultivars) and simulated (red line) water limited aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, CropSyst model

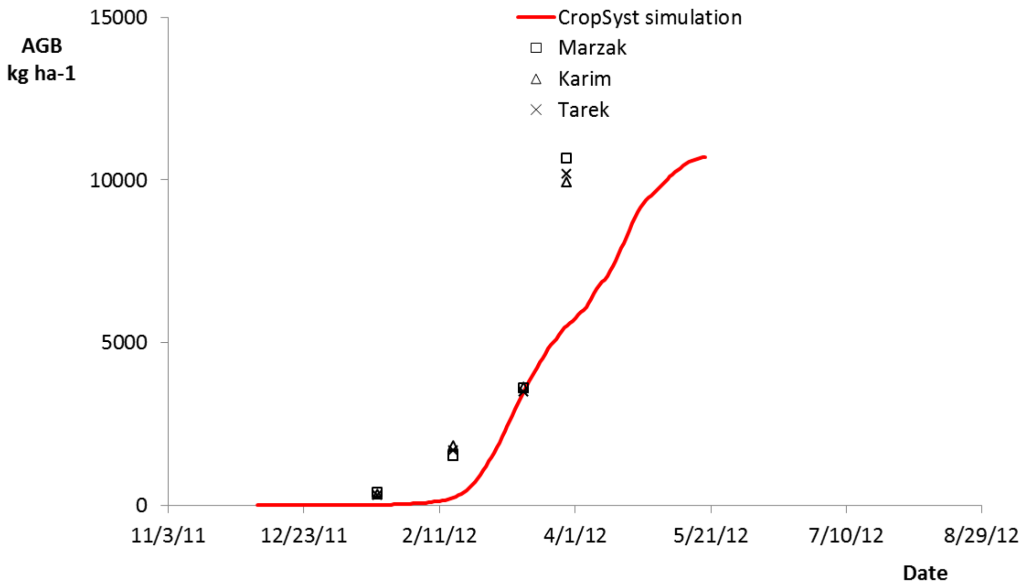

Figure 31. Comparison between measured (squares, triangles and crosses identify the different cultivars) and simulated (red line) water limited aboveground biomass of durum wheat in 2011-2012 cropping season. Marchouch, CropSyst model

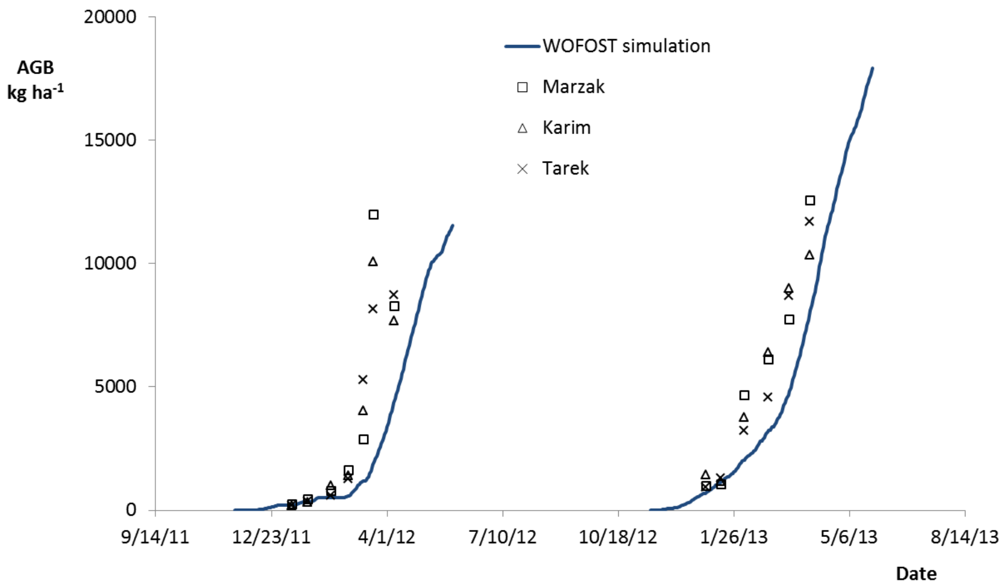

Figure 32. Comparison between measured (squares, triangles and crosses identify the different cultivars) and simulated (blue line) water limited aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, WOFOST model

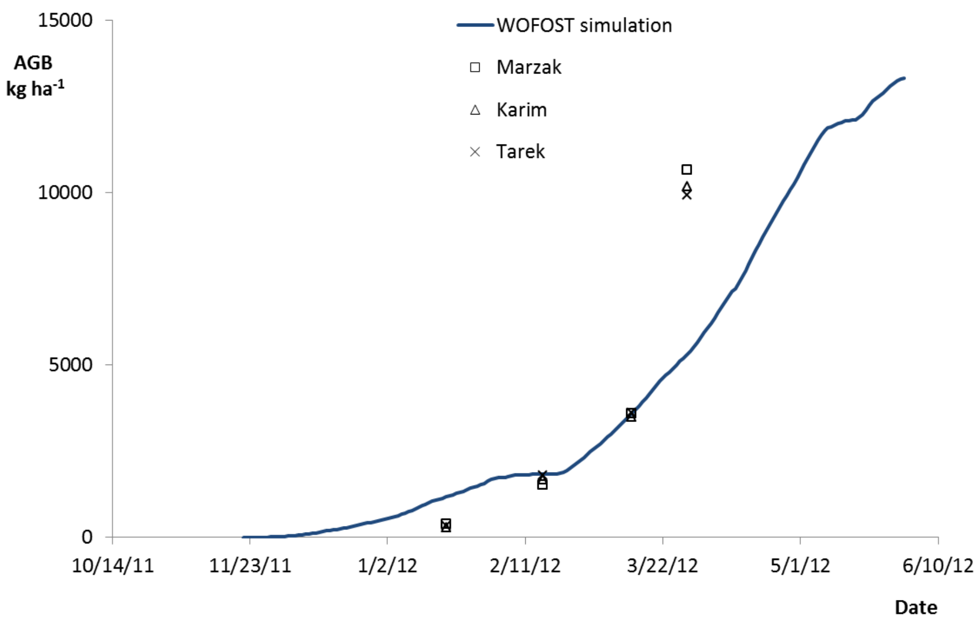

Figure 33. Comparison between measured (squares, triangles and crosses identify the different cultivars) and simulated (blue line) water limited aboveground biomass of durum wheat in 2011-2012 cropping season. Marchouch, WOFOST model

There is a clear imbalance between the CropSyst performance in reproducing durum wheat growth in the two experimental sites. In fact this model succeeded in reproducing the aboveground biomass values measured in Sidi-El-Aydi, even if the precipitation regimes experimented by the crop are very different in the two years. In fact, as emerged from the meteorological analysis carried out in paragraph 1.1.2.3., cropping season 2012-2013 was characterized by decided more humid conditions, especially in the first months of 2012. Conversely, the simulation of aboveground biomass evolution in Marchouch experimental site is not accurate, denoting a clear underestimation of the first phases of wheat growth and thus a delay in the simulation of biomass accumulation. By analyzing WOFOST simulations in Sidi-El-Aydi experimental site, it emerges that the model tends to slightly underestimate measured aboveground biomass, whereas the application of the parameter sets developed for potential conditions led to a better performance of this model in Marchouch with respect to the CropSyst model. In order to better analyze models performances, in Table 12 and Table 27 the values of some fitting indices are presented for the CropSyst and WOFOST model, respectively, quantifying the agreement between measured and simulated data.

Table 26. Indices of agreement between measured and simulated AGB values referred to the durum wheat datasets under water limited conditions for the CropSyst model

				Evaluation				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_WL_A	509.40	39.91	0.90	-0.11	0.73	0.83	138.45	0.95
SEA_11_WL_B	825.49	53.05	0.78	-0.29	0.54	0.73	111.82	0.97
SEA_11_WL_C	490.60	26.77	0.94	-0.15	0.78	0.88	-25.86	0.98
MAR_11_WL_A	1736.07	115.45	-0.33	-0.75	0.28	0.54	125.82	0.87
MAR_11_WL_B	1618.58	102.05	-0.04	-0.70	0.33	0.59	-9.41	0.88
MAR_11_WL_C	1604.03	106.09	-0.12	-0.70	0.31	0.57	91.11	0.87
SEA_12_WL_A	1830.24	55.21	0.66	-0.50	0.61	0.85	-997.38	0.97
SEA_12_WL_B	1408.07	42.45	0.80	-0.38	0.69	0.87	-763.12	0.98
SEA_12_WL_C	1685.80	51.51	0.70	-0.46	0.78	0.95	-1412.08	0.94
AVERAGE	***1300.92***	***65.83***	***0.48***	***-0.45***	***0.56***	***0.76***	***-304.52***	***0.93***

Table 27. Indices of agreement between measured and simulated AGB values referred to the durum wheat datasets under water limited conditions for the WOFOST model

				Evaluation				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_WL_A	1522.62	91.63	0.56	0.22	4.52	2.00	-1665.61	0.78
SEA_11_WL_B	964.31	35.41	0.87	0.11	1.77	1.30	-555.22	0.94
SEA_11_WL_C	1041.14	67.62	0.70	0.18	3.35	1.80	-1335.10	0.89
MAR_11_WL_A	1239.96	50.63	0.74	0.30	2.25	1.68	-708.42	0.99
MAR_11_WL_B	1151.63	43.42	0.78	0.28	1.97	1.54	-435.70	1.00
MAR_11_WL_C	1158.75	46.21	0.77	0.28	2.13	1.60	-609.49	0.99
SEA_12_WL_A	574.33	13.90	0.96	0.01	0.91	0.94	387.04	0.97
SEA_12_WL_B	474.37	13.72	0.97	-0.07	0.86	0.93	26.43	0.98
SEA_12_WL_C	807.99	20.23	0.91	-0.02	0.71	0.82	881.59	0.95
AVERAGE	***992.79***	***42.53***	***0.81***	***0.14***	***2.05***	***1.40***	***-446.05***	***0.94***

As emerged from the Figures, the performance of the CropSyst model in Sidi-El-Aydi experimental site are very good, especially in the 2011-2012 cropping season. In fact average modelling efficiencies at Sidi-El-Aydi are 0.873 in 2011-2012 and 0.72 in 2012-2013 cropping season. Also RRMSE values follow the same trend, with an average value of 39.91 in 2011-2012 and of 49.72 in 2012-2013. This model tends to slightly underestimate the measured biomass trends in this site (CRM values always negative) and show a very good correlation between simulation and measurements (R^2 in the range 0.95-0.98). Modelling efficiencies in Marchouch site are always negative, thus denoting a problem encountered by the model in this site, even if correlation values are good (R^2 in the range 0.87-0.88).
The overall performance of CropSyst are thus affected by the poor behaviour of this model in the Marchouch experimental site, but they can be considered sufficient (e.g., average EF=0.48, average RRMSE=65.83, average R^2=0.93).
WOFOST performances in reproducing durum wheat growth under water limited conditions are decidedly better, with higher values of modelling efficiencies in 2012-2013 cropping season at Sidi-El-Aydi (EF in the range 0.91-0.97), but with very good values also in Marchouch experimental site (EF in the range 0.74-0.77). On the whole, average model performances are very good (e.g., average EF=0.81, average RRMSE=42.53, average R^2=0.94).
In general the performances of the two models in reproducing water limited growth of durum wheat are very different, highlighting a decided better performance of the WOFOST model in the explored conditions.

2.2.2.2. Soft wheat – low productivity

The AGB trends simulated by the CropSyst model in the calibration and evaluation datasets of soft wheat – low productivity grown under water limited conditions are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 35 (Marchouch experimental site, only 2011-2012 cropping season available), compared with data collected at different stages of wheat growth. The AGB trends simulated by the WOFOST model in the calibration and evaluation datasets of durum wheat grown under water limited conditions are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 37 (Marchouch experimental site), compared with data collected at different stages of wheat growth.

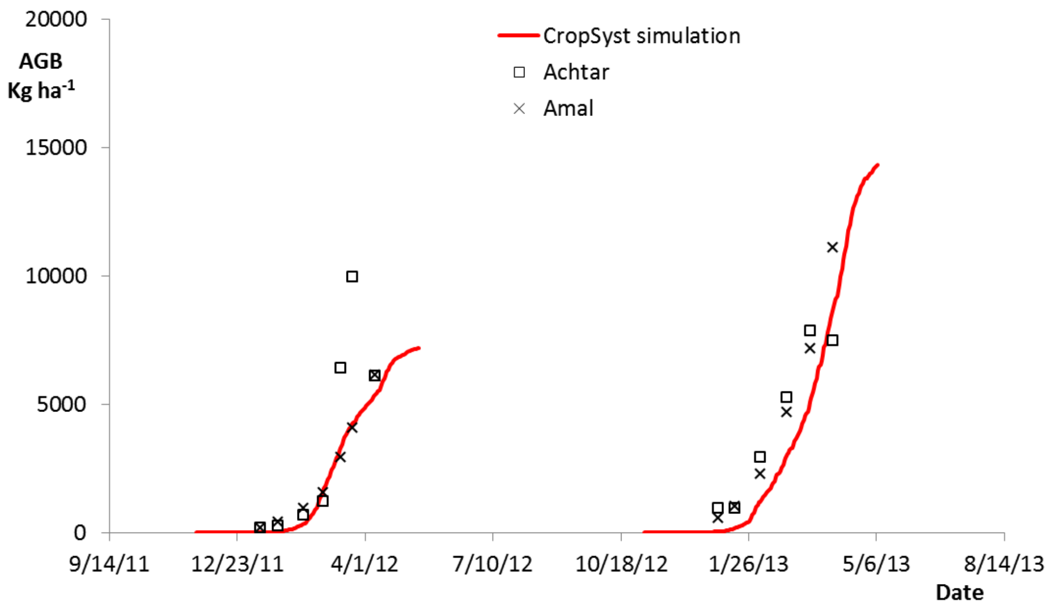

Figure 34. Comparison between measured (squares and crosses identify the different cultivars) and simulated (red line) water limited aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, CropSyst model

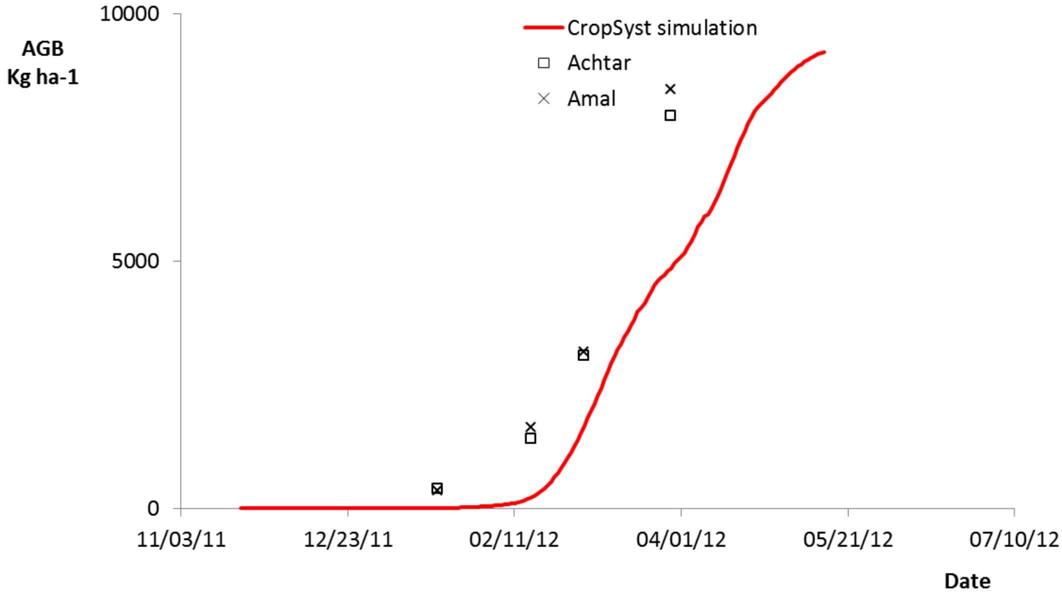

Figure 35. Comparison between measured (squares and crosses identify the different cultivars) and simulated (red line) water limited aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Marchouch, CropSyst model

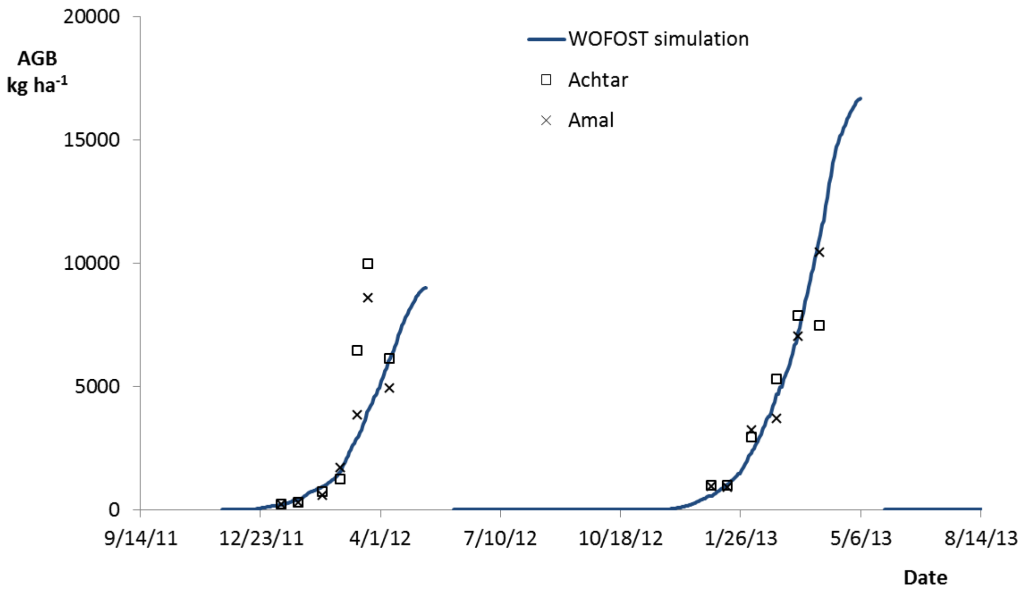

Figure 36. Comparison between measured (squares and crosses identify the different cultivars) and simulated (red line) water limited aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, CropSyst model

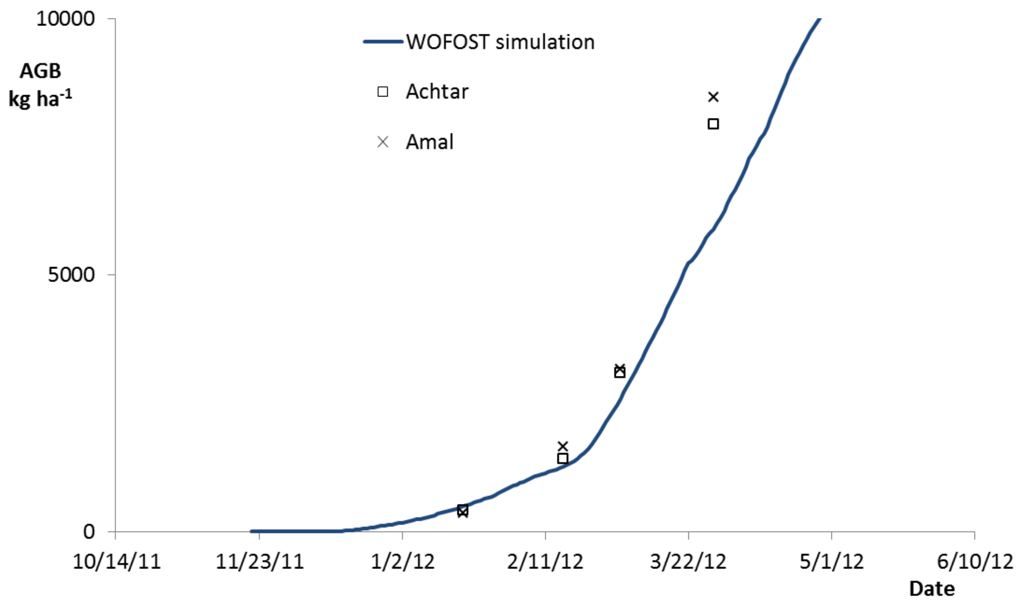

Figure 37. Comparison between measured (squares and crosses identify the different cultivars) and simulated (blue line) water limited aboveground biomass of durum wheat in 2011-2012 and 2012-2013 cropping seasons. Marchouch, WOFOST model

As already discussed for durum wheat, there is a clear imbalance between the CropSyst performances in reproducing soft wheat – low productivity growth in the two experimental sites. In fact this model showed a very good accuracy in the simulation of aboveground biomass values at Sidi-El-Aydi experimental site, denoting a marked ability to respond to the very different meteorological conditions characterizing the two cropping seasons considered. On the contrary the simulation of aerial biomass in Marchouch experimental site is shifted, with an underestimation of wheat growth, even if this situation is not so marked as observed for durum wheat. In general, WOFOST simulations are closer to the measured values, with a good reproduction of the measured aboveground biomass trends in all the explored conditions. In order to better analyze models performances, in Table 12 and Table 29 the values of some fitting indices are presented for the CropSyst and WOFOST model, respectively, quantifying the agreement between measured and simulated data.

Table 28. Indices of agreement between measured and simulated AGB values referred to the durum wheat – low productivity datasets under water limited conditions for the CropSyst model

				Evaluation				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_WL_D	711.79	80.81	0.60	-0.40	0.51	0.69	63.62	0.88
SEA_11_WL_E	285.91	18.21	0.97	-0.07	1.15	1.07	-262.01	0.98
MAR_11_WL_D	867.76	53.05	0.79	-0.51	0.75	0.93	-696.31	0.99
MAR_11_WL_E	1716.98	123.20	-0.16	-1.01	0.30	0.62	-434.95	0.99
SEA_12_WL_D	2126.22	55.03	0.72	-0.06	2.41	1.37	-2114.05	0.78
SEA_12_WL_E	1453.56	34.50	0.89	-0.17	1.35	1.14	-1531.67	0.93
AVERAGE	***1193.70***	***60.80***	***0.64***	***-0.37***	***1.08***	***0.97***	***-829.23***	***0.93***

Table 29. Indices of agreement between measured and simulated AGB values referred to the durum wheat – low productivity datasets under water limited conditions for the WOFOST model

				Evaluation				
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_WL_D	1693.23	89.86	0.44	0.46	3.50	2.62	-1291.59	0.95
SEA_11_WL_E	1037.18	62.96	0.61	0.19	1.90	1.16	173.81	0.66
MAR_11_WL_D	693.12	32.80	0.87	0.20	1.78	1.40	-365.61	1.00
MAR_11_WL_E	915.53	39.10	0.81	0.25	1.90	1.49	-404.29	1.00
SEA_12_WL_D	1007.78	36.96	0.69	-0.05	0.57	0.70	1114.23	0.86
SEA_12_WL_E	543.78	14.74	0.96	-0.03	0.83	0.90	330.14	0.98
AVERAGE	***981.77***	***46.07***	***0.73***	***0.17***	***1.75***	***1.38***	***-73.89***	***0.91***

In general, the agreement indices of the CropSyst model are decidedly better for soft wheat – low productivity with respect to the ones of durum wheat. In fact only in one dataset, MAR_11_WL_E, the agreement indices obtained poor values (EF=-0.16, RRMSE=123.2), whereas in the other datasets CropSyst model shows good performances. For this wheat type, there are no substantial differences between model behaviour in Sidi-El-Aydi in the two available cropping seasons. On the whole, this model obtains an average EF value of 0.64, an average RRMSE of 60.8 and a very good correlation between simulated and measured AGB (R^2=0.93), whereas the average mean absolute error is 1193 kg ha^{-1}. WOFOST performances in reproducing soft wheat – low productivity growth under water

limited conditions are slightly worse than the ones obtained by this model for durum wheat, but in general they are satisfactory. Average modelling efficiencies is 0.73, average RRMSE is 46.07, average R^2 is 0.91 and average mean absolute error is 981.77 kg ha^{-1}.
On the complex, the performances of the two models in reproducing water limited growth of soft wheat – low productivity are good, highlighting a good ability of the two models in reproducing aboveground biomass in the explored conditions.

2.2.2.3. Soft wheat – high productivity

The AGB trends simulated by the CropSyst model in the calibration and evaluation datasets of soft wheat – high productivity grown under water limited conditions are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 39 (Marchouch experimental site, only 2011-2012 cropping season available), compared with data collected at different stages of wheat growth. The AGB trends simulated by the WOFOST model in the calibration and evaluation datasets of durum wheat grown under water limited conditions are shown in **Error! Reference source not found.** (Sidi-El-Aydi experimental site) and Figure 41 (Marchouch experimental site), compared with data collected at different stages of wheat growth.

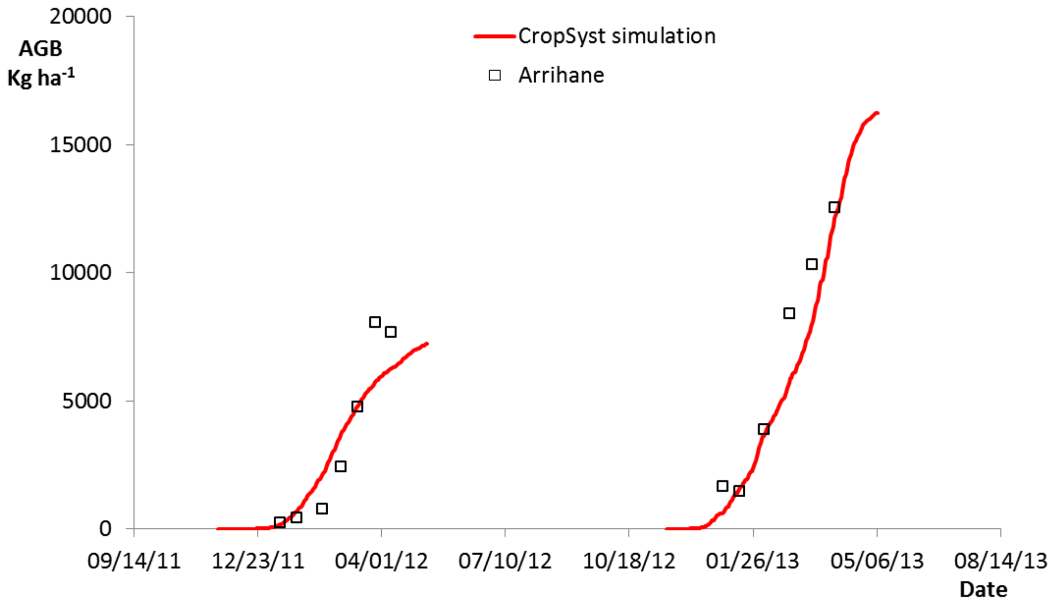

Figure 38. Comparison between measured (squares identify the Arrihanne cultivar) and simulated (red line) water limited aboveground biomass of soft wheat- high productivity in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, CropSyst model

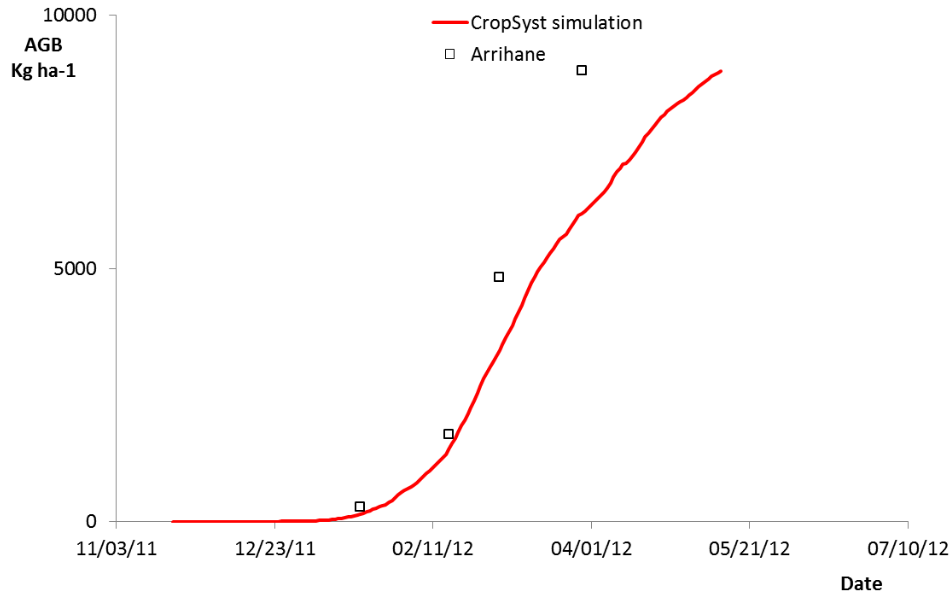

Figure 39. Comparison between measured (squares identify the Arrihanne cultivar) and simulated (red line) water limited aboveground biomass of soft wheat- high productivity in 2011-2012 cropping season. Marchouch, CropSyst model

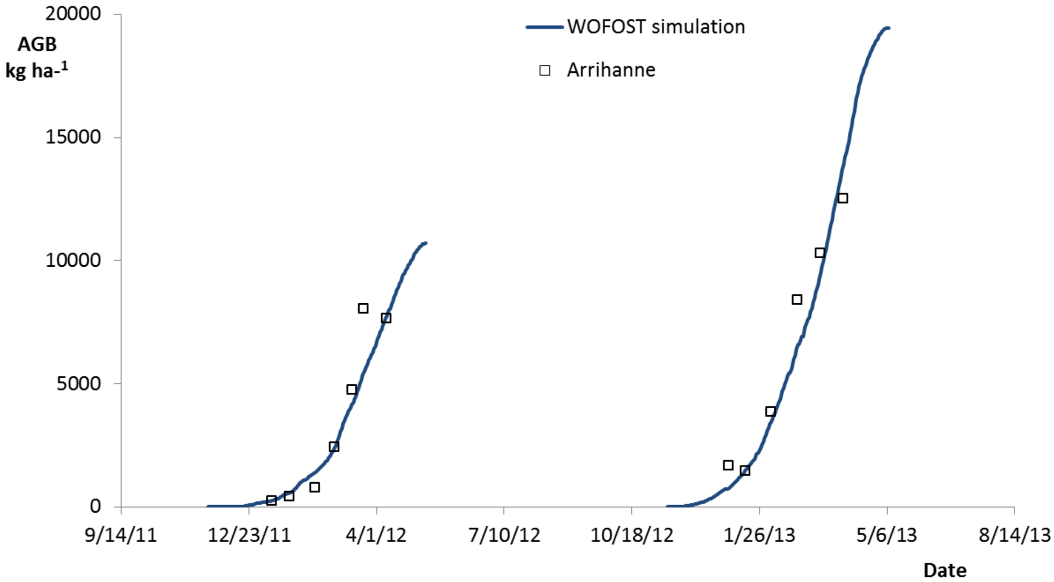

Figure 40. Comparison between measured (squares identify the Arrihanne cultivar) and simulated (blue line) water limited aboveground biomass of soft wheat- high productivity in 2011-2012 and 2012-2013 cropping seasons. Sidi-El-Aydi, WOFOST model

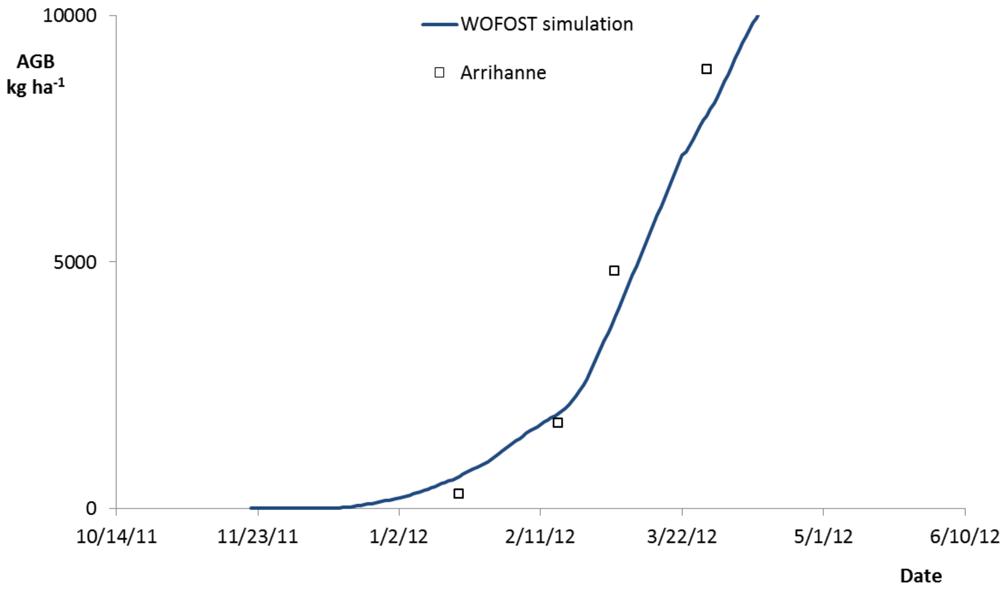

Figure 41. Comparison between measured (squares identify the Arrihanne cultivar) and simulated (blue line) water limited aboveground biomass of soft wheat- high productivity in 2011-2012 cropping season. Marchouch, WOFOST model

The simulation of aboveground biomass of soft wheat – high productivity by the two models is in general very good. In this case both the CropSyst and the WOFOST models succeeded in reproducing the measured trends in all the esperimental sites, even if with some differences. As discussed for the other two wheat types, the two models perform better in the Sidi-El-Aydi experimental site with respect to the Marchouch one, with a marked ability to respond to the very scarce precipitations experimented by the crop in 2011-2012 cropping season. However, also in this case, it can be observed a better reproduction of the biomass trend in Marchouch by WOFOST, thus confirming the better overall performance of this model with respect to the CropSyst one. Table 12 and Table 31 report the values of some fitting indices for the CropSyst and WOFOST model, respectively, quantifying the agreement between measured and simulated data.

Table 30. Indices of agreement between measured and simulated AGB values referred to the durum wheat – low productivity datasets under water limited conditions for the CropSyst model

	Evaluation							
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_WL_F	957.06	36.71	0.70	-0.04	0.51	0.68	995.04	0.90
SEA_12_WL_F	1074.17	27.03	0.87	-0.20	0.80	0.90	-403.10	0.95
MAR_11_WL_F	1175.63	57.63	0.49	-0.43	0.41	0.68	95.03	1.00
AVERAGE	***1068.95***	***40.46***	***0.69***	***-0.22***	***0.57***	***0.75***	***228.99***	***0.95***

Table 31. Indices of agreement between measured and simulated AGB values referred to the durum wheat – low productivity datasets under water limited conditions for the WOFOSTmodel

	Evaluation							
ID	**MAE**	**RRMSE**	**EF**	**CRM**	**CD**	**Slope**	**Intercept (t/ha)**	**R^2**
SEA_11_WL_F	588.40	29.51	0.89	0.10	1.44	1.16	-176.30	0.92
SEA_12_WL_F	898.71	16.89	0.94	0.07	0.84	0.90	1024.66	0.96
MAR_11_WL_F	610.13	17.66	0.96	0.08	1.41	1.19	-349.74	0.99
AVERAGE	***699.08***	***21.35***	***0.93***	***0.08***	***1.23***	***1.08***	***166.21***	***0.96***

As emerged from the figures, the simulation of soft wheat – high productivity grown under water limited conditions carried out by the CropSyst model is more accurate than the one of the other two wheat types. In this case, the model obtained satisfactory results also in the Marchouch experimental site (i.e., EF=0.49, RRMSE=57.63, R^2=1). At Sidy-El-Aydi, the model confirms the good performances already discussed, and obtains an average EF value of 0.69, an average RRMSE of 40.46 and a very good correlation between simulated and measured AGB (R^2=0.95), with an average mean absolute error of 1068.95 kg ha^{-1}. WOFOST performances in reproducing soft wheat – high productivity growth under water limited conditions are very good in all the available datasets. The model obtained and average modelling efficiency of 0.93, average RRMSE of 21.35, an average R^2 of 0.96 and an average mean absolute error of 699.08 kg ha^{-1}.

On the whole, the performances of the two models in reproducing water limited growth of soft wheat – high productivity are very good, thus indicating a marked ability of CropSyst and WOFOST to respond to the different meteorological conditions tested.

2.3. Summary evaluation of the models WOFOST and CropSyst under potential and water limited conditions

Figure 42 and Figure 43 report the scatterplots relative to the simulation of aboveground biomass carried out by CropSyst and WOFOST model in all the available datasets, under potential and water limited conditions, respectively.

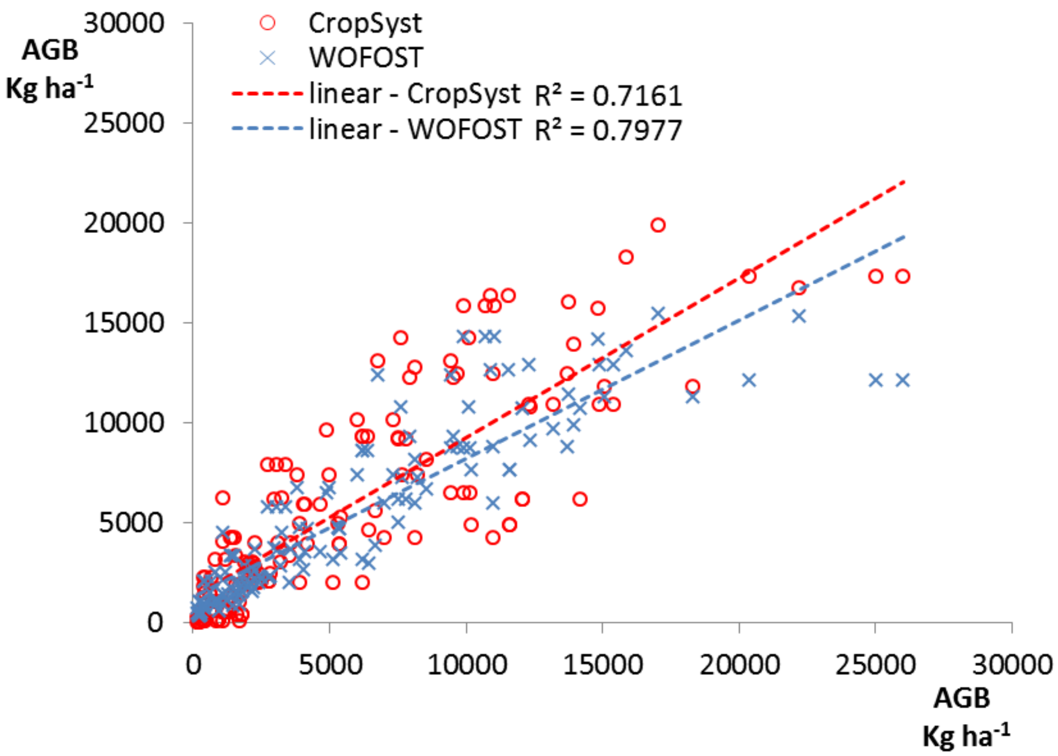

Figure 42. Scatter plot showing the correlation between the simulated and the measured aboveground biomass in all the available field experiments grown in potential conditions for WOFOST and CropSyst model

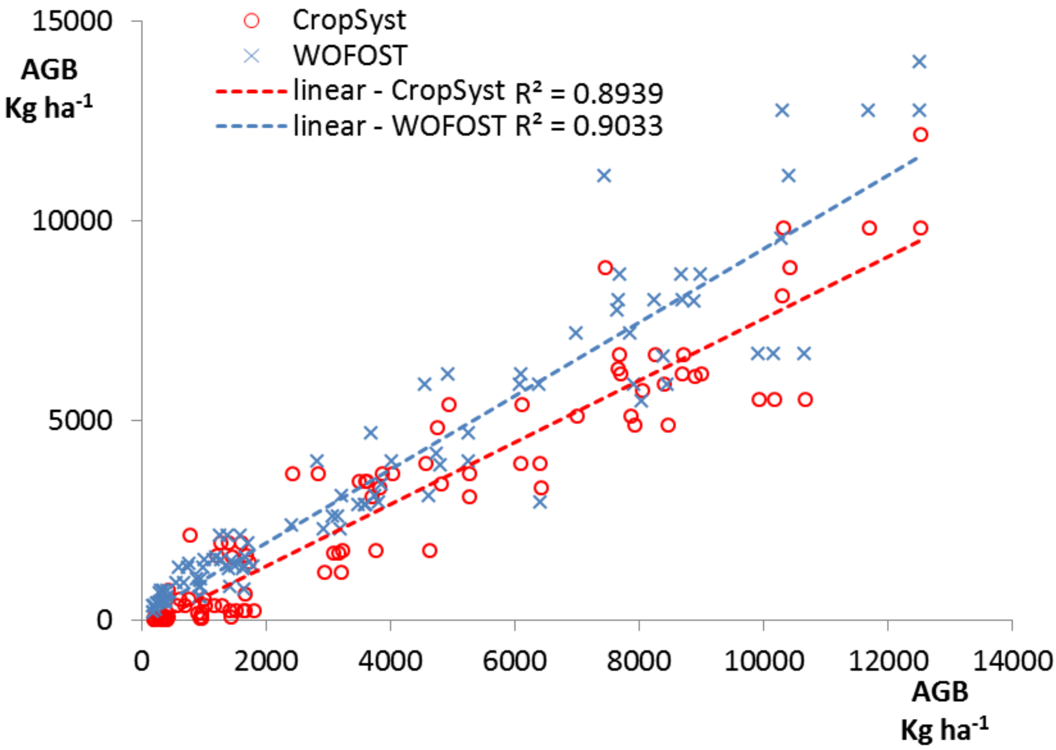

Figure 43. Scatter plot showing the correlation between the simulated and the measured aboveground biomass in all the available field experiments grown in water limited for WOFOST and CropSyst model

The aim of this analysis is to show the overall ability of the two models in reproducing the measured values of aboveground biomass by considering all the measurements of durum wheat, soft wheat – low productivity and soft wheat – high productivity. In general the two models provided a good simulation of aboveground biomass under both potential and water limited conditions. WOFOST performances are better than the CropSyst ones both in potential (WOFOST R^2=0.7977, CropSyst R^2=0.7161) and in water limited conditions (WOFOST R^2=0.9033, CropSyst R^2=0.8939). The fact that the models showed a better simulation of aboveground biomass measured in field experiments grown under water limitation is very encouraging, because most of the Moroccan wheat area is rainfed, and thus their application in this specific conditions is advantaged.

3. Conclusions

The evaluation of the WOFOST and CropSyst models for the simulation of durum and soft wheat development and growth in Morocco was carried out in three steps: (i) calibration of the models by using data coming from the field experiments grown under potential conditions, (ii) evaluation of models performances in potential datasets by using the calibrated parameter sets and (iii) evaluation of models performances in datasets in which wheat crop was grown in rainfed conditions. The strategy to follow in the calibration of the two models was decided in agreement with INRA-Morocco partners during the E-Agri meeting held in Rabat on 19-21 March 2013. During that meeting it was decided to develop three indendent sets of parameters for each model, one for durum wheat, one for soft wheat – low productivity and one for soft wheat – high productivity. At the same time some unexpected behaviours related to the field data collected in the 2011-2012 cropping season were clarified (see section 1.1.1 of this document).

The calibration of phenological development and of aboveground biomass accumulation in potential conditions allowed to obtain a good simulation of all the available datasets with small differences between the performances of the CropSyst and WOFOST models. The simulation of water limited datasets highlighted the higher accuracy of the WOFOST model with respect to the CropSyst one, especially in the Marchouch experimental site, which presented very low values of aboveground biomass in 2011-2012 cropping season. The quantitative evaluation by means of the fitting indices allowed to investigate model behaviour under different perspectives. This led to obtain clear indications about models functioning and to discretize model performances in the different datasets. In general the two models showed a very good simulation of water limited datasets, with a higher correlation with respect to the potential one. This issue is very important because most of the wheat growing area is actually rainfed, thus an accurate simulation of the impact of water stress on aboveground accumulation is essential to provide effective forecasts about crop productivity in these specific conditions.

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

Parameter	Unit	Value	Det.
Base temperature for emergence (TBASEM)	°C	0	D
Maximum temperature for emergence (TEFFMX)	°C	30	D
Temperature sum emergence (TSUMEM)	°C-d	100	C
Temperature sum from emergence to anthesis (TSUM1)	°C-d	800	C
Temperature sum from anthesis to maturity (TSUM2)	°C-d	515	C
Daily increase in temperature sum at Tavg[b] = 0 (DTSMTB)	°C; °C-d	0	C
Daily increase in temperature sum at Tavg = 24 (DTSMTB30)	°C; °C-d	24.5	C
Daily increase in temperature sum at Tavg = 34 (DTSMTB42)	°C; °C-d	0	C
PhotoInhibition (DLC)	hour	8	C
PhotoInsensitivity (DLO)	hour	13.5	C
Leaf area index at emergence (LAIEM)	m^2 m^{-2}	0.15	D
Relative leaf area growth rate (RGRLAI)	°C d^{-1}	0.003	C
Specific leaf area at DVS[a] = 0 (SLATB00)	ha kg^{-1}	0.0035	C
Specific leaf area at DVS[a] = 35 (SLATB35)	ha kg^{-1}	0.0017	C
Specific leaf area at DVS[a] = 200 (SLATB200)	ha kg^{-1}	0.0015	C
Life span of leaves growing at 35°C (SPAN)	d	32	D
Base temperature for leaves aging (TBASE)	°C	0	C
Extinction coefficient for diffuse visible light at DVS = 0 (KDIF000)	-	0.6	D
Extinction coefficient for diffuse visible light at DVS = 200 (KDIF200)	-	0.6	D
Light use efficiency at Tavg = 10°C (EFFTB10)	kg ha^{-1} h^{-1} J^{-1}	0.40	C
Light use efficiency at Tavg = 40°C (EFFTB40)	kg ha^{-1} h^{-1} J^{-1}	0.55	C
Maximum CO_2 assimilation rate at DVS = 00 (AMAXTB00)	kg ha^{-1} h^{-1}	28	C
Maximum CO_2 assimilation rate at DVS = 35 (AMAXTB35)	kg ha^{-1} h^{-1}	35	C
Maximum CO_2 assimilation rate at DVS = 100 (AMAX100)	kg ha^{-1} h^{-2}	35	C
Maximum CO_2 assimilation rate at DVS = 150 (AMAX150)	kg ha^{-1} h^{-1}	35	C
Maximum CO_2 assimilation rate at DVS = 200 (AMAX200)	kg ha^{-1} h^{-1}	0	C
AMAX reduction factor at Tavg = 2°C (TMPFTB2)	-	0	C
AMAX reduction factor at Tavg = 10°C (TMPFTB10)	-	0.5	C
AMAX reduction factor at Tavg = 15°C (TMPFTB15)	-	1	C
AMAX reduction factor at Tavg = 29°C (TMPFTB29)	-	1	D
AMAX reduction factor at Tavg = 34°C (TMPFTB34)	-	1	D
Gross Assimilation reduction factor at T_{min}[c] = -2 (TMNFTB)	-	0	C
Gross Assimilation reduction factor at T_{min} = -1 (TMNFTB)	-	0.3	C
Efficiency of conversion into leaves (CVL)	kg kg^{-1}	0.754	D
Efficiency of conversion into storage organs (CVO)	kg kg^{-1}	0.8	D
Efficiency of conversion into roots (CVR)	kg kg^{-1}	0.694	D

Efficiency of conversion into stems (CVS)	kg kg^{-1}	0.754	D
Relative increase in respiration rate for 10°C of temp increase (Q10)	-	2.5	C
Relative maintenance respiration rate for leaves (RML)	kg CH_2O kg^{-1} d^{-1}	0.05	C
Relative maintenance respiration rate for storage organs (RMO)	kg CH_2O kg^{-1} d^{-1}	0.01	D
Relative maintenance respiration rate for roots (RMR)	kg CH_2O kg^{-1} d^{-1}	0.015	D
Relative maintenance respiration rate for stems (RMS)	kg CH_2O kg^{-1} d^{-1}	0.012	C
Fraction of total biomass to roots at DVS = 0 (FRTB000)	kg kg^{-1}	0.5	D
Fraction of total biomass to roots at DVS = 10 (FRTB10)	kg kg^{-1}	0.5	D
Fraction of total biomass to roots at DVS = 20 (FRTB20)	kg kg^{-1}	0.4	D
Fraction of total biomass to roots at DVS = 35 (FRTB35)	kg kg^{-1}	0.22	D
Fraction of total biomass to roots at DVS = 40 (FRTB40)	kg kg^{-1}	0.17	D
Fraction of total biomass to roots at DVS = 50 (FRTB50)	kg kg^{-1}	0.13	D
Fraction of total biomass to roots at DVS = 70 (FRTB70)	kg kg^{-1}	0.07	D
Fraction of total biomass to roots at DVS = 90 (FRTB90)	kg kg^{-1}	0.03	D
Fraction of total biomass to roots at DVS = 120 (FRTB120)	kg kg^{-1}	0	D
Fraction of total biomass to roots at DVS = 200 (FRTB200)	kg kg^{-1}	0	D
Fraction of aboveground dry matter to leaves at DVS = 0 (FLTB000)	kg kg^{-1}	0.65	D
Fraction of aboveground dry matter to leaves at DVS = 10 (FLTB010)	kg kg^{-1}	0.50	C
Fraction of aboveground dry matter to leaves at DVS = 25 (FLTB025)	kg kg^{-1}	0.50	C
Fraction of aboveground dry matter to leaves at DVS = 50 (FLTB050)	kg kg^{-1}	0.40	C
Fraction of aboveground dry matter to leaves at DVS = 64.6 (FLTB064)	kg kg^{-1}	0.30	D
Fraction of aboveground dry matter to leaves at DVS = 95 (FLTB095)	kg kg^{-1}	0	D
Fraction of aboveground dry matter to leaves at DVS = 200 (FLTB200)	kg kg^{-1}	0	D
Fraction of aboveground dry matter to storage organs at DVS = 0 (FOTB000)	kg kg^{-1}	0	C
Fraction of aboveground dry matter to storage organs at DVS = 90 (FOTB090)	kg kg^{-1}	0	C
Fraction of aboveground dry matter to storage organs at DVS = 100 (FOTB100)	kg kg^{-1}	1	C
Fraction of aboveground dry matter to storage organs at DVS = 200 (FOTB200)	kg kg^{-1}	1	C
Fraction of aboveground dry matter to stems at DVS = 0 (FSTB000)	kg kg^{-1}	0.35	D
Fraction of aboveground dry matter to stems at DVS = 10 (FSTB010)	kg kg^{-1}	0.50	C
Fraction of aboveground dry matter to stems at DVS = 25 (FSTB025)	kg kg^{-1}	0.50	C
Fraction of aboveground dry matter to stems at DVS = 50 (FSTB050)	kg kg^{-1}	0.60	C
Fraction of aboveground dry matter to stems at DVS = 64.6 (FSTB064)	kg kg^{-1}	0.70	D
Fraction of aboveground dry matter to stems at DVS = 95 (FSTB095)	kg kg^{-1}	1	D
Fraction of aboveground dry matter to stems at DVS = 100 (FSTB100)	kg kg^{-1}	0	D
Fraction of aboveground dry matter to stems at DVS = 200 (FSTB200)	kg kg^{-1}	0	D
Relative death rate of roots at DVS = 0 (RDRRTB0)	kg kg^{-1} day^{-1}	0	D
Relative death rate of roots at DVS = 150 (RDRRTB150)	kg kg^{-1} day^{-1}	0	D

Relative death rate of roots at DVS = 151 (RDRRTB151)	kg kg^{-1} day^{-1}	0.02	D
Relative death rate of roots at DVS = 200 (RDRRTB200)	kg kg^{-1} day^{-1}	0.02	D
Relative death rate of stems at DVS = 0 (RDRSTB0)	kg kg^{-1} day^{-1}	0	D
Relative death rate of stems at DVS = 150 (RDSRTB150)	kg kg^{-1} day^{-1}	0.2	C
Relative death rate of stems at DVS = 151 (RDSRTB151)	kg kg^{-1} day^{-1}	0.2	C
Relative death rate of stems at DVS = 200 (RDSRTB200)	kg kg^{-1} day^{-1}	0.2	C
Specific stem area at DVS = 0 (SSA000)	ha kg^{-1}	0	D
Specific stem area at DVS = 200 (SSA200)	ha kg^{-1}	0	D
Initial total crop dry weight (TDWI)	kg ha^{-1}	210	D
Development Stage at harvest (DVSEND)	-	3	C
Maximum rooting depth (RDM)	cm	125	D
Maximum daily increase in rooting depth	cm d^{-1}	1.2	D
Maximum relative death rate leaves due to water stress	kg kg^{-1} d^{-1}	0.01	D

[a] Development stage code (unitless; 0: emergence, 100: flowering, 200: physiological maturity)
[b] Average air daily temperature (°C)
[c] Minimum air daily temperature (°C)

Appendix B. Parameter values and determination for high productivity –HP – and low productivity – LP – soft wheat (C: calibrated parameters; L: literature; D: default) relative to WOFOST model.

Parameter	Unit	Value HP*	Value LP*	Det.
Base temperature for emergence (TBASEM)	°C	0	0	D
Maximum temperature for emergence (TEFFMX)	°C	30	30	D
Temperature sum emergence (TSUMEM)	°C-d	134.6	134.5	C
Temperature sum from emergence to anthesis (TSUM1)	°C-d	629.1	556.7	C
Temperature sum from anthesis to maturity (TSUM2)	°C-d	602.4	1127.4	C
Daily increase in temperature sum at Tavg[b] = 0 (DTSMTB)	°C; °C-d	0		C
Daily increase in temperature sum at Tavg = 23 (DTSMTB24)	°C; °C-d	23	23	C
Daily increase in temperature sum at Tavg = 33 (DTSMTB34)	°C; °C-d	0	0	C
PhotoInhibition (DLC)	hour	8.53	8.53	C
PhotoInsensitivity (DLO)	hour	14	13.16	C
Leaf area index at emergence (LAIEM)	$m^2\ m^{-2}$	0.15	0.15	D
Relative leaf area growth rate (RGRLAI)	$°C\ d^{-1}$	0.003	0.003	C
Specific leaf area at DVS[a] = 0 (SLATB00)	$ha\ kg^{-1}$	0.0035	0.0030	C
Specific leaf area at DVS = 35 (SLATB35)	$ha\ kg^{-1}$	0.0025	0.0025	C
Specific leaf area at DVS = 200 (SLATB200)	$ha\ kg^{-1}$	0.0020	0.0020	C
Life span of leaves growing at 35°C (SPAN)	d	28	28	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 = 200 (KDIF200)	-	0.6	0.6	D
Light use efficiency at Tavg = 10°C (EFFTB10)	$kg\ ha^{-1}\ h^{-1}\ J^{-1}$	0.36	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 = 00 (AMAXTB00)	$kg\ ha^{-1}\ h^{-1}$	20	30	C
Maximum CO_2 assimilation rate at DVS = 35 (AMAXTB35)	$kg\ ha^{-1}\ h^{-1}$	30	35	C
Maximum CO_2 assimilation rate at DVS = 100 (AMAX100)	$kg\ ha^{-1}\ h^{-2}$	40	40	C
Maximum CO_2 assimilation rate at DVS = 190 (AMAX190)	$kg\ ha^{-1}\ h^{-1}$	25	35	C
Maximum CO_2 assimilation rate at DVS = 200 (AMAX200)	$kg\ ha^{-1}\ h^{-1}$	0	0	C
AMAX reduction factor at Tavg = 0°C (TMPFTB0)	-	0	0	C
AMAX reduction factor at Tavg = 10°C (TMPFTB10)	-	0.6	0.6	C
AMAX reduction factor at Tavg = 16°C (TMPFTB16)	-	1	1	C
AMAX reduction factor at Tavg = 29°C (TMPFTB29)	-	1	1	C
AMAX reduction factor at Tavg = 33°C (TMPFTB33)	-	0.8	0.7	C
AMAX reduction factor at Tavg = 40°C (TMPFTB40)	-	0	0	C
Gross Assimilation reduction factor at T_{min}[c] = 0 (TMNFTB)	-	0.5	0.5	C

Gross Assimilation reduction factor at T_{min} = 2.5 (TMNFTB)	-	1	1	
Efficiency of conversion into leaves (CVL)	kg kg^{-1}	0.754	0.754	C
Efficiency of conversion into storage organs (CVO)	kg kg^{-1}	0.8	0.754	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 for 10°C of temp increase (Q10)	-	2	2	C
Relative maintenance respiration rate for leaves (RML)	kg CH_2O kg^{-1} d^{-1}	0.03	0.025	C
Relative maintenance respiration rate for storage organs (RMO)	kg CH_2O kg^{-1} d^{-1}	0.01	0.01	C
Relative maintenance respiration rate for roots (RMR)	kg CH_2O kg^{-1} d^{-1}	0.015	0.01	C
Relative maintenance respiration rate for stems (RMS)	kg CH_2O kg^{-1} d^{-1}	0.015	0.01	C
Fraction of total biomass to roots at DVS = 0 (FRTB000)	kg kg^{-1}	0.50	0.50	D
Fraction of total biomass to roots at DVS = 10 (FRTB10)	kg kg^{-1}	0.50	0.50	D
Fraction of total biomass to roots at DVS = 20 (FRTB20)	kg kg^{-1}	0.40	0.40	D
Fraction of total biomass to roots at DVS = 35 (FRTB35)	kg kg^{-1}	0.22	0.2	D
Fraction of total biomass to roots at DVS = 40 (FRTB40)	kg kg^{-1}	0.17	0.13	D
Fraction of total biomass to roots at DVS = 50 (FRTB50)	kg kg^{-1}	0.13	0.1	D
Fraction of total biomass to roots at DVS = 70 (FRTB70)	kg kg^{-1}	0.07	0.07	D
Fraction of total biomass to roots at DVS = 90 (FRTB90)	kg kg^{-1}	0.03	0.03	D
Fraction of total biomass to roots at DVS = 120 (FRTB120)	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}	0.70	0.60	C
Fraction of aboveground dry matter to leaves at DVS = 50 (FLTB050)	kg kg^{-1}	0.50	0.50	C
Fraction of aboveground dry matter to leaves at DVS = 64.6 (FLTB064)	kg kg^{-1}	0.30	0.30	D
Fraction of aboveground dry matter to leaves at DVS = 95 (FLTB095)	kg kg^{-1}	0	0	D
Fraction of aboveground dry matter to leaves at DVS = 200 (FLTB100)	kg kg^{-1}	0	0	D
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	kg kg^{-1}	0.35	0.35	D

(FSTB000)				
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}	0.30	0.50	C
Fraction of aboveground dry matter to stems at DVS = 50 (FSTB050)	kg kg^{-1}	0.50	0.50	C
Fraction of aboveground dry matter to stems at DVS = 64.6 (FSTB064)	kg kg^{-1}	0.70	0.70	D
Fraction of aboveground dry matter to stems at DVS = 95 (FSTB095)	kg kg^{-1}	1	1	D
Fraction of aboveground dry matter to stems at DVS = 100 (FSTB100)	kg kg^{-1}	0	0	D
Fraction of aboveground dry matter to stems at DVS = 200 (FSTB200)	kg kg^{-1}	0	0	D
Relative death rate of roots at DVS = 0 (RDRRTB0)	kg kg^{-1} day^{-1}	0	0	D
Relative death rate of roots at DVS = 150 (RDRRTB150)	kg kg^{-1} day^{-1}	0	0	D
Relative death rate of roots at DVS = 151 (RDRRTB151)	kg kg^{-1} day^{-1}	0.02	0.02	D
Relative death rate of roots at DVS = 200 (RDRRTB200)	kg kg^{-1} day^{-1}	0.02	0.02	D
Relative death rate of stems at DVS = 0 (RDRSTB0)	kg kg^{-1} day^{-1}	0	0	D
Relative death rate of stems at DVS = 150 (RDSRTB150)	kg kg^{-1} day^{-1}	0	0	C
Relative death rate of stems at DVS = 151 (RDSRTB151)	kg kg^{-1} day^{-1}	0.02	0.02	C
Relative death rate of stems at DVS = 200 (RDSRTB200)	kg kg^{-1} day^{-1}	0.02	0.02	C
Specific stem area at DVS = 0 (SSA000)	ha kg^{-1}	0	0	D
Specific stem area at DVS = 200 (SSA200)	ha kg^{-1}	0	0	D
Initial total crop dry weight (TDWI)	kg ha^{-1}	210	210	C
Development Stage at harvest (DVSEND)	-	2.4	2.1	C
Maximum rooting depth (RDM)	cm	125	125	D
Maximum daily increase in rooting depth	cm d^{-1}	1.2	1.2	D
Maximum relative death rate leaves due to water stress	kg kg^{-1} d^{-1}	0.01	0.01	D

[a] Development stage code (unitless; 0: emergence, 100: flowering, 200: physiological maturity)
[b] Average air daily temperature (°C)
[c] Minimum air daily temperature (°C)

Appendix C. Parameter values and determination for durum wheat (C: calibrated parameters; L: literature; D: default) relative to CropSyst model

Parameter	Unit	Value	Det.
Development			
Base temperature (Tbase)	°C	0	C
Cutoff temperature (Tcutoff)	°C	24.5	C
GDD emergence (GDDem)	°C-d	100	C
GDD flowering (GDDfl)	°C-d	900	C
GDD from flowering to maturity (GDDm)	°C-d	1455	C
PhotoInhibition	hour	8	C
PhotoInsensitivity	hour	13.5	C
Growth			
Biomass-transpiration coefficient (BTR)	kPa kg m^{-3}	8	C
Maximum radiation use efficiency (RUEmax)	g MJ^{-1}	3.2	C
Specific leaf area (SLA)	m^2 kg^{-1}	27	C
Stem/leaf partition coefficient (SLP)	-	4.5	C
Leaf duration (LeafDur)	°C-d	580	C
Extinction coefficient for solar radiation (k)	-	0.55	C
Base temperature for growth (Tbase)	°C	2	C
Optimum temperature for growth (Topt)	°C	15	C
Initial leaf area index (LAIini)	m^2 m^{-2}	0.0003	C
Full canopy coefficient (Kc)	-	1.05	D

Appendix D. Parameter values and determination for high productivity –HP – and low productivity – LP – soft wheat (C: calibrated parameters; L: literature; D: default) relative to CropSyst model.

Parameter	Unit	Value LY*	Value HY*	Det.
		Development		
Base temperature (Tbase)	°C	0	0	C
Cutoff temperature (Tcutoff)	°C	24	22.7	C
GDD emergence (GDDem)	°C-d	134.6	135	C
GDD flowering (GDDfl)	°C-d	760	850	C
GDD from flowering to maturity (GDDm)	°C-d	1390	1400	C
PhotoInhibition	hour	8.53	8.53	C
PhotoInsensitivity	hour	14	13.16	C
		Growth		
Biomass-transpiration coefficient (BTR)	kPa kg m^{-3}	6	6	C
Maximum radiation use efficiency (RUEmax)	g MJ^{-1}	2.9	3.1	C
Specific leaf area (SLA)	m^2 kg^{-1}	26	29	C
Stem/leaf partition coefficient (SLP)	-	4.5	4.5	C
Leaf duration (LeafDur)	°C-d	580	580	C
Extinction coefficient for solar radiation (k)	-	0.55	0.55	C
Base temperature for growth (Tbase)	°C	0	0	C
Optimum temperature for growth (Topt)	°C	15	15	C
Initial leaf area index (LAIini)	m^2 m^{-2}	0.0005	0.0075	C
Full canopy coefficient (Kc)	-	1.05	1.05	D