



## Article

# Performance Evaluation of the WOFOST Model for Estimating Evapotranspiration, Soil Water Content, Grain Yield and Total Above-Ground Biomass of Winter Wheat in Tensift Al Haouz (Morocco): Application to Yield Gap Estimation

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**Abstract:** The main goal of this investigation was to evaluate the potential of the WOFOST model for estimating leaf area index (LAI), actual evapotranspiration (ET<sub>a</sub>), soil moisture content (SM), above-ground biomass levels (TAGP) and grain yield (TWSO) of winter wheat in the semi-arid region of Tensift Al Haouz, Marrakech (central Morocco). An application for the estimation of the Yield Gap is also provided. The model was firstly calibrated based on three fields data during the 2002–2003 and 2003–2004 growing seasons, by using the WOFOST implementation in the Python Crop simulation Environment (PCSE) to optimize the different parameters that provide the minimum difference between the measured and simulated LAI, TAGP, TWSO, SM and ET<sub>a</sub>. Then, the model validation was performed based on the data from five other wheat fields. The results obtained showed a good performance of the WOFOST model for the estimation of LAI during both growing seasons on all validation fields. The average R<sup>2</sup>, RSME and NRMSE were 91.4%, 0.57 m<sup>2</sup>/m<sup>2</sup>, and 41.4%, respectively. The simulated ET<sub>a</sub> dynamics also showed a good agreement with the observations by eddy covariance systems. Values of 60% and 72% for R<sup>2</sup>, 0.8 mm and 0.7 mm for RMSE, 54% and 31% for NRMSE are found for the two validation fields, respectively. The model's ability to predict soil moisture content was also found to be satisfactory; the two validation fields gave R<sup>2</sup> values equal to 48% and 49%, RMSE values equal to 0.03 cm<sup>3</sup>/cm<sup>3</sup> and 0.05 cm<sup>3</sup>/cm<sup>3</sup>, NRMSE values equal to 11% and 19%. The calibrated model had a medium performance with respect to the simulation of TWSO (R<sup>2</sup> = 42%, RSME = 512 kg/ha, NRMSE = 19%) and TAGP (R<sup>2</sup> = 34% and RSME = 936 kg/ha, NRMSE = 16%). After accurate calibration and validation of the WOFOST model, it was used for analyzing the gap yield since this model is able to estimate the potential yield. The WOFOST model allowed a good simulation of the potential yield (7.75 t/ha) which is close to the optimum value of 6.270 t/ha in the region. Yield gap analysis reveals a difference of 5.35 t/ha on average between the observed yields and the potential yields calculated by WOFOST. Such difference is ascribable to many factors such as the crop cycle management, agricultural practices such as water and fertilization supply levels, etc. The various simulations (irrigation scenarios) showed that early sowing is more adequate than late sowing in saving water and obtaining adequate grain yield. Based on various simulations, it has been shown that the early sowing (mid to late December) is more adequate than late sowing with a total amount of water supply of about 430 mm and 322 kg (140 kg of N, 80 kg of P and 102 kg of K) of fertilization to achieve the potential yield. Consequently, the WOFOST model can be considered as a suitable tool for quantitative monitoring of winter wheat growth in the arid and semi-arid regions.

**Keywords:** crop modelling; WOFOST; Tensift Morocco; evapotranspiration; crop yield estimation; soil moisture; leaf area index; total biomass; winter wheat; gap yield

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## 1. Introduction

Agricultural systems are in constant evolution all over the world. This is due to the consequences of globalization, human actions on the environment and climate, changes in market expectations, new agrotechnology, etc. [1]. While plants naturally try to adapt to all these changes, humans also try to help them by adapting agricultural practices to new conditions. Thus, scientists have directed significant efforts to assess plant adaptation through the development of models that predict crop. In this regard, several crop growth models have been developed and have progressed significantly since 1980 [2,3].

Crop models are computer programs that simulate the actual behavior of crops, their growth and development. In addition to predicting final yield, they also provide quantitative information about major crop cycle processes [4]. Traditionally, field experiments have provided insight into many of the plant production functions through statistical analyses. However, they do not take into account the underlying biological or physical principles involved. A qualitative understanding of the variables and their interaction in cropping systems has, therefore, been made possible through regression and correlation analyses [4].

However, the quantitative information inferred can only be applicable in similar areas. In addition, climate variability requires a 10-year period to develop a fairly robust statistical relationship. More than 40% of total variation is generally associated with experimental errors [5]. Currently, thanks to technological progress and the birth of powerful and intelligent machines, we are able to move from the qualitative to the quantitative. Thus, soil, climate and plant systems can be combined to more accurately predict crop yields [6]. In a consistent quantitative approach, crop growth models bring together current knowledge from several fields (plant physiology, agrometeorology, agronomy and soil science).

The WOFOST model that is originally developed by Wageningen University in the Netherlands has had at least 10 different implementations of the same concept [7]. It is a dynamic and mechanistic system that simulates daily crop growth based on agro- and pedoclimatic data. It has been used extensively, notably in the MARS crop yield forecasting system in Europe but also in many other locations and for quite varied purposes. For example, in China, it has been used to simulate and predict the yield of perennial jujube. The incorporation of tree age has significantly improved the performance of the model [8]. Its performance has also been successfully tested to analyze the effect of yield variability between cropping seasons, on different soil types and in the context of climate change [9–11]. Over the years, some research progresses have contributed to the improvement of the WOFOST model. In Italy, a study led to the establishment of the WOFOST-GTC model which is a model derived from WOFOST. They reduced the complexity of WOFOST by reducing the number of parameters from 97 to 35. Despite this reduction, WOFOST-GTC was found to be accurate. The derived model was used for a good simulation of the oil content and composition of COLZA seed [12]. In 2019, WOFOST was also used to simulate multi-species plant communities in mowed grasslands. It was combined with the CropSyst and CoSMO model to reduce biases in the estimation of harvested aboveground biomass and to have a dynamic simulation of the relative presence of species [13]. In China, in order to effectively assess heavy metal stress levels in rice, a study developed an improved assimilation method to incorporate the remotely detected LAI by a PSO assimilation algorithm. The improved WOFOST model was able to continuously monitor heavy metal stress levels [14].

In Morocco, WOFOST and many other models applicable in semi-arid to arid areas have been used. The use of a yield prediction system really started in 2000 thanks to the “Drought Program” launched by the World Bank and the Moroccan government. The objective was to identify farmers who were members of the insurance scheme and

eligible for compensation. Therefore, long data sets were needed, yet their availability was still a major constraint at the time [15]. Since then, with a concomitant effort by national institutions, the Crop Growth Monitoring System (CGMS) model for Morocco has been developed. The forecasts made by this model use meteorological, satellite and statistical data and are based on two methods: similarity analysis and multiple regression equation models [16]. In addition, the effect of climate stress is felt more in recent years on Moroccan agriculture, especially on its cereal sector. Thus, in order to address the problem of water availability, yield decline, probable food insecurity at the national level and to reduce the yield gap, many crops growth models have been tested, calibrated and validated. Their application has proven useful and beneficial. For example, a study evaluated the AquaCrop model for yield prediction of soft wheat in Meknes province. It compared the performance of this model with the CGMS-Morocco and concluded that the latter was less accurate than the AquaCrop model. Also, Séverine Demerre successfully evaluated the AquaCrop model for soft wheat yield prediction in Meknes province. She compared the effectiveness of this model with CGMS-Morocco and concluded the latter was less accurate than the AquaCrop [16]. Similarly, Aquacrop was found to be quite efficient for estimating evapotranspiration, soil moisture, grain yield of durum wheat in Tensift AL Haouz region [17]. An application for irrigation water management was well deduced and the discrepancy between potential and observed yields in the region was also highlighted [17]. On the other hand, a study in the semi-arid region of Morocco opted for a multi-model approach (WOFOST and CropSyst) and were able to improve the estimation of yield for different wheat varieties. However, in their calibration approach they did not take into account the temporal evolution of leaf area, nor that of soil moisture, even less evapotranspiration [18].

The use of crop models has been clearly helpful in reducing field investigation time, sampling losses, improving field performance and reducing yield gaps. Moreover, they are increasingly used in the fight against food insecurity.

The yield gap is the difference between the yield allowed by soil and climate conditions without any biotic or abiotic limitations and the actual yield achieved by farmers [19]. Wheat, whether rainfed or irrigated, is one of the crops with a still very high yield gap to date; a gap of about 50% on average is estimated between global production and water-limited potential production [20]. This gap can vary significantly from one locality to another. In the Mediterranean, for example, a gap of 41% and 29% is recorded in Morocco for rainfed and irrigated wheat, respectively [21], while in Spain a gap of 49% to 66% is observed for rainfed wheat [22]. In addition, yield gap analysis and the importance of finding the main reasons that limit actual yields has been widely studied around the world [21,23–25] and increasingly in Africa [26]. Many agronomic causes are often behind these deficits [27], and they can be lack of nitrogen fertilizer [25,27,28], limited number of spikes per hectare [29], inappropriate sowing date [25,28], soil fertility level [25], biotic stresses [30], water stress [22], low seeding rate, summer fallow, and tillage [31], etc. Other research has incorporated the concept of gross margin gap to demonstrate the value of achieving potential yield [21]. Simple and less expensive methods have also been introduced to help developing countries analyze and reduce their yield gap [32]. The WOFOST model used successfully in Europe to analyze the yield gap in autumn-sown wheat [33]. Concerning the evaluation of the yield gap by the WOFOST model in Morocco, only the World Atlas of Yield Gaps project provides an overview [20]. In this work, we provide new assessments of the strengths and limitations of this model in the analysis of the yield gap of wheat in the semi-arid area of Marrakech by taking fully advantage of large amount of ground truth to assess the performance the different components of the models.

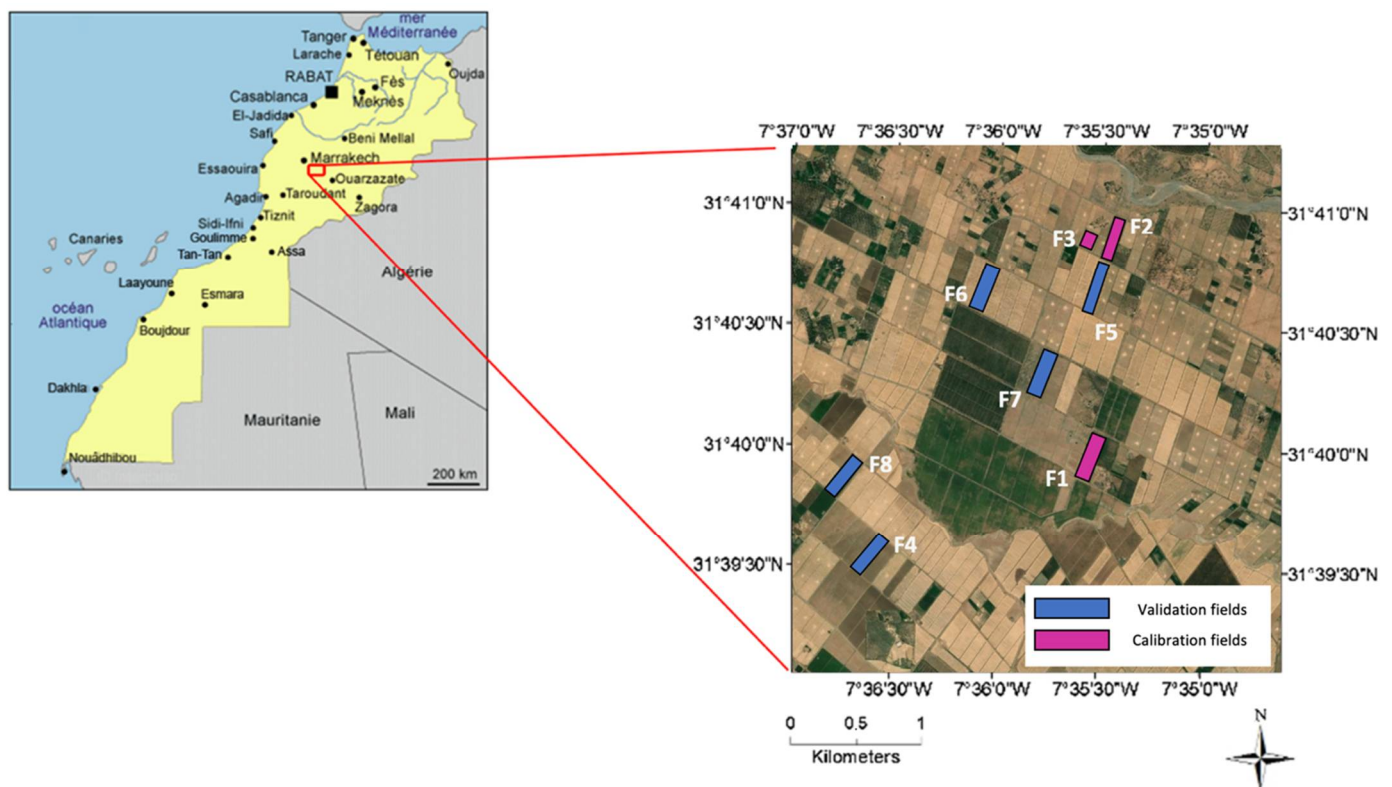
In this same vein, the objective of this work is first to calibrate the WOFOST model over flooding irrigation wheat fields using ground observations obtained over three fields (F1, F2, F3), and to validate it over five different other wheat fields (F4 to F8). The targeted

variables were soil moisture (SM), evapotranspiration (ETa), leaf area index (LAI), total biomass (TAGP), and grain yield (TWSO).

## 2. Materials and Methods

### 2.1. Description of Study Area

The experimental site is located in central Morocco, in the R3 irrigated area located about 40 km east of the city of Marrakech (Figure 1). The climate in this area is semi-arid Mediterranean with a very high atmospheric demand of about 1600 mm/year [34,35]. While the annual precipitation level, generally recorded between November and the end of April, is in the range 190 to 250 mm/year [34–36].



**Figure 1.** Location of the experiment sites: on the left, the general map of Morocco highlights the Marrakech city and the experimental site; on the right, the whole irrigated zone R3 with the location of the different fields used for the calibration (F1, F2 and F2) and the validation ones (from F4 to F8) during the 2002/2003 and 2003/2004 cropping seasons.

Since 1999, the Office Régional de Mise en Valeur Agricole du Haouz (ORMVAH) has been managing this almost flat area covering 2800 ha. The colluvial materials of the High Atlas range have served to develop the deep soil of this area, which is of the xerosol type. The texture is fine, clay to silty-clay (47% clay, 33% silt and 20% sand) [34]. The soil being homogeneous, its hydraulic characteristics are almost identical throughout the site. Values of 0.32, 0.17 and 0.45 m<sup>3</sup>/m<sup>3</sup> are noted for field capacity (SMFCF), permanent wilting point (SMW), saturation point (SM0), respectively. The default value of hydraulic conductivity (K0) for clayey loam soils was used (100 mm/day). No influence of the groundwater was taken into account, the water table being at a depth of more than 50 m due to an intense overexploitation. An annual decrease of about 0.5 to 1.5 m is noted [37].

Given the rather difficult soil and climate conditions of the R3 zone, the main crop grown is Karim durum wheat as it is more suitable for the region.

## 2.2. Field Description

Eight fields were used in this experiment. Figure 1 shows the spatial distribution of these fields in the R3 zone. In the case of the latter, two of the fields (F1 and F4) were cultivated during the 2002/2003 crop season, while the rest (F2, F3, F5, F6, F7 and F8) were cultivated during the 2003/2004 crop seasons. They were all sown with the variety Karim at different sowing dates, except for fields F5 and F2, which were sown on the same day, i.e., 21 November 2004 (Table 1).

**Table 1.** Sowing date, sowing rate, plant density and amount of fertilizer.

	Calibration Field				Validation Field			
	F1	F2	F3	F4	F5	F6	F7	F8
Sowing date	11-January-03	21-November-03	20-December-03	17-December-02	21-November-03	15-December-03	19-December-03	24-December-03
Seeding rate (kg/ha)	100	100	100	150	150	150	100	140
Plant density (plants/m <sup>2</sup> )	225	225	225	337.3	337.3	337.3	225	315
Fertilization (kg) NPK (14-28-14)	100	- <sup>a</sup>	-	-	50	-	100	50

<sup>a</sup> Means no fertilization was applied.

They did not require any vernalization and were harvested at the end of May. The pre-tillage was identical for all fields. Their water requirement was provided by gravity irrigation when available. In 2002/2003, each irrigation event consisted of 30 mm per field. In 2003/2004, this rate was 60 mm per field. Nutrient inputs were relatively low for fields F5 and F8, which received 50 kg/ha of NPK fertilizer (14-28-14), while fields F1 and F7 received 100 kg/ha of the same fertilizer. For the remaining fields (F4, F2, F6 and F3), no fertilization was applied. The recommendations for the region in terms of nutrient supply for the wheat crop are 225 kg/ha of NPK for non-limiting soil fertility. With respect to this value, no field was free of nutrient stress. This is because fertilization was dependent on the economic capacity of the farmer. All the details concerning the technical itinerary of these fields are recorded in Tables 1 and 2.

**Table 2.** Irrigation events.

	Calibration Field				Validation Field			
	F1 *	F2	F3	F4 *	F5	F6	F7	F8
1st irrigation	01-February-03	16-January-04	16-January-04	28-January-03	20-January-04	20-January-04	18-January-04	26-January-04
2nd irrigation	21-February-03	17-February-04	16-February-04	22-February-03	23-February-04	15-February-04	24-February-04	21-February-04
3rd irrigation	14-March-03	28-March-04	26-March-04	10-April-03	01-April-04	17-March-04	21-April-04	27-March-04
4th irrigation	24-March-03							
5th irrigation	07-April-03							
6th irrigation	24-April-03							

\* Fields were periodically irrigated by applying 30 mm in each irrigation event. The remaining fields were irrigated with 60 mm during each irrigation event.

## 2.3. Description of the Data

Conventional automatic sensors were mounted on a tower installed on a well-watered clipped grass. These sensors located very close to the fields of interest recorded incoming solar radiation (CNR1, Kipp & Zonen, Delft, The Netherlands), air temperature and vapor pressure (HMP45C, Vaisala, Helsinki, Finland), wind speed (A100R anemometer, RM Young Company, Traverse City, MI, USA) and precipitation (FSS500 automatic bucket rain gauge, Campbell Inc., Logan, UT, USA) The daily reference evapotranspiration ETo

(mm/day) was obtained according to the FAO-56 Penman–Monteith equation [38], by calculating the daily mean values of the climatic data. A detailed analysis of the temporal profile of ETo during the experimental period is provided by Er-Raki et al. [35,39].

For the measurement of actual evapotranspiration (ETa), an Eddy Co-variance (EC) system was installed on each field (F1 & F4) during the 2002/2003 season. The ETa data are thus acquired using high frequency measurements of three-dimensional (3D) fluctuations of air speed, temperature and water vapour. The EC system consists of an open path infrared gas analyzer (Li7500, Licor Inc., Lincoln, NE, USA) or a fast hygrometer (KH2O, Campbell Scientific Inc., Logan, UT, USA) and a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd. Logan, UT, USA). More detailed descriptions of the EC measurements and data processing are given in [34].

A split tube sampler was used to collect several soil samples at different depths: (5-10-20-30-50 cm). The water contents for these different depths were deduced from the difference between the fresh weight and the dry weight (dried in an oven at 105 °C for about 72 h) of each sample. This was used to monitor soil moisture content during the 2002–2003 crop year (F4). A TDR (time-domain reflectometry) was also used. It was placed in field F1 (during 2002–2003) and in field F7 (during 2003–2004). It was used to record soil water content at a 30 min time step at depths of 5-10-20-30-45 cm. The initial soil moisture content was set at 0.245 cm<sup>3</sup>/cm<sup>3</sup> because soil moisture was not measured at the beginning of the crop year. This value, which is equal to half of the total available water, was chosen because farmers in the area plant wheat after a major rain event, when soil moisture has become conducive to tillage and germination.

Canopy cover (CC) data are obtained using photographs of the hemispheric canopy using a Nikon Coolpix 950 camera with a FC-E8 fisheye lens converter, field of view 183°. We refer to the work of [34,40,41] for more details on this technique and the software processing used to derive CC. Leaf area index (LAI) values were then calculated using the following formula [14]:

$$LAI = \frac{1}{K} \text{Log} \left( \frac{1}{1 - CC} \right) \quad (1)$$

where K is the light extinction coefficient. For a random direction of the radiation and for a homogeneous distribution of the plant cover, a value of K = 0.5 is widely used.

The final grain yield of all fields is measured towards the end of May. The protocol adopted to make these final yield measurements is as follows: five quadrats (0.25 m<sup>2</sup>, i.e., 0.5 m × 0.5 m) were randomly selected in each field, and used to sample plants for grain yield (TWSO) and total biomass (TAGP) measurements.

In the second crop year (2003–2004), measurements similar to those described above were made on one field (F7). For the remaining fields (F4, F5, F6, F8), only CC, TWSO and TAGP measurements were taken.

In addition to the measurements listed above, observations were conducted to record phenological times: Emergence (coleoptile breaks through the soil surface), Time from sowing to maximum CC, Time from sowing to the beginning of senescence, and Maturity dates (caryopsis is hard and difficult to cut in half with the fingernail) were observed in order to calibrate the phenological parameters and to validate the simulated performance for the phenological development time. Flowering (appearance of anthers) itself was not observed, it was deduced approximately using the above observations.

These phenological observations were only made on calibration field F1. On the other two calibration fields (F2 and F3), these phenological times were called manually.

#### 2.4. Crop Growth Model

The WOFOST (WORLD FOOD STUDIES) crop model is a dynamic and mechanistic model that allows the quantitative analysis of the daily production and growth of annual field crops. Its physical principle is based on the main basic physiological processes of the crop: CO<sub>2</sub> assimilation, light interception, growth and maintenance respiration, phenological

development, transpiration losses, and assimilate distribution in different organs. Specific descriptions and mathematical details can be referenced to existing studies [7,42].

WOFOST also takes into account the effects of weather and soil conditions through the soil, climate and ASTRO modules. The assimilation of carbohydrates which constitute the backbone of the plant is simulated through the ASTRO and climate modules. These modules also allow WOFOST to determine the intensity of light intercepted by the plant for its photosynthesis. These assimilations are strongly influenced by solar radiation, temperature variation, precipitation level and crop characteristics during a day. WOFOST applies the ratio of actual transpiration to potential transpiration of the crop as a factor in reducing the gross assimilation rate. A portion of the assimilates formed is used for maintenance respiration and growth respiration. Maintenance respiration is the energy expended to maintain plant organ respiration while growth respiration is the net loss of carbohydrates due to the conversion of carbohydrate to structural plant material, such as cellulose and protein (dry matter). Maintenance respiration is estimated on the basis of the dry weight of individual organs and their chemical composition, modified by ambient temperature.

The remaining net assimilate quantity is distributed among the organs (roots, stems, leaves and storage organs) according to the phenological development stage taken into account by the DVS (Development Stage) parameter. For example, from DVS equal to 1 (flowering), all the assimilates are directed to the storage organs.

The Soil module allows to follow the soil moisture content and to draw up the daily water balance. In WOFOST, four soil water balance sub-models are distinguished according to the implementation. For more details, the reader can refer to [42].

WOFOST allows for the separate calculation of soil evaporation and plant transpiration to simulate the actual evapotranspiration (ET<sub>a</sub>). ET<sub>a</sub> is deduced from the potential evapotranspiration (ETP) which is itself calculated by referring to the Penman–Monteith formula. Since the potential evapotranspiration of some crops may be higher than that calculated by the Penman–Monteith formula, WOFOST multiplies the Penman evapotranspiration by a crop-dependent correction factor called CFET to obtain the maximum evapotranspiration ET<sub>m</sub> [43]. Then, ET<sub>a</sub> is obtained by correcting ET<sub>m</sub> by water stress factors caused by either waterlogging (Ros factor) or depletion (Rws factor).

### 2.5. Calibration

As is known, the sensitivity analysis is needed before the model calibration, which can identify the most sensitive crop parameters. However, in this work, we strictly followed the guideline given by Boogaard and Allard [43] when they provided detailed procedures for calibrating the different parameters of the WOFOST model as well as the data needed to achieve a good calibration.

Therefore, the WOFOST model was calibrated on fields F1, F2 and F3, then validated on fields F4 to F8. The calibration and validation were done on a mixture of fields from two seasons to cover different conditions. That is to say, of the two fields cultivated during the 2002–2003 season, one was placed among the group of calibration fields (it is the field F1) and the other among the validation fields (it is the field F4). Additionally, of the five fields grown in the 2003–2004 season, two were in the calibration group (F2 and F3), and the rest were in the validation group (F5, to F8).

The WOFOST model has two types of parameters, tabular parameters and scalar parameters. The first type is those that change their value according to the growth stage of the plant, the second type keep an identical value during the whole crop cycle, Table 3 [7].

However, all these parameters are listed in four types of files that constitute the inputs of the model: crop file, climate file, soil information file and crop management file. In general, in the literature, the climatic parameters are provided by the weather stations of the study area. The soil parameters were identical on all 8 fields because of the homogeneity of the soil. The crop management parameters do not require calibration because they

are entered directly by the user. Thus, only the crop parameters were considered in the calibration process for the water-limited growth simulation.

**Table 3.** Different processes described in WOFOST and the number of associated parameters [7].

Process	Scalar	Tabular	Total
Phenological development	13	2	15
Leaf growth, senescence and assimilation	9	3	12
Root formation	4	2	6
Respiration	5	1	6
Transpiration	5	0	5
Storage organ formation	2	1	3
Stem formation	2	2	4

First, the length of the growing period (between wheat emergence and the date of maturity or harvest) and the different phenological stages were calibrated based on the sums of the cumulative effective temperatures [43]. WOFOST simulates emergence using the parameters TBASEM (lower temperature threshold for emergence), TSUMEM (sum of temperatures from sowing to emergence) and TEFFMX (maximum effective temperature for emergence). For the Karim wheat variety grown in the Moroccan climate, the values of 5 and 33 °C are more suitable for TBASEM and TEFFMX, respectively. In our study, however, the value of TEFFMX was reduced to 32 °C because this is the maximum limit considered by WOFOST. The TSUMEM were different between the three calibration fields since they have different sowing dates. The sum of the temperatures from emergence to flowering (TSUM1), from flowering to maturity (TSUM2), was calibrated using the phenological observations (mainly LAI) described in Section 2.3.

As phenology and length of growth period are closely dependent on temperature, the parameter DTSMTB (daily temperature sum increase) was then calibrated based on the calculated mean effective temperature.

In a second step, the CO<sub>2</sub> assimilation parameters were calibrated. The diffuse visible light extinction coefficient (KDIFTB) was set to 0.50 throughout the plant cycle, and the single leaf light use efficiency (EFFTB) was set to 0.45 [17]. The maximum CO<sub>2</sub> assimilation rate (AMXTB) was corrected using observations of total biomass and grain yield and LAI. The assimilation rate reduction factor as a function of mean temperature (TMPFTB) and as a function of minimum temperature (TMNFTB) were left at their default values.

In the third step, the initial and canopy parameters were adapted. The parameters TDWI (initial total dry weight) and SPAN (leaf life at 35 °C) were not observed in the field, so they were optimized using LAI observations and the SUBPLEX optimization algorithm implemented in the NLOPT optimization library. The use of this algorithm is generally well adapted to the optimization of noisy functions of high dimension. In our case, it minimizes the absolute difference between the measured values and those estimated by WOFOST. The leaf area index at emergence (LAIEM) and the maximum relative increase in LAI (RGRLAI) kept their default values for the winter wheat crop. On the other hand, the specific leaf area according to the development stage (SLATB) was calibrated on the basis of the measured values of LAI and TAGP.

In a fourth step, we adjusted the assimilate conversion efficiencies in different organs (root: CVR, stem: CVS, leaves: CVL and finally storage: CVO), the dry matter distribution parameters in these different organs (root: FRTB, stem: FSTB, leaves: FLTB and storage organs: FOTB) and their different conversion rates (root: RMR, stem: RMS, leaves: RML and storage organs: RMO) through field observations on total biomass, grain yield and LAI.



Finally, the parameters related to water use were calibrated using soil moisture and evapotranspiration data collected in the field. Thus, CFET (correction factor for respiration rate), and DEP NR (correction factor for water stress sensitivity) were adjusted, see Table 4. Initial rooting depth (IRD) and maximum rooting depth (MRD) were recorded in the field and their respective values were 10 and 55 cm. The maximum daily rooting increase (MRI) kept its default value (1.2 cm/day). Table 4 summarizing the values of the main calibrated crop parameters with their acceptable range [44] can be found here.

**Table 4.** Main soil parameters for the R3 zone.

Parameters	Units	Values
SMW (soil moisture content at wilting point)	(cm <sup>3</sup> /cm <sup>3</sup> )	0.170
SMFCF (soil moisture content at field capacity)	(cm <sup>3</sup> /cm <sup>3</sup> )	0.320
SM0 (soil moisture content at saturation)	(cm <sup>3</sup> /cm <sup>3</sup> )	0.450
K0 (hydraulic conductivity of saturated soil)	(cm day <sup>-1</sup> )	10
SOPE (maximum percolation rate root zone)	(cm day <sup>-1</sup> )	10
KSUB (maximum percolation rate subsoil)	(cm day <sup>-1</sup> )	10
RDMSOL (rooting depth allowed by soil)	(cm)	100

Concerning the soil parameters, their values were identical for all fields (Table 4) as the soil is homogenous over the whole study area [34,35].

The parameters SOPE, KSUB and RDMSOL also depend on the soil type. The values considered here are the default values for fine textured soils provided in the WOFOST database.

### 2.6. Model of Evaluation

In order to evaluate the performance of WOFOST in predicting total biomass, grain yield level, leaf area index, daily soil moisture change and evapotranspiration of Karim wheat crop in TENSIFT region, we selected the following statistical parameters:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \tilde{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - \tilde{y}_i)^2}{n}} \quad (3)$$

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^n (y_i - \tilde{y}_i)^2}{n}}}{\bar{y}_i} \times 100 \quad (4)$$

where  $y_i$  represents the measured value,  $\tilde{y}_i$  represents the simulated value,  $\bar{y}_i$  is the average value of the measured values, and  $n$  is the number of samples.

The coefficient of determination ( $R^2$ ) provides an indication of the quality of the linear regression between the field observations and the model estimates. It varies between 0 and 1; the better the quality of the model, the closer  $R^2$  will be to 1. The root mean square error (RMSE) indicates the average distance between the values predicted by the model and the measured values. The closer RMSE is to 0, the closer the simulations are to the observations. NRMSE expresses the quality of the model accuracy.  $NRMSE \leq 10\%$  indicates extremely high precision,  $10\% < NRMSE \leq 20\%$  indicates high precision,  $20\% < NRMSE \leq 30\%$  indicates medium precision, and  $NRMSE > 30\%$  indicates low precision.

### 3. Results and Analysis

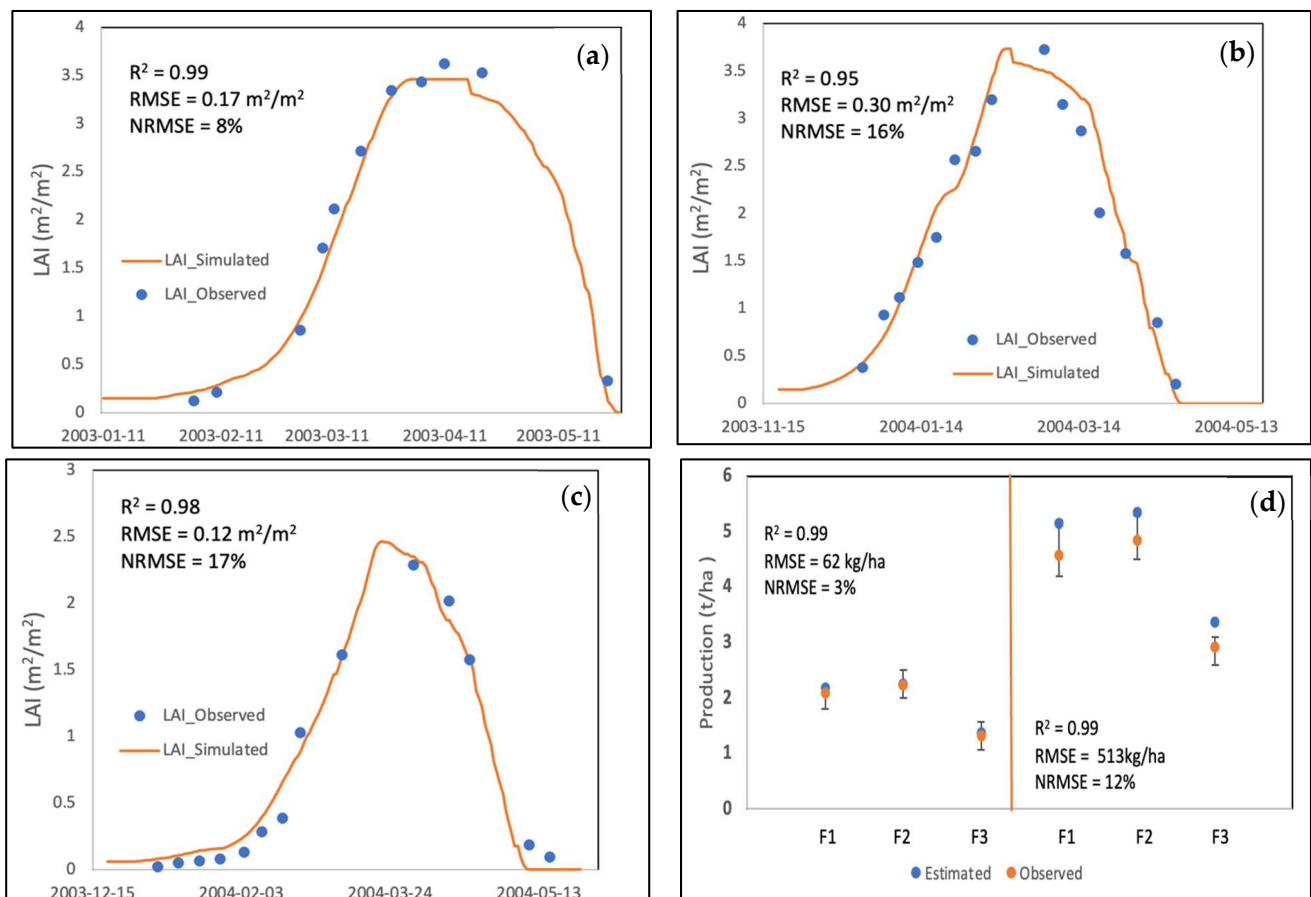
In this section, the results of the calibration and the validation of the WOFOST model by exploiting the data collected during two successive cropping seasons (2002/2003 and 2003/2004) are presented. The calibration and validation fields were selected to cover the different conditions observed during the two growing seasons (2002/2003 and 2003/2004).

The calibration of the WOFOST model was carried out using data collected on fields F1 (2002–2003), F2 and F3 grown in 2003–2004. We then assessed the performance of the model on five fields, one cultivated in 2002–2003 (field F4), and the others cultivated in 2003–2004 (fields F5 to F8).

### 3.1. Model of Calibration

#### 3.1.1. Performance of the Calibration in the Estimation of LAI, TAGP and TWSO

The temporal evolution of the leaf area of a crop strongly influences the production of the total above-ground biomass and thus the expected yield level. Thus, a prediction as accurate as possible of the LAI parameter by the model will also lead to a fairly good simulation of the TAGP and TWSO parameters. We have calibrated WOFOST to optimize its prediction of these parameters (Figure 2). The statistical evaluation of this calibration shows that WOFOST has been well calibrated. Average  $R^2$  values equal to 97.3%, 99% and 99% were found for LAI, TAGP and TWSO, respectively. A very small deviation was also observed between the estimated and measured values (RMSE of  $0.20 \text{ m}^2/\text{m}^2$ ,  $513 \text{ kg}/\text{ha}$  and  $60 \text{ kg}/\text{ha}$  for LAI, TAGP and TWSO, respectively). All NRMSE values were below 20%, showing a high accuracy of the model when calibrating LAI, TWSO and TAGP.

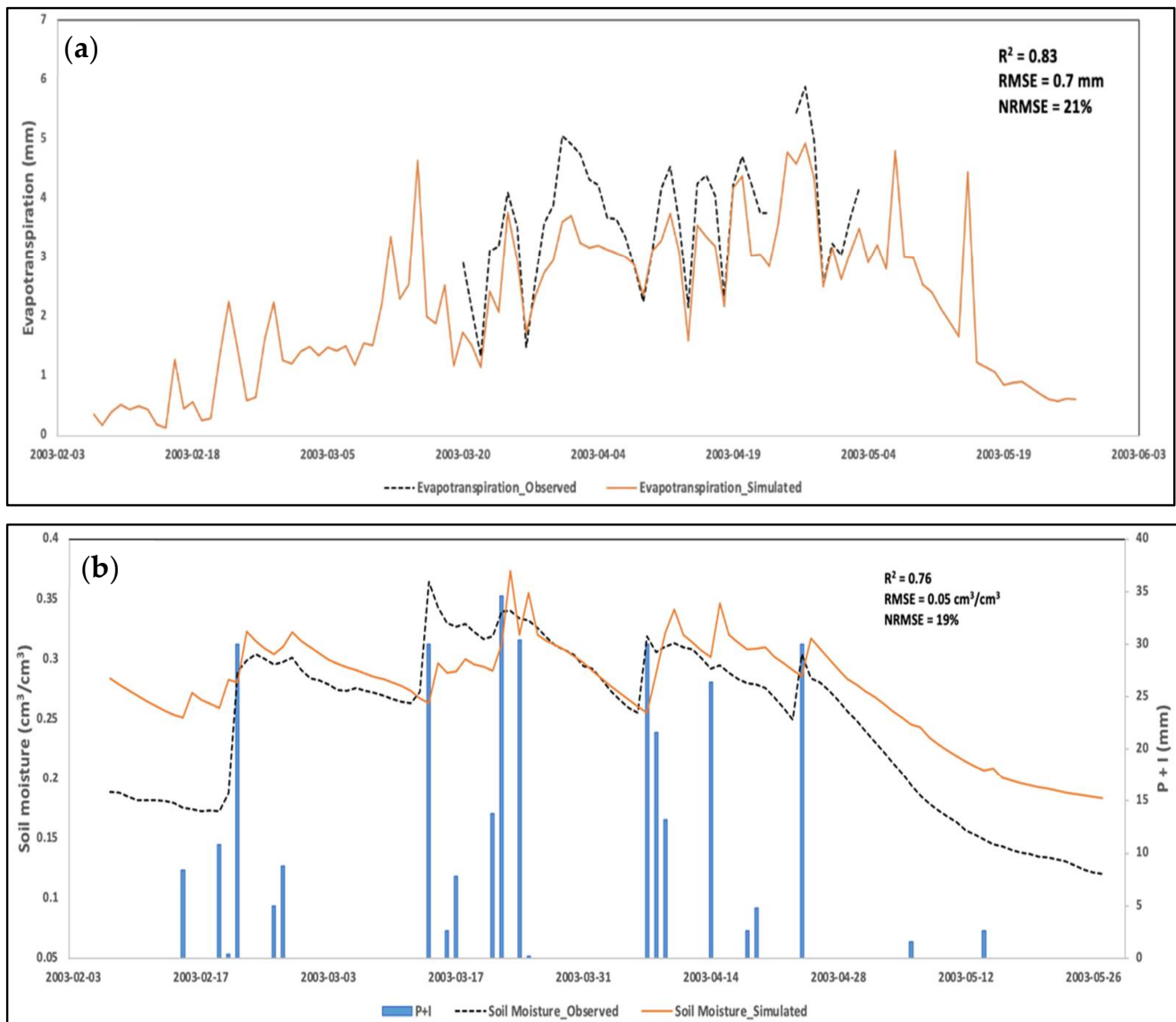


**Figure 2.** Simulated versus Measured LAI Field F1 (a), LAI Field F2 (b), LAI Field F3 (c), TWSO ((d), on the left) and TAGP (d, on the right) based on calibrated crop parameters. Vertical bars in figure (d) indicate standard deviations.

#### 3.1.2. Performance of the Calibration in the Estimation of SM and ETa

The amount of water available in the soil for the plant and soil to satisfy the atmospheric demand by evapotranspiration is also crucial in the simulation done by a crop model. The time series of SM and ETa based on the soil parameters of R3 zone and the crop parameters calibrated on field F1 are expressed in Figure 3. It is concluded that WOFOST

was well calibrated with respect to SM and ETa, the  $R^2$  were 76% and 83%, respectively, for SM and ETa and the RMSE were  $0.05 \text{ cm}^3/\text{cm}^3$  and  $0.7 \text{ mm}$ , respectively, for SM and ETa. Medium model precision was found in the ETa calibration (NRMSE = 21%) while the SM calibration showed high precision (NRMSE = 19%).



**Figure 3.** Simulated versus Measured ETa (a) and SM (b) based on calibrated soil and crop parameters in Field F1.

The analysis of Figure 3a shows a systematic underestimation of evapotranspiration by WOFOST. This is due to the fact that the correction factor for potential evapotranspiration (CFET) used by the model is low. It is generally equal to 1. However, for semi-arid to arid areas, it is advised to use the value of 1.2 (maximum limit allowed by WOFOST). This is the value that was used in our simulation, but it must be noted that it is still low given the high atmospheric demand in the Tensift region.

The simulations as well as the measurements of SM respond well to water supply (irrigation and rainfall). The WOFOST model tends to overestimate the estimate of soil moisture at the beginning of the simulation, as can be seen in Figure 3b and even during the validation on fields F4 and F7.

We often find under- and over-estimation in the prediction made by WOFOST. It should be noted that WOFOST does not handle the calculation of the water balance in the soil. This task is reserved to the different soil models implemented in WOFOST [44]. The link between WOFOST and these soil water balance models is that WOFOST provides the crop rooting depth and transpiration rate to the soil model, while the soil model provides the soil moisture content (or matrix suction) to WOFOST. Therefore, the soil model establishes the water balance based on these two pieces of information provided by WOFOST. That is, if WOFOST underestimates evapotranspiration, the water balance calculation will automatically be overestimated and vice versa. This would explain the trend observed in Figure 3b.

### 3.2. Validation of Model

After the calibration of the WOFOST model, model validation was performed using the dataset collected over five other wheat fields: F4 (grown during 2002/2003 season), and fields F5 to F8 (grown during 2003/2004 season). Thus, the performance of WOFOST in predicting TAGP, TWSO, LAI, SM and Eta is discussed in this section.

#### 3.2.1. Performance of the Validation in the Estimation of LAI, TAGP and TWSO

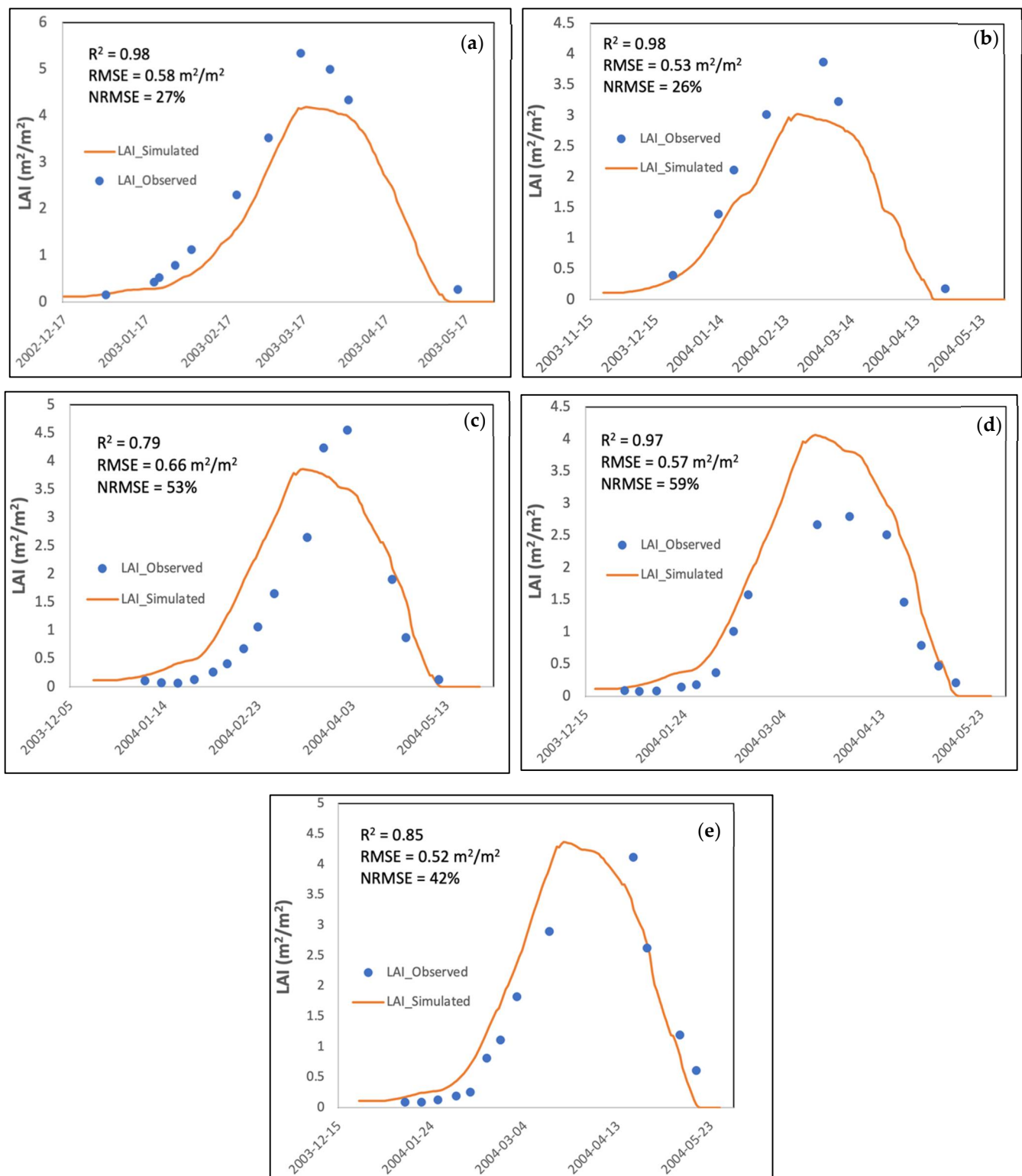
The dynamics of LAI growth simulated by the model on the validation fields showed good agreement with the values measured in the field, as the average and minimum  $R^2$  were 91.4% and 79%, respectively (Figure 4). This figure shows this comparison on all the validation fields in relation to the temporal evolution of the simulated versus observed LAI. This figure also shows a mean and maximum RMSE of  $0.57 \text{ m}^2/\text{m}^2$  and  $0.66 \text{ m}^2/\text{m}^2$ , respectively. The NRMSE values show medium accuracy on fields F4 (NRMSE = 27%) and F5 (NRMSE = 26%), while low accuracy was found on fields F6 (NRMSE = 53%), F7 (NRMSE = 59%) and F8 (NRMSE = 42%). We can also notice a slight shift in the LAI simulation on the F6 field, this is certainly due to the fact that this field required many more degree days compared to the average observed during this experiment. That is to say that this field was practically the only one to reach the maximum value of LAI at the beginning of April while the others reached it around mid-March.

Furthermore, the simulation on fields F4 and F5 underestimates the maximum LAI values, while these values are underestimated on field F7. This can be explained by the large difference between the values of the SLATB (specific leaf area as a function of development stage) parameter observed on each field. This parameter could vary from 0.0014 to 0.0035 while the average value for wheat is normally 0.00212. Therefore, the calibration of this parameter on the three calibrations fields can underestimate the LAI estimates on fields F4 and F5 and give an overestimate on field F7.

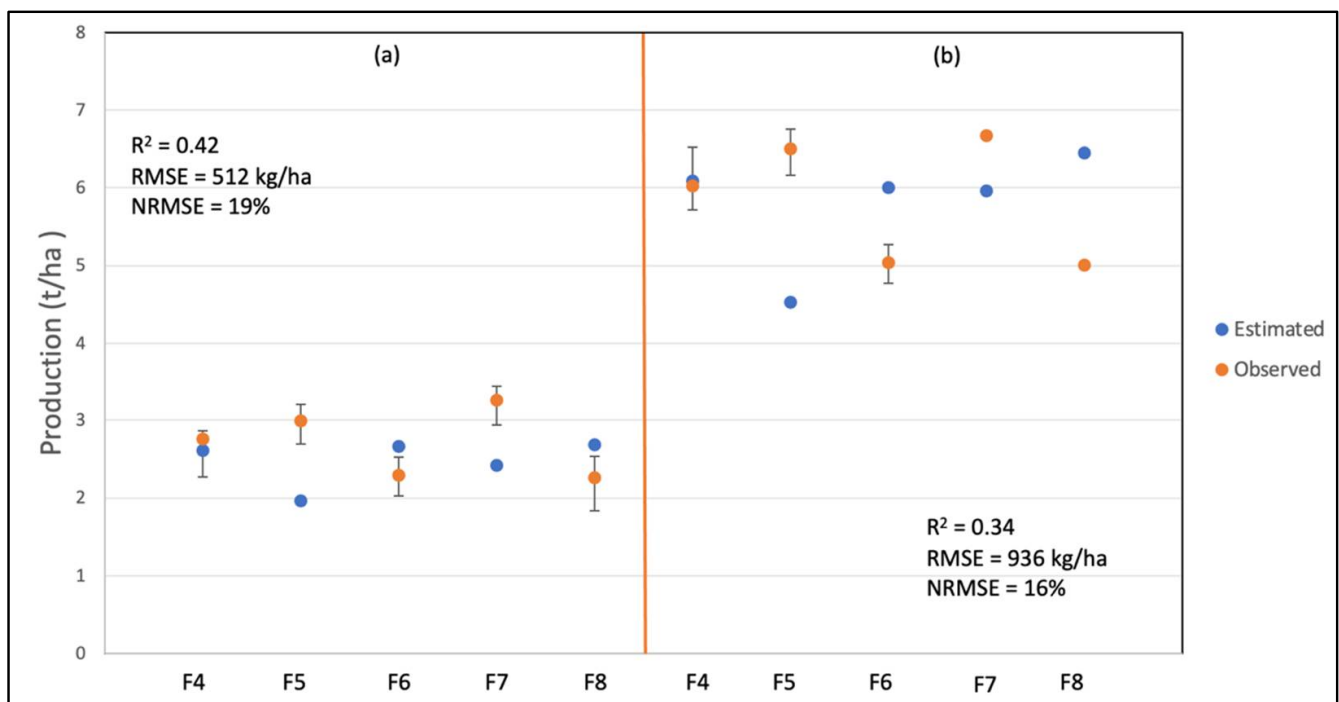
In contrast, the analysis of simulated and measured TAGP and TWSO (Figure 5) reveals a relatively moderate ability of the model to estimate this output. The  $R^2$  were 42% and 34% for TWSO and TAGP, respectively. This is also reflected in the moderately good RMSE, which were 512 kg/ha for TWSO and 936 kg/ha for TAGP. However, NRMSE values indicate high accuracy for prediction of TWSO (NRMSE = 19%) and TAGP (NRMSE = 16%).

#### 3.2.2. Soil Moisture (SM) and Actual Evapotranspiration (ETa)

The monitoring of soil water balance and ETa losses estimated by WOFOST was also compared to data collected on fields F4 and F7 where measurements are available. In general, the model was well validated (Figure 6).



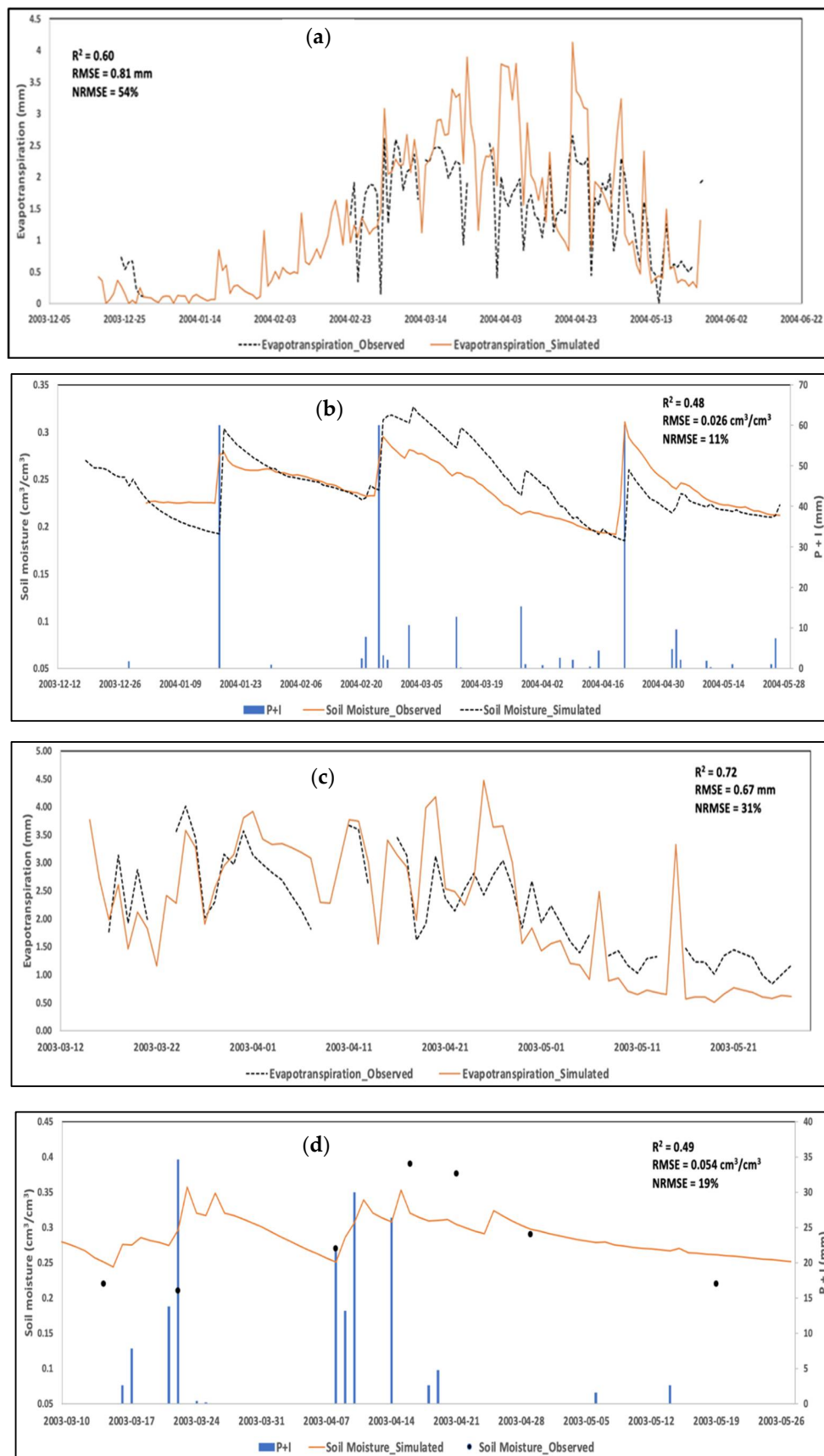
**Figure 4.** Validation of WOFOST model for leaf area index (LAI) estimating on field F4 (a), F5 (b), F6 (c), F7 (d) and F8 (e).



**Figure 5.** Comparison between the grain yields (a) and total aboveground biomass (b) simulated by the WOFOST model and those measured on the five validation fields during the 2002/2003 and 2003/2004 growing seasons. The vertical bars correspond to the standard deviations of TWSO and TAGP measurements observed on each field.

Concerning the prediction for evapotranspiration, the coefficient of determination values was 60% and 72% for the F7 and F4 fields, respectively, and the RMSE values were 0.8 mm and 0.7 mm for the F7 and F4 fields, respectively. NRMSE values show low model accuracy (NRMSE > 30% for both fields). On the other hand, one can notice an overestimation on the F7 field (Figure 6a). This is explained by the fact that the model overestimates the leaf area index (see Figure 4d). The F4 field shows a good agreement with the field measurements except for some significant deviations observed around 20 and 25 April, then towards the end of the season that can be attributed to a bias of the model.

Regarding the validation of the SM, the discrepancy between the measured and estimated SM is  $0.03 \text{ cm}^3/\text{cm}^3$  and  $0.05 \text{ cm}^3/\text{cm}^3$  for fields F7 and F4, respectively. The  $R^2$  values were relatively medium: 48% and 49%, respectively, for F7 and F4. The NRMSE values indicate a high accuracy of the model, they were 11% and 19%, respectively, for F7 and F4. We often notice under- or over-estimates. This can be explained by the fact that the soil model implemented in WOFOST estimates soil moisture based on the information provided by WOFOST (root depth and plant transpiration). Thus, the periods where we notice underestimates of soil moisture coincide with those where WOFOST overestimates the evapotranspiration rate (vice versa).

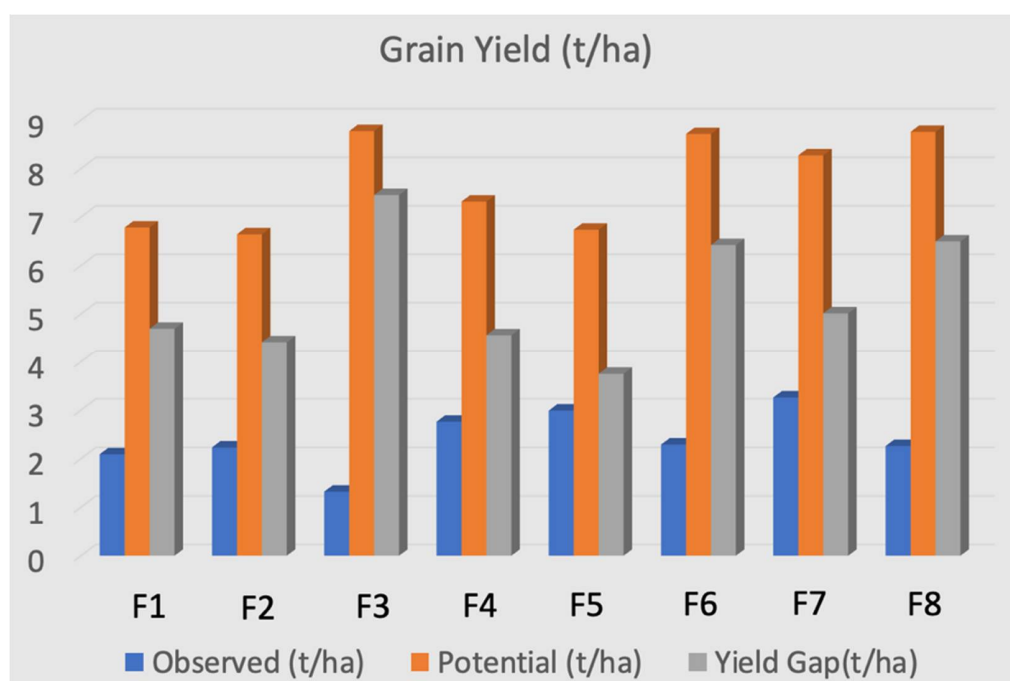


**Figure 6.** Time series of observed and simulated soil water moisture and evapotranspiration on the F7 validation field (a,b) and on the F4 validation field (c,d).

#### 4. Estimation of the Yield Gap

As the WOFOST model can estimate the potential yield of the region, it is of interest to investigate how well as this crop model can be used as a potential tool to calculate the yield gap. Let us remember that the yield gap is estimated as the difference between the average simulated potential yield (crop production without water stress) and the on-farm actual yield. This potential yield is the yield level that the weather conditions allow it to reach. Therefore, it depends only on the climate components. That is to say that all fields cultivated in the same region with the same climate will normally give the same potential yield.

Figure 7 shows the potential and the actual yields as well as the yield gap for each field considered in this study. It is clear that there is a big difference between both yields and such difference varied from one field to another. According to this figure, it can be concluded that the average potential yield for the area is 7.75 t/ha. Yield gap analysis reveals a difference of 5.35 t/ha on average between the observed yields and the potential yields calculated by WOFOST.



**Figure 7.** The yield gap estimated by WOFOST for the 8 study fields in the R3 area.

In order to further analyze the observed difference between the measured yields and the potential yields calculated by WOFOST, the authors of [45] pointed out the following reasons:

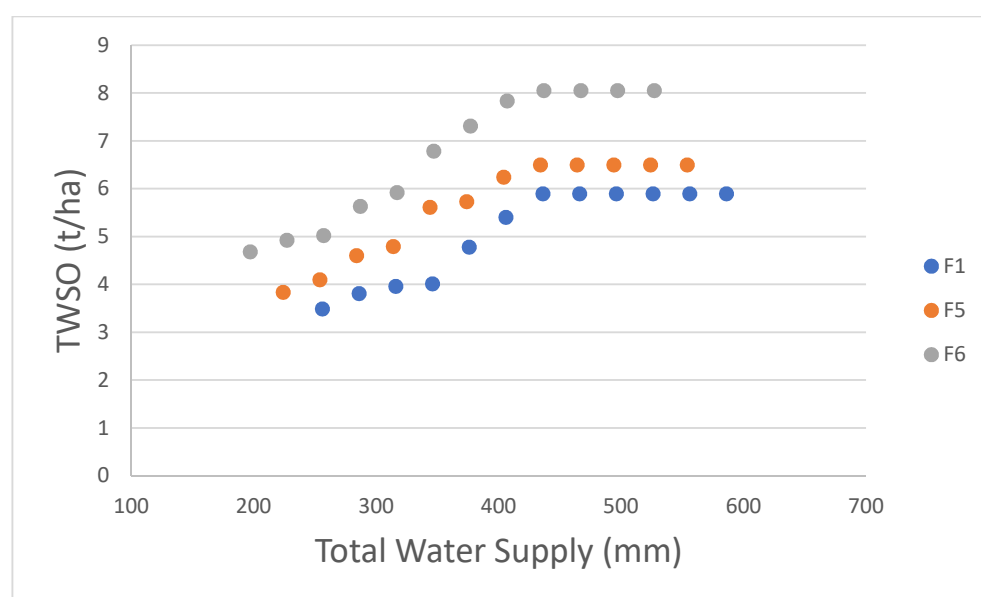
- The choice of the variety of wheat crop in this study was optimal because the Karim variety has good vigor, good grain quality, and acceptable resistance to major diseases;
- The pre-tillage operations were probably also optimal;
- However, fertilizer inputs were considerably limited. The best fertilized fields received only 100 kg of NPK fertilizer (14-28-14), while the recommendations are 150 kg of nitrogen, 85 kg of P<sub>2</sub>O<sub>5</sub>, and 110 kg of K<sub>2</sub>O for a grain yield of 50 qx/ha [45];
- The optimal seeding rate range (120–200 kg/ha) was respected on some fields (F4, F5, F6 and F8) but not on others (F1, F2, F3 and F7). It is certainly for this reason that in 2002–2003, field F4 had a higher yield compared to F1 field; and during 2003–2004, fields F5, F6 and F8 had a higher yield than the others, with the exception of field F7 (compensated by a fertilization of 100 kg of NPK fertilizer);



- The recommended crop water requirement is 380–520 mm [36]. Fields considered in the study received 180 mm (Field F1 to F8 except F4) or 90 mm (Field F4) of irrigation; therefore, in addition to the rain, Field F1 received a total of 346 mm, Fields F4 received a total of 307 mm, Field F2 and F5 received a total of 354, Field F3, F6, F7 and F8 received 277 mm. We can thus say that all the fields did not endure a great water stress.
- Finally, the large differences between actual and observed yield levels can also be explained by less optimal management of plant maintenance during growth (weed, insect and disease management probably not adequate).

In order to further investigate the factors provided below, we have run a series of simulations in order to see the effect of water and fertilization supplies. For this purpose, we selected three fields according to the sowing date and the level of fertilization applied: F1 (late sowing on 11 January with 100 kg of NPK), F5 (early sowing on 21 November with 50 kg of NPK) and F6 (normal sowing on December 15 with no fertilization).

The WOFOST model allows the calculation of the water-limited production by choosing the Wofost71\_WLP\_FD sub-model implemented in the WOFOST, thus allowing us to simulate only the impact of irrigation on the crop production because the model considers that fertilizer inputs are largely sufficient. The three selected fields had already received a total water supply of 346 mm, 354 mm and 277 mm for F1, F5 and F6, respectively. However, it turns out that all this water was not really useful for the plant. It was noted that removing, for example, 90 mm of water from field F1 did not reduce the yield at all. Similarly, a total of 130 mm and 80 mm of water were superfluous on F5 and F6, respectively. This means that excessive watering had no impact on wheat yields in the area, since fertilization limited the level of production anyway. For this reason, it was important to first remove the excess water volumes in order to see the real impact of additional water inputs under a condition where fertilization is not a limitation. Thus, Figure 8 shows the results obtained from the 12 simulations performed with the WOFOST\_WLP\_FD module, which allows us to calculate only the effect of water inputs on yield decoupled from the effect of fertilization. At each simulation, we added 30 mm of water. That is, for field F1, the first point corresponds to the yield obtained with a total water input of 256 mm, and the second point corresponds to the yield obtained with a total input of 286 mm, and so forth. It can be seen that from 430 mm of total water input, the increase in yield is no longer significant. With this amount of water, the yield gap is considerably reduced, i.e., 0.885, 0.240 and 0.661 t/ha, respectively, for F1, F5 and F6.



**Figure 8.** Impact of water supply on wheat grain yield in the Tensift region and without stress fertilization.

In addition, we also notice that field F6 consistently gives the highest yields despite the fact that it initially received the lowest volume of water (197 mm). This confirms the effect of the sowing date on the production of wheat grain yield.

On the other hand, we also note a significant effect of water supply on yield after 340 mm. This is because after 340 mm, the additional amount of 30 mm of water brings us closer to the recommended range of total water required for wheat; this range is 380–520 mm [46].

Then, in an attempt to quantify the impact of fertilizer inputs on yield levels, we varied the fertilization amounts as shown in Table 5. This is possible by using the WOFOST sub-model called WOFOST\_NPK, which calculates NPK-limited production without considering water stress. The zero level corresponds to the fertilization observed during the experiment. Levels 1, 2, and 3 are supplied in relation to nitrogen (application of 20, 40 and 100 kg). The amount of phosphorus and potassium are then obtained by respecting the recommended balance: 1-0.57-0.73 [45]. For example, for level 1, if 20 kg of nitrogen is added, the quantities of P and K must be 11 and 15, respectively, in order to respect the balance. Finally, level 4 corresponds to the quantities of fertilizer required to reach the potential yield. The results of these simulations are shown in Figure 9. As expected, the grain yield increased with the increase of fertilization supply for all fields, which justify the large difference between the potential yield and the actual yield. It can be seen, for example, that with an additional of 160 kg of N, 57 kg of P and 173 kg of K the yield of field F6 increases until reaches the potential yield (8.7 t/ha). A balanced fertilizer application with 124 and 136 kg N (on F1 and F5, respectively) also allowed these two fields to reach their yield potential. It can be also noted that the increase from level 0 to level 1 does not significantly affect the grain yield; however, from level 1 to level 4, the yield clearly increased. The application of level 1 was intended to highlight the importance of a balanced supply of nutrients in fertilization. Indeed, the amount of fertilizer in level 1 is not too different from level 0, but a relative increase in yield is nevertheless noticed.

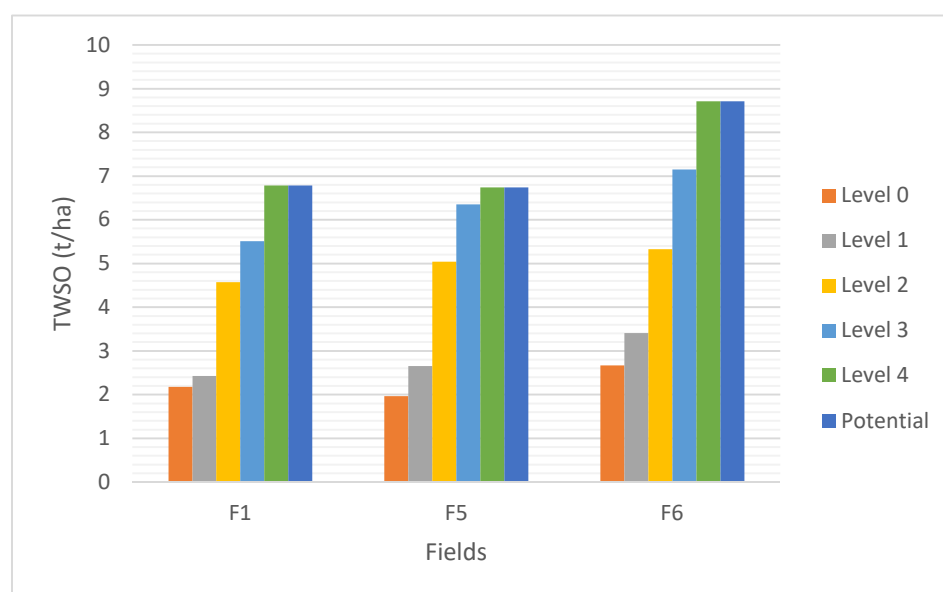
**Table 5.** Different levels of fertilization according to WOFOST model to be applied to assess the effect on grain yield on three fields of study with different sowing dates: F1, F5 and F6.

	F1			F5			F6		
	N	P	K	N	P	K	N	P	K
Level 0	14	28	14	7	14	7	0	0	0
Level 1	20	11	15	20	11	15	20	11	15
Level 2	60	34	44	60	34	44	60	34	44
Level 3	100	57	73	100	57	73	100	57	73
Level 4	124	57	111	136	57	124	160	57	173

The most significant yield increase in all three fields is observed when moving from level 1 to level 2. That is, a balanced application of 20 kg of nitrogen is still very limiting, whereas a balanced application of 60 kg of nitrogen is more beneficial for the plant.

However, when we go from level 3 to level 4, we notice that the yield increase is more significant for F1 and F6 than for F5. This is certainly due to the fact that the F5 field had the longest reproductive phase. Because they were harvested on the same day (May 27) and they needed almost the same number of degree days to reach their flowering stage (about 711–713 degree days), but field F5 was sown well before the other two. This gave it much more time to form and fill its grains sufficiently. It is certainly for this reason that with level 3 the yield almost reached the potential yield and that there was less effect with the level 4 input.

Finally, we also note that regardless of the level of fertilization, field F6 shows the best yields, thus confirming the advantage of sowing between December 15 and 31.



**Figure 9.** Evolution of wheat grain yield in Tensift region according to different fertilizer inputs.

With regard to these results, we can recommend an average total amount of irrigation water of 430 mm and an average fertilizer input of 140 kg of N, 80 kg of P and 102 kg of K (these values are the average of the level 4 fertilization of the three fields while respecting the balance) to reach the average potential yield of the region which is 6.270 t/ha.

## 5. Discussion

Our results found that the WOFOST model often overestimates, underestimates or slightly offsets the LAI estimate. This can be explained by a slight bias in the estimation of the degree day (case of the offset) or by the wide range of the SLATB parameter observed in the study area (case of overestimation or underestimation). This resulted in relatively moderate values of the model accuracy (average NRMSE were 41.4%). However, these results are in accordance with other studies used the WOFOST model for LAI simulation for different crops such as: wheat [47], jujube [8] and corn [48]. For the seasonal ETa predictions, an average difference of about 8 mm between estimated and e measured ETa has been found. This value was 33–66 mm in the study using WOFOST on different soil types in 2004 [10]. On the other hand, the average difference between observed and estimated daily evapotranspiration was 0.75 mm, and this is in agreement with [20]. Concerning the soil moisture estimates, the overestimation by WOFOST is noticed at the beginning of the cropping season, which is confirmed by other work [48]. The observed over or under estimation is certainly due to a slight bias in the estimation made by the soil model implemented in WOFOST [44]. However, it should be noted that these results are relatively weak compared to the work conducted by Wu et al. (2021) [47] on winter wheat, where they found a modeling efficiency greater than 80%. However, Eweys et al. (2017) worked on maize in the eastern Netherlands and have a modeling efficiency  $EF < -4$  with an associated large error (RMSE > 45%) [48]. Additionally, Toumi et al. (2016) used Aquacrop model and obtained a value of 42% and  $0.022 \text{ cm}^3/\text{cm}^3$  for  $R^2$  and RMSE, respectively, [17].

The short data set per plot and the large variability between plots in terms of management make the task of calibrating the model somewhat difficult, in addition to possible biases related to the model itself. This may explain the relatively low values obtained during the simulation of TWSO and TAGP. Our findings are corroborated by the work [47] where they found somewhat similar values when simulating winter wheat grain yield with WOFOST in China. Values of 48% and 801 kg were obtained for  $R^2$  and RMSE for the TWSO parameter, respectively. However, they are better than the results obtained by

Huang et al. (2016) who found a prediction efficiency of wheat grain yield equal to 14% and an RMSE of 647 kg/ha [49].

A large gap between potential and actual yield were founded by WOFOST model. The difference in sowing date and/or in tillage practices can be the cause [50]. The average potential yield observed in our study area which is 6.270 t/ha [51] while the value found by WOFOST were 7.75 t/ha. A study, based on the comparison of the potential simulated by CropSyst model, yield data from experimental stations and nearby farmers' fields, also showed that irrigated wheat in Morocco has deviations ranging from 46 to 82% [51]. All fields in our study are in this range except for field F3 which shows a variance of 84%. This may be due to the fact that this field received no fertilization and has the highest potential. Other studies have shown that the higher the potential of a field, the greater the yield gap observed will also be [22,30]. The yield difference for wheat in Europe estimated with WOFOST is about 2–4 t/ha [33]. Therefore, the gap observed in Morocco is much higher, which makes some sense because on average the actual yields in Europe are higher compared to Morocco due to differences in management practices dues to farmers professionalism and economic capacity. The maximum simulated yield potential is observed in fields F3, F6 and F8 which exceeded 8.7 t/ha. These fields were sown on 20, 15 and 24 December 2004, respectively. Thus, the best sowing date in this region can be said to be in the mid- to late December period. This is somewhat in accordance with the recommended planting dates for irrigated durum wheat: mid-November to mid-December [45].

The series of simulations carried out in order to highlight the effect of additional water supply allowed to establish a threshold of 430 mm. This amount of water supply can be recommended in the region and is in agreement with previous works [36]. This series of simulations, therefore, confirmed the effect of water supply on the dominant factor of the yield gap. Indeed, in the Mediterranean Ebro Valley, Spain, a study noted that in high potential years, the main constraint to growth was lack of water [22]. Another study also highlighted the importance of supplemental irrigation and efficient use of rainfall and irrigation water in reducing wheat yield gaps in the Middle East and North Africa (MENA) region [51].

Other studies have also confirmed the impact of sowing date choice on wheat yield potential mentioned on field F6. A work in China found that the yield gap of wheat reduced from 400 to 1200 kg/ha with adjustment of sowing date [25]. Studying small farms (characteristics of Wheat farms in Morocco) of wheat in the North China Plain, another work noticed that sowing date was the most limiting factor of spikes per hectare (spikes per hectare were the most limiting factor of potential yield) [29]. Similarly, sowing date clearly influences wheat yield potential significantly in Pakistan [28].

The present study showed a significant effect of additional fertilizer application on the reduction of the yield gap in wheat. This has been confirmed by several studies. Yield gaps in dryland wheat in Australia were closed in 25% of wheat crops with increased N inputs [30]. A total of 22% of wheat crops were almost indifferent to this increase (due to biotic stress). Remember that in our case, 100% of the fields closed their gap because the simulation is done by WOFOST does not consider any biotic stress. Winter wheat in China could record a yield gap variation between 700 and 2200 kg/ha with nitrogen fertilizer addition [25]. A study in the North China Plain advised a basal N supply between 90 and 180 kg/ha to significantly reduce the yield gap of winter wheat [29]. A total of 40% loss occurred in wheat yields in Australia due to nitrogen deficiency [31]. In Pakistan, a study highlighted the importance of soil nutrient balance noting that despite high soil nitrogen, wheat yields may be limited by the absence of other nutrients, particularly P and K [28]. With a balanced application of 60 kg, we observed the most significant yield increase in all three fields. Abeledo et al. (2008) reported that with a N availability of 50 kg/ha, the average achievable yield of wheat in Spain was 1.8 t/ha. This value increased to 2.8 t/ha at higher N availability (100–250 kg/ha). They added that this increase was highly impacted by rainfall [22].

Regional recommendations are 150 kg N, 85 kg P<sub>2</sub>O<sub>5</sub> and 110 kg K<sub>2</sub>O for a grain yield of 5 t/ha [45] with a recommended water requirement of about 380–520 mm [36]. Considering the results obtained from the WOFOST simulations that tried to show the effect of additional nutrient and water inputs, it is noted that this model led to recommendations similar to those of the region. The latter can then be used to monitor the quantitative production of winter wheat in arid to semi-arid areas.

## 6. Conclusions

The main goal of this research was to evaluate the potential of the WOFOST model for estimating the leaf area index (LAI), the above-ground biomass levels (TAGP) and grain yield (TWSO), the actual evapotranspiration (ETa) and soil moisture content (SM) of winter wheat in the semi-arid region of Tensift Al Haouz, Marrakech (central Morocco). The performance of the model simulations was based on field data collected over eight fields during two consecutive growing seasons (2002/2003 and 2003/2004). The WOFOST model simulations were also used for exploring the key drivers of wheat yield gap in the study area.

Simulation results showed that the model adequately simulated LAI, ETa, SM, TAGP and TWSO for both seasons. The average RMSE values between observed and measured LAI, ETa, SM, TAGP and TWSO were 0.57 m<sup>2</sup>/m<sup>2</sup>, 0.75 mm, 0.04 cm<sup>3</sup>/cm<sup>3</sup>, 936 kg/ha and 512 kg/ha, respectively. After calibration and validation of the WOFOST model for winter wheat, we used this model to determine the main factors affecting the wheat yield gap in different field of study. For this purpose, several scenarios based on different water and different fertilizer supplies have been performed. The Yield Gap analysis revealed an average potential yield for the region equal to 7.75 t/ha and a deviation of 5.35 t/ha from the observed yields. This allowed us to deduce an optimal period of sowing date (mid-December); with optimum water and fertilization supplies, it has been shown that an amount of water supply for wheat in the region (430 mm), and 140 kg of N, 80 kg of P and 102 kg of K as amount of fertilization, are needed to achieve the potential yield. Thus, this work shows that food security in Morocco and Africa must be articulated around three components: training of farmers (to optimize sowing dates, for example), judicious irrigation and reasoned fertilization in order to reduce the yield gap.

In addition, this study proposes to consider new experiments allowing us to have a longer series of observations in order to further minimize the possible biases of the model and to extend its calibration on the whole Moroccan territory. Further studies can be conducted in this region to see the impact of fertilizer inputs with respect to their use efficiency. An approach to reducing yield gaps in the Tensift region while analyzing gross margin gains would also be beneficial.

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## References

- van Ittersum, M.K.; Ewert, F.; Heckelei, T.; Wery, J.; Olsson, J.A.; Andersen, E.; Bezlepikina, I.; Brouwer, F.; Donatelli, M.; Flichman, G.; et al. Integrated Assessment of Agricultural Systems—A Component-Based Framework for the European Union (SEAMLESS). *Agric. Syst.* **2008**, *96*, 150–165. [[CrossRef](#)]
- Boote, K.J.; Jones, J.W.; Pickering, N.B. Potential Uses and Limitations of Crop Models. *Agron. J.* **1996**, *88*, 704–716. [[CrossRef](#)]
- de Vries, F.W.P. *Simulation of Ecophysiological Processes of Growth in Several Annual Crops*; Simulation Monographs; Pudoc: Wageningen, The Netherlands, 1989; ISBN 978-90-220-0937-6.
- Oteng-Darko, P.; Yeboah, S.; Addy, S.N.T.; Amponsah, S.; Danquah, E.O. Crop Modeling: A Tool for Agricultural Research—A Review. *J. Agric. Res. Dev.* **2013**, *2*, 1–6.
- Jame, Y.W.; Cutforth, H.W. Crop Growth Models for Decision Support Systems. *Can. J. Plant Sci.* **1996**, *76*, 9–19. [[CrossRef](#)]
- Jones, J.W. *Decision Support Systems for Agricultural Development*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1993; pp. 459–471.
- Boogaard, H.; de Wit, A. 25 years of the WOFOST cropping systems model. *Agric. Syst.* **2019**, *168*, 154–167. [[CrossRef](#)]
- Bai, T.; Wang, T.; Zhang, N.; Chen, Y.; Mercatoris, B. Growth Simulation and Yield Prediction for Perennial Jujube Fruit Tree by Integrating Age into the WOFOST Model. *J. Integr. Agric.* **2020**, *19*, 721–734. [[CrossRef](#)]
- Confalonieri, R.; Acutis, M.; Bellocchi, G.; Donatelli, M. Multi-Metric Evaluation of the Models WARM, CropSyst, and WOFOST for Rice. *Ecol. Model.* **2009**, *220*, 1395–1410. [[CrossRef](#)]
- Eitzinger, J.; Trnka, M.; Hösch, J.; Žalud, Z.; Dubrovský, M. Comparison of CERES, WOFOST and SWAP Models in Simulating Soil Water Content during Growing Season under Different Soil Conditions. *Ecol. Model.* **2004**, *171*, 223–246. [[CrossRef](#)]
- Kroes, J.G.; Supit, I. Impact Analysis of Drought, Water Excess and Salinity on Grass Production in The Netherlands Using Historical and Future Climate Data. *Agric. Ecosyst. Environ.* **2011**, *144*, 370–381. [[CrossRef](#)]
- Gilardelli, C.; Stella, T.; Frasso, N.; Cappelli, G.; Bregaglio, S.; Chiodini, M.E.; Scaglia, B.; Confalonieri, R. WOFOST-GTC: A New Model for the Simulation of Winter Rapeseed Production and Oil Quality. *Field Crop. Res.* **2016**, *197*, 125–132. [[CrossRef](#)]
- Movedi, E.; Bellocchi, G.; Argenti, G.; Paleari, L.; Vesely, F.; Stagliano, N.; Dibari, C.; Confalonieri, R. Development of Generic Crop Models for Simulation of Multi-Species Plant Communities in Mown Grasslands. *Ecol. Model.* **2019**, *401*, 111–128. [[CrossRef](#)]
- Jin, M.; Liu, X.; Wu, L.; Liu, M. An Improved Assimilation Method with Stress Factors Incorporated in the WOFOST Model for the Efficient Assessment of Heavy Metal Stress Levels in Rice. *Int. J. Appl. Earth Obs. Geoinf.* **2015**, *41*, 118–129. [[CrossRef](#)]
- Balaghi, R. *Document Définissant la Méthodologie d’Evaluation des Pertes de Rendements. Composante 3: Définition de Modèles de Gestion Efficace des Risques Climatiques. Projet d’Adaptation au Changement Climatique de l’Agriculture du Maghreb*; Institut National de la Recherche Agronomique du Maroc: Rabat, Morocco, 2015; 35p.
- Séverine, D. Evaluation de la Performance du Modele Aquacrop pour la Prevision des Rendements du ble Tendre (*Triticum Aestivum*) au Maroc (Province de Meknes). Master’s Thesis, Université de Liège, Liège, Belgique, 2017; 24p.
- Toumi, J.; Er-Raki, S.; Ezzahar, J.; Khabba, S.; Jarlan, L.; Chehbouni, A. Performance Assessment of AquaCrop Model for Estimating Evapotranspiration, Soil Water Content and Grain Yield of Winter Wheat in Tensift Al Haouz (Morocco): Application to Irrigation Management. *Agric. Water Manag.* **2016**, *163*, 219–235. [[CrossRef](#)]
- Bregaglio, S.; Frasso, N.; Pagani, V.; Stella, T.; Francone, C.; Cappelli, G.; Acutis, M.; Balaghi, R.; Ouabbou, H.; Paleari, L.; et al. New Multi-Model Approach Gives Good Estimations of Wheat Yield under Semi-Arid Climate in Morocco. *Agron. Sustain. Dev.* **2015**, *35*, 157–167. [[CrossRef](#)]
- Lobell, D.B.; Cassman, K.G.; Field, C.B. Crop Yield Gaps: Their Importance, Magnitudes, and Causes. *Annu. Rev. Environ. Resour.* **2009**, *34*, 179–204. [[CrossRef](#)]
- Home-Global Yield Gap Atlas. Available online: <https://www.yieldgap.org/> (accessed on 12 October 2021).
- Devkota, M.; Yigezu, Y.A. Explaining Yield and Gross Margin Gaps for Sustainable Intensification of the Wheat-Based Systems in a Mediterranean Climate. *Agric. Syst.* **2020**, *185*, 102946. [[CrossRef](#)]
- Abeledo, L.G.; Savin, R.; Slafer, G.A. Wheat Productivity in the Mediterranean Ebro Valley: Analyzing the Gap between Attainable and Potential Yield with a Simulation Model. *Eur. J. Agron.* **2008**, *28*, 541–550. [[CrossRef](#)]
- Agus, F.; Andrade, J.F.; Edreira, J.I.R.; Deng, N.; Purwantomo, D.K.G.; Agustiani, N.; Aristya, V.E.; Batubara, S.F.; Herniwati; Hosang, E.Y.; et al. Yield Gaps in Intensive Rice-Maize Cropping Sequences in the Humid Tropics of Indonesia. *Field Crop. Res.* **2019**, *237*, 12–22. [[CrossRef](#)]
- Lobell, D.B. The Use of Satellite Data for Crop Yield Gap Analysis. *Field Crop. Res.* **2013**, *143*, 56–64. [[CrossRef](#)]
- Yao, F.; Li, Q.; Zeng, R.; Shi, S. Effects of Different Agricultural Treatments on Narrowing Winter Wheat Yield Gap and Nitrogen Use Efficiency in China. *J. Integr. Agric.* **2021**, *20*, 383–394. [[CrossRef](#)]
- Khechba, K.; Laamrani, A.; Dhiba, D.; Misbah, K.; Chehbouni, A. Monitoring and Analyzing Yield Gap in Africa through Soil Attribute Best Management Using Remote Sensing Approaches: A Review. *Remote Sens.* **2021**, *13*, 4602. [[CrossRef](#)]
- Meier, E.A.; Hunt, J.R.; Hochman, Z. Evaluation of Nitrogen Bank, a Soil Nitrogen Management Strategy for Sustainably Closing Wheat Yield Gaps. *Field Crop. Res.* **2021**, *261*, 108017. [[CrossRef](#)]
- Khaliq, T.; Gaydon, D.S.; Ahmad, M.-D.; Cheema, M.J.M.; Gull, U. Analyzing Crop Yield Gaps and Their Causes Using Cropping Systems Modelling—A Case Study of the Punjab Rice-Wheat System, Pakistan. *Field Crop. Res.* **2019**, *232*, 119–130. [[CrossRef](#)]
- Cao, H.; Li, Y.; Chen, G.; Chen, D.; Qu, H.; Ma, W. Identifying the Limiting Factors Driving the Winter Wheat Yield Gap on Smallholder Farms by Agronomic Diagnosis in North China Plain. *J. Integr. Agric.* **2019**, *18*, 1701–1713. [[CrossRef](#)]

30. Lawes, R.; Chen, C.; Whish, J.; Meier, E.; Ouzman, J.; Gobbett, D.; Vadakattu, G.; Ota, N.; van Rees, H. Applying More Nitrogen Is Not Always Sufficient to Address Dryland Wheat Yield Gaps in Australia. *Field Crop. Res.* **2021**, *262*, 108033. [[CrossRef](#)]
31. Hochman, Z.; Horan, H. Causes of Wheat Yield Gaps and Opportunities to Advance the Water-Limited Yield Frontier in Australia. *Field Crop. Res.* **2018**, *228*, 20–30. [[CrossRef](#)]
32. Hajjarpoor, A.; Soltani, A.; Zeinali, E.; Kashiri, H.; Aynehband, A.; Vadez, V. Using Boundary Line Analysis to Assess the On-Farm Crop Yield Gap of Wheat. *Field Crop. Res.* **2018**, *225*, 64–73. [[CrossRef](#)]
33. Boogaard, H.; Wolf, J.; Supit, I.; Niemeyer, S.; van Ittersum, M. A Regional Implementation of WOFOST for Calculating Yield Gaps of Autumn-Sown Wheat across the European Union. *Field Crop. Res.* **2013**, *143*, 130–142. [[CrossRef](#)]
34. Duchemin, B.; Hadria, R.; Erraki, S.; Boulet, G.; Maisongrande, P.; Chehbouni, A.; Escadafal, R.; Ezzahar, J.; Hoedjes, J.C.B.; Kharrou, M.H.; et al. Monitoring Wheat Phenology and Irrigation in Central Morocco: On the Use of Relationships between Evapotranspiration, Crops Coefficients, Leaf Area Index and Remotely-Sensed Vegetation Indices. *Agric. Water Manag.* **2006**, *79*, 1–27. [[CrossRef](#)]
35. Er-Raki, S.; Chehbouni, A.; Guemouria, N.; Duchemin, B.; Ezzahar, J.; Hadria, R. Combining FAO-56 Model and Ground-Based Remote Sensing to Estimate Water Consumptions of Wheat Crops in a Semi-Arid Region. *Agric. Water Manag.* **2007**, *87*, 41–54. [[CrossRef](#)]
36. Er-Raki, S.; Chehbouni, A.; Duchemin, B. Combining Satellite Remote Sensing Data with the FAO-56 Dual Approach for Water Use Mapping in Irrigated Wheat Fields of a Semi-Arid Region. *Remote Sens.* **2010**, *2*, 375–387. [[CrossRef](#)]
37. Abourida, A. Approche Hydrogéologique de la Nappe du Haouz (Maroc) par Teledetection, Isotopie, Sig et Modelisation. Ph.D. Thesis, Université Cadi Ayyad, Marrakesh, Morocco, 2007; pp. 1–197.
38. Allen, R.G. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper; Food and Agriculture Organization of the United Nations: Rome, Italy, 1998; ISBN 978-92-5-104219-9.
39. Er-Raki, S.; Chehbouni, A.; Ezzahar, J.; Khabba, S.; Lakhal, E.K.; Duchemin, B. Derived Crop Coefficients for Winter Wheat Using Different Reference Evapotranspiration Estimates Methods. *J. Agr. Sci. Tech.* **2011**, *13*, 209–221.
40. Duchemin, B.; Hagolle, O.; Mougnot, B.; Benhadj, I.; Hadria, R.; Simonneaux, V.; Ezzahar, J.; Hoedjes, J.; Khabba, S.; Kharrou, M.H.; et al. Agrometeorological Study of Semi-arid Areas: An Experiment for Analysing the Potential of Time Series of FORMOSAT-2 Images (Tensift-Marrakech Plain). *Int. J. Remote Sens.* **2008**, *29*, 5291–5299. [[CrossRef](#)]
41. Khabba, S.; Duchemin, B.; Hadria, R.; Er-Raki, S.; Ezzahar, J.; Chehbouni, A.; Lahrouni, A.; Hanich, L. Evaluation of Digital Hemispherical Photography and Plant Canopy Analyzer for Measuring Vegetation Area Index of Orange Orchards. *J. Agron.* **2009**, *8*, 67–72. [[CrossRef](#)]
42. de Wit, A.; Boogaard, H.; Supit, I.; van den berg, M. *System Description of the WOFOST 7.2 Cropping Systems Model*; Wageningen Environmental Research: Wageningen, The Netherlands, 2020; pp. 1–120.
43. Diepen, V.; Wolf, J.; Keulen, H.; Rappoldt, C. WOFOST: A Simulation Model of Crop Production. *Soil Use Manag.* **1989**, *5*, 16–24. [[CrossRef](#)]
44. de Wit, A.; Boogaard, H. *A Gentle Introduction to WOFOST*; Wageningen Environmental Research: Wageningen, The Netherlands, 2021; pp. 1–47.
45. Alaoui, S.B. *Référentiel Pour la Conduite Technique de la Culture du Blé Dur*; Fella-Trade: Rabat, Maroc, 2005; p. 15.
46. Er-Raki, S.; Chehbouni, A.; Khabba, S.; Simonneaux, V.; Jarlan, L.; Ouldabba, A.; Rodriguez, J.C.; Allen, R. Assessment of Reference Evapotranspiration Methods in Semi-Arid Regions: Can Weather Forecast Data Be Used as Alternate of Ground Meteorological Parameters? *J. Arid Environ.* **2010**, *74*, 1587–1596. [[CrossRef](#)]
47. Wu, S.; Yang, P.; Ren, J.; Chen, Z.; Li, H. Regional Winter Wheat Yield Estimation Based on the WOFOST Model and a Novel VW-4DnSRF Assimilation Algorithm. *Remote Sens. Environ.* **2021**, *255*, 112276. [[CrossRef](#)]
48. Eweys, O.A.; Elwan, A.A.; Borham, T.I. Integrating WOFOST and Noah LSM for Modeling Maize Production and Soil Moisture with Sensitivity Analysis, in the East of The Netherlands. *Field Crop. Res.* **2017**, *210*, 147–161. [[CrossRef](#)]
49. Huang, J.; Sedano, F.; Huang, Y.; Ma, H.; Li, X.; Liang, S.; Tian, L.; Zhang, X.; Fan, J.; Wu, W. Assimilating a Synthetic Kalman Filter Leaf Area Index Series into the WOFOST Model to Improve Regional Winter Wheat Yield Estimation. *Agric. For. Meteorol.* **2016**, *216*, 188–202. [[CrossRef](#)]
50. Silva, J.V.; Baudron, F.; Reidsma, P.; Giller, K.E. Is Labour a Major Determinant of Yield Gaps in Sub-Saharan Africa? A Study of Cereal-Based Production Systems in Southern Ethiopia. *Agric. Syst.* **2019**, *174*, 39–51. [[CrossRef](#)]
51. Pala, M.; Oweis, T.; Benli, B.; De Pauw, E.; El Mourid, M.; Karrou, M.; Jamal, M.; Zencirci, N. *Assessment of Wheat Yield Gap in the Mediterranean: Case Studies from Morocco, Syria and Turkey*; International Center for Agricultural Research in the Dry Areas (ICARDA): Aleppo, Syria, 2011; iv+36p, ISBN 92-9127-257-4.