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Optimizing Genetic Parameters of CSM-CERES Wheat and CSM-CERES Maize for Durum Wheat, Common Wheat, and Maize in Italy

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Abstract: The expected increase in population and the pressure posed by climate change on agricultural production require the assessment of future yield levels and the evaluation of the most suitable management options to minimize climate risk and promote sustainable agricultural production. Crop simulation models are widely applied tools to predict crop development and production under different management practices and environmental conditions. The aim of this study was to parameterize CSM-CERES-Wheat and CSM-CERES-Maize models, implemented in the Decision Support System for Agrotechnology Transfer (DSSAT) software, to predict phenology and grain yield of durum wheat, common wheat, and maize in different Italian environments. A 10-year (2001–2010) dataset was used to optimize the genetic parameters for selected varieties of each species and to evaluate the models considering several statistical indexes. The generalized likelihood uncertainty estimation method, and trial and error approach were used to optimize the cultivar-specific parameters of these models. Results show good model performances in reproducing crop phenology and yield for the analyzed crops, especially with the parameters optimized with the trial and error procedure. Highly significant ($p \leq 0.001$) correlations between observed and simulated data were found for both anthesis and yield in model calibration and evaluation ($p \leq 0.01$ for grain yield of maize in model evaluation). Root mean square error (RMSE) values range from six to nine days for anthesis and from 1.1 to 1.7 t ha^{-1} for crop yield and index of agreement (d-index) from 0.96 to 0.98 for anthesis and from 0.8 to 0.87 for crop yield. The set of genetic parameters obtained for durum wheat, common wheat, and maize may be applied in further analyses at field, regional, and national scales to guide operational (farmers), strategic, and tactical (policy makers) decisions.

Keywords: Crop modeling; decision support system; calibration; evaluation; DSSAT; GLUE; wheat; maize

1. Introduction

The expected world population growth, the limited availability of arable land, and the impacts of climate change on cereal production indicate the need to increase the quantity and quality of global grain production to meet the growing demand of food and dietary requirements [1]. Transformative changes in agricultural systems are required to increase the adaptive capacity of the sector, guarantee farmer income, and enhance the fulfillment of Sustainable Development Goals (SDGs) under present and future climatic conditions. However, the choice of adaptation and mitigation strategies is closely related to specific environmental conditions. Crop Simulation Models (CSMs) have been widely tested and applied worldwide to assess the relations between crops and environment and to evaluate the effects of alternative management options in different environmental conditions. CSMs are indeed capable of quantifying the interaction of genotype (G), environment (E), and management (M) and their effects on crop yield and other outputs [2]. Recently, CSMs have become agricultural system models that incorporate the capability to analyze a variety of issues, including changes in soil carbon, greenhouse gas emissions, plant breeding, resource use and efficiency, ecosystem services, pests and diseases, food security, yield-gap analysis, and climate change mitigation and adaptation [3] to support the decision making process. They can be applied as "what if" tools, in addition to field and farm experiments that require large amounts of time and resources to support farmers and policy makers to manage agricultural systems under different conditions, and provide guidelines for a sustainable agricultural management with environmental, social, and economic benefits.

CSMs are generally developed and applied for field-scale simulations, but they have been used from local to global scale by combining with geospatial data using different approaches and purposes, including climate change [4–9]. Some studies also evaluated the application of CSMs with seasonal forecast for crop yield predictions [10–12]. However, the model applications at large scale are often constrained by limited availability of observations for model calibration and evaluation, which reduce the reliability of model simulations [13]. Notwithstanding the importance of model calibration and evaluation when applied for new locations or new varieties, many studies use coefficients obtained by model developers or from other studies, increasing the uncertainty of model output [14]. An accurate parameterization of crop models at an appropriate scale is required to test their predictive capacity [10] and reduce the degree of uncertainty [15].

Recent literature highlights the need for multi-crop model assessments to reduce the uncertainty associated with model simulations [2,16] and especially for large-scale model intercomparison studies, it is useful to have crop parameters based on a wide range of conditions and tested in different environments.

Long-term observations from different experimental sites result in model calibration with greater robustness, especially if high quality weather, soil, crop management, crop phenology, and production data are available.

This study aims to contribute to the available literature on crop model parameterization to simulate durum wheat (*Triticum durum* Desf.), common wheat (*Triticum aestivum* L.), and maize (*Zea mays* L.) using CSM-CERES-Wheat and CSM-CERES-Maize models and multi-site and multi-year observations. The CSM-CERES-Wheat and CSM-CERES-Maize are commonly used in climate change impact assessment at different scales and are widely tested and applied in model intercomparison studies [2,5,17], providing good performances in reproducing observations [15,18]. This research provides parameterization at a national level for wheat and maize crops considering observations from field trials located in different agroclimatic and management conditions in Italy in order to explore a wide range of G × E × M interactions and obtain robust parameterization to be applied in further studies at both local and national scales.

Wheat and maize are staple cereal crops with a high economic and social relevance for Europe and worldwide, as they provide a large part of the food energy intake for human consumption and livestock feed. According to FAOSTAT [19], maize and wheat are the first two cultivated crops worldwide (in terms of harvested area) and the first and fourth in Europe (in terms of both harvested area and production). In Italy, maize is the main grown cereal, with a production of 6.0 million tons in 2017, followed by wheat (4.2 for durum wheat and 2.8 for common wheat), which together account for 78.6% of the total cereal harvested area and 80.9% of total cereal production [20]. Predicting growth and yield of these crops under present climate conditions and future scenarios is pivotal to guide crop management. Indeed, if the potential effects of sustainable crop management practices, as conservation agriculture [21] and in general climate smart agriculture solutions [22], are quite well explored, especially under the present climate conditions, there is still a paucity of literature exploring the effects of different management practices (e.g., changes in crop calendars, application of precision agriculture, and the use of well adapted crops) as adaptation strategies to cope with climate changes and on the synergic effects between adaptation and mitigation options. The results of this work would serve model applications at field, regional, and national scales to simulate average and interannual variability of crop phenology and yield and inform decision makers and stakeholders on how to manage agricultural systems by sustainably increasing crop productivity and improving their resilience to climate change.

2. Materials and Methods

2.1. CSM-CERES-Wheat and CSM-CERES-Maize

CSM-CERES-Wheat [23,24] and CSM-CERES-Maize [24,25] implemented in the Decision Support System for Agrotechnology Transfer (DSSAT) v.4.6.1.0 [26,27] were applied in this study to simulate phenology and yield of specific varieties of durum wheat, common wheat, and maize in Italy. The DSSAT is a software package that includes independent dynamic models to simulate crop growth, development, and yield of more than 25 crops by considering weather, soil, crop genetics, and agronomic management, for single or multiple seasons, at sites where the minimum input data required for model calibration and operation are available [14,26]. CSMs implemented in DSSAT calculate cropping system processes within a homogeneous area on a daily time-step and simulate crop growth stages as a function of temperature and day length. The potential growth is simulated as a function of photosynthetically active radiation and its interception, where the biomass production is constrained by temperature, nitrogen, and water stress. A number of Cultivar-Specific Parameters (CSPs)determine the life cycle and reproductive growth rate of specific crop varieties by considering phase modifiers (e.g., vernalization and photoperiod sensitivity) and vegetative and reproductive attributes [28]. See Table 1 for the CSPs of wheat and maize considered in DSSAT. Moreover, DSSAT includes specific modules to simulate soil dynamics, soil temperature and water, and nitrogen and carbon processes, including changes in soil organic matter content according to environmental conditions and agronomic management [26,29]. CSMs implemented in DSSAT also consider the effects of the CO_2 atmospheric concentration on photosynthesis and water-use efficiency [14].

Table 1. Cultivar-specific parameters (CSPs) for CSM-CERES-Wheat and CSM-CERES-Maize crop models.

Wheat CSPs	**Definition**
P1V	Vernalization sensitivity coefficient (%/d of unfulfilled vernalization)
P1D	Photoperiod sensitivity coefficient (% reduction/h near threshold)
P5	Grain filling (excluding lag) phase duration (degree days)
G1	Kernel number per unit canopy weight at anthesis (#/g)
G2	Standard kernel size under optimum conditions (mg/day)
G3	Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g)
PHINT	Interval between the appearance of leaf tips (degree days)
Maize CSPs	**Definition**
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant is not responsive to changes in photoperiod
P2	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod, beyond the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours)
P5	Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C)
G2	Maximum possible number of kernels per plant
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)
PHINT	Phyllochron interval (degree days)

2.2. Experimental Sites and Minimum Data set for Model Calibration and Evaluation

The minimum data set for model calibration includes soil characteristics, daily weather data of minimum and maximum temperature, precipitation, solar radiation, crop management, and CSPs [26,30].

In this study, observations of anthesis date, grain yield, and crop management (e.g., sowing and harvesting dates, fertilization and irrigation dates and rates, and tillage) were collected for three varieties of durum wheat, common wheat, and maize (see Table 2) from the experimental field trials (Figure 1) of the national network of varietal comparison and published annually in dedicated special issues. See [31–56] for durum wheat, [57–77] for common wheat, and [78–86] for maize.

Table 2. Main characteristics of the crop varieties from [87–89].

Cultivar Characteristics	Iride (Durum Wheat)	Bologna (Common Wheat)	Eleonora (Maize)
Release	1996	1999	1995
Cultivar type	Spring durum wheat	Winter common wheat	FAO class 700
Heading time	Precocious	Medium-Late	Medium-Late
Potential production	Very high	Very high	Very high
Adaptability to different environments	High	High	Very high
Resistance to cold	Good	Medium-High	Medium-High
Resistance to lodging	Good	Medium-High	High
Resistance to the main diseases	Medium	Medium	Medium-High
Flour quality	Medium-High	Very high	-
Main uses	Grain	Grain	Grain - Silage

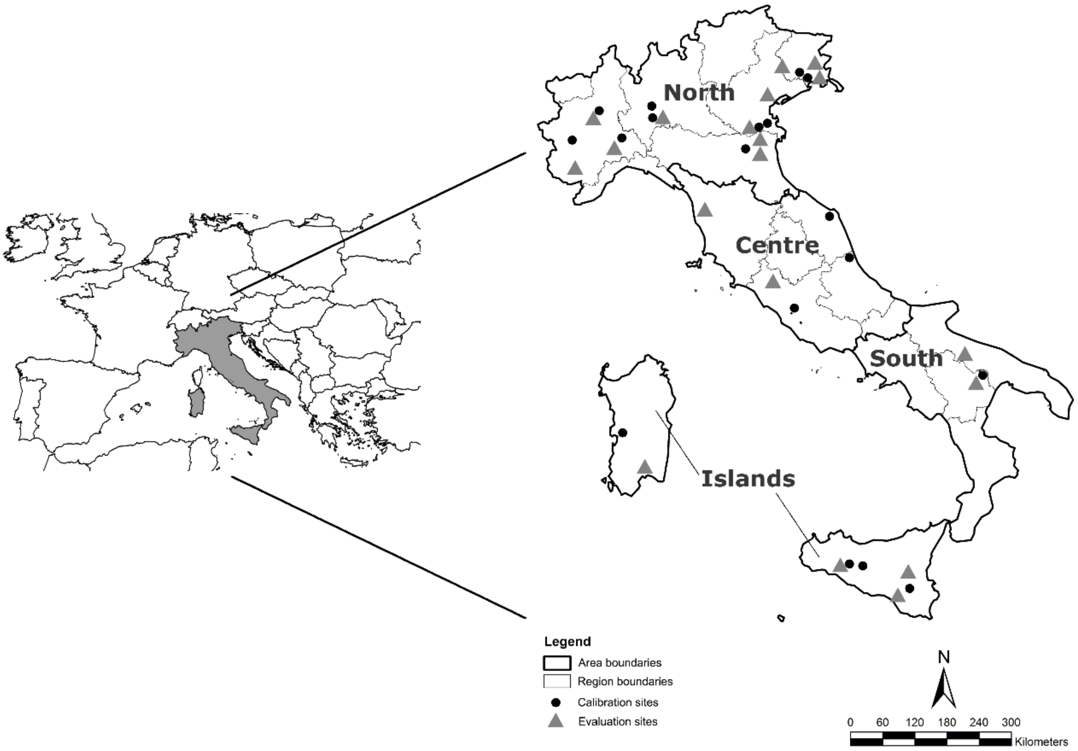

Figure 1. Location of the experimental sites for model calibration and evaluation in Italy.

The crop varieties were selected as representative of very-high productivity potential and high/very-high adaptability to different environments (Table 2). The crop management information followed the ordinary practices applied in the variety trials of the different Italian regions (North, Centre, South, and Islands) and were recorded from the available literature, as well as observations of anthesis date and grain yield [31–86]. The size of the experimental plots was 10 m^2 for each crop. Sowing density was of 450 plants/m^2 for northern and central Italy and 350 plants/m^2 for southern-peninsular area, Sicily, and Sardinia for durum wheat, and 450 plants/m^2 for common wheat in all sites. For maize, each plot consisted of four rows of 11 m including a transverse portion of 70–80 cm between the various parcels. The plant density (ranging from 5.5 to 7.5 plants/m^2 in the different field trials) was obtained with the manual thinning of the plants at the stage of 4th-5th leaf. Wheat sowing dates ranged from the last week of October (in northern and central Italy) to the last week of December (in southern Italy); while sowing dates for maize ranged from the beginning of April to the end of May. The ordinary tillage for wheat is conventional tillage with moldboard plowing in late summer when the soil is in the right humidity conditions and disk harrow and tine harrow before sowing to prepare a proper seedbed. For maize, the ordinary tillage comprised of plowing and harrowing before sowing.

The anthesis date (expressed in dap = days after planting) for phenology and the grain yield (in t ha^{-1}) accounting for biomass production were considered for crop models calibration and evaluation. The observed values of anthesis dates were estimated from the observed heading dates and the observed grain yield values were corrected to 0% water, as required by the CSMs. Weed control, pests, and diseases were not considered.

The main characteristics of each experimental site are given in Table 3.

Table 3. Characterization of the experimental sites.

Experimental Site	Latitude	Longitude	Weather Station	Tmax* (°C)	Tmin* (°C)	PP* (mm)	Soil Type
Agugliano	43°32′N	13°24′E	Potenza Picena	20.3	10.8	760.9	Silty loam
Alba Adriatica	42°49′N	13°55′E	Monsampolo	20.4	9.5	726.1	Silty loam
Alessandria	44°53′N	08°36′E	Alessandria Lobbi	18.8	7.4	908.8	Medium loam
Ambrogio	44°55′N	11°56′E	Rovigo	19.2	8.4	678.2	Medium loam
Basiliano	46°01′N	13°08′E	Cividale del Friuli	18.5	8.8	1477.3	Medium loam
Caleppio di Settala	45°26′N	09°22′E	Montanaso Lombardo	18.1	8.9	876.4	Medium loam
Caltagirone	37°14′N	14°30′E	Santo Pietro	22.3	11.9	576.0	Medium loam
Cammarata	37°37′N	13°39′E	Pietranera	23.5	8.6	676.4	Clay loam
Castel di Judica	37°29′N	14°40′E	Libertinia	24.3	10.0	534.3	Silty loam
Castellazzo Bormida	44°44′N	08°27′E	Basaluzzo	18.3	6.9	593.3	Medium loam
Ceregnano	45°03′N	11°51′E	Rovigo	19.2	8.4	678.2	Clay loam
Cigliano	45°19′N	08°03′E	Candia	17.6	6.7	944.7	Clay loam
Codroipo	45°58′N	12°56′E	Fiume Veneto	19.2	8.3	1177.7	Silty loam
Cuneo	44°22′N	07°33′E	Fossano	17.0	8.0	525.2	Clay loam
Gela	37°06′N	14°16′E	Santo Pietro	22.9	10.8	590.3	Silty loam
Gravina	40°57′N	16°05′E	Genzano di Lucania	18.4	10.7	656.2	Medium loam
Latisana	45°47′N	13°01′E	Fiume Veneto	19.2	8.3	1177.7	Clay loam
Malalbergo	44°43′N	11°32′E	Gualdo	20.1	8.9	667.4	Clay loam
Matera	40°39′N	16°36′E	Matera	21.0	8.7	666.2	Silty loam
Mogliano Veneto	45°35′N	12°14′E	Susegana	18.4	8.0	1,356.3	Medium loam
Ostellato	44°44′N	11°56′E	Gualdo	20.1	8.9	667.4	Clay loam
Palazzolo dello Stella	45°52′N	13°11′E	Fiume Veneto	19.2	8.3	1177.7	Silty clay loam
Roma	41°57′N	12°30′E	Roma Collegio Romano	21.3	12.5	697.0	Loam
San Piero a Grado	43°41′N	10°21′E	San Piero a Grado	20.6	8.5	872.6	Medium loam
Santa Lucia	39°58′N	08°37′E	Santa Lucia	22.9	10.8	590.3	Medium loam
Sant’Angelo Lodigiano	45°14′N	09°24′E	Montanaso Lombardo	18.1	8.9	876.4	Clay loam
Santo Stefano Quisquina	37°37′N	13°29′E	Pietranera	23.5	8.6	676.4	Clay loam
Ussana	39°24′N	09°05′E	Ussana	24.5	11.6	454.2	Clay loam
Vigone	44°50′N	07°29′E	Cumiana	19.0	7.8	924.7	Medium loam
Villadose	45°05′N	11°53′E	Rovigo	19.2	8.4	678.2	Medium loam
Viterbo	42°25′N	12°05′E	Caprarola	18.4	9.6	922.3	Medium loam
Zoppola	46°1′N	12°35′E	Fiume Veneto	19.2	8.3	1177.7	Silty loam

* Tmax (Maximum temperature), Tmin (Minimum Temperature), and PP (Precipitation) are the mean values recorded in the period of the analysis.

The daily weather data were collected for the period 2001–2010, from the available weather stations of the national database of the Agricultural Research Council’s Research Unit for Climatology and Meteorology applied to Agriculture (CRA-CMA, 2011) and the regional Italian Agencies. Specifically, data for the Ussana site were provided by the Agency for Agricultural Research of the Autonomous Region of Sardinia (AGRIS Sardegna) and data for experimental sites located in Piedmont (Alessandria Lobbi, Basaluzzo, Candia, Fossano, and Cumiana) were from the Regional Agency for Environmental Protection of Piedmont (ARPA Piemonte). For each experimental field, the nearest available weather stations were considered.

Soil profiles and information were from the ISRIC-WISE v.1.2 data set [90]. For the Ussana experimental site (in Sardinia), the soil profile was provided by AGRIS Sardegna.

All the collected observations (weather, soil, climate, and crop management) were organized in the form required by DSSAT and the experimental files (EXP) were created accordingly.

Before proceeding with the CSM-CERES-Wheat and CSM-CERES-Maize model calibration and evaluation, a sensitivity analysis for CSPs that characterize the development and productivity of each crop variety (Table 1) was performed. A detailed description of the sensitivity analysis and the optimization and evaluation of CSPs for CSM-CERES-Wheat and CSM-CERES-Maize models is presented in the following sections.

2.3. Sensitivity Analysis

A sensitivity analysis was performed to study the influence of each CSP of the CSM-CERES-Wheat and CSM-CERES-Maize models on the variation of model output [91,92], in this case anthesis date and grain yield for durum and common wheat, and grain yield for maize. The sensitivity analysis aims to guide the calibration phase focusing on parameters that mainly affect the model outputs. The analysis was performed considering the experimental sites used in model calibration and calculating the sensitivity index (SI) for each CSP as follows [93]:

$$SI = ((O_2 - O_1)/O_{avg})/((I_2 - I_1)/ I_{avg}), \tag{1}$$

where I_1, I_2, and I_{avg} are the maximum, minimum, and average values of a specific input parameter, while O_1, O_2, and O_{avg} are the maximum, minimum, and average values of the crop model output under consideration.

2.4. CSM-CERES-Wheat and CSM-CERES-Maize Calibration and Evaluation

Model calibration and evaluation were performed comparing model simulations with field observations of anthesis dates and crop yields for multiple years and sites (Table 4). Sites were grouped for calibration and evaluation experiments, considering at least two sites—one for calibration and one for evaluation—for each geographical area (North, Center, South, and Islands) (see Figure 1 and Table 4). Overall, 14 experimental sites were selected for durum wheat (67 combinations site × year), 12 sites for common wheat (38 combinations site × year), and 13 sites for maize (23 combinations site × year).

Table 4. Experimental sites and relative number of years (in brackets) for model calibration (C) and evaluation (E).

Crop	Calibration (C)	Evaluation (E)
Durum wheat	Agugliano (5); Caltagirone (6); Cigliano (2); Matera (5); Roma (5); Santa Lucia (7); Santo Stefano Quisquina (7)	Castel di Judica (6); Ceregnano (4); Gela (4); Gravina (2); Ostellato (3); Ussana (6); Viterbo (5)
Common wheat	Alba Adriatica (1); Caltagirone (3); Cammarata (5); Ceregnano (2); Malalbergo (2); Sant'Angelo Lodigiano (5)	Basiliano (3); Cigliano (3); Matera (5); Mogliano Veneto (3); San Piero a Grado (3); Santo Stefano Quisquina (3)
Maize	Alessandria (1); Caleppio di Settala (1); Codroipo (1); Latisana (3); Vigone (6); Villadose (1)	Ambrogio (2); Castellazzo Bormida (1); Cigliano (1); Cuneo (1); Palazzolo dello Stella (2); Sant'Angelo Lodigiano (2); Zoppola (1)

The anthesis date and grain yield were considered for CSM-CERES-Wheat calibration and evaluation, while for the CSM-CERES-Maize crop model, only grain yield was calibrated and evaluated and a date of maturity equal to 132 dap was considered as reported by the producer (Pioneer) for the length of growing period of the selected hybrid.

The CSPs were modified to minimize the differences between model simulations and observations. The Generalized Likelihood Uncertainty Estimation (GLUE) method [94] was applied using the GLUE R program, implemented in DSSAT v.4.6.1.0. GLUE was run 6000 times to obtain the set of CSPs. Moreover, the trial and error (TE) approach [95] was applied to further improve the simulation results by modifying the CSPs through an iterative procedure to minimize the Root-Mean-Square Error (RMSE) as suggested by [96] and optimize other statistical indexes described in the paragraph "Statistical Analysis".

The DEFAULT cultivar of the WHCER046.CUL file of DSSAT was used as the starting point for model calibration for both durum and common wheat, while for maize, the parameterization started from the MEDIUM SEASON hybrid of the file MZCER046.CUL. The first step simulated by the DSSAT CSMs is crop development and, consequently, the process of parameterization started with the CSPs related to phenological stages (P1V, P1D, and P5 for CSM-CERES-Wheat and P1, P2, and P5 for CSM-CERES-Maize). The coefficients that affect grain yield (G1, G2, and G3 for CSM-CERES-Wheat and G2, G3, and PHINT for CSM-CERES-Maize) were subsequently parameterized. According to the results of sensitivity analysis, only the parameters that showed a sensitivity on anthesis date and grain yield were modified. In the TE method, P1V coefficient was set to 5.0 for both durum and common wheat, as suggested for the varieties that does not require vernalization [97] and the PHINT coefficient was set equal to 95, as the suggested value for durum wheat and common wheat in the

Mediterranean area [98]. The G3 coefficient was set equal to 1.8 for durum wheat as the average value of those reported in other studies for the calibration of durum wheat in Italy [99,100]. Finally, the two set of CSPs obtained with GLUE and trial and error were evaluated considering an independent data set of field observations for anthesis dates and crop yields (as reported in Table 3).

2.5. Statistical Analysis

The performance of CSM-CERES-Wheat and CSM-CERES-Maize in calibration and evaluation were evaluated using five statistical indexes, mainly based on the calculation of correlation and differences between simulated (Ei) and observed (Mi) values of each variable, exploring absolute and relative differences: (1) Pearson correlation coefficient (r), (2) coefficient of determination (R2), (3) root-mean-square error (RMSE), (4) coefficient of residual mass (CRM), and (5) index of agreement (d-Index). Since the use of a single statistical index is not sufficient for evaluating simulation models, multiple indexes were selected among the most commonly used indexes in crop model evaluation [14,99]. The identified indexes are calculated as follows:

$$r = \frac{\sum_{i=1}^{n}\left(E_i - \overline{E}\right)\left(M_i - \overline{M}\right)}{\sqrt{\sum_{i=1}^{n}\left(E_i - \overline{E}\right)^2 \sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2}}, \tag{2}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(E_i - \overline{E}\right)\left(M_i - \overline{M}\right)\right]^2}{\sum_{i=1}^{n}\left(E_i - \overline{E}\right)^2 \sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2}, \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{n}}, \tag{4}$$

$$CRM = 1 - \frac{\sum_{i=1}^{n} E_i}{\sum_{i=1}^{n} M_i}, \tag{5}$$

$$d - Index = 1 - \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|E_i - \overline{M}\right| + \left|M_i - \overline{M}\right|\right)^2}, \tag{6}$$

where E_i and M_i, respectively, represent the simulated and measured annual values of the year i, n is the number of annual values, and $\overline{E}$ and $\overline{M}$ are the mean simulated and observed data values, respectively.

3. Results

3.1. Sensitivity Analysis

The results of sensitivity analysis of the CSPs for the phenology and grain yield of durum wheat and common wheat are reported in Table 5, while results for maize are displayed in Table 6. The P1D coefficient of CSM-CERES-Wheat crop model was the most sensitive CSP for the anthesis date, especially for Iride cultivar. Regarding grain yield, the coefficients with the highest SI were G1 and G2, followed by the P5 coefficient. The G3 coefficient showed no sensitivity for grain yield of durum wheat and very low sensitivity for grain yield of common wheat. Results for the Eleonora cultivar indicated a high sensitivity of the CSM-CERES-Maize to the P5 coefficient, followed by the P1 and PHINT coefficients. The sensitivity index of the P2 coefficient was very low. The most sensitive parameter on grain yield was P5, followed by the G3 and G2 coefficients. The other coefficients had a minor influence on grain yield.

Table 5. Sensitivity index of the CSPs of CSM-CERES-Wheat crop model for anthesis date (ANT) and grain yield (GY) of Iride and Bologna cultivars and range are considered.

CSPs	Durum wheat (Iride Cultivar)			Common Wheat (Bologna Cultivar)		
	ANT	GY	RANGE	ANT	GY	RANGE
P1V	0.05	0.08	0–100	0.03	0.03	0–100
P1D	0.21	0.12	0–100	0.17	0.11	0–100
P5	0.00	0.35	0–999	0.00	0.29	0–999
G1	0.00	0.60	0.1–100	0.00	0.61	0.1–100
G2	0.00	0.61	0–100	0.00	0.62	0–100
G3	0.00	0.00	0.2–3.0	0.00	0.01	0.2–3.0
PHINT	0.00	0.22	15–100	0.00	0.17	15–100

Table 6. Sensitivity index of the CSPs of CSM-CERES-Maize crop model for maturity date (MAT) and grain yield (GY) of Eleonora hybrid and range are considered.

CSPs	Maize (Eleonora Hybrid)		
	MAT	GY	RANGE
P1	0.26	0.37	100–300
P2	0.03	0.03	0–1
P5	0.42	1.39	500–900
G2	0.00	0.80	600–999
G3	0.00	1.00	0–10
PHINT	0.15	0.16	0.1–99

3.2. CSM-CERES-Wheat and CSM-CERES-Maize Calibration

The set of CSPs obtained with GLUE method TE method are reported in Table 7.

Table 7. CSPs of durum wheat, common wheat, and maize obtained with TE and GLUE methods.

Crop	Calibration Method	CSPs						
		P1V	P1D	P5	G1	G2	G3	PHINT
Durum wheat (Iride cv)	GLUE	25.2	61.9	776.6	28.6	41.1	2.0	97.1
	TE	5.0	65.0	500.0	20.0	40.0	1.8	95.0
Common wheat (Bologna cv)	GLUE	64.9	94.8	589.3	15.1	20.5	2.0	63.9
	TE	5.0	98.0	700.0	20.0	50.0	1.3	95.0
		P1	P2	P5	G2	G3	PHINT	
Maize (Eleonora cv)	GLUE	398.4	1.0	704.6	683.5	14.5	22.4	
	TE	223.0	0.6	803.0	907.9	7.5	38.9	

TE, trial and error; GLUE, Generalized Likelihood Uncertainty Estimation.

The results of simulated crop phenology and yield are presented in Figure 2 for each analyzed year and the associated statistics are summarized in Tables 8–10. Overall, the simulated values of anthesis date were quite well reproduced by CSM-CERES-Wheat for both durum and common wheat, explaining more than 89% of the variation (Figure 2). The correlation between the observed and simulated data was highly significant ($p \leq 0.001$) (Table 8). The good correlation between simulated and measured anthesis date was confirmed also by the high values of d-Index (ranging from 0.97 to 0.99) and the values of CRM very close to 0 (Table 8).

The statistical indexes obtained for anthesis with the set of CSPs parameterized with the GLUE method were quite similar to those obtained with the TE procedure, while for grain yield, the TE allowed to improve the values of statistical indexes, especially for durum wheat (Table 9) and maize (Table 10).

The results obtained for CSM-CERES-Wheat calibration for grain yield (Figure 2 and Table 9) showed lower model performances respect to simulation of crop phenology, even if the correlation between the observed and simulated data was highly significant ($p \leq 0.001$). In this case, the TE procedure allowed an improvement of the statistical indexes with respect to the set of CSPs obtained with GLUE, in particular for R^2 (0.48 vs. 0.34), RMSE (1.54 vs. 2.19 t ha^{-1}), and d-Index (0.82 vs. 0.74) for durum wheat and R^2 (0.62 vs. 0.54), RMSE (1.52 vs. 3.72 t ha^{-1}), and d-Index (0.87 vs. 0.52) for common wheat.

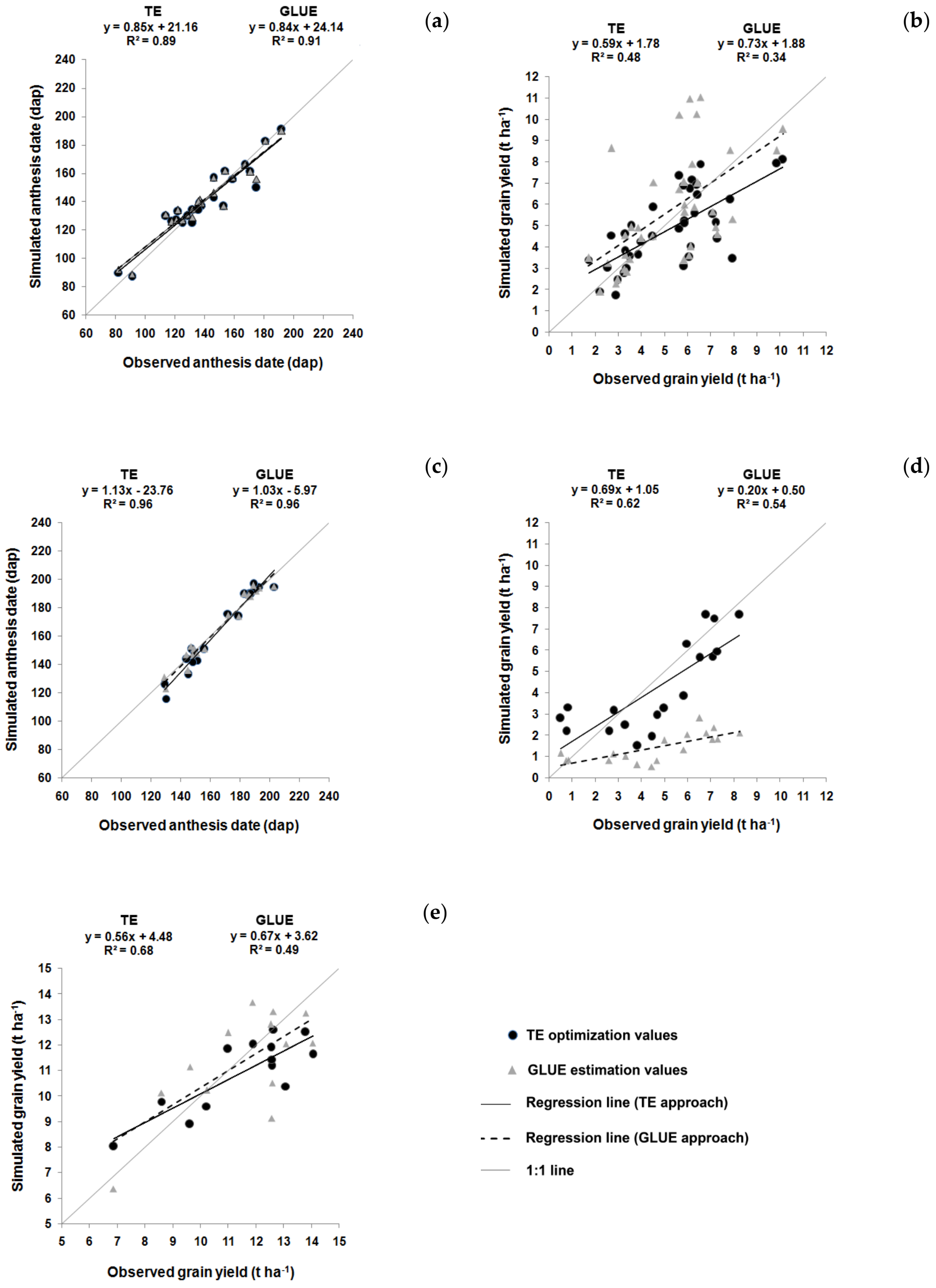

Figure 2. Calibration results for anthesis date (**a**) and grain yield (**b**) of durum wheat (Iride cv), anthesis date (**c**) and grain yield (**d**) of common wheat (Bologna cv), and grain yield of maize (Eleonora hybrid) (**e**) with TE and GLUE methods.

The results of CSM-CERES-Maize calibration for grain yield are reported in Figure 2 and Table 10. A mean maturity date of 132 dap (as reported in the literature for an FAO class 700 hybrid) was obtained for the selected years and locations. A good correlation between simulated and observed yield was achieved, particularly with the CSPs optimized through the trial and error approach (0.83 ($p \leq 0.001$) versus 0.70 ($p \leq 0.01$)) (Table 10).

Table 8. Statistical results of observed (OBS) and simulated (SIM) values of anthesis date (in days after planting = dap) for durum wheat (Iride cv) and common wheat (Bologna cv) for the calibration of CSM-CERES-Wheat model.

	Durum Wheat (Iride cv)			**Common Wheat (Bologna cv)**		
	OBS	**TE SIM**	**GLUE SIM**	**OBS**	**TE SIM**	**GLUE SIM**
Mean	140	140	142	166	164	166
Standard deviation	27	24	24	24	27	25
Min	82	87	89	129	116	123
Max	192	191	190	203	197	196
N	23			18		
r		0.94 ***	0.95 ***		0.98 ***	0.98 ***
R^2		0.89	0.91		0.96	0.96
RMSE		9	8		6	5
CRM		0.00	−0.01		0.01	0.00
d-Index		0.97	0.97		0.98	0.99

*** $p \leq 0.001$; ns = not significant. OBS = observed values; TE = simulated values with trial and error; GLUE SIM = simulated values with GLUE.

Table 9. Statistical results of observed (OBS) and simulated (SIM) values of grain yield (t ha^{-1}) for durum wheat (Iride cv) and common wheat (Bologna cv) for the calibration of CSM-CERES-Wheat model.

	Durum Wheat (Iride cv)			**Common Wheat (Bologna cv)**		
	OBS	**TE SIM**	**GLUE SIM**	**OBS**	**TE SIM**	**GLUE SIM**
Mean	5.25	4.87	5.74	4.63	4.24	1.45
Standard deviation	2.06	1.75	2.59	2.43	2.12	0.68
Min	1.69	1.73	1.92	0.50	1.53	0.55
Max	10.12	8.11	11.04	8.23	7.68	2.82
N	37			18		
r		0.70 ***	0.59 ***		0.79 ***	0.74 ***
R^2		0.48	0.34		0.62	0.54
RMSE		1.54	2.19		1.52	3.72
CRM		0.07	−0.09		0.08	0.69
d-Index		0.82	0.74		0.87	0.52

*** $p \leq 0.001$; ns = not significant. OBS = observed values; TE SIM = simulated values with trial and error; GLUE SIM = simulated values with GLUE.

Table 10. Statistical results of observed (OBS) and simulated (SIM) values of grain yield (t ha^{-1}) of maize (Eleonora hybrid) for the calibration of CSM-CERES-Maize model.

	Maize (Eleonora Hybrid)		
	OBS	**TE SIM**	**GLUE SIM**
Mean	11.49	10.92	11.33
Standard deviation	2.13	1.44	2.05
Min	6.86	8.04	6.37
Max	14.04	12.62	13.68
N	13		
r		0.83 ***	0.70 **
R^2		0.68	0.49
RMSE		1.32	1.57
CRM		0.05	0.01
d-Index		0.85	0.84

** $p \leq 0.01$; *** $p \leq 0.001$; ns = not significant. OBS = observed values; TE SIM = simulated values with trial and error; GLUE SIM = simulated values with GLUE.

3.3. CSM-CERES-Wheat and CSM-CERES-Maize Evaluation

The results for model evaluation confirm the good performances of CSM-CERES-Wheat in reproducing crop phenology, with high significant results ($p \leq 0.001$) obtained for anthesis with both the sets of CSP parameters (Figure 3 and Table 11).

The simulations of grain yield for wheat with the evaluation dataset showed a good agreement with observations, with not big differences for durum wheat between the two set of CSPs, while for common wheat, the set of CSPs adjusted with the TE procedure allowed to obtain better results, according to the statistical indexes considered (Figure 3 and Table 12). The TE parameterization reduced the RMSE and CRM values (RMSE from 2.74 to 1.73 t ha^{-1} and CRM from -0.36 to −0.17 for durum wheat and RMSE from 4.02 to 1.60 t ha^{-1} and CRM from 0.69 to 0.06 for common wheat) and increased the d-Index (from 0.68 to 0.80 for durum wheat and from 0.50 to 0.84 for common wheat) (Table 12).

Table 11. Statistical results of observed (OBS) and simulated (SIM) values of anthesis date (in days after planting = dap) for durum wheat (Iride cv) and common wheat (Bologna cv) for the evaluation of CSM-CERES-Wheat model.

	Durum Wheat (Iride cv)			**Common Wheat (Bologna cv)**		
	OBS	**TE SIM**	**GLUE SIM**	**OBS**	**TE SIM**	**GLUE SIM**
Mean	138	141	143	177	180	180
Standard deviation	23	24	23	23	27	25
Min	112	118	120	94	95	102
Max	192	184	186	201	208	207
N	19			20		
r		0.95 ***	0.96 ***		0.95 ***	0.94 ***
R^2		0.91	0.93		0.90	0.89
RMSE		8	8		9	9
CRM		−0.02	−0.03		−0.02	−0.02
d-Index		0.97	0.97		0.96	0.96

*** $p \leq 0.001$; ns = not significant. OBS = observed values; TE SIM = simulated values with trial and error; GLUE SIM = simulated values with GLUE.

The performances of CSM-CERES-Maize in the evaluation phase are summarized in Figure 3 and Table 13. Results showed a better correlation between simulated and observed grain yield for maize with the CSPs optimized through the TE approach with respect to the GLUE method (r-values of 0.65 ($p \leq 0.01$) versus 0.5 ($p \leq 0.05$) and higher values of d-Index and lower values of RMSE and CRM (Table 13).

In summary, the simulated anthesis date and the grain yield of the three crops with the evaluation dataset showed results comparable with the calibration dataset.

Table 12. Statistical results of observed (OBS) and simulated (SIM) values of grain yield (t ha^{-1}) for durum wheat (Iride cv) and common wheat (Bologna cv) for the evaluation of CSM-CERES-Wheat model.

	Durum Wheat (Iride cv)			**Common Wheat (Bologna cv)**		
	OBS	**TE SIM**	**GLUE SIM**	**OBS**	**TE SIM**	**GLUE SIM**
Mean	4.36	5.11	5.93	5.19	4.86	1.62
Standard deviation	1.69	2.35	3.23	2.25	2.00	0.64
Min	1.14	2.44	2.38	1.65	1.80	0.45
Max	7.92	10.73	16.19	7.98	7.89	2.52
N	30			20		
r		0.74 ***	0.74 ***		0.72 ***	0.64 **
R^2		0.55	0.55		0.52	0.41
RMSE		1.73	2.74		1.60	4.02
CRM		−0.17	−0.36		0.06	0.69
d-Index		0.80	0.68		0.84	0.50

** $p \leq 0.01$; *** $p \leq 0.001$; ns = not significant. OBS = observed values; TE SIM = simulated values with trial and error; GLUE SIM = simulated values with GLUE.

Table 13. Statistical results of observed (OBS) and simulated (SIM) values of grain yield (t ha^{-1}) of maize (Eleonora hybrid) for the evaluation of CSM-CERES-Maize model.

	Maize (Eleonora Hybrid)		
	OBS	**TE SIM**	**GLUE SIM**
Mean	10.70	10.36	9.47
Standard deviation	1.36	1.39	2.36
Min	7.29	8.07	6.13
Max	12.66	12.36	13.80
N	10		
r		0.65 **	0.50 *
R^2		0.43	0.25
RMSE		1.14	2.31
CRM		0.03	0.11
d-Index		0.80	0.58

* $p \leq 0.05$; ** $p \leq 0.01$; ns = not significant. OBS = observed values; TE SIM = simulated values with trial and error; GLUE SIM = simulated values with GLUE.

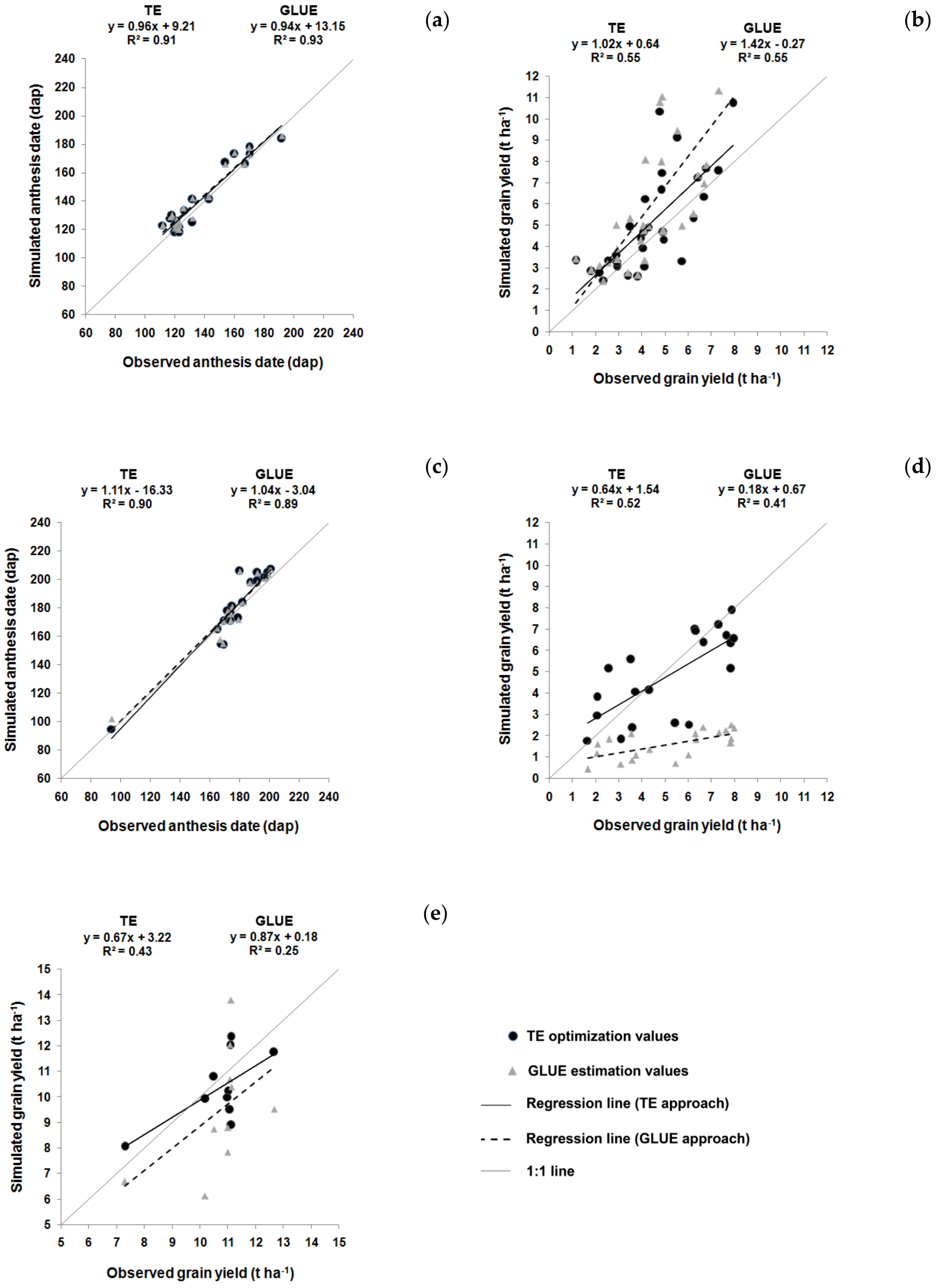

Figure 3. Evaluation results for anthesis date (**a**) and grain yield (**b**) of durum wheat (Iride cv), anthesis date (**c**) and grain yield (**d**) of common wheat (Bologna cv), and grain yield of maize (Eleonora hybrid) (**e**) with TE and GLUE methods.

4. Discussion

The results of this study offer a set of CSPs for CSM-CERES-Wheat and CSM-CERES-Maize, successfully tested over a large dataset of experimental observations for anthesis date and grain yield of durum and common wheat and grain yield of maize.

The optimized CSPs for durum and common wheat provide simulated values of anthesis date in good agreement with observations data for different Italian environments, both in calibration and evaluation tests, confirming the good performance of CSM-CERES-Wheat in predicting crop phenology. Similar results were reported in other studies [15,99]. The parameterization obtained with GLUE and TE methods shows comparable performances in reproducing anthesis date, while unsatisfactory results were obtained in reproducing crop yield using GLUE, especially for common wheat both in the calibration and evaluation tests. On the contrary, the adjustment of model parameters with the TE procedure allowed to obtain good model performances also in reproducing grain yield, both in the calibration and evaluation phases, although with lower accuracy than in reproducing crop phenology. This is explained by the high number of factors that influence variability in crop production, recorded from North to South Italy. Results for durum wheat show a slight tendency to underestimate the grain yield in model calibration and a low tendency to overestimate it in model evaluation. For common wheat, there is a slight tendency to underestimate grain yield in both calibration and evaluation. Regarding maize, simulated yields show good agreement with observed yields for the studied hybrid, particularly in model calibration with the TE procedure that showed a better model performance than GLUE in reproducing grain yields. The lower simulation performance in reproducing observed maize yields compared to wheat yields may be due to the lower availability of observed data used to optimize the CSPs of maize with respect to the number of the available data used to define the optimal set of CSPs of wheat.

The comparison between the CSPs obtained in this work for CSM-CERES-Wheat and CSM-CERES-Maize and those obtained in other studies for durum wheat, common wheat, and maize in Europe and the Mediterranean Basin [98–107] has only a limited value due to the differences in the scale of the analysis at which the parameterization was performed. There were differences in the characteristics of the cultivars and in the versions of the crop simulation models used. The results of the statistical analysis (e.g., d-Index or RMSE) of the model performances in reproducing field observations show results similar to, or even better than, those obtained in other studies [14,99,102,108]. The added value of this work is a robust parameterization of the CSM-CERES-Wheat and CSM-CERES-Maize models for three representative varieties of durum wheat, common wheat, and maize, performed over several Italian regions having a wide range of environmental conditions and management options. The parameterizations of CSM-CERES-Wheat and CSM-CERES-Maize models should be further evaluated if applied to simulate other aspects (e.g., date of physiological maturity, leaf area index, etc.) that were not tested in this study. Further improvement of model performance could result from including other experimental sites and additional information of environmental conditions, crop management, crop growth, and production. As in this study, the data used for model parameterization were not collected for crop modeling purposes and the lack of detailed and appropriate data may affect the model results [99,109,110].

5. Conclusions

The set of CSPs found for CSM-CERES-Wheat and CSM-CERES-Maize in this study confirm that the performances of the two crop models are good if applied in Mediterranean environmental conditions to predict phenology and yield of durum wheat, common wheat, and maize. Overall, the CSPs optimized with the TE method show higher performances, especially in reproducing grain yield, with respect to the set of CSPs obtained with GLUE. The set of CSPs optimized considering a wide range of meteoclimatic, pedological, and management conditions allowed to explore the interactions between genotype, environment, and crop management and produce robust parameterization to simulate anthesis date and grain yield of durum and common wheat, and maize grain yield. The derived set of CSPs may serve to further applications of the CSM-CERES-Wheat and CSM-CERES-Maize in geographical areas and for cultivars similar to those considered in this study, taking into consideration that the simulation of other model outputs, not evaluated in this study, require further assessments. The parameterized crop models may be applied to assess the effect of alternative management options on grain yield under the present climate conditions, seasonal forecasts, and/or future climate projections, to support farmers and policy makers in making operational, strategic and tactical decisions. Informing on the optimal agronomic practices is pivotal to help the decision-making process and drive the development of the agricultural sector in line with the principles of the climate-smart agriculture, to increase the adaptive capacity of system to cope with weather and climate hazards and make the agricultural sector more productive and sustainable.

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