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Sensitivity analysis of crop growth simulation model performance to crop and weather input data

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Abstract

Sensitivity analysis is a useful tool for understanding the model's mechanism. A sensitivity analysis of model determined the effect of input parameters on output parameter and it's necessary for model calibration and validation. This study focuse on investigation the permormance of WOFOST (World Food Studies) crop growth simulation model for determination of important Variable for model calibration. The model was run in potential production state for 11 years (2005-2016) with Qazvin station weather parameters. Crop and weather variables was changed in acceptable domain and variation of output was examined. Three of most important output was selected for sensitivity analysis. Total above grand production (TAGP), the total weight of storage organs (TWSO) and potential evapotranspiration (ETP) were investigated versus input parameters variation. The most effective variables on TAGP and TWSO were maximum leaf assimilation rate (AMAXTB), specific leaf area (SLATB), extinction coefficient for diffuse visible light (KDIFTB) in crop parameters and SLATB was most effective variables on ETP. TAGP and TWSO didn't have any sensitivity against wind speed and vapor pressure, but ETP has been sensitive toward all variables. The maximum sensitivity model in term of crop evapotranspiration is related to radiation. Maximum temperature and radiation change the TAGP up to 42 and 55.8 percent respectively. Based on the result the leaf expansion, light interception, assimilation and phenological parameters play key roles in the WOFOST model. This result aid in future model understanding and accuracy of model calibration.

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Introduction

Calibration is a demanding and critical step for using crop growth simulation models (Gilardelli *et al.*, 2018). It has been shown that application of a crop growth simulation model outside the domain for which it was developed and calibrated for, often leads to disappointing results (Kabat *et al.*, 1995). Before calibration understanding the model behavior versus each input variables is necessary. Sensitivity analysis is a helpful method for increasing the knowledge about model performance. WOFOST model is used in several research domain such as climate change (Gilardelli *et al.*, 2018), yield forecasting (Ma *et al.*, 2013), yield gap (Boogaard *et al.*, 2013) water stress (Kroes and Supit, 2011) and data assimilation (de Wit *et al.*, 2012; Gilardelli *et al.*, 2018; Huang *et al.*, 2015; Ma *et al.*, 2013). Therefore choosing the appropriated variables for calibration and measurement in the field is important for using of WOFOST applying.

Sensitivity analysis "SA" is a procedure to determine the effect of different value of input parameters on output parameters. Sensitivity analysis is used to find important and most effective variables on any model outputs. There are basically two general methods for sensitivity analysis, local and global methods. In the local methods, one input is varied and other inputs are kept fixed as default value. This method is used in several types of research because it is a quick and easy to use (Wang *et al.*, 2013). Another method is global sensitively analysis, which in this method the entire range of inputs are considered. There are many algorithms for global SA such as screening methods, regression-based methods, and variance-based methods (Confalonieri *et al.*, 2012).

Screening methods is based on calculation of elementary effects of each factor as well as their average, then estimating the total factor importance on the model outputs that are known as the Morris method(Campolongo *et al.*, 2007). Richtera *et al* (2010) used Morris method to yield formation of Durum wheat and prove that Morris is a reliable and effective method for determining effective and important parameters for model optimizing (Richtera *et al.*, 2010b).

Confalonieri *et al.* 2010 used Morris and Sobol sensitivity analysis methods for the rice model WARM in Europe in deferent climate and locations (Confalonieri *et al.*, 2010). Regression-based methods such as Latin Hypercube Sampling (LHS) Random and Quasi-Random LpTau is based on the computation of standard or partial regression coefficients. this method is assessing the effect of changing variables (Confalonieri *et al.*, 2012). Variance-based methods is used for computation of the variance of the output(s) into terms corresponding to the different inputs and their interactions (Marzban, 2013).

Sensitivity is a technique exploring model uncertainty as well as identifying the contribution of each parameter to the model response (Oakley and O'Hagan, 2004; Richtera *et al.*, 2010a).

Confalonieri *et al.* (2006) have assessed the sensitivity analysis of WOFOST for rice biomass simulations. Based on this research final biomass showed high variability toward the inputs especially CO_2 assimilation rates and partitioning coefficients was the most relevant.(Confalonieri *et al.*, 2006b).

Wang and *et al* used Fourier Amplitude Sensitivity Test method for WOFOST sensitivity analysis and show that some parameters don't have a direct effect on biomass but play a key role in certain stage through the plant growth. Farhadi and *et al.* (2009) survey the sensitivity of WOFOST model to daily solar radiation estimation methods and their result show that sensitivity analysis is necessary for model use and maximum deviation for winter barley and silage maize was 9% variability (Bansouleh *et al.*, 2009) Kanellopoulos *et al.* (2014) used the WOFOST model for climate change assessment in socio economic scenario for assessment the impact of climate change and socio-economic scenarios on arable farming system (Kanellopoulos *et al.*, 2014).

Sensitivity analysis can be helpful for improvement of model calibration and can be used as a guide for use of model. The aim of this research is to investigate the WOFOST model performance toward weather and crop variable variation of Qazvin plean.

Materials and methods

Model

The WOFOST model is a tool for assessing the crop growth and production under a wide range of weather and soil conditions. WOFOST model is used not only for crop production limitations such as light, moisture and macro-nutrients but also for estimate what improvement is possible. The WOFOST use plant physiology and environmental variables to simulation plant growth and calculation yield and dry matter production in potential and water and nutrient limitation (van Diepen *et al.*, 1989) Simulation of crop growth in WOFOST model is done based on weather parameters (temperature, sunshine, vapor pressure, wind speed, and rain) soil properties (moisture in field capacity (FC), wilting point (WP), hydraulic conductivity in saturation (k0) and soil depth) and crop physiological and phenological properties (Boogaard *et al.*, 2014). WOFOST model is used in CGMS1 for monitoring growth in regional and nationals scale. Model is linked to geographic system and related database for yield forecasting and crop state monitoring in several studies (Boogaardb *et al.*, 2013; KODEŠOVÁ1 and BRODSKÝ2, 2006; LAZAR *et al.*, 2009).

WOFOST is a dynamic model for simulation crop growth in daily rate and in three conditions, a Potential production that crop growth may be limited by light and temperature regime only. In this condition, water and nutrient supply are taken to be optimum. In water, limited production water supply may be limited in crop growth period while nutrient supply is taken to be optimum. The last model state is Nutrient limited production, in this model state in addition to water limitation, soil nutrient supply is also considered limiting factor for production (Ittersum and Rabbinge, 1997). In this research, based on literature survey (Bahman, 2009; Bansouleh *et al.*, 2009; Confalonieri *et al.*, 2006b; Vazifedoust, 2007) some of the more important parameters (crop, and weather) were chosen for sensitivity analysis (Table 1 and 2). Crop and weather variables: Table 1 and Table 2 Present the selected crop, weather variables for investigation the model behavior toward the increasing and decreasing trend of these variables. The WOFOST model was calibrated based of phonological date of field study and temperature sum from emergence to flowering (TSUM1) and for flowering to maturity (TSUM2) for barley which was calculated receptivity 780,800.

Table 1. Crop parameters for sensitivity analysis.

Parameter	Unit	Rang	Default Value	Description
SLATB	Ha/kg	0.00070- 0.00420	0 0.3 0.9 1.45 2 0.002 0.0035 0.0025 0.0022 0.0022	Specific leaf area as a function of DVS
KDIFTB	-	0.44- 1.0	0 2 0.44 0.44	extinction coefficient for diffuse visible light as a function of DVS
EFFTB	kg /(ha hr)	0.4-0.5	0 40 0.4 0.4	light-use efficiency, single leaf as function of daily mean temp.
AMAXTB	kg/(ha.hr)	1-70	0 1.2 2 35 35 5	maximum leaf CO2 assimilation as function of DVS
span	days	17-50	25	life span of leaves growing at 35 Celsius
TDWI	Kg/ha	0.5-300	150	Initial total crop dry weight
CFET	-	0.8-1.2	1.19	Correction factor for evapotranspiration in relation to the reference crop
RGRLAI	Ha/(ha.d)	0.007-0.5	0.0075	Maximum relative increase in LAI
TSUM1	°C/d	150-1050	1123	Thermal time from emergence to anthesis
TSUM2	°C/d	600-1550	893	Thermal time from anthesis to maturity

Table 2. Weather parameters for sensitivity analysis.

Parameter	Unit	Default value
minimum temperature	°c	Weather station reports
maximum temperature	°c	Weather station reports
vapor pressure	KPa	Weather station reports
mean wind speed	m/ s	Weather station reports
precipitation	Mm/ d	Weather station reports
irradiation	kJ /(m d)	Weather station reports

Stady area

The study area is Qazvin plain that located in the north-west of Iran (Fig. 1). QAZVIN station is located in 36 15N and 50 3E and in 1279.2 meter elevation from the sea surface. Mean annual precipitation and average of minimum and maximum temperature during the years 1987 until 2003, was 210mm, 2 and 18°C, respectively. In this study daily weather parameters of Qazvin station were used (2000-2011).

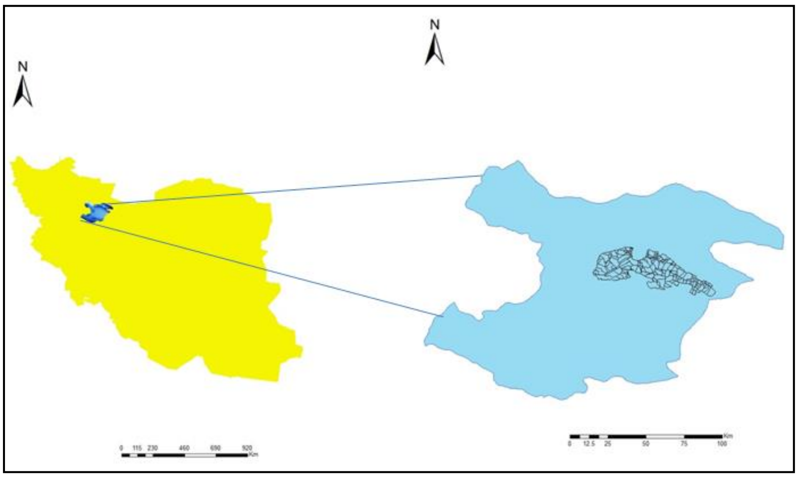

Fig. 1. The study area (The location of Qazvin province and Qazvin plain in Iran).

Sensitivity analysis

Sensitivity analysis was done based on the variation of one variable in time. Variation was done based on the acceptable domain of each variable for the model. The model was run for winter barley with Qazvin daily weather parameters. For investigating the impact of variables changing to outputs The WOFOST model was run in increasing and decreasing trend of variables. In increasing Trent The variables were changed between +10% to +50% with 10% steps and in decreasing trend changing was done between -10% to -50% with -10% steps. The trend has been stopped upon some variables got out of range of acceptablity.

There are some exception because 10% cause to high values for some variables. TSUM1 and TSUM 2 was change in -10% to +10% domain with 2% steps and for CEFT between +10% to -10% with 5% steps.

Total above ground production (TAGP), the total weight of storage organ (TWSO) and potential evapotranspiration (ETP) was selected for monitoring the variation in output parameters.

Sensitivity index (SI)

The equation for sensitivity index is Absolute Sensitivity. This question is for linearized sensitivity equation, can be used "rate of change in one factor with respect to change in another factor" that can show the linearized sensitivity.

$$SI = \frac{(O_2 - O_1)}{(I_2 - I_1)}$$

Where $O_2 - O_1$ is the change in model output for a change in model input $I_2 - I_1$.(QUINTON, 1994). Sensitivity index was calculated for Biomass, crop yield and evapotranspiration versus such input variables.

Results

Crop variables

Sensitivity analysis of crop variables measured by TAGP shows the result of sensitivity analysis for crop variables measured by TAGP. Table 3, present the sensitivity index (SI) of TAGP, TWSO and ETP against crop variables variation.

Model has different behavior with variables variation. SLATB, KDIFTB and AMAXTB have most effective parameters on TAGP variation. TAGP values are between 1800-2300 kg/ha including any outliers but actual maximum and minimum are 7500 and 23000kg/ha respectively (Fig. 3). Outliers are the result of -50% SLATB variations that is more than ±1.5 interquartile range. The distribution is skewed left because most of the observations are concentrated on the low end of the scale. All TAGP values are less than normal run (without any variation in output) but in positive variation (+10 to +40%) TAGP variation has an upward tendency with low slope but in negative variation (-10% to -50%) present a downward tendency but with a slop higher than upward (Fig. 2.A). SI for SLATB is 1.03 that confirms the model sensitivity to this variable.

Table 3. Sensitivity analysis index (SI) of output for crop variables.

Variables	TAGP	TWSO	ETP
SLATB	0.55	0.43	0.44
KDIFTB	0.70	0.56	0.21
SPAN	1	0.51	0.41
TDWI	0.79	0.01	0.09
EFFTB	0.72	0.67	0.14
RGRLAI	0.05	6.58	0.09
AMAXTB	0.75	0.13	0.75
TSUM1	0.59	0.78	0.83
TSUM2	0.32	0.48	0.22

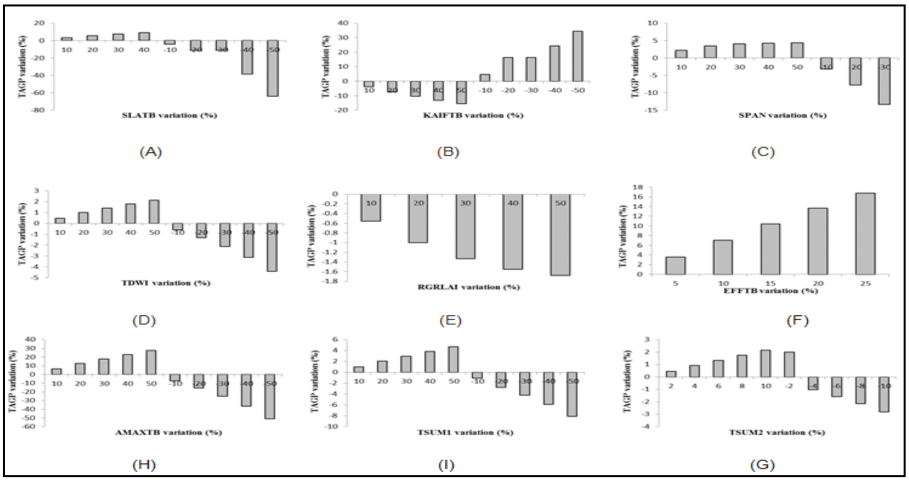

Fig. 2. TAGP variation versus variation of crop parameters (%).

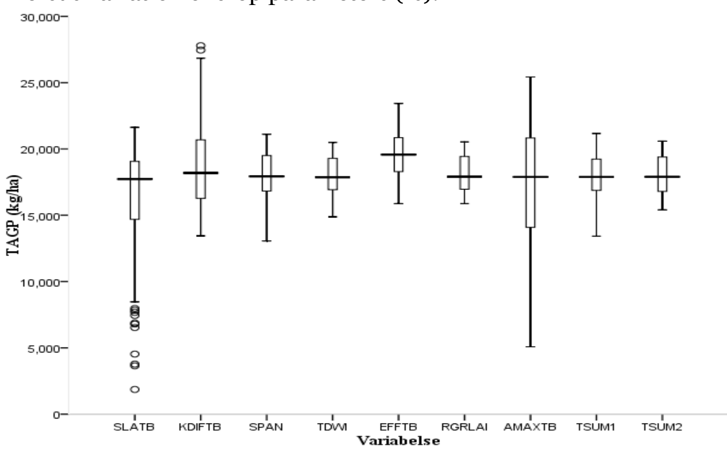

Fig. 3. Distribution of TAGP versus crop variable variation.

KDIFTB has changed TAGP with right skewed with 0.7 for sensitivity index (SI) (Fig.3). Model is more sensitive against to decreasing the KDIFTB values because the slope of increasing trend higher than decreasing trend (Fig. 2.B).

TAGP has same behavior toward variation of SPAN but with SI=1 (Table 3 and Fig. 2). TAGP has a normal distribution with TDWI variation (The middle half of a data set falls within the interquartile range). One of the data was considered as the outlier that is output in 2012-2013 without any variation in input. SI was achieved 0.79 for this parameter and it is shown moderate model sensitivity versus TDWI. Distribution of TAGP within EFFTB variation is approximately same as TDWI but with higher values and left skewed (Fig.2). TAGP has right skewed with RGRLAI variation (Fig. 2.E) .The model SI was achieved 0.05 that present the low model sensitivity versus these variables.

The highest variation for TAGP is occurred with AMAXTB variation with 0.76 for SI. TAGP variation is between 8200-28700 kg/ha with a little right skewed. TAGP has increasing trend with positive variation and vice versa for negative variation. Model behavior against TSUM1 and TSUM2 is different although median (of the cross line in the middle) is same for this variation. TAGP variations have right skewed while TSUM2 has normal distribution. Model SI for these variables was achieved 0.62 and .32 for TSUM1 and TSUM2 respectively.

Sensitivity analysis of crop variables measured by TWSO:

Fig. 4 shows the behavior of total weight of storage organ vesus crop variable variation and Fig. 5 represents the wariation of this parameter toward variable variation. TWSO is more sensitive against to decreasing the KDIFTB values because the slope of increasing trend higher than decreasing trend. Distribution of TWSO values is normal with 0.44 value for SI. Maximum variation for increasing SLATB is 6% while for negative variation is 58% of default value.

TWSO sensitivity is moderate (SI=0.56) and with right skewed distribution versus variation of KDIFTB (Table 4 and Fig. 4). Maximum vaiation in TWSO is 42% with half of default value for EFFTB. SNAP variation has made a normal distribution of TWSO with 0.51 for sensitivity index. While Maximum variation was achieved 24% for -50% variation in the span (Fig. 4.C).

Model has very low Sensitivity toward RGRLAI and TWSO variations with SI= 0.02 and 0.07 respectivity. TWSO distribution with variation in AMAXTB has the high value compare with other variables with normal distribution. Model sensitivity for decreasing pattern is more than increasing pattern of AMAXTB. SI value for these variables is 0.75 that shows the high sensitivity of TWSO toward AMAXTB variables.

TWSO shows approximately same behavior with TSUM1 and TSUM2 variation but outlets for TSUM1 is for 2012-2013 but for TSUM2 2010-2011. TWSO has normal and left skewed distribution for TSUM1 and TSUM2 variations.SI is 0.48 and 0.79 for TSUM1 and TSUM2 respectively that shows TWSO is more sensitivity toward TSUM2. Fig 4.H and Fig 4. I confirm this because maximum variation with TSUM1 variation is 10% while for TSUM2 is around 6 percent.

Sensitivity analysis of crop variables measured by ETP

Fig.6 and Fig.7 show the behavior of ETP against crop variables variation. Based on the results SLATB cause the highest variation of ETP. ETP has varied between 211-510mm with left skewed and 0.44 value for SI. Outlets appear when SLATB decreased until 50% of difult value. ETP sensitivity for reducing the SLATB is more than increasing (42% for 50% reducing). Variation has right skewed and SI index was calculated 0.21 for KADIFTB variation and same as previous variables modle sensitivity versus decreasing trend is more than the inversing trend. One of important variable that effected on ETP is SPAN .SI index for this variable is ached 0.41 .Variation domain is same as KDIFTB but with more values and left skewed and one outlet for -50% in 2010 -2011. Variation percent is maximum 9% and -20% for increasing trend.

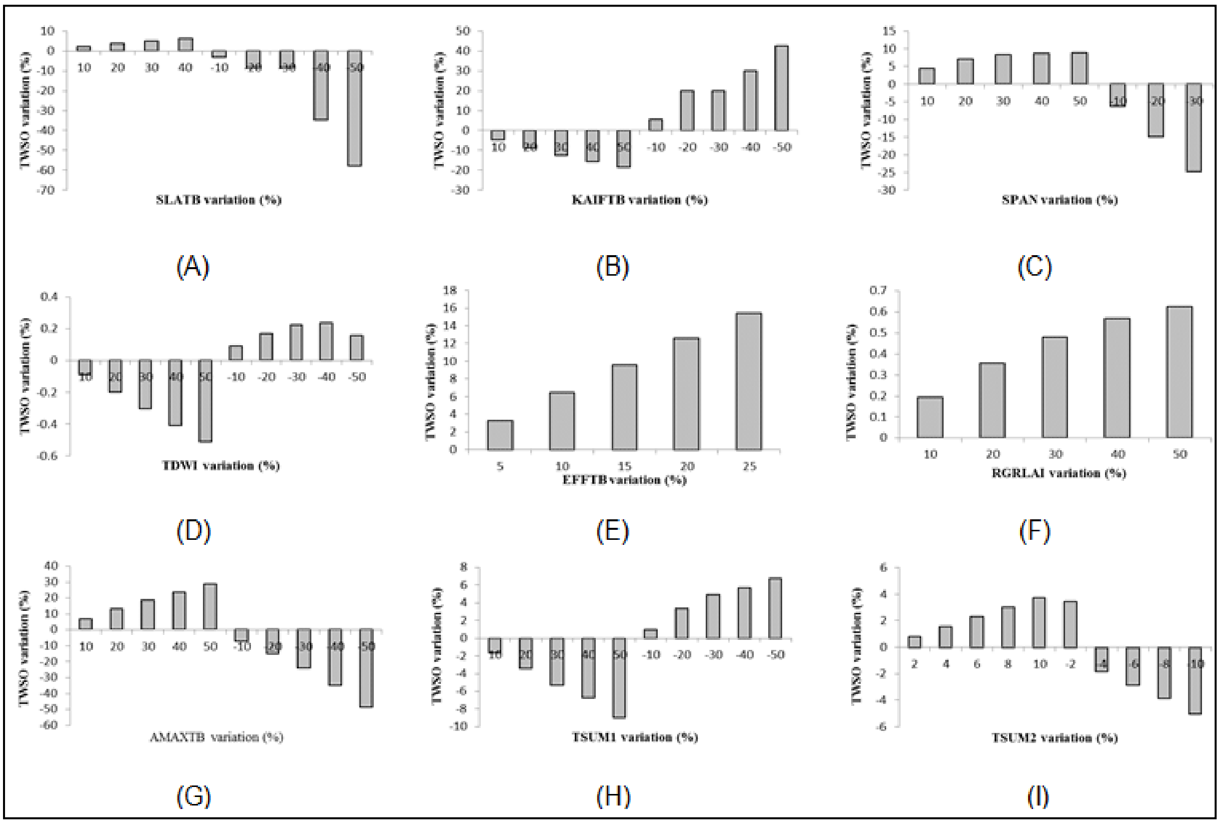

Fig. 4. TWSO variation versus crop variation (%).

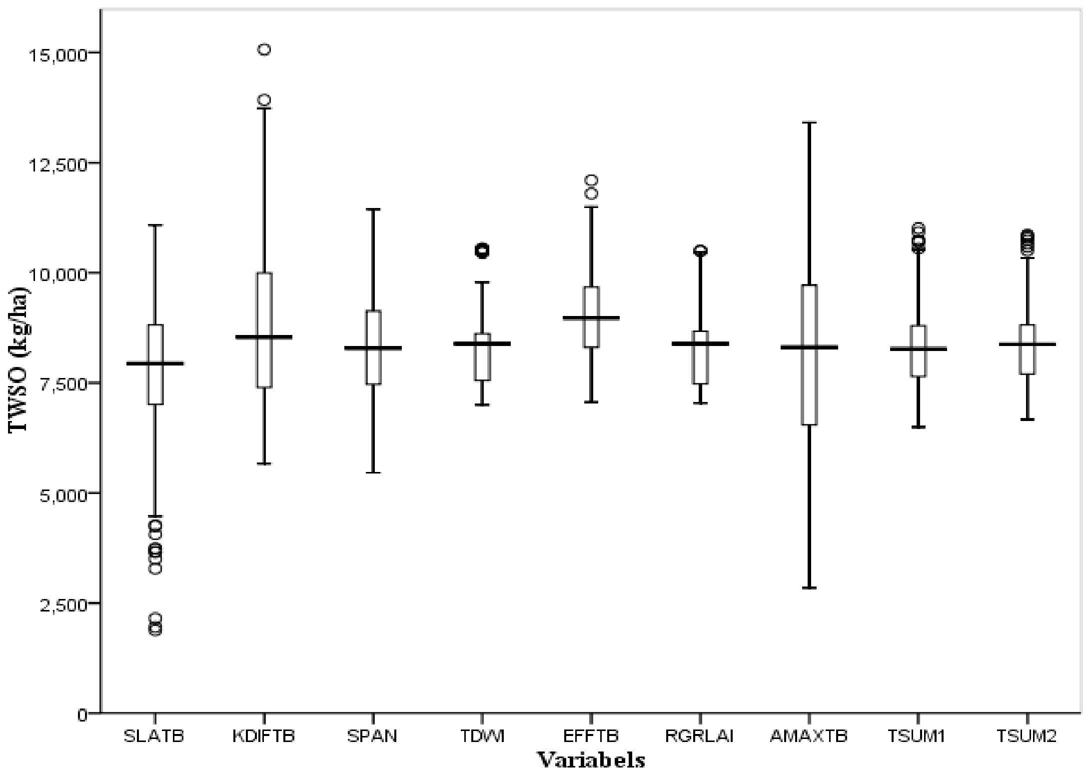

Fig. 5. Distribution of TWSO versus crop variable variation.

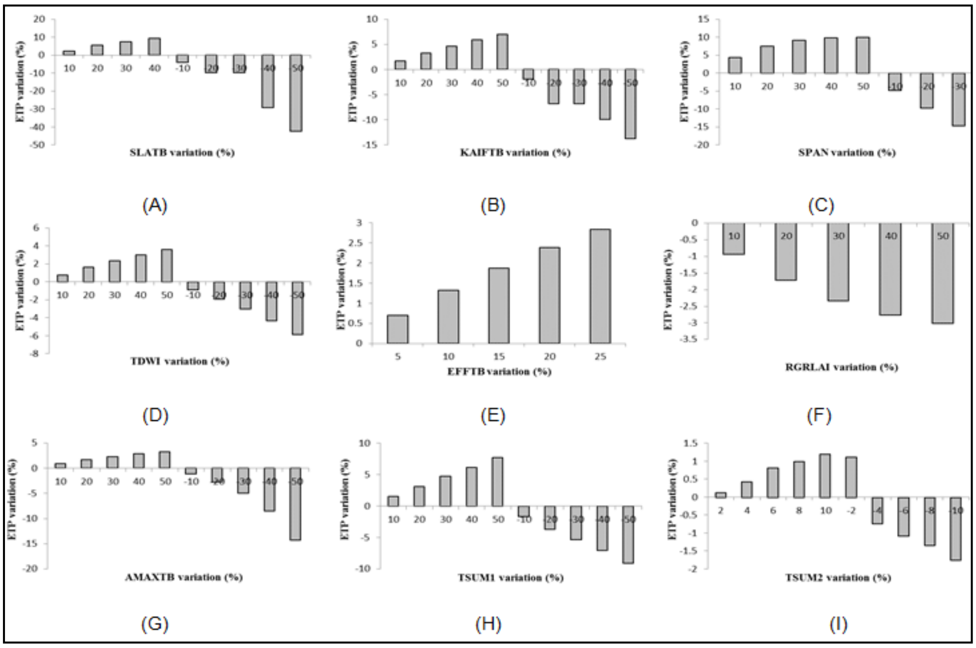

Fig. 6. ETP variation versus crop variation (%).

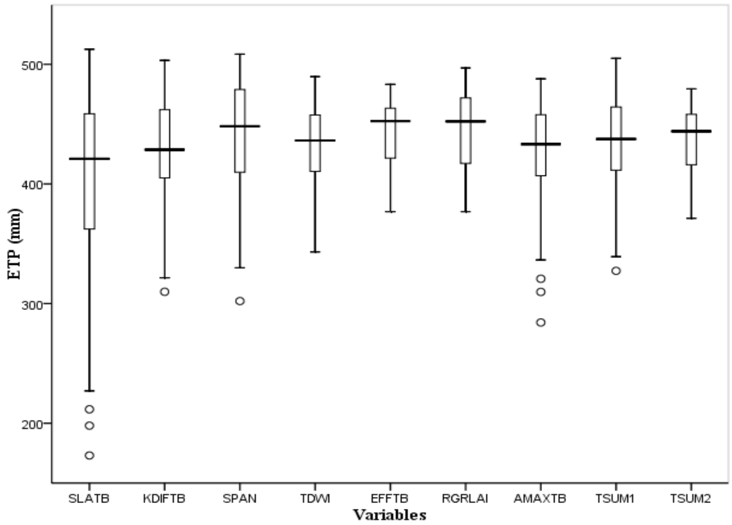

Fig. 7. Distribution of ETP versus crop variable variation.

ETP values have left skewed variation against TDWI and EFFTB and right skewed RGRLAI variation. SI index for these variables are 0.09, 0.14 and 0.1 that confirmed model sensitivity toward EFFTB values. As it is shown in Fig. 6.D ETP is varied maximum 3.6 and 5.9% for increased and decreasing trend of TDWI while EFFTB change ETP up to 2.8% with 25% changing Fig.6.I. AMAXTB cause a left skewed distribution for ETP with outlets that are effect of -50% variations in AMAXTB.

SI index of ETP values was calculate 0.13 for this variable and maximum present of variation are 3 and 14 present for increasing and decreasing trend of this variable. TSUM1 and TSUM2 show a different effect on ETP values. Both of them have left skewed but different distribution. SI was achieved 0.83 and 0.23 for TSUM1 and TSUM. Fig. 6.H and Fig. 6.I shows maximum 7.7 and 9% variation in ETP values for increasing and decreasing trend. Maximum variation for TSUM 2 is 1.1-1.7% that confirms the low sensitivity of ETP toward TSUM2.

Weather variables

Sensitivity analysis of weather variables measured by TAGP:

In this part the effect of weather input model was investigated on outputs (TAGP, TWSO, and ETP). Variation of rainfall was ignored because the model was run in the potential situation. Minimum temperature (Tmin), maximum (Tmax), vapor pressure, radiation and wind speed that Was varied between 10 to 50 percent in increasing trend (with 10% steps) and -10 to -50 percent (with -10% steps). Fig.8 and Fig.9 show the impact of input variables variation on TAGP. Based on result vapor pressure and wind speed didn't have any effect on TAGP. TAGP has a right-skewed distribution of Tmin. There are two outlets and one extreme point on the chart. These values are related to 30, 40 and 50 percent increase in Tmin and all occur in 2015-2016. The extreme point represents those values more than three times the height of the boxes. In these cases, the mean is greater than the median and the greater mean is caused by these outliers. Based on result, TAGP show decreasing with increasing (maximum 8.7%) Tmin values and vice versa for decreasing values (maximum 5.5%).

TAGP distribution with Tmax variation is high in comparison with Tmin. Fig.8.B is confirmed the high sensitivity of TAGP toward Tmax values and represent a trend same as Tmin. Distribution of TAGP for radiation variation is between 4800-22500 kg/ha with right skewed. As it is clear in Fig 8.C model sensitivity toward increasing trend of variations (maximum 11.7) is very lower than decreasing trend (maximum 55.8%)

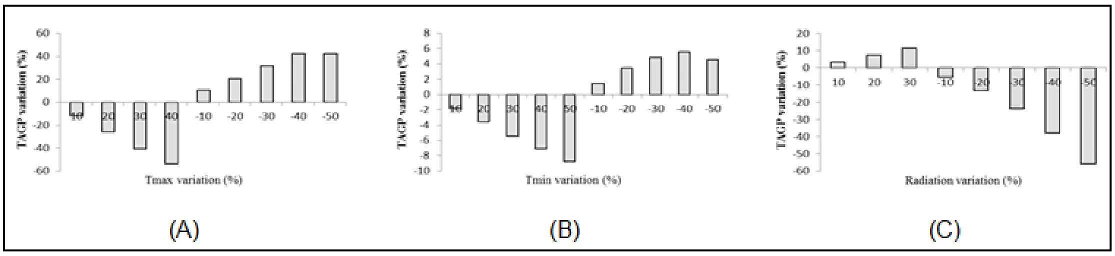

Fig. 8. TAGP variation versus weather variation (%).

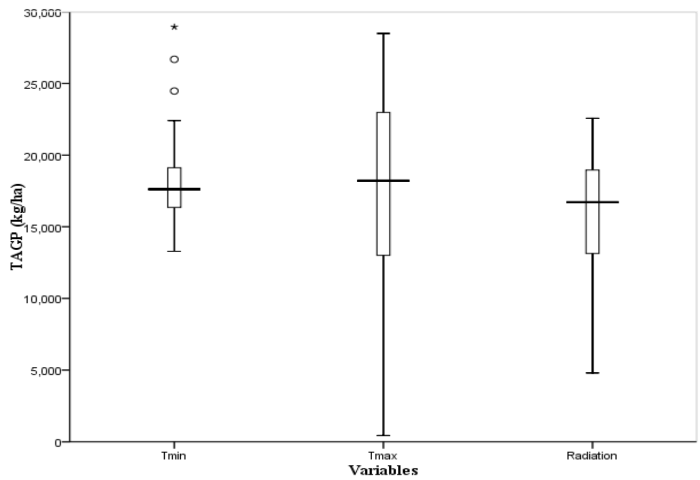

Fig. 9. Distribution of TAGP versus weather variable variation.

Sensitivity analysis of weather variables measured by TWSO:

As it is shown in Fig.11 TWSO behavior is different for each variable. Tmin variation created a right-skewed distribution for TWSO. It is decracing maximum 14% for increasing trend of Tmin and 18% for decreasing trend. TWSO variation in the result of Tmax variation has right-skewed distribution. Outlets and extreme are the result of 40% increase in Tmax values that decreasing 44% of TWSO (Fig. 10.B) while for increasing trend the TWSO variation increasing with a mild slope up to 16.5%. Variation of TWSO values has a normal distribution and with unlike trend of other weather parameters because it has increasing trend for positive variation and decreasing trend with negative variation (Fig. 11).

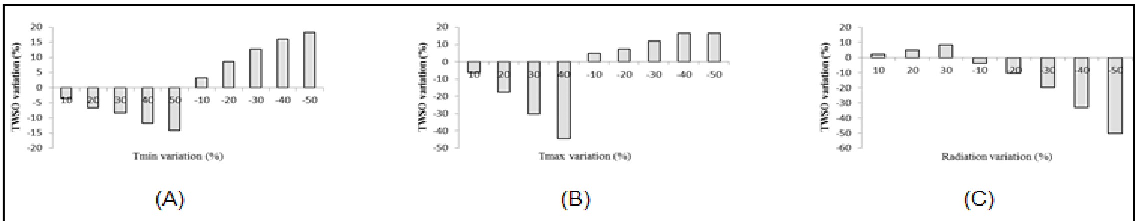

Fig. 10. TWSO variation versus weather variation (%).

Fig. 10. TWSO variation versus weather variation (%).

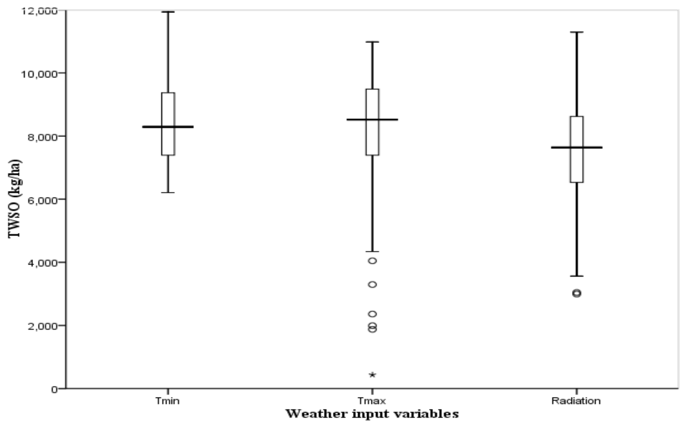

Fig. 11. Distribution of TWSO versus weather variable variation.

Sensitivity analysis of weather variables measured by ETP:

TAGP and TWSO didn't have any sensitivity against wind speed and vapor pressure but ETP has been sensitive toward all variables. The maximum sensitivity model in term of crop evapotranspiration is related to radiation. ETP is varied between 212-547 mm with right-skewed. Tmax variation was changing ETP in increasing trend maximum -24% and 17% in discerning trend. Tmin causes a left-skewed distribution with maximum-3.58 and 3.38 % variation for increasing and decreasing trend of Tmin. ETP distribution is same for wind speed and vapor pressure. Wind speed has direct effect on ETP. In increasing trend of wind speed maximum ETP variation is 10% while in decreasing trend is -12% (Fig. 12. A).

The percent of vapor pressure is -11% and 11% for increasing and decreasing trend of Vapor pressure (Fig. 12.C).

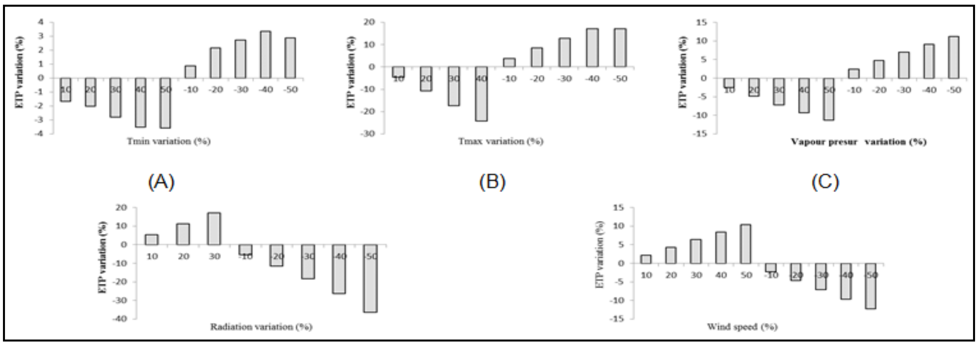

Fig. 12. ETP variation versus weather variation (%).

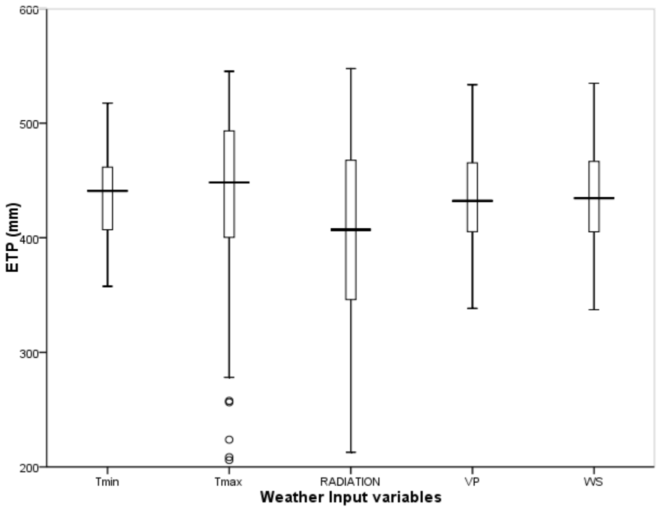

Fig. 13. Distribution of ETP versus weather variable variation.

Discussion

Sensitivity of Crop growth simulation model (WOFOST) was investigated toward weather and crop input variables. Model showed different behavior with variation of each variable. TAGP have the highest sensitivity to AMAXTB and SLATB in crop parameters and highest range for SLATB generates outlets values .Median of TAGP values is same for all crop variables except SLATB and EFFTB but the distribution of variables was different (Fig.2 and Fig.3). The result of Confalonieri et at showed that AMAXTB is one of the most important variables in initial and final stage of crop growth period (Confalonieri *et al.*, 2006a).

Model behavior in term of TWSO is a little different. TWSO was sensitive to AMAXTB, SLATB, KDIFTB and SPAN.AMAXTB generated the highest variation for TWSO. AMAXTB show the highest effect on TWSO and TAGP because its present the Maximum leaf CO_2 assimilation rate as a function of development stage of the crop that it has a direct effect on dray matter production.This result is agree with the result of Gilardelli and *et al* (2018) results. ETP values were sensitive to parameter that depended on leaf properties. The highest effective variable is SLATB that is present the specific leaf area as a function of development stage that this variable shows the evapotranspiration surface. KDIFTB that present extinction coefficient for diffuse visible light and SPAN present the life span of leaves growing at 35 Celsius that these variables have almost same effect on ETP. TSUM1 had more effect on ETP because maximum leaf area index occur near flowering and TSUM1 indicate duration between emergences to flowering.

In the next step sensitivity of mode investigated versus weather parameters input as well. Model was run in potential condition so rain variation hadn't any effect on model output because in the potential situation model assume that soil moister is in field capacity level. TAGP had highest sensitivity versus Tmax variation and this variables change the TAGP value up to -53.7% and 42% increasing and decreasing trend. TAGP had -56.7% reductions when radiation was reduced 50% of initial values. Distribution for TWSO followed the TAGP pattern but with lower values but high variation cause outlets and extreme point.

All weather variables are included in ETP variation. As it is expected TMAX and radiation have the most effect on ETP values based on energy balance. TMAX contain outlets that are the result of high value of TMAX. Vapor pressure and wind speed cause same distribution for ETP. As it is showen in this research some parameters play a key role in the final yield output and its changing make significant uncertainity in final yield .Other variables maybe have impact on other satage of crop growth (Wang *et al.*, 2013).

Based on the result the leaf expansion, light interception, assimilation and phenological parameters play key roles in the WOFOST model.

Base on the result of this research model calibration should be done with consideration the sensitivity of model to each parameter. The Model have uncertainty for input variables but its height for some of them so, the various roles of the models and parameters must be considered and this result aid in future model understanding. Therefore data measurements should be done with high accuracy and model should run for several years for minimizing that model uncertainty toward weather input variables.

References

Bahman FB. 2009. Development of a spatial planning support system for agricultural policy formulation related to land and water resources in Borkhar & Meymeh district, Iran. Phd Thesis Wageningen University,Netherland **279.**

Bansouleh BF, Sharifi MA, Keulen HV. 2009. Sensitivity analysis of performance of crop growth simulation models to daily solar radiation estimation methods in Iran.Energy Conversion and Management **50,** 2826–2836. https://doi.org/10.1016/j.enconman.2009.06.028.

Boogaard H, Wolf J, Supit I, Niemeyer S, van Ittersum M. 2013. A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union. Field Crops Research **143,** 130-142. https://doi.org/10.1016/j.fcr.2012.11.005.

Boogaard H, Wit AJWD, Roller JAT, Diepen CAV. 2014. User's guide for the WOFOST Control Centre 2.1 and WOFOST 7.1.7 crop growth simulation model. Alterra, Wageningen University & Research Centre,Wageningen p. 133.

Campolongo F, Cariboni J, Saltelli A. 2007. An effective screening design for sensitivity analysis of large models. Environmental Modelling & Software **22**, 1509-1518. https://doi.org/10.1016/j.envsoft.2006.10.004.

Confalonieri R, Acutis, M, Bellocchi G, Iacopo Cerrani, Tarantola S, Donatelli M, Genovese G. 2006. Exploratory Sensitivity Analysis Of Cropsyst, Warm And Wofost: A Case-Study With Rice Biomass Simulations.Italian Journal of Agrometeorology **17,** 17-25. DOI: 10.1.1.565.3007&REP=REP1&TYPE=PDF.

Confalonieri R, Acutis M, Bellocchi G, Iacopo Cerrani1, Tarantola S, Donatelli M, Genovese G. 2006b. Exploratory Sensitivity Analysis Of Cropsyst, Warm and Wofost: A Case-Study With Rice Biomass Simulations. Italian Journal of Agrometeorology **17,** 17-25.

Confalonieri R, Bellocchi G, Tarantola S, Acutis M, Donatelli M, Genovese G. 2010. Sensitivity analysis of the rice model WARM in Europe: Exploring the effects of different locations, climates and methods of analysis on model sensitivity to crop parameters. Environmental Modelling & Software **25,** 479-488. https://doi.org/10.1016/j.envsoft.2009.10.005.

Confalonieri R, Bregaglio S, Cappelli G, Francone C, Carpani M, Acutis M, Zhiming W. 2012. Sensitivity Analysis Report Reference.E-AGRI_D32.1_Sensitivity analysis report _1.0, E-AGRI_D34.1, p. 479-488.

De Wit A, Duveiller G, Defourny P. 2012. Estimating regional winter wheat yield with WOFOST through the assimilation of green area index retrieved from MODIS observations. Agricultural and Forest Meteorology **164,** 39-52.

Gilardelli C, Confalonieri R, Cappelli GA, Bellocchi G. 2018. Sensitivity of WOFOST-based modelling solutions to crop parameters under climate change. Ecological Modelling **368,** 1-14. https://doi.org/10.1016/j.ecolmodel.2017.11.003.

Huang J, Tian L, Liang S, Ma H, Becker-Reshef I, Huang Y, Su W, Zhang X, Zhu D, Wu W. 2015. Improving winter wheat yield estimation by assimilation of the leaf area index from Landsat TM and MODIS data into the WOFOST model. Agricultural and Forest Meteorology **204,** 106-121. https://doi.org/10.1016/j.agrformet.2015.02.001.

Ittersum MKV, Rabbinge R. 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations .Field Crops Research **52,** 197-208.
https://doi.org/10.1016/S0378-4290(97)00037-3

Kabat P, Marshall B, Broek BJVD, Vos J, KeulenHV. 1995. Modelling and parameterization of the soil-plant-atmosphere system; a comparison of potato growth models," Wageningen Pers, Wageningen.

Kanellopoulos A, Reidsma P, Wolf J, van Ittersum MK. 2014. Assessing climate change and associated socio-economic scenarios for arable farming in the Netherlands: An application of benchmarking and bio-economic farm modelling. European Journal of Agronomy **52,** 69-80. https://doi.org/10.1016/j.eja.2013.10.003.

Kodešová1 R, Brodský2 L. 2006. Comparison of CGMS-WOFOST and HYDRUS-1D Simulation Results for One Cell of CGMS-GRID50. Soil & Water Research **2,** 39-48. 10.17221/6504-SWR.

Kroes JG, Supit I. 2011. Impact analysis of drought, water excess and salinity on grass production in The Netherlands using historical and future climate data. Agriculture, Ecosystems & Environment **144,** 370-381. https://doi.org/10.1016/j.agee.2011.09.008.

Lazar C, Baruth B, Micale F, Lazar DA. 2009. Adaptation of Wofost Model From Cgms To Romanian Conditions. Plant Develop **16,** 97-102.

Ma G, Huang J, Wu W, Fan J, Zou J, Wu S. 2013. Assimilation of MODIS-LAI into the WOFOST model for forecasting regional winter wheat yield. Mathematical and Computer Modelling **58,** 634-643.

Marzban C. 2013. Variance-Based Sensitivity Analysis: An Illustration on the Lorenz'63 Model. Monthly Weather Review **141,** 4069-4079. https://doi.org/10.1016/j.mcm.2011.10.038.

Oakley JE, O'Hagan A. 2004. Probabilistic sensitivity analysis of complex models:a Bayesian approach.Journal of the Royal Statistical Society: Series B (Statistical Methodology) **66,** 751-769. https://doi.org/10.1111/j.1467-9868.2004.05304.x

Quinton JN. 1994. the validation of physically based erosion models with particular reference to eurosem. Phd thesis cranfield university 46-53.

Richtera GM, Acutisb M, Trevisiol P, Latiri K, Confalonierib R. 2010. Sensitivity analysis for a complex crop model applied to Durum wheat in the Mediterranean.European Journal of Agronomy **32,** 127-136.
https://doi.org/10.1016/j.eja.2009.09.002.

Van Diepen CA, Wolf J, van Keulen H, Rappoldt C. 1989. WOFOST: a simulation model of crop production. Soil Use and Management **5,** 16-24. https://doi.org/10.1111/j.1475-2743.1989.tb00755.x.

Vazifedoust M. 2007. Development of an agricultural drought assessment system (Integration of agrohydrological modelling, remote sensing and geographical information). Phd Thesis Wageningen University, Netherland 171.

Wang J, Li X, Lu L, Fang F. 2013. Parameter sensitivity analysis of crop growth models based on the extended Fourier Amplitude Sensitivity Test method. Environmental Modelling & Software **48,** 171-182. https://doi.org/10.1016/j.envsoft.2013.06.007.