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Global sensitivity analysis of yield output from the water productivity model

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ABSTRACT

This study includes a global sensitivity analysis of the water productivity model AquaCrop. The study rationale consisted in a comprehensive evaluation of the model and the formulation of guidelines for model simplification and efficient calibration. The global analysis comprehended a Morris screening followed by a variance-based Extended Fourier Amplitude Sensitivity Test (EFAST) under diverse environmental conditions for maize, winter wheat and rice. The analysis involved twenty-two different climate-crop-soil-meteorology combinations. The main objectives were to distinguish the model's influential and non-influential parameters, and to examine the yield output sensitivity. For the AquaCrop model, a number of non-influential parameters could be identified. Making these parameters fixed would be a step towards model simplification. Also, a list of influential parameters was identified. Despite the dependence of parameter ranking on environmental conditions, guiding principles for priority parameters were formulated for calibration in diverse conditions, valuable to model users. For this model that focuses on modelling yield response to water, parameters describing crop responses to water stress were not often among those showing highest sensitivity. Instead, particular root and soil parameters, relevant in the determination of water availability, were influential under various conditions and merit attention during calibration. The considerations made in this study about sensitivity analysis method (Morris vs. EFAST), prior parameter ranges, target functions and ranking variation according to environmental conditions can be extrapolated to other conditions and models, if done with the necessary precaution.

1. Introduction

To understand the interplay between environmental and management conditions and crop growth, models are appropriate tools, more than ever in relation to global changes. Being a mathematical representation of natural processes, the model's equations and parameterization inevitably entail assumptions and simplifications of reality, which leads to output uncertainty and inaccuracy (Saltelli et al., 2000). A sensitivity analysis (SA) quantifies the influence of each uncertain factor (parameter or driving variable) on the model's output variability and is a key step in understanding the model behaviour in response to changes in these factors (Cariboni et al., 2007; Confalonieri et al., 2010a). The SA is useful to identify (i) low-impact parameters that may be converted to fixed values to simplify the model, (ii) high-impact parameters to concentrate on during calibration or guide management strategies and agriculture policy, and (iii) model imbalance when few parameters have a relevance that is significantly higher than others (Cariboni et al., 2007; Confalonieri, 2010; Refsgaard et al., 2007). Subjection of crop models to global SA is essential (Jakeman et al., 2006), yet not common practice and if done often limited to a few parameters or one climate-year setting (Confalonieri, 2010; Confalonieri et al., 2010a; Makowski et al., 2006; Richter et al., 2010). SA results depend on environmental conditions for which the model is run, such as different climate regions, soil types and dry-normal-wet precipitation conditions. Thus, altering the environmental conditions is crucial to examine the model's general sensitivity (Confalonieri et al., 2010a, 2010b).

Abbreviations: (E)FAST, (Extended) Fourier Amplitude Sensitivity Test; *ETo*, reference evapotranspiration; GDD, growing degree days; SA, sensitivity analysis; TAW, total available water content of the soil.

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Typically, local and global SA techniques are distinguished (Cariboni et al., 2007; Saltelli et al., 2000). A local SA investigates the effect of changes in one parameter on the model output while all the other parameters are fixed to an arbitrary value (Cariboni et al., 2007). Local methods are criticized for being unsuitable for non-linear models (Saltelli and Annoni, 2010). A global SA examines the average response of the model output when all parameters are varied within a defined range. This powerful technique considers parameter interactions or non-linear responses but requires repeated model evaluations for parameter values varying over the parameter space and is thus computationally demanding (Cariboni et al., 2007; Elsawwaf et al., 2010; Saltelli et al., 2000). Different global SA techniques exist, among which screening methods and variance-based methods that were used in this study. The screening method proposed by Morris (1991) identifies a limited set of influential parameters among all model parameters. A variance-based method decomposes the model output variance according to the influence of each contributing parameter (Cariboni et al., 2007; Willems, 2012). It determines not only the individual effect of a parameter but also quantifies potential interactions among parameters. Different techniques within the variance-based methods distinguish themselves by the way the parameter space is sampled.

In this study, a global SA was conducted for the first time for the process-based, multi-crop simulation model, AquaCrop, assuming diverse environmental conditions. The model has been validated for different crops in diverse environments (e.g. Geerts et al., 2009; Heng et al., 2009; Hsiao et al., 2009; Tsegay et al., 2012) and is broadly used to develop (deficit) irrigation schemes or management strategies to improve food security (e.g. Abrha et al., 2012; Andarzian et al., 2011; Zinyengere et al., 2011; Shrestha et al., 2013) but a global SA has not yet been performed. The objectives of this study were (i) to distinguish influential and non-influential model parameters and (ii) to examine the yield output sensitivity of the AquaCrop model to changes in crop and soil parameters for three important crops (maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.)) in diverse environments and under a variety of meteorological conditions. The identification of influential parameters contributes to recognize important parameters for model calibration. The identification of non-influential parameters contributes to recognize parameters that can be fixed for model simplification.

Table 1
Crop and soil parameters of the AquaCrop model considered in the SA.

	Description	Units
CROP PARAMETERS		
Canopy and phaenological development		
mat	Total length of crop cycle from sowing to maturity	Growing degree days (GDD)
eme	Period from sowing to emergence	GDD
ccs	Soil surface covered by an individual seedling at 90% emergence	cm^2
den	Number of plants per hectare	–
cgc	Increase in canopy cover	Fraction GDD^{-1}
ccx	Maximum canopy cover	Fraction of 1
sen	Period from sowing to start senescence	GDD
cdc	Decrease in canopy cover	Fraction GDD^{-1}
hilen	Period of harvest index building-up during yield formation	GDD
flo	Period from sowing to flowering	GDD
flolen	Length of flowering	GDD
Root development		
root	Period from sowing to maximum rooting depth	GDD
rtx	Maximum effective rooting depth	m
rtshp	Shape factor describing root zone expansion	–
rtexup	Maximum root water extraction in top quarter of root zone	m^3 m^{-3} soil d^{-1}
rtexlw	Maximum root water extraction in bottom quarter of root zone	m^3 m^{-3} soil d^{-1}
Transpiration		
kc	Crop coefficient when canopy is complete but prior to senescence	–
kcdcl	Decline of crop coefficient as a result of ageing, nitrogen deficiency	% d^{-1}
evardc	Effect of canopy cover in reducing soil evaporation in late season stage	
Biomass and yield production		
wp	Water productivity normalized for *ETo* and CO$_2$	g m^{-2}
hi	Reference harvest index (HI)	%
exc	Excess of potential fruits	%
Water and temperature stress		
pexup	Upper threshold of soil water depletion limiting canopy expansion	Fraction TAW
pexlw	Lower threshold of soil water depletion limiting canopy expansion	Fraction TAW
pexshp	Shape factor for water stress limiting canopy expansion (0.0 = straight line)	–
psto	Upper threshold of soil water depletion limiting stomatal conductance	Fraction TAW
pstoshp	Shape factor for water stress limiting stomatal conductance (0.0 = straight line)	–
psen	Upper threshold of soil water depletion inducing early canopy senescence	Fraction TAW
psenshp	Shape factor for water stress inducing early canopy senescence (0.0 = straight line)	–
ppol	Upper threshold for soil water depletion for pollination limitation	Fraction TAW
anaer	Anaerobic point below saturation limiting aeration	vol%
hipsflo	Possible increase of harvest index due to water stress before flowering	%
hipsveg	Coefficient for positive impact of restricted vegetative growth during yield formation on HI	–
hingsto	Coefficient for negative impact of stomatal closure during yield formation on HI	–
hinc	Allowable maximum increase of HI	%
polmn	Minimum air temperature limiting pollination	°C
polmx	Maximum air temperature limiting pollination	°C
stbio	Minimum growing degrees for full biomass production	GDD d^{-1}
SOIL PARAMETERS		
cn	Curve number	–
sat	Soil water content at saturation	vol%
fc	Soil water content at field capacity	vol%
pwp	Soil water content at wilting point	vol%
ksat	Saturated hydraulic conductivity	mm d^{-1}

2. Materials & methods

Yield output uncertainty caused by crop and soil parameter values was considered. The analysis was performed using long term weather data of years with different meteorological characteristics (e.g., wet, normal, dry years) for different regions including a temperate maritime climate in Western Europe, a sub-tropical sub-humid climate in Southern Africa and a sub-tropical humid climate in South-east Asia. The Morris screening method (Morris, 1991) was applied for identification of the most influential parameters. First- and higher-order effects of these most influential model parameters on the selected model output were quantified using the Extended Fourier Amplitude Sensitivity Test method (EFAST; Saltelli et al., 1999).

2.1. Crop simulation model

AquaCrop is a water productivity model that simulates aboveground biomass production in exchange for water transpired by the crop (Steduto et al., 2009). The model can be run in two modes, i.e. thermal or calendar time. For this study, model version 3.1+ was run in thermal time. A brief description of the AquaCrop model follows, provided that the model procedures are completely described by Raes et al. (2009).

The model requires local weather data (precipitation, minimum and maximum temperature, reference evapotranspiration (*ETo*)) to simulate daily crop growth and development. The crop canopy development and phaenology are driven by temperature. The canopy cover determines the amount of water transpired by the crop. Cumulative biomass production is obtained via summation of the daily ratio of crop transpiration and *ETo* during the period when biomass is produced. The proportional factor between biomass and standardized transpiration is the water productivity (WP^*):