EXPLORATORY SENSITIVITY ANALYSIS OF CROPSYST, WARM AND WOFOST: A CASE-STUDY WITH RICE BIOMASS SIMULATIONS

ANALISI ESPLORATIVA DELLA SENSIBILITÀ DI CROPSYST, WARM AND WOFOST: UN CASO DI STUDIO CON SIMULAZIONI DI BIOMASSA DEL RISO

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Abstract

Knowledge about model uncertainty is essential for crop modelling and provides information crucial for a real understanding of models behavior and for parameterization purposes. This work addresses an exploratory sensitivity analysis on the parameters involved with biomass accumulation of three crop models decidedly differing in the way they interpret the concept of growth. The models used in the sensitivity analysis were CropSyst, WARM and WOFOST. We used the Morris screening method, supplied with software for sensitivity analysis SimLab, to determine, at a reasonable cost in terms of model evaluations, which parameters have a substantial influence on a static biomass output (rice aboveground biomass at physiological maturity). Assumptions about the settings of the analysis in terms of parameters estimated distribution and uncertainty are discussed. As case study, we performed the sensitivity analysis using meteorological and management data from an experiment carried out in Opera (Milan, Northern Italy) during 2006. The site can be considered representative of temperate rice in Europe. The screening revealed some important features of the models in terms of their input parameters. The variability of simulated rice biomass was generally high, and few physiological parameters emerged as mostly influential on the biomass output. The biomass-transpiration coefficient of CropSyst was the most important parameter determining final biomass. In WOFOST, CO_2 assimilation rates and partitioning coefficients were found to be the most relevant parameters. The majority of the parameters in CropSyst and WOFOST (75-80%) resulted not very influential on the final biomass with the inputs used. On the other hand, WARM is more relevant than the others in that most of its input parameters actually cause variation in the model response.

Keywords: Crop growth modelling, Morris method, *Oryza sativa* L., sensitivity analysis, SimLab

Riassunto

La conoscenza dell'incertezza legata all'uso dei modelli è essenziale per la modellazione delle colture e offre informazioni utili per una effettiva comprensione del comportamento dei modelli e per la loro parametrizzazione. Un'analisi di tipo esplorativo è stata effettuata per valutare la sensibilità di tre modelli colturali ai parametri legati all'accumulo di biomassa. I tre modelli usati – CropSyst, WARM e WOFOST – si basano su approcci alternativi per la stima della crescita. Per l'analisi della sensibilità, il software SimLab è stato applicato per determinare mediante il metodo di Morris e in maniera relativamente efficiente i parametri maggiormente influenti sul valore di biomassa aerea simulato a maturazione fisiologica. Le assunzioni relative alla distribuzione dei parametri e alla loro incertezza sono state discusse. Come caso di studio, l'analisi della sensibilità è stata condotta utilizzando dati meteorologici e tecnici relativi a un esperimento condotto a Opera (Milano, Nord Italia) nel corso del 2004. Il sito sperimentale può essere considerato rappresentativo degli ambienti temperati di coltivazione del riso in Europa. Lo screening eseguito sui parametri ha rivelato alcune importanti caratteristiche dei modelli in rapporto ai loro parametri di input. La variabilità della biomassa simulata è stata generalmente alta e alcuni parametri fisiologici sono emersi come i più influenti nel determinare questo output. Per CropSyst, il coefficiente biomassa-traspiratione è risultato il parametro più importante nel determinare la biomassa finale. In WOFOST, i tassi di assimilazione della CO_2 *e i coefficienti di ripartizione sono risultati i parametri maggiormente rilevanti. In rapporto agli input usati, la maggior parte dei parametri di CropSyst e WOFOST (75-80%) è risultata scarsamente influente sulla stima della biomassa finale. In WARM, al contrario, la maggior parte dei parametri ha determinato variazioni importanti nell'output del modello.*

Parole chiave: *Modellazione della crescita delle colture, metodo di Morris,* Oryza sativa *L., analisi della sensibilità, SimLab*

Introduction

Crop simulation models are increasingly used to study the behaviour of complex agricultural systems and to understand the interactions between soil and plant under different meteorological conditions (e.g. volume 18 of the European Journal of Agronomy: issues 1-2, 2002; issues 3-4, 2003). These models estimate crop growth and development by mathematical representations of biophysical processes, which incorporate knowledge from several disciplines. Crop models are often used to evaluate the impact of management or climatic scenarios, and their reliability is still judged mainly on their accuracy in estimating the crop biomass at the end of the growing season and, consequently, the crop production.

The suitability of a crop model is assessed, on one hand, by the authenticity of the basic equations describing the crop processes while, on the other hand, by the quality of its input data (Fodor and Kovács, 2003; Rivington *et al.*, 2006). They both should be coherent with the level of detail used by the model in order to "reproduce" the real system. Besides soil and weather inputs, the considerable detail facilitated by these models often requires the inclusion of a large number input parameters, which values are often not known with certainty (especially for the most empirical ones). The values of many parameters are set either as observed in local experiments or extracted from literature sources. Some crop parameters that tend to fluctuate among cultivars are often calibrated to match selected data with model outputs (Makowski *et al.*, 2006). Crop parameters are known to vary temporally but, in spite of this, some models simulate crop processes using single values of crop parameters over entire seasons and multi-year simulations. Models do not always behave intuitively (in particular when there are nonlinearities involved) and, since parameterization errors are one of the primary sources of uncertainty with many models (e.g. Quinton, 1997), the understanding of model response to the variation of parameter values is needed as one of the pre-requisites for model use.

Multiple values of the parameters can be used for the simulations, allowing confidence limits to be assigned to the model output. A model whose outputs differ largely as a consequence of minor changes to its parameter values is of suspect reliability, especially if the sensitive parameters are difficult to estimate accurately. Sensitivity analysis (Saltelli *et al.*, 2000; Monod *et al.*, 2006) calculates how much the outputs of a model depend to its inputs and is an important step of model evaluation to address parameter uncertainty, indirectly revealing the reliability of model estimates (Martorana and Bellocchi, 1999). Sensitivity analysis is also helpful to identify parameters respect to which an output is rather or entirely insensitive to, so that such redundant parameters may be ignored in subsequent analyses or modelling. One of the main objectives of modelling teams is to develop simulation approaches that require a minimum number of model parameters, using those which are biologically meaningful (hence not or minimally correlated). This requires the use of sensitivity analysis which may be supportive of an overall model evaluation. Advanced software tools are required to perform sensitivity analysis in a simple way, and make results easily understandable.

Sensitivity analysis methods have not kept up with the rapid increase in available computational power and, more importantly, the resultant increase in model size and complexity. An important objective of complex models is to increase the understanding of the directions and magnitudes of change of the system under composite sets of equations (and, in turn, sets of parameters). The complexity of the models determines the difficulty of finding and fitting probability distributions of all uncertain parameters, a feature commonly required in sensitivity analysis. Further, the complex nature of integrated models requires a sensitivity analysis approach that is flexible and can be implemented regardless of model structure.

Crop models currently available and used are often dissimilarly structured, with equations and input parameters of different nature, different organizational levels, as well as different capabilities in representing the actual system. A list of the most widespread models to simulate crop development and growth follows: APSIM (Keating *et al.*, 2003), CropSyst (Stöckle *et al.*, 2003), DSSAT (Jones *et al.*, 2003), models from the Wageningen school such as LINTUL, SUCROS, ORYZA, WOFOST, INTERCOM (van Ittersum *et al.*, 2003), STICS (Brisson *et al.*, 2003).

This paper reports on the results of a sensitivity analysis of three crop models, namely CropSyst (Stöckle *et al.*, 2003), WARM (Confalonieri *et al.*, 2005a) and WOFOST (van Keulen and Wolf, 1986; Boogaard *et al.*, 1998), which are exemplary of different model types. CropSyst is a generic crop simulator, meant to represent the behaviour of diverse arable crops using sets of equations and parameters which are common to any crop. Its development is strongly oriented to the evaluation of management scenarios. For CropSyst, the simulation of aboveground biomass is mainly based on the efficiency of the conversion of transpired water into biomass and, subordinately, to radiation use efficiency (RUE). WOFOST is a generic crop simulator too, limited to the simulation of plant behaviour: interactions between plant and soil are limited to a simplified estimation of water limitation to growth. No management options are implemented. Biomass accumulation is based on the assimilation of CO_2 and the model is strictly derived by SUCROS (van Keulen *et al.*, 1982). WARM (Confalonieri *et al.*, 2005a) is a crop-specific model, specifically designed for simulation of rice systems. Its development is driven by the attempt of considering all the biotic and a-biotic specificities of the represented system which have an impact on production. The biomass accumulation is based on the concept of RUE. The objective of this paper is to present the results of a comparative sensitivity analysis, with discussion on: (i) uncertainty bounds

Tab. 1 - CropSyst: parameters and statistical settings used for sensitivity analysis.
***Tab. 1 -** Parametri di CropSyst e input statistici per l'analisi della sensibilità.*

Parameter	Unit	Mean value	Standard deviation	Truncation	Source
Biomass-transpiration coefficient (BTR)	kPa kg m^{-3}	5	1	0.05	Confalonieri and Bocchi (2005)
Radiation use efficiency (RUE)	g MJ^{-1}	3	0.5	0.05	Boschetti *et al.* (2006)
Actual to potential transpiration ratio to limit leaf growth (ActPotTrLeaf)	-	0.8	0.1	0.05	local experience
Actual to potential transpiration ratio to limit root growth (ActPotTrRoot)	-	0.5	0.1	0.05	local experience
Optimum temperature for growth (T_{opt})	ºC	28	2	0.05	Confalonieri and Bocchi (2005)
Maximum water uptake (MaxWupt)	mm d^{-1}	10	1	0.05	Confalonieri and Bocchi (2005)
Initial leaf area index (LAI_{ini})	m^2 m^{-2}	0.01	0.005	0.20	Boschetti (unpublished data)
Maximum leaf area index (LAI_{max})	m^2 m^{-2}	7	0.5	0.05	Boschetti (unpublished data)
Fraction of maximum leaf area index at physiological maturity (LAI-fractMaturity)	-	0.5	0.1	0.05	local experience
Specific leaf area (SLA)	m^2 kg^{-1}	27	2	0.05	Boschetti *et al.* (2006)
Stem-leaf partition (SLP)	m^2 kg^{-1}	2	0.8	0.10	Boschetti (unpublished data)
Leaf duration (LeafDuration)	ºC-d	700	80	0.10	Confalonieri and Bocchi (2005)
Extinction coefficient (K)	-	0.5	0.04	0.10	Boschetti *et al.* (2006)
Crop coefficient (Kc)	-	1.05	0.15	0.10	FAO (1998)
Base temperature for growth (T_{base})	ºC	12	0.6	0.10	Confalonieri and Bocchi (2005)

for crop growth estimation, (ii) identification of parameters that should be determined with more accuracy, and (iii) establishment of priorities for research.

Materials and Methods

Simulation study

A simulation study was performed to model rice (*Oryza sativa* L.) growth with CropSyst, WARM and WOFOST. CropSyst is a multi-year, multi-crop simulation model, widely used to evaluate crop production and management strategies worldwide (http://www.sipeaa.it/tools/CropSyst/CropSyst.htm). WOFOST is widely used too, and is incorporated in the European Crop Growth Monitoring System (CGMS, http://agrifish.jrc.it/marsstat/Crop_Yield_Forecasting/cgms.htm) of the MARS project (Monitoring Agriculture with Remote Sensing, http://www.marsop.info) for yield forecasts at regional and national scale in Europe. WARM is a model of recent creation and is used within CGMS for rice yield forecasts. Details about CropSyst and WOFOST are given in the seminal literature and are not reproduced here. A general description of WARM has been provided by Confalonieri *et al.* (2005a), while details about the processes related with crop growth are given by Confalonieri *et al.* (2006a). The interested user may also refer to the model web sites: CropSyst, http://www.bsyse. wsu.edu /cropsyst; WARM, http://agrifish.jrc.it/ marsstat/warm; WOFOST, http://www2. alterra.wur.nl/UK/prodpubl/modellen/WOFOST/wofost_intro.htm.

The scenario assumed for this simulation study was that of an experiment carried out in 2004 in Opera (province of Milan, latitude 45° 23' North, longitude 9° 13' East), with the crop grown under potential conditions (unlimited supply of water and nitrogen, and absence of weeds and pests) on a silty-loam soil (Confalonieri *et al.*, 2006b). Daily weather inputs required by the models were obtained by a floating weather station (Confalonieri *et al.*, 2002; Confalonieri *et al.*, 2005b) placed into the field. Crop management options were set to closely imitate local farming practices for flooded rice.

Sensitivity analysis

The variation of aboveground biomass at physiological maturity (AGB), as model parameters change, was investigated. AGB was chosen as it is a synthetic representation of the culmination of many different biophysical processes. AGB is also a product of all crop parameters, acting in conjunction with each other.

Whenever possible, a set of measured/estimated values was associated to each parameter, deriving them from literature or unpublished data (Tables 1, 2, 3). For some parameters of Table 3, the acronyms in brackets are followed by two or three figures, indicating values of average daily air temperature (T_{avg}) and development stage (DVS) respectively. DVS codes are explained in the WOFOST documentation (http://www2.alterra.wur.nl/UK/prodpubl/modellen/WOFOST/wofost_intro.htm).

Those are changing factors, according to either DVS or T_{avg}, and then they do not represent parameters *stricto sensu*. Since this exploratory sensitivity analysis does not target at the best fitting between simulation results and observations, the couples DVS-parameter value (or T_{avg}-parameter value) were deliberately reduced in number to focus on the most relevant ones. The uncertainty of some parameters at particular DVS or T_{avg} values (e.g. specific leaf area at late stages) is known to be negligible, and sensitivity analysis was not performed in such cases. The simplifications introduced allowed avoiding incoherencies between values which are likely to occur when sample values are generated in the course of sensitivity analysis (e.g. larger parameter values at stages when the same parameter is known to assume smaller values). Means and standard deviations were calculated for each parameter, and statistical tests (Shapiro-Wilks, Kolmogorov-Smirnov, D'Agostino-Pearson) were applied to test the assumption of the normality of the distributions.

Based on the sample statistics and the associated probability distribution of input parameters, random variates of the same parameters were generated using the sampling technique for sensitivity analysis known as Morris method (Morris, 1991) and further improved by Campolongo *et al.* (2003), which deals efficiently with models containing a large number of input parameters without relying upon strict assumptions about the model such as, for instance, additivity or monotonicity of the input-output relationship. The method is effective to screen a subset of few important input parameters among a large number of them contained in a model. In the screening method each input parameters can assume a discrete number of values, called levels, which are chosen within the ranges of uncertainty of parameters.

The first measure (μ*) is obtained by computing a number of incremental ratios at different points of the input space, and then taking the average of their absolute values. Each incremental ratio is defined as:

$$d_i(\mathbf{x}) = \frac{y(x_1,...,x_{i-1},x_i+\Delta,x_{i+1},...,x_k) - y(\mathbf{x})}{\Delta}$$

where $\mathbf{x} = (x_1, x_2, ..., x_k)$ is any selected value in the space of the parameters, Δ is a predetermined multiple of the distance between levels, and *y* is the model prediction. μ* is successful in ranking parameters in order of importance and performs capably when the setting is that of identifying non-influential parameters.

The second measure (σ) is the standard deviation of the distribution of the incremental ratios. This is useful to detect parameters involved in interaction with other parameters, or whose effect is non-linear (Saltelli *et al.*, 2004).

With this convention the more "dangerous" parameters are in the top right quadrant of the σ versus μ plot ("danger zone"), where both sensitivity and strength are high. A large (absolute) measure of central tendency indicates an input with an important overall influence on the output (total effect), whilst a large measure of spread indicates an input with non-linear effect on the output, or an input involved in interaction with other factors (second-order effect).

Tab. 2 - WARM: parameters and statistical settings used for sensitivity analysis.
Tab. 2 - *Parametri di WARM e input statistici per l'analisi della sensibilità.*

PARAMETER	UNIT	MEAN VALUE	STANDARD DEVIATION	TRUNCATION	SOURCE
Radiation use efficiency (RUE)	g MJ^{-1}	3	0.5	0.01	Boschetti *et al.* (2006)
Extinction coefficient (k)	-	0.5	0.04	0.01	Boschetti *et al.* (2006)
Base temperature for growth (T_{base})	ºC	12	0.6	0.01	Confalonieri and Bocchi (2005)
Optimum temperature for growth (T_{opt})	ºC	28	2	0.01	Confalonieri and Bocchi (2005)
Ceiling temperature for growth (T_{max})	ºC	42	2	0.01	local experience
Initial leaf area index (LAI_{ini})	m^2 m^{-2}	0.01	0.005	0.01	Boschetti (unpublished data)
Initial specific leaf area (SLA_{ini})	m^2 kg^{-1}	27	2	0.01	Boschetti *et al.* (2006)
Specific leaf area at tillering (SLA_{till})	m^2 kg^{-1}	18	3	0.01	Kropff *et al.* (1994); Diepen *et al.* (1988); Confalonieri (unpublished data)
Partition coefficient to leaf at early stages ($RipL_0$)	kg kg^{-1}	0.7	0.1	0.01	Confalonieri (unpublished data); Kropff *et al.* (1994)
Leaf duration (LeafLife)	ºC-d	700	80	0.01	Confalonieri and Bocchi (2005)

SimLab

Simlab is a free software package for global uncertainty and sensitivity analysis developed at the Joint Research Centre of Ispra and freely distributed at http://simlab.jrc.it (Simlab, 2004). Simlab consists of separate modules that allow the user to select between various methods of parameter combination generation, to run with the parameter combinations generated, and to perform uncertainty and sensitivity analysis. SimLab was used to generate sets of random samples that represent different parameterizations for crop simulations in CropSyst, WARM and WOFOST. The results of the simulations were used to compute the corresponding sensitivity indices in Simlab. In particular, we used Simlab to calculate mean and standard deviation of the elementary effects in the Morris method. The number of model executions was computed as r·(k+1), where r is the number of trajectories (sequences of points starting from a random base vector in which two consecutive elements differ only for one component) and *k*, the number of input parameters. For each parameter, the Morris method operates on selected levels, corresponding to the quantiles of the parameter distribution (details are given in Saltelli *et al.*, 2004). As SimLab can only run simple models expressed as simple mathematical formulas, an interface code was created to receive the simulation file generated by SimLab, launch CropSyst and WOFOST simulations, recover the aboveground biomass at each simulation, and generate the input file for the SIMLAB statistical post-

Tab. 3 - WOFOST: parameters and statistical settings used for sensitivity analysis
Tab. 3 - *Parametri di WOFOST e input statistici per l'analisi della sensibilità.*

Parameter	Unit	Mean value	Standard deviation	Truncation	Source
Leaf area index at emergence (LAI_{em})	$m^2\ m^{-2}$	0.01	0.005	0.001	Boschetti (unpublished data)
Relative leaf area growth rate (RGR_{LAI})	$°C\ d^{-1}$	0.00855	0.000482	0.001	after Casanova *et al.* (2000)
Specific leaf area as a function of DVS (SLATB035)	$ha\ kg^{-1}$	0.0035	0.000525	0.001	Dingkuhn *et al.* (1999)
Specific leaf area as a function of DVS (SLATB045)	$ha\ kg^{-1}$	0.00262	0.0002128	0.001	Dingkuhn *et al.* (1999)
Specific leaf area as a function of DVS (SLATB065)	$ha\ kg^{-1}$	0.0023	0.000276	0.001	Dingkuhn *et al.* (1999)
Life span of leaves growing at 35 ºC (SPAN)	d	35	3.5	0.001	Kropff *et al.* (1994)
Base temperature for leaf ageing (T_{base})	ºC	9	1.5	0.001	Kropff *et al.* (1994)
Extinction coefficient for diffuse visible light (KDIFTB000)	-	0.436	0.1	0.001	Dingkuhn *et al.* (1999); Casanova *et al.* (2000); Kiniri *et al.* (2001); Boschetti *et al.* (2006)
Extinction coefficient for diffuse visible light (KDIFFTB100)	-	0.625	0.02	0.001	Casanova *et al.* (2000); Boschetti *et al.* (2006)
Light use efficiency as a function of DVS (EFFTB10)	$kg\ ha^{-1}\ hr^{-1}\ J^{-1}\ m^2\ s$	0.55	0.04	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988)
Light use efficiency as a function of DVS (EFFTB40)	$kg\ ha^{-1}\ hr^{-1}\ J^{-1}\ m^2\ s$	0.35	0.04	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988)
Maximum leaf CO_2 assimilation rate (AMAXTB000)	$kg\ ha^{-1}\ hr^{-1}$	40.24	10.2	0.001	Ziska and Teramura (1992); Choudhury (2001); Da Matta *et al.* (2001)
Maximum leaf CO_2 assimilation rate (AMAXTB200)	$kg\ ha^{-1}\ hr^{-1}$	40.24	10.2	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Reduction factor for AMAX as a function of average temperature (TMPFTB14)	ºC	0.2	0.08	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Reduction factor for AMAX as a function of average temperature (TMPFTB23)	ºC	0.8	0.02	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Correction factor for transpiration rate (CFET)	-	1	0.08	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Efficiency of conversion into leaves (CVL)	$kg\ kg^{-1}$	0.5	0.14	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Efficiency of conversion into storage organs (CVO)	$kg\ kg^{-1}$	0.5	0.14	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Efficiency of conversion into roots (CVR)	$kg\ kg^{-1}$	0.5	0.14	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Efficiency of conversion into stems (CVS)	$kg\ kg^{-1}$	0.5	0.14	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Relative increase in respiration rate per 10 ºC of temperature increase (Q10)	-	1.8	0.1	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Relative maintenance respiration rate for leaves (RML)	$kg\ CH_2O\ kg^{-1}\ d^{-1}$	0.028	0.0005	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Relative maintenance respiration rate for storage organs (RMO)	$kg\ CH_2O\ kg^{-1}\ d^{-1}$	0.01	0.003	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Relative maintenance respiration rate for roots (RMR)	$kg\ CH_2O\ kg^{-1}\ d^{-1}$	0.012	0.0011	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Relative maintenance respiration rate for stems (RMS)	$kg\ CH_2O\ kg^{-1}\ d^{-1}$	0.018	0.001	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Fraction of total biomass to roots as a function of DVS (FRTB000)	$kg\ kg^{-1}$	0.45	0.058	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Fraction of total biomass to roots as a function of DVS (FRTB100)	$kg\ kg^{-1}$	0.25	0.042	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Fraction of above-ground dry matter to leaves as a function of DVS (FLTB000)	$kg\ kg^{-1}$	0.7	0.083	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Fraction of above-ground dry matter to leaves as a function of DVS (FLTB050)	$kg\ kg^{-1}$	0.45	0.16	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Fraction of above-ground dry matter to storage organs as a function of DVS (FOTB082)	$kg\ kg^{-1}$	0.2	0.043	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Fraction of above-ground dry matter to storage organs as a function of DVS (FOTB100)	$kg\ kg^{-1}$	0.65	0.083	0.001	Kropff *et al.* (1994); van Diepen *et al.* (1988); Casanova *et al.* (2000)
Specific stem area as a function of DVS (SSATB030)	$ha\ kg^{-1}$	0.000919	0.000269	0.001	after Casanova *et al.* (2000)
Specific stem area as a function of DVS (SSATB120)	$ha\ kg^{-1}$	0.000216	3e-005	0.001	after Casanova *et al.* (2000)
Specific stem area as a function of DVS (SSATB150)	$ha\ kg^{-1}$	0.000335	9e-006	0.001	after Casanova *et al.* (2000)

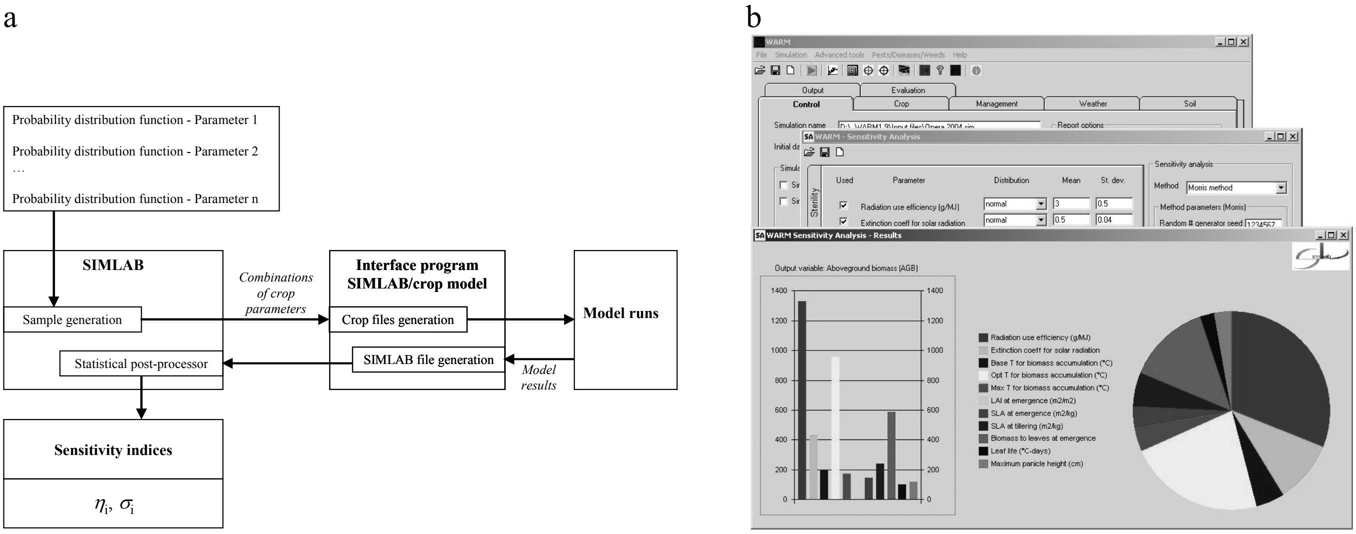

Fig. 1 - Morris analysis with SimLab: general approach on crop models.
Fig. *1 - Analisi di Morris con SimLab: approccio generale applicato ai modelli colturali.*

processor, which computes the sensitivity indices. The general methodology is presented in Figure 1a.
The concepts represented in the flowchart shown in Figure 1.a are the same used for the sensitivity analysis of WARM. This model, however, is equipped with a dedicated/integrated tool (the interface is shown in Figure 1.b) which allows WARM users to run sensitivity analysis using the SIMLAB procedures directly in the WARM environment. In this case, a DLL implementing the SIMLAB algorithm is used directly inside the simulation model.

Results

Model parameters

The three models are completely different in the functions they use for simulating crop growth and these functions have a different number of parameters, or parameters of a different nature. The parameters selected for this study are listed in Table 1 (CropSyst), Table 2 (WARM), and Table 3 (WOFOST). Other model parameters were not used in this analysis because not directly related to crop growth. They were kept constant at their average value.
Sample statistics (mean, standard deviation) characterizing crop parameters were derived either from literature, unpublished data or local experience. Departures from normality were not observed. Truncations in the range 0.001-0.1 (probability level on both sides of normal distribution) prevented parameters from showing negative (unrealistic) values.

Morris analysis

The results of the Morris analysis for aboveground biomass with CropSyst, WARM and WOFOST were combined to produce the diagnostic diagrams of Figures 2, 3, and 4, respectively.

CropSyst

In general, results of the Morris analysis show for CropSyst that each parameter with a high value for μ also has a high value for σ, indicating an overall importance of the parameter including interactions with others. The results of Morris analysis also show that the input biomass-transpiration coefficient (BTR) yields the highest value of either μ or σ (Figure 2). This parameter - the only one placed in the top-right quadrant of the diagram - is clearly separated from the remaining parameters. Of these, base temperature (T_{base}) and radiation use efficiency can be grouped into one set of parameters with second-high rank. The remaining parameters, decreasing without discontinuities from the right to the left of the mean scale, show various overlaps and have little influence on the biomass output. Crop parameters characterizing plant morphology are included in this group and are therefore not very important. The parameters really effective in CropSyst are those closely related to the energy use (water- or light-driven), including T_{base} which affects temperature-based correction factor of radiation-dependent growth.

WARM

For WARM, the sensitivity response looks a bit more complex than CropSyst because a particular parameter is not shown to be as markedly different from others (Figure 3). From the right to the left of the μ scale, values of μ do not always decrease smoothly, but with discontinuities permitting to distinguish the most influential parameters from other less or non influential parameters. Two groups of parameters with quite distinct boundaries are evident, plus an isolate parameter well separated from the rest.
A cluster of high-rank parameters in the top right quadrant is clearly separated from the others. In this group of parameters, radiation use efficiency (RUE) is noticeably the most influential. Optimum air temperature for growth

(T_{opt}) is also important, together with the parameter governing the early stage partition to leaves (RipL0). With mean of about 900 (against ~400 as general mean), this cluster indicates a large influence on growth and can be considered a "danger zone". The standard deviation provides interesting considerations, because ranking the rate coefficients according to their standard deviation differs from the ranking that results from the means. T_{opt} in particular is ranked higher on the mean scale than on the standard deviation scale. This can be due to the fact that this parameter is important and, at the same time, without much interaction with other parameters (or, that the parameter's uncertainty provided as an input is conservative relatively to other parameters' range). Inherently to its nature, RipL0 is effective in the early stages of crop growth but in such a way to affect the general partition dynamics.
The second high-ranked set of parameters includes base and ceiling temperatures (respectively T_{base} and T_{max}) for crop growth, both modulating in WARM the radiation-dependent growth. Yet separated, the parameters of the second group are quite close to the "danger zone". Again, a different ranking is given by the mean and the standard deviation scales. Such feature is noticeable for the initial specific leaf area (SLA_{ini}), as reflected by its low ranking on the standard deviation scale.
Isolated into the lower-left quadrant, the initial leaf area index is the least sensitive parameter in WARM and very far from the dangerous zone.

WOFOST
In comparison to the other models investigated, WOFOST includes the largest number of parameters (Table 3), thus turning into numerous overlaps in the diagnostic diagram (Figure 4). Three clusters can be roughly distinguished, although their boundaries are not very well defined. A set of six most influential parameters is given in the top right quadrant of Figure 4, including the partitioning factors (conversion efficiency and fractions) to the diverse plant organs (efficiency of conversion into storage organs [CVO], into stems [CVS], into roots [CVR] and fraction of aboveground biomass to leaves at mid stem elongation [FLTB050]) plus the maximum CO_2 assimilation rate at early stages and at maturity (respectively AMAXTB000 and AMAXTB200). Eight other parameters follow immediately. From the right to the left on the μ scale, values of μ for the remaining parameters decrease smoothly and with variously overlaps. Of the six dominant parameters, AMAXTB000 has a large bearing on the biomass accumulation according to the mean scale but has only weak spread because of its role limited to the beginning of crop growth simulation. CVS and CVO exhibit instead the largest spread values.

Discussion and Conclusions
Significant areas of applications of complex crop models imply the estimation of the crop yield at point and regional scales. In these fields, the most important topics include the dynamic simulation of biomass accumulation at given conditions and the estimate of crop biomass at maturity. In this paper, we presented sensitivity analysis

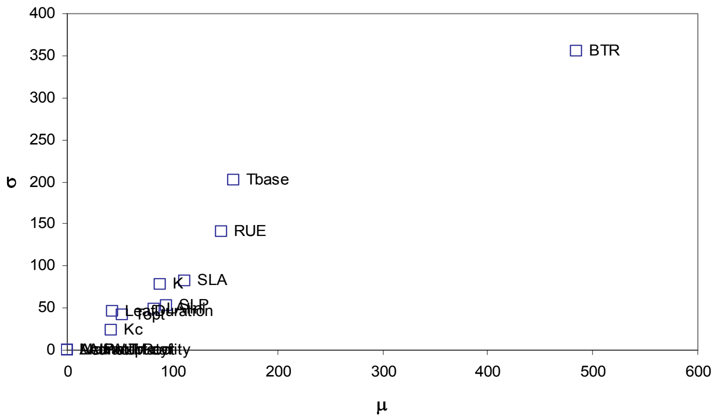

Fig. 2 - The mean and the standard deviation effects, calculated with the Morris method for rice aboveground biomass at physiological maturity simulated with CropSyst.
Fig. 2 - *Simulazioni con CropSyst: effetti della media e della deviazione standard, calcolati con il metodo di Morris per la biomassa aerea del riso a maturazione fisiologica.*

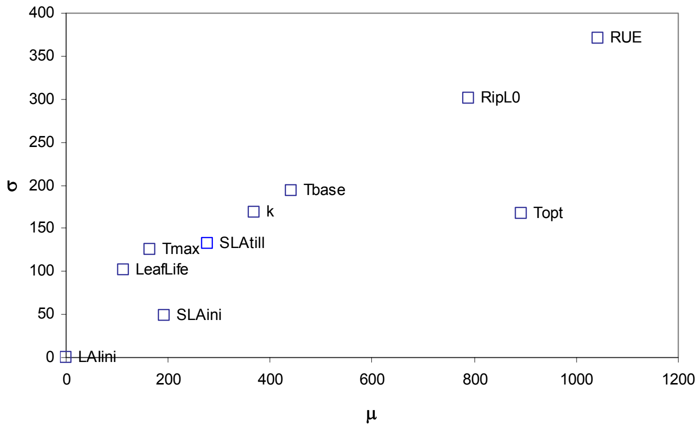

Fig. 3 - The mean and the standard deviation effects, calculated with the Morris method for rice aboveground biomass at physiological maturity simulated with WARM.
Fig. 3 - *Simulazioni con WARM: effetti della media e della deviazione standard, calcolati con il metodo di Morris per la biomassa aerea del riso a maturazione fisiologica.*

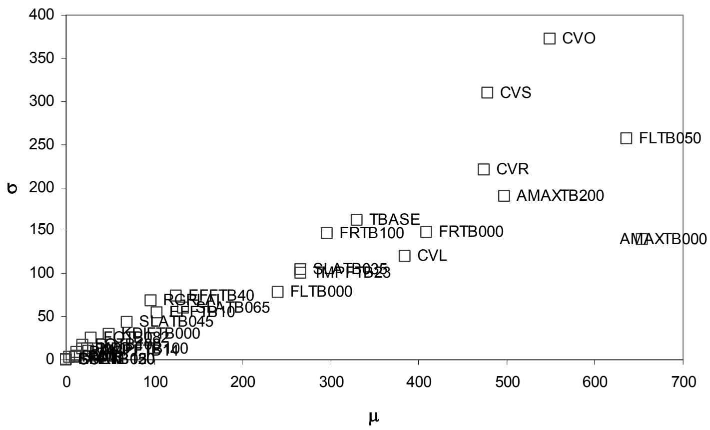

Fig. 4 - The mean and the standard deviation effects, calculated with the Morris method for rice aboveground biomass at physiological maturity simulated with WOFOST.
Fig. 4 -. *Simulazioni con WOFOST: effetti della media e della deviazione standard, calcolati con il metodo di Morris per la biomassa aerea del riso a maturazione fisiologica.*

for models of different type used to estimate rice biomass in Northern Italy. A critical point in the methodology used is the access to literature sources for information (means and standard deviation) about some model parameters. Complex crop models are organized into a hierarchy of processes where parameters placed at an upper level in the hierarchy (close to the level where the estimation is made) dominate over the others. Their values may summarize many lower-level processes and a large amount of uncertainty is likely associated to them. Moreover, they are often the result of a calibration procedure not necessarily representing the processes under study. Adjustments to such parameters are common in the modelling practice to account for either input data inadequacy or shortcomings in the simulated processes. Upper-level parameters are likely the ones which the model is more sensitive to, and a large uncertainty associated to them likely has a noticeable impact on the results of a sensitivity analysis.
Contribution of the various crop parameters to the uncertainty of the results were investigated via the Morris method as implemented in SimLab. The same parameters were ranked in terms of their effect on the estimated aboveground biomass. Combining results from the parameter spread and strength, diagnostic diagrams provided a convenient way in which to view each of the key parameters in terms of their relative contribution to crop biomass. For each model and for the explored weather and management conditions, it is clear from the diagrams which parameters have relatively lower priority when one aims to increase the insightfulness and reliability of model simulations, and which ones are more substantial contributors to overall uncertainty.
An important finding from the Morris analysis is that, for each model, few parameters cause most of the uncertainties whilst most parameters contribute little (that is the same parsimony principle stated by Trocine and Malone, 2000). One parameter out of 15 is really important in CropSyst, while three on 10 in WARM and six on 34 in WOFOST have noticeable contribution to the uncertainty of final rice biomass. This sensitivity analysis helps eliciting insights about the multi-facet effects of each crop parameter on the crop biomass because the results indicate a range of attributes for the key model parameters. For some parameters there is in fact reasonable consistency across the model results, indicating a common view of the underpinnings of these parameters. As an example, quantitative energy-related CO_2 assimilation parameters are of great importance in either CropSyst (parameter BTR and, to a lesser extent, RUE), WOFOST (parameters of the AMAXTB group), or WARM (parameter RUE) simulated biomass. Uniqueness of WARM in comparison to the others is the implementation of a non-linear equation (i.e., beta-function, Yan and Hunt, 1999) to adjust the radiation-dependent biomass accumulation. The non-linearity implies that critical parameters of beta-function - optimum and, to a lesser extent, base and maximum air temperatures - tend to play an important role on crop growth. One implication from these results is that more research in this area may decrease uncertainties by revealing new complexities (i.e. non-linear interaction) not accounted for earlier. Another example is biomass partition to plant organs, which is accounted for in WARM by a set of quadratic functions all governed by a single parameter. The impact of such partition coefficient on the crop biomass is therefore much larger with WARM than with other models. In CropSyst, stem-leaf partition is less impacting because of the simplified solution to partitioning implemented in this model. In WOFOST, the same process is governed by many parameters, none of which is really more influential than the others.
In this study we have used for the first time the Morris method on crop models of such a complexity as CropSyst, WARM and WOFOST. The results give support to the thought that the method can usefully be adapted and used for other complex crop models as well. This exploratory analysis is a preliminary action towards other forms of sensitivity analysis, not yet applied at this stage. More sophisticated sensitivity methods (e.g., Sobol's method based on variance decomposition) focus research efforts on the potentially most problematic parameters while, at the same time, pinpointing specific weaknesses in these parameters. Application of such advanced sensitivity analysis approaches is an objective of the continuation of this first work. Given that the scenario analyzed in this work was limited to rice growth at one site only, different scenarios will be considered in future work to let possible interactions with soil and weather inputs to come up.

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