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Simulating crop damages due to abiotic events: case studies using the AbioticDamage model library

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Abstract: One of the largest consequences of projected climate change is an increased frequency of extreme weather events or conditions. They impact heavily on crops as they are out of the range of variability which crops are adapted to. As an example, air temperature is a driving variable involved in the simulation of plant development, and it is used for estimating both crop development and photosynthesis limitation at any given level of intercepted solar radiation. Although with different algorithms, these processes are basically included in all crop simulation models. The reduction of leaf area index or the possible death of the plant due to frost are usually not included in crop growth models, as well as the yield losses due to pre-flowering cold shocks inducing spikelet sterility, although these processes are driven by the same variable (temperature). Another example is ozone concentration in the air; it has traditionally been ignored in modelling because taken for constant in a given environment, hence assuming crops being adapted to its concentration. However, if ozone concentration changes, and given its toxicity, its impact on crop growth must be included in models used for scenario analysis. The impact of many extreme events or conditions is usually not included in the simulation models used for the analysis of crop response to climate change scenarios. This is a limitation which needs to be overcome because such conditions are key elements characterizing the weather scenarios as estimated by global circulation models.

The .NET C# library AbioticDamage implements models to simulate events the plant is not physiologically prepared to deal with. Models for the simulation of the main damages affecting the production of herbaceous crops due to abiotic factors are implemented in an extensible library, to be linked to crop development and growth models. It implements six categories of damages: frost, cold-induced spikelet sterility, lodging, ozone, salinity, and heat-induced spikelet sterility: The modelling solutions are taken from peer reviewed sources. The component encapsulates the ontology of the variables and parameters defined which is also used to implement optional run-time data quality tests following the design-by-contract approach. The architecture allows for alternate models to simulate the impact of abiotic factors, and it permits extension by third parties. The component is provided together with the documentation of all the equations, the documentation of the code, a set of unit tests, where all the sub-models implemented were tested against the numerical results obtained with the same inputs in a different environment.

In this paper we present two case studies where the component AbioticDamage was run linked to the component CropML (Crop Model Library). Gridded weather data with coverage of 27 member states of the European Union (EU-27) for the years 2002 - 2008 were used to simulate abiotic stresses: frost and spikelet sterility on winter wheat and rice grain yields, respectively. Results are discussed in terms of deviation of simulated yields from simulations run without accounting for the impact of stresses. Year 2002 is signalled for severe frost damages affecting France and other important winter wheat EU-27 producing countries. For rice, simulations indicate a roughly constant degree of spikelet sterility (about 5%) affecting the cultivations of Eastern Europe countries. For Mediterranean countries, summer temperature falls may cause severe sterility problems in some years (e.g., 2007). The case studies presented are illustrative of the type of output attainable for dedicated tools for simulation of abiotic damages in cultivated plant species, and their usefulness to interpret the impact of climatic alterations that have occurred in Europe in the last years.

Keywords: *Climate change, crop production, spikelet sterility, frost, rice, wheat*

1. INTRODUCTION

Solar radiation, air temperature, atmospheric CO_2 concentration, soil, water, and nutrients are the major abiotic factors influencing crop performance. Each of these environmental factors, when available at their optima, would result in achieving maximum potential yield or biomass. Any deviation from the defined optima would affect growth, development, and finally yield. As a matter of fact, crops experience disturbances or stresses from abiotic agents that are known to be causing extensive losses to agricultural production worldwide (e.g. Boyer, 1982; Mooney et al., 1991). Human activities are also causing alarming changes to the environment (Intergovernmental Panel on Climate Change, 2007) which are expected to exacerbate the yield-limiting factors even more in the coming decades. Elevated carbon dioxide (CO_2) and ozone (O_3) are indeed increasing worldwide due largely to human activities, and many plant species are experiencing stress in this altered atmosphere (Fuhrer, 2003).

Controlled environment facilities make the determination of potential crop productivities possible, enabling the integration of results, the development of functional relationships between crop parameters and abiotic factors, and the quantification of the effects of abiotic factors on crop growth and development (Wilkerson et al., 1983; Horie et al., 2000; Ewert et al., 2002; Kim et al., 2006; Fleisher et al., 2006; Timlin et al., 2006).

Several abiotic constraints that reduce crop productivity have the risk of becoming more serious threats because of climate change. There is concern that the interaction of multiple stressors resulting from the rise in greenhouse gases and climate change will lead to a destabilization of agricultural systems during transition and adaptation to a changing environment (IPCC, 2007). The effects of extreme abiotic disturbances need to be included in crop models to provide a realistic picture of yield under field conditions. Indeed, crops stressed by one factor, e.g. accelerated warming as result of climate change, may become more susceptible to secondary disturbances such as insects, disease, or invading weed species. Warming and elevated CO_2 impacts were estimated using eco-physiological models by the IPCC, but the reliability of model assumptions remains controversial since the models failed, for instance, to consider stressors including O_3 and heat shock. Atmospheric ozone concentration has traditionally been ignored in models as it was taken at a constant value in a given environment, hence assuming crop adaptation to its concentration. However, it is known that ozone concentration changes, and given its toxicity, its impact on crop growth must be included in models used for scenario analysis. Air temperature, on the contrary, it is a driving variable involved in the simulation of plant development, and it is used for estimating both crop development and photosynthesis limitation at any given intercepted solar radiation. Although with different algorithms, these processes are basically included in all crop simulation models (van Ittersum and Donatelli, 2003). However, some effects are partially or not at all modelled. For instance, the reduction of leaf area index or the possible death of the plant due to frost are usually not included in crop growth models, as well as the yield losses due to pre-flowering cold shocks inducing spikelet sterility, although these processes are likewise temperature-driven.

One of the most important effects of climate change is an increased frequency of extreme events or weather conditions, meaning environmental variables which vary out of the range a crop is adapted to. In general, the impact of extreme events or conditions is usually not included in the simulation models used for the analysis of crop response to climate change scenarios. This is a limitation which needs to be overcome because such conditions are key elements characterizing the weather scenarios as estimated by global circulation models. Future changes in climate need to be specified in a suitable degree of detail to support sound estimations on the impacts to agriculture, as well as to forestry and natural systems. A projection stating that total growing season precipitation will increase by some millimetres or that season average temperature will rise by so many degrees does not provide enough information to assess impacts to agriculture. It is therefore crucial to improve quantitative estimation of the effect on crops of ecologically and agriculturally important traits affected by climate change.

Improving the understanding of the response of crop species to abiotic stresses, and developing crop models for them, is of great value in crop management, as well as being useful in projecting climate change impacts. Tools that enable the integration of available knowledge effects from abiotic factors that shape crop response in agricultural systems are desirable. A study was started at European Commission’s Joint Research Centre (JRC), Institute for Protection and Security of the Citizens (IPSC), aimed at developing modelling approaches for computer-assisted simulation for the analysis of crop growth and soil-plant-water relations under climate change environmental conditions. This broad study is an attempt to translate the main abiotic factors determining the productivity of arable crops into modular software tools to support the estimation of crop productivity under a variety of conditions (including scenarios of climate change). In particular, a software library (namely, AbioticDamage) was recently developed for modelling plant responses to abiotic stresses, and incorporated into a library (namely, CropML) of process-based models for estimation and monitoring of crop growth and health. Using a gridded weather dataset, an analysis was run in this study to simulate crop responses in Europe for determining the effect of abiotic stresses. The analysis was performed using rice (*Oryza sativa* L.) and winter wheat (*Triticum aestivum* L.) - cereal crops that are central to the economy of many regions worldwide - to gather information under stress conditions. Both cereal crops are affected by climate change as climate extremes are known to affect their growth and reduce their productivity (e.g. Jagadish et al., 1995; Tao et al., 2004). For rice, rising temperatures could make spikelets - the slender branches containing rice flowers - sterile, and grain yields fall (e.g. Matthews and Wassmann, 2003, Mohammed and Tarpley, 2009; Patil et al., 2009).

In this paper, we focus on the European Union (EU-27) with the aim to illustrate the potential power of modelling tools in capturing the effect of abiotic disturbances on cereal yield. Annual grain yield was chosen as it is a singular representation of the culmination of diverse biophysical processes. In Section 2, we present the study area, the weather database, and the modelling tools for simulation of crop growth and abiotic stresses. In Section 3, the spatial pattern of abiotic disturbances on rice (spikelet sterility) and winter wheat (frost) yields are shown. Results are discussed mainly comparing simulation runs with and without the simulation of the impact of either abiotic stress factor. Finally, remarks are made concerning the bearing of the findings on a wider interpretation of climate impacts and the need for future studies.

2. MATERIALS AND METHODS

2.1. The crops and study area

Wheat is one of the main crops grown in Europe, covering about 50% of the total area sown with grain crops. The European Union is the world first producer of this crop (124.7 million metric ton in 2007, FAOSTAT, http://faostat.fao.org/, with France and Germany the main producers, EUROSTAT New Cronos database, http://ec.europa.eu/eurostat). In the EU, winter wheat is predominantly grown. The winter exposes young wheat seedlings to many kinds of stresses: direct frost effects, cold winds, snow cover, intense freezing and glaciation of the soil, frost lifting in spring and various diseases which thrive in or can withstand the cold.

Rice is not a major food crop in Europe. The 27-country European Union (EU-27) is only 17th among the main world rice producers. However, rice consumption has steadily increased during the last years and, also for this crop, the European Commission is interested in periodic production estimates at EU-27 level (Confalonieri et al., 2009a). The rice growing area within the European Union is mainly around the Mediterranean area, where Italy and Spain are the main producers. Mediterranean climate is characterized by summer drought and by a cool wet period in winter. In general, the period of high temperatures and water stress in spring and summer imposes restrictions to crop yields. High variation in rainfall between years also determines important variability in grain yields, with little impact on rice crops run in paddy soils. Damage to rice yield caused by spikelet sterility is one of the most severe constraints in rice production, largely depending on cold air irruption occurring during the panicle initiation-heading period.

Although there are uncertainties about the degree of the projected changes, projections anticipate that the mean European temperature will rise by 1.0-5.5 °C by the end of the 21st century (IPCC, 2007). In winter, this warming trend is expected to be greater over Eastern Europe, whereas in summer it is expected to be more important over Western and Southern Europe (Georgi et al., 2004). In Northern Europe, winter warming is projected to be greater than in summer, with the reverse trend expected for Southern and Central Europe (Raeisaenen et al., 2004). Cold winters, which occurred on average once every 10 years in the period from 1961 to 1990, are likely to become rare in Europe (European Environmental Agency, 2005). While it is likely that future climate with increasing minimum temperatures will cause overall fewer cold days, the risk for spikelet sterility might not be lower as it is affected by the timing of phenological events.

2.2. The modelling tools

Two software components – CropML and AbioticDamage – were developed in C# under the Microsoft .NET platform and linked to the MARS (Monitoring Agriculture with Remote Sensing) database (Micale and Genovese, 2004) of the European Commission - Joint Research Centre (Ispra, Italy). Spatial resolution of weather and management data is 50 km × 50 km, the standard of the Crop Growth Monitoring System (CGMS) of the European Commission (Micale and Genovese, 2004).

CropML is a library implementing different approaches to model crop growth and development. Models are implemented using a fine granularity, and they are also used in composite structures which can be used as simulation models in applications. The modeling approaches currently operational are CropSyst (Stöckle et al., 2003) and WARM (Water Accounting Rice Model; Confalonieri et al., 2009a, b). Other approaches (e.g.

WOFOST [WOrld FOod STudies], CERES [Crop Environment REsource Synthesis], STICS [Simulateur mulTIdisciplinaire pour les Cultures Standard]) are under development or testing.

AbioticDamage is a component implementing several approaches for the simulation of abiotic damages affecting crops. Models are implemented using the strategy pattern, with a fine granularity. The models currently implemented belong to six categories: lodging, frost, cold-induced spikelet sterility, heat-induced spikelet sterility, ozone, and salinity. 'Lodging' is implemented using the approach proposed by Baker et al. (1998), modified by Acutis et al. (2008), assuming that the dominant factor affecting lodging is the wind inducing a bending moment at the stem base. 'Frost' (Ritchie, 1991) calculates crown temperature, hardening and de-hardening index, the possible reduction in leaf area index, and evaluates if the crop has been killed by the frost event. 'SterilityCold' implements two alternate approaches, proposed respectively by Confalonieri et al. (2009a) and Shimono et al. (2005). A context strategy allows the automatic choice between them according to the availability of inputs. The Confalonieri approach is based on the computation of hourly stresses which are summed to compute the daily stress. The Shimono approach is based on the direct computation of daily stress but requires the calibration of some empiric parameters. The different susceptibility to sterility in the period between panicle initiation and heading is accounted for by both the models. 'SterilityHeat' implements the approach proposed by Challinor et al. (2005) for the simulation of high temperature stress. It calculates the critical temperatures, according to the different sensitivities to heat stress of three groups of genotypes, the flowering distribution and the actual fraction of pods which set. 'Ozone' contains a complex model for the simulation of damage due to atmospheric ozone concentration. It implements a model for leaf aerodynamic and boundary layer resistance (Spiker et al., 1992), the calculation of average leaf conductance proposed by Georgiadis et al. (1995), and the fractional reduction of plant production as a function of the ozone flux through the stomata and the leaf conductance of water, using the approach of Sitch et al. (2007). 'Salinity' implements two different approaches, proposed respectively by Ferrer-Alegre and Stöckle (1999) and by Karlberg et al. (2006). The former is based on the calculation of plant conductance and then of a function for the estimation of salinity stress at different layers of the vegetation. The Karlberg approach calculates the reduction of nutrients partitioned to the leaves due to salinity stress on the roots.

Both the components (available at http://agsys.cra-cin.it/tools together with related help files and code documentations) can be freely used and distributed by modellers and developers in their own applications, if the application contains either a dedicated menu item or a dedicated button calling the `Info()` method of the component, and links to the original help file. This method displays information about the component and a button which activates the help of the component.

2.3. The case studies

Two illustrative case studies are presented using the two components. The first is based on the CropML – CropSyst model, parameterized for winter wheat, and on the AbioticDamage – Frost model. The crop is sown in autumn and the effects of frost events at spring restart are presented. The second case study aims at simulating the effect of cold air irruptions on rice spikelet sterility during the pre-flowering period. In this case, AbioticDamage – Sterility (Confalonieri modelling solution) and CropML – WARM are used. In both case studies, the climate variability was simulated using datasets covering the selected cultivation area (EU-27) over the period 2002 - 2008.

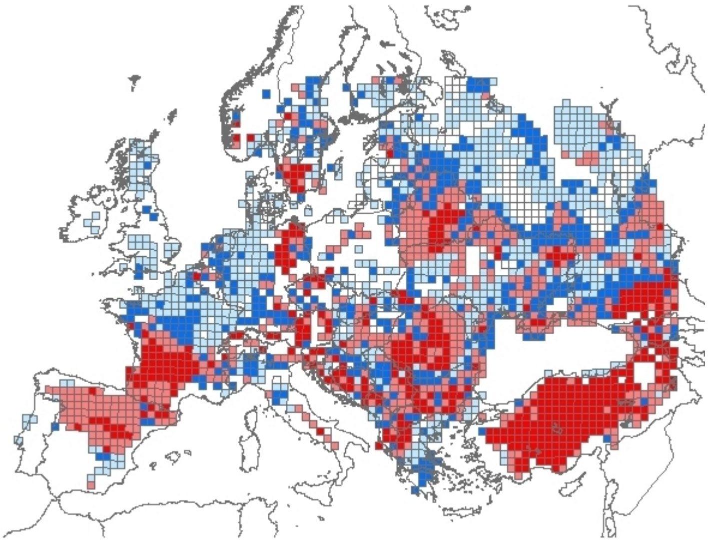

Figure 1. Average (years 2002 - 2008) percentage of winter wheat aboveground biomass reduction due to frost damages.

3. RESULTS AND DISCUSSION

For both the case studies, simulated damages (percentage of wheat above ground biomass reduction or percentage of rice spikelet sterility) are indicated as follows: no cell refers to undamaged crop; white cells refer to less than 1% damage; light blue refers to damage between 1% and 5%; dark blue refers to damage between 5% and 10%; light red refers to damage between 15% and 20%; dark red refers to more than 20% damage.

3.1. Case study 1. Frost damages to winter wheat aboveground biomass at spring restart

Average (years 2002 - 2008) and 2002 percentages of aboveground biomass reduction due to frost damages are shown in Figures 1 and 2 respectively.

It is possible to notice that, although average values present widespread damages due to the occurrence of frost events in different parts of Europe in the different years, 2002 is characterized by severe damages in some of the most important European winter wheat producers (e.g., France).

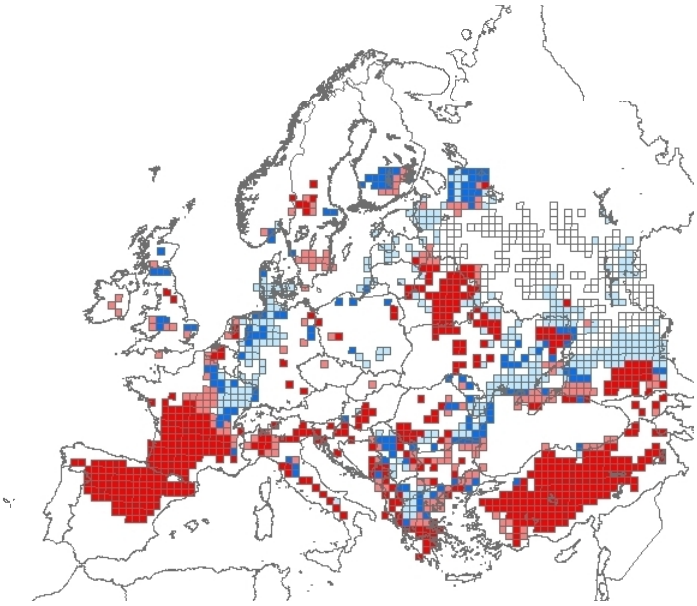

Figure 2. Percentage of winter wheat aboveground biomass reduction due to frost damages for the year 2002.

3.2. Case study 2. Rice spikelet sterility caused by pre-flowering cold air irruptions

Simulated percentage of rice spikelet sterility due to pre-flowering cold air irruptions is shown in Figure 3 (average for the years 2002 - 2008) and 4 (year 2007).

Rice producing countries from Eastern Europe constantly experience a certain degree of sterility (about 5%). Mediterranean countries are normally less affected, although summer temperature falls may cause severe sterility problems in some years (e.g. 2007; Figure 4). In case of frost damages to winter wheat, if the crop is not killed by the frost event, the percentage of damages simulated immediately after an event does not give a reliable indication about the consequent yield losses. On the contrary, the percentage of spikelet sterility is a suitable indicator of the expected yield losses. This gives an idea of the importance of the damages shown in Figure 4.

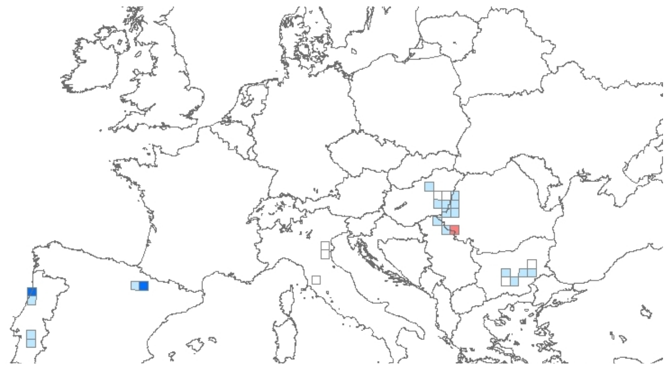

Figure 3. Average (years 2002 - 2008) percentage of rice spikelet sterility due to pre-flowering to cold air irruptions.

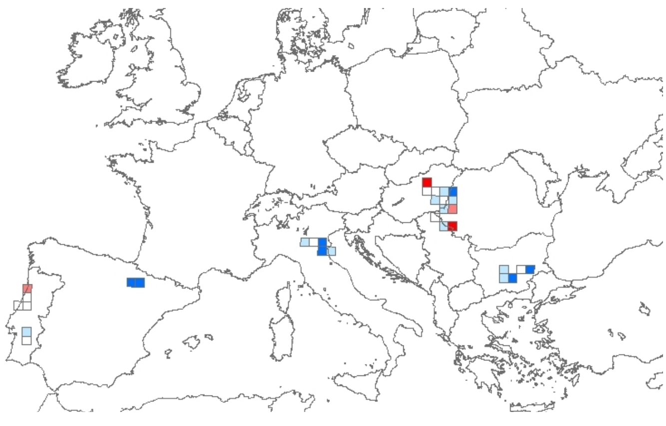

Figure 4. Percentage of rice spikelet sterility due to cold air irruptions for the year 2007.

4. CONCLUSIONS

The present study offers an evaluation of abiotic stress models developed from the domain research but to-date only partially translated into modelling tools of large use. Two modelling libraries of new creation (and developed according to modern software engineering tendencies) were used to quantitatively assess the distribution of abiotic conditions over Europe in relation to winter wheat and rice grain yields. Although only illustrative, the simulations presented in this paper proved useful in interpreting the impact of climatic alterations that have occurred in Europe in the last 7 years.

The identification of climate boundaries (areas with homogeneous climate) of abiotic scenarios (e.g. frost scenarios) on a regional scale is important for understanding the climatic features and their potential impact on local agro-systems. The results gained from the present study encourage the use of modelling tools to develop finer estimations or probability maps of the abiotic stresses. Because of the spatial and temporal variability and multiple impacts of abiotic disturbances, there is a need to improve the tools and data available for mapping and monitoring these phenomena at a variety of scales.

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