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Improving cereal yield forecasts in Europe – The impact of weather extremes

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ABSTRACT

The impact of extreme events (such as prolonged droughts, heat waves, cold shocks and frost) is poorly represented by most of the existing yield forecasting systems. Two new model-based approaches that account for the impact of extreme weather events on crop production are presented as a way to improve yield forecasts, both based on the Crop Growth Monitoring System (CGMS) of the European Commission. A first approach includes simple relations – consistent with the degree of complexity of the most generic crop simulators – to explicitly model the impact of these events on leaf development and yield formation. A second approach is a hybrid system which adds selected agro-climatic indicators (accounting for drought and cold/heat stress) to the previous one. The new proposed methods, together with the CGMS-standard approach and a system exclusively based on selected agro-climatic indicators, were evaluated in a comparative fashion for their forecasting reliability. The four systems were assessed for the main micro- and macro-thermal cereal crops grown in highly productive European countries. The workflow included the statistical post-processing of model outputs aggregated at national level with historical series (1995–2013) of official yields, followed by a cross-validation for forecasting events triggered at flowering, maturity and at an intermediate stage. With the system based on agro-climatic indicators, satisfactory performances were limited to microthermal crops grown in Mediterranean environments (i.e. crop production systems mainly driven by rainfall distribution). Compared to CGMS-standard system, the newly proposed approaches increased the forecasting reliability in 94% of the combinations crop × country × forecasting moment. In particular, the explicit simulation of the impact of extreme events explained a large part of the inter-annual variability (up to +44% for spring barley in Poland), while the addition of agro-climatic indicators to the workflow mostly added accuracy to an already satisfactory forecasting system.

1. Introduction

The agricultural sector needs timely and reliable crop production forecasting and early warning systems, which are increasingly becoming important in both developed and developing countries (Bouman, 1995; Atzberger, 2013). This need reflects increasing pressures from food demand, price-competition induced by market globalization as well as food price levels and volatility (G20 Agriculture Action Plan, http://www.amis-outlook.org/fileadmin/user_upload/amis/docs/2011-agriculture-plan-en.pdf). In addition to several agronomic and economic factors, agricultural production strongly depends on the varying weather conditions from season to season and year to year (Supit, 1997). Policy decisions relating to food security (that is, food-supply chains through procurement, stock management, marketing, and distribution networks) would be enhanced if supported by a reliable system for food crop production forecasting (Lazar and Genovese, 2004). For instance, early warning in case of anomalous seasons (e.g., owing to severe heat and water stress) may enhance the

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capacity of regional and national decision makers to assure food imports and regulate the agricultural market (Bannayan and Crout, 1999; Atzberger, 2013). The variety of systems developed in the last decades for the forecasting of crop yields are usually nationwide (e.g., Bezuidenhout and Singels, 2007a, 2007b; Duveiller et al., 2013). Most of these systems are based on the single or combined use of agro-climatic indicators (e.g., Balaghi et al., 2012), remote-sensing information (Wang et al., 2010; Fernandes et al., 2011; Son et al., 2014) and crop models (Vossen and Rijks, 1995; de Wit et al., 2010; Kogan et al., 2013). The effect of weather conditions on agricultural production can be quantified by predictive models built on statistical relationships between a few agro-climatic indicators and crop yields. However, only where crop production fluctuations are driven by a few main meteorological factors these simple relationships can accurately explain the inter-annual variability of crop productivity and reliably forecast final yields (Balaghi et al., 2012). Other, more reliable methods, are used by policy makers in the provision of crop yield forecasts based on simulation modelling. To the best of authors' knowledge, the most sophisticated forecasting system in agriculture at present is the Crop Growth and Monitoring System (CGMS). It was developed by the European Commission Joint Research Centre (JRC), within the Monitoring Agricultural ResourceS (MARS) activities, to provide short-term (in-season) forecasts of the yield of the main food crops in Europe (Vossen and Rijks, 1995; Lazar and Genovese, 2004; de Wit et al., 2005). The MARS system is based on the WOFOST crop model (van Keulen and Wolf, 1986; Rabbinge and van Diepen, 2000), used to simulate development and growth for all crops but rice. For the latter, the rice-specific WARM model (Confalonieri et al., 2009) is used.

The simulation tools used within forecasting systems are based on models of plant response to environment, which were developed for conditions of good adaptation and often designed for seasonal patterns reflecting temperature and precipitation regimes of temperate environments. Consequently, the effects of unusual meteorological events over crop performance – including crop failure – are thus often overlooked or unsatisfactorily simulated by the available crop models. In general, they are able to adequately predict mean yields but not the inter-annual variability of productivity, due to their inability to handle climate extremes (Eitzinger et al., 2013; Sanchez et al., 2013). This limitation is critical to investigate the crop response under ongoing climatic change, which is expected to bring increased levels of extreme weather and problems for the agricultural sector in many regions of the world (Parry et al., 1999; IPCC, 2007b). Europe (the focus of this study) is one of the most productive food suppliers in the world. The harvested production of cereals in the EU-28 represented about 13% of global production in 2014 (FAO; http://www.fao.org/faostat/en), making EU a major world producer of cereal grains. Many studies have been focused on the impacts and adaptation of European crop productivity to climate change (Falloon and Betts, 2010; Reidsma et al., 2010; Olesen et al., 2011). Significant warming is projected by the 2030s, affecting winter season in the North of Europe, and summer months in southern and central European countries (IPCC, 2007a). Moreover, an increase in the frequency, intensity and duration of extreme weather events, which have already caused huge yield losses in the past years, is expected in Europe. An increased occurrence of heat waves and related drought events have already been registered in large parts of western and eastern countries, especially in the Mediterranean belt (Trenberth et al., 2007). As an example, in 2003, the combined occurrence of heat and drought in large parts of Europe led to considerable losses in agriculture (Ciais et al., 2005). It is very likely that the frequency and severity of drought spells and heat waves will further increase especially in southern and central parts of the continent (Beniston et al., 2007; Calanca, 2007). An increase of the intensity of rainfall events has been observed in most parts of the continent with severe damages caused by summertime flooding (Christensen and Christensen, 2003). In spite of the warming climate, cold shocks, including both chilling and freezing injuries, is still an important abiotic stress factor for agricultural plants (Kasuga et al., 1999; Lang et al., 2005). Indeed, the current trend toward an increased number of days with frost events in some areas is expected to remain stable until the mid–2030 s (Crimp, 2014).

Most of the abiotic shocks affecting plant growth (e.g., heat and cold waves, frost events, water shortage) are caused by dynamics in weather variables for which the crop is not able to provide a suitable physiological response during the most sensitive phenological phases. Studies do exist in which models have been developed to better reproduce the effects of extreme weather events on crop yields. For instance, the effect of high (Prasad et al., 2008) and low (Thakur et al., 2010) temperatures on spikelet sterility during the reproductive phase of crop plants were extensively studied. Different approaches were developed to reproduce cold/heat effects on crop growth and yield formation (Challinor et al., 2005; Shimono et al., 2005; Confalonieri et al., 2009; Asseng et al., 2011; Eyshi Rezaei et al., 2014; van Oort et al., 2015). Damages on winter crops caused by frost stress have been observed at each growing stage (Fuller et al., 2007), with increased frost sensitivity during new shoot development (vegetative recovery) in spring. Different approaches were developed which account for frost effects on leaf area development (CERES-Wheat – Jones et al., 2003; InfoCrop – Aggarwal et al., 2006), leaf senescence (APSIM – Holzworth et al., 2014) and total biomass accumulation (EPIC – Williams et al., 1989). The crop model STICS (Brisson et al., 2003) quantifies the impact of frost on seedling density, leaf senescence and grain number.

Considering that more than half of wheat production areas worldwide already experience heat stress during the most sensitive moments of the growth cycle (Cossani and Reynolds, 2012; Alderman et al., 2013), special attention is placed in the modelling of wheat response to rising temperatures. For instance, Asseng et al. (2015) used an ensemble approach to evaluate the reduction of wheat yields in artificially heated field experiments.

For other extreme weather events (e.g., hail, wind-induced lodging, flooding) the relation with crop growth and production may be less straightforward. The circumscribed nature of these events makes difficult to obtain reliable input data for the modelling purpose and it is essentially for these reasons that only a few studies are available that look at the impact of weather extremes on crop production. For instance, the approach by Baker et al. (1998) calculates the risk of stem and root lodging from crop parameters and soil characteristics.

In this paper, we present novel approaches for the simulation of the impacts of extreme weather events (i.e., heat, cold, frost and water stress), as developed within the activities of the EU FP7 project MODEXTREME – Modelling vegetation response to extreme events (http://modextreme.org) and incorporated within the CGMS forecasting system.

We evaluated the new system for the most representative cereal crops in Europe.

2. Methods

Four alternative forecasting systems were assessed for their ability in explaining inter-annual crop yield fluctuations in Europe:

- "simple", based on agro-climatic indicators (Section 2.2.1);
- "standard", i.e. CGMS used for crop yield forecast in Europe (Section 2.2.2);
- "improved", based on CGMS with the inclusion of approaches for the simulation of the effects of extreme meteorological events on crop yield (Section 2.2.3);
- "hybrid", which combines the three previous systems.

2.1. *The forecasting methodology*

According to the standard methodology used by the European Commission (de Wit et al., 2005; Pagani et al., 2017), the outputs generated by the four forecasting systems (see Table 1) were