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Crop planting date matters: Estimation methods and effect on future yields

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ABSTRACT

Productivity of arable lands highly depends on the management techniques and their timing. Climate change urges the need for adaptive management tools, such as methods for optimization of planting date (PD). In existing crop models PD is usually specified by the user as a fixed date or through a set of rules which depend on diverse environmental conditions. However, validated rules of PD calculation are rare in the existing literature. In this study we strived to develop methods that could reliably estimate the PDs based on soil temperature and soil moisture, as well as to provide tool for PD projections under climate change. PD data from 294 agricultural enterprises in Hungary during the period from 2001 to 2010 were used to validate the PD methods. Effect of climate change on the timing of PD was evaluated using an ensemble of 10 climate change projections. Meteorological and soil data were obtained from the Open Database for Climate Change Related Impact Studies in Central Europe (FORESEE) and Soil and Terrain (SOTER) databases. The 4M crop model was used for crop yield simulations. Relative to the present day conditions, our analysis predicts a shift to earlier PDs for maize (approx. 12 days) and later PD for winter wheat (approx. 17 days) for the 2071–2100 period. The results indicated that maize PDs should be changed according to the earlier start of the growing season in spring. In contrast, currently used PDs should be preserved for winter wheat to avoid climate change related yield loss. Our analyses showed that the proposed PD estimation methods performed better than other eight tested methods. The advantage of our novel rules is that they could be applied for other crop models, as well.

1. Introduction

Food security is one of the most important global challanges with respect to the continuously growing population (Godfray et al., 2010; Foley et al., 2011). At global scale, arable land covers ~12% of the terrestrial land surface (Drewniak et al., 2013). The productivity of agricultural lands is greatly affected by applied management practices (e.g. planting, irrigation, fertilizing, tilling, harvesting, weed management) and their timing (Twine et al., 2004). Sustainable agricultural production is essentially required to provide food and fibre for the world's population, and to feed the livestock, which could be potentially supported by appropriate, adaptive management practices (Godfray et al., 2010; Tilman et al., 2011).

Agro-ecological models are often used in climate change and food security related studies (Rosenzweig and Parry, 1994; Parry et al., 2004; Ewert et al., 2005; Bondeau et al., 2007; Fodor and Pásztor, 2010; Bassu et al., 2014) to predict the future crop production. The models typically use climate, soil, crop ecophysiological parameters and management information to provide estimates of future yields as well as of the effect of diverse management practices (Mo and Beven, 2004; Baigorria et al., 2008; Ewert et al., 2002; Ma et al., 2012). Specific "*in silico* agronomic trials", where modellers keep specific conditions unchanged (e.g. management, crop genotypes) and only test effects of changes in some model parameters were found supportive to identifying variables which are worth to be addressed by management decisions (Alexandrov et al., 2002;

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Alexandrov and Eitzinger 2005; Olesen et al., 2011). This approach is particularly useful as future crop production will be modulated by changes in a multitude of factors, such as temperature, precipitation patterns, atmospheric CO_2, extreme events, pests, change of crop cultivars, irrigation practices etc., which are difficult to capture and evaluate by farmers (Gornall et al., 2010; Olesen et al., 2011). Such complex issues can be addressed by models effectively, and responses of production indicators to selected treatments can be tested. Still, field experiments are inevitably needed to parameterize the models and justify the relevance of modelling outputs.

Planting date (PD) is a fundamental management information, which is typically required by crop models (Waha et al., 2012). Timing of sowing has a considerable effect on the yields (Kucharik, 2008) due to the variability of weather (timing and amount of wet and dry periods, temperature variability) that strongly interacts with crop phenophases (Drewniak et al., 2013; Tsimba et al., 2013; Wolf et al., 2015).

Climate change has already been found to modify plant phenology mainly due to the extension of the growing season in many areas (Penuelas and Filella, 2001; Estrella et al., 2007; Lobell and Field, 2007; Olesen et al., 2011). Shifts in precipitation patterns (e.g. the expected decrease in summer precipitation in Central Europe; Pongrácz et al., 2011; Dobor et al., 2015) together with earlier growing season start require reconsideration of existing PDs in order to avoid drought induced yield loss. In order to create adaptive agro-ecological simulations, realistic estimations of human management practices are needed, including planting practice and its potential changes in the future.

Three PD estimation methods are used in crop modelling for different purposes (Waha et al., 2012). The first method uses predefined, constant PDs based on observations, typically representing average planting time for some period (De Noblet-Ducoudré et al., 2004; Fodor and Pásztor, 2010; Cammarano et al., 2012; Drewniak et al., 2013; Elliott et al., 2015). Some studies optimized the PDs in order to maximize the yield (Stehfest et al., 2007; Waongo et al., 2015; Wolf et al., 2015). The third approach uses climate data to estimate the optimal conditions for a given crop for planting (Jones et al., 2003; Bondeau et al., 2007; Waha et al., 2012; Holzworth et al., 2014), and can be particularly useful in climate change impact studies. The present study mainly focuses on the first and the third methods.

In addition to the fixed PD option, the majority of state-of-the-art crop models allow to define the so-called rule-based PDs (Moore et al., 2014). For example, the CropSyst model (version 4.12.10) determines the PD by air temperature and the actual soil water content (Stöckle and Nelson, 1996; Stöckle et al., 2003). The STICS model uses soil moisture and precipitation thresholds to determine the PD (version 5.0; Brisson et al., 2003). In the DSSAT model soil water content, management depth for water and soil temperature thresholds need to be set to estimate PD within a given sowing window (version 4.6, Jones et al., 2003; Hoogenboom et al., 2015). The APSIM model provides opportunity for user-defined sowing rules based on any internally calculated model variable (version 7.7, Keating et al., 2003; Holzworth et al., 2014), which provides more flexibility than the other models.

It is notable that in these state-of-the-art models the modeller has a large degree of freedom in rule definition, and no region-specific, ready-to-use (default for a given region and/or crop) rules are available. This means that the modeller might (unintentionally) choose rules that provide unrealistic PDs for a given region.

Most of the studies in the literature estimate PDs based on air temperature only (De Noblet-Ducoudré et al., 2004; Drewniak et al., 2013; Waha et al., 2012; Deryng et al., 2011) but fixed-day have been used as well (De Noblet-Ducoudré et al., 2004; Drewniak et al., 2013; Elliott et al., 2015). Another approach is to use the so-called crop calendars that were constructed based on long term observations providing a fix PD for a given location (MIRCA2000, Portmann et al., 2010; Crop Calendar, Sacks et al., 2010). A few studies consider soil moisture and precipitation (Leenhardt and Lemaire, 2002; Maton et al., 2007; Trnka et al., 2011).

Available, climate dependent methods (e.g. Waha et al., 2012) perform quite well on global or continental scale, but their applicability in smaller scales is questionable (Sacks et al., 2010; Waha et al., 2012; Drewniak et al., 2013). Consequently, a lack of region-specific and ready-to-use, validated rules hampers the application of crop models. In this study, we exploited of a unique PD database to test the applicability of the methods. Application of this observation-based dataset ensures the realism in the PD modelling methods.

In many crop land areas (including Hungary, which is investigated in this study), PDs depend on meteorological conditions of the given year. Farmers start sowing when they find the conditions suitable for germination. In the Hungarian agricultural sector, soil temperature is measured at 10–12 cm depth, where the temperature required for different cultivars of maize is 8–12 °C (Vágvölgyi and Varga, 2011). Soil moisture has been also used in Central Europe to define the PDs (Eitzinger et al., 2012); specifically, low moisture holds seed germination, while too high moisture may prevent the farmers to use the sowing machinery in the field.

Weather forecasts are also used to support the decisions on PDs definition (Das et al., 2012). If soil conditions are favourable, farmers might use a weather forecast to determine the optimal time for the pre-emergent weed control. The chance of rain in the forthcoming days might trigger sowing especially if the soil is dry.

Availability of the machinery needed for sowing also affects the PD. In practice, the tractors used for sowing might be available for the farmer within a given time frame which can clearly overwrite other considerations.

The mathematical representation of the farmers' decisions that affect the PD is challenging because of a large portion of subjective factors included in such decisions. In our study we focused only on those factors that can be quantitatively described in order to construct a PD estimation method that can support crop models, and can be used to evaluate the effect of climate change on PD timing, as well.

The main aims of this study are: 1) evaluate the performance of available, literature-based PD estimation methods in Hungary; 2) develop new, rule-based methods that improve the PD calculations for maize and winter wheat; 3) identify PD estimation methods that best match the observed PDs and can be used for PD determination in crop models; 4) estimate the impact of climate change on the calculated PDs and subsequently on crop yields; 5) develop recommendations for sowing date planning under changing climate.

The paper focuses on maize and winter wheat due to dominance of these crops in Central Europe. This study strives to support crop yield modelling in Europe by regional calibration of crop models, focusing particularly on PD assessment, and thus improve the options for planning under transient environmental conditions.

2. Materials and methods

2.1. Climate data and target area

Weather dependent PDs were simulated based on the FORESEE database (Open Database for Climate Change Related Impact Studies in Central Europe; Dobor et al., 2015). FORESEE was developed to support the research of, and adaptation to climate change in Central and Eastern Europe. FORESEE contains the seamless combination of gridded daily observation-based data (1951–2013) built on the E-OBS (Haylock et al., 2008) and CRU TS 1.2 datasets (Mitchell et al., 2004), and a collection of climate projections (2014–2100).