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Modelling the effects of climate variability on spring wheat productivity in the steppe zone of Russia and Kazakhstan

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ABSTRACT

Spring wheat is the principal crop in the steppe zone of Russia and Kazakhstan, but wheat productivity levels are currently low and susceptible to weather and climate anomalies. Water scarcity during the growing season represents a major stress factor and is expected to negatively affect wheat production in the future as well. In this paper we present a simple mechanistic model for assessing the impact of climate variability on spring wheat productivity in the steppe zone of Russia and Kazakhstan. The novel aspect of the model development is represented by the adoption of an adaptive approach for the formulation of growth partitioning. In spite of simplifying assumptions the model is shown to satisfactorily reproduce yield levels observed both at the local scale under controlled conditions as well as at the regional scale. The model is able to capture a significant percentage of the observed year-to-year variability of wheat yields. Results of the model application indicate that, for the steppe zone of Russia and Kazakhstan, seasonal water shortage is likely to cause yield deficits of 20–25%, with deficits of up to 40% in extreme years, and an increase in the coefficient of variation of yields.

1. Introduction

Russia and Kazakhstan are, along with the Ukraine, main grain producing and exporting countries and are expected to become a major player in the global grain market during the coming decades (Liefert et al., 2010), providing a substantial contribution to meet the anticipated demand for grains of an steadily increasing world population (Tilman et al., 2011; OECD/FAO, 2012; Ray et al., 2013).

The agricultural sector in Russia and Kazakhstan has experienced remarkable structural changes in the early 1990s after the collapse of the former Soviet Union (de Beurs and Henebry, 2004; Lioubimtseva and Henebry, 2012), which had implications for agricultural production. As a result, in these countries today's wheat productivity is relatively low, averaging to 1.9 t ha^{-1} in Russia and 1.1 t ha^{-1} in Kazakhstan (Rosstat, 2013; National Agency of Statistics of the Republic of Kazakhstan, 2013). Besides, yield levels are increasing only slowly, at an annual rate of approximately 0.025 t $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ in Russia and 0.015 t $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ in Kazakhstan, which could reflect the negative impacts of climatic trends observed in recent decades (Lobell et al., 2008).

According to the Köppen–Geiger classification, the wheat cultivation areas of the Northern Caucasus, the Volga region, Ural, Siberia and Northern Kazakhstan are characterized by a temperate continental climate in the north and a cold semi-arid climate in the south (Peel et al., 2007). Climatic conditions for agriculture are thus for the most part very harsh, with extremely cold winters, a short growing season, frequent droughts and often unfavourable field conditions at harvest. This seriously limits the potential for crop productivity and explains substantial yield variations from year to year (Doraiswamy et al., 2002; de Beurs and Henebry, 2004). In spite of the adoption of improved wheat cultivars (Lioubimtseva and Henebry, 2012) seasonal drought represents a major stress factor (Morgounov et al., 2001) and has been identified as the main reason for the yield drops recorded in 2010 and 2012 (UNDP, 2012; USDA, 2013). Based on the analysis of long-term climatic records, Dronin and Kirilenko (2008) estimated that in the area between the lower Volga and the Urals arid conditions during the growing season of wheat prevail in about every other year.

Given this background, the question of how climate fluctuations and water scarcity affects wheat production in Russia and Kazakhstan under current and future conditions is of primary concern. Because of the limited possibilities to examine relevant processes and interactions in field experiments, modelling tools are essential to understand how crop growth responds to weather and climate anomalies. Crop simulation models are also valuable instruments for assessing the effectiveness of different technological and

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agronomic options on crop productivity. In the light of climate change, they become indispensable for exploring possibilities for adaptation.

The goal of this paper is to present a simple model of spring wheat productivity that is suitable for assessing the effects of climate variability and change on wheat yields in Russia and Kazakhstan on the basis of standard agro-meteorological information. The work reported here is a continuation of past efforts carried out at the National Research Institute on Agricultural Meteorology to develop both process-based crop simulation models for operational forecasting and climate change impact assessments (e.g. Sirotenko, 1996, 1997, 2012; Sirotenko et al., 1997) as well as statistical models (Sirotenko and Pavlova, 2010).

As opposed to earlier models written by the National Research Institute on Agricultural Meteorology, in particular the WEATHER-YIELD model (Sirotenko et al., 1997), and other widely used models and decision support systems, e.g. WOFOST (van Diepen et al., 1989), Sirius (Jamieson et al., 1998), DSSAT (Jones et al., 2003) or CropSyst (Stöckle et al., 2003), the one presented here has the advantage of being less demanding in terms of input data and computational time. It is therefore well suited for sensitivity analyses and operational applications at scales ranging from the local to the national.

Compared to production functions widely used in agricultural economics (Just and Pope, 1978, 1979; Carew et al., 2009), models of the FAO type that estimate yields on the basis of a crop-water production function (Doorenbos and Kassam, 1979) or statistical models (Sirotenko, 1996; Lobell et al., 2008; Sirotenko and Pavlova, 2010), the present model offers the advantage of relying on a mathematical formulation of the main processes determining crop dynamics: timing of developmental phases, assimilation of carbon via photosynthesis, acquisition of water and nutrient by the root system, and allocation of assimilates to one of three compartments (above-ground vegetative organs, grains, and the root system).

Although management decisions have a considerable influence on crop productivity, up till now the focus of the model development was on a realistic formulation of rainfed wheat production. A key feature of the model is that it adopts an adaptive approach to express the partitioning of newly assimilated biomass into various plant compartments. In dynamic crop models of the first generation growth functions were implemented according to morphogenetic principles as deterministic analytic functions of plant biological time, measured by the sum of effective air temperatures (cf. e.g. van Noordwijk and de Willigen, 1987; Wilson, 1988). It is clear, however, that a deterministic approach cannot account for adaptive mechanisms in response to environmental constraints (Brouwer, 1962, 1983). To date, a number of adaptive models have been proposed, in which growth functions are essentially found by solving a problem of optimal control (e.g. Poluektov et al., 2006).

Given the goal of our study and the fact that in semi-arid and arid climates the soil moisture regimes is the crucial factor controlling the acquisition of water as a resource, the adaptive approach is formulated here by including specific response functions to water shortage for growth of the roots and the grains.

2. Materials and methods

2.1. Study area and data

The study area encompasses the steppe belt stretching from southern Russia (lower Volga) to north-eastern Kazakhstan. Four sites within this area were considered for developing and testing the model (Fig. 1). As seen from the basic climate statistics listed in Table 1, compared to the Russian site (Yershov) the three sites in Kazakhstan (Atbasar, Shortandy and Tselinograd) are characterized by slightly lower temperatures, lower annual precipitation amounts, but higher seasonal precipitation amounts during May–July, i.e. the critical months for spring wheat growth (Morgounov et al., 2001; Sommer et al., 2013).

Fig. 1. Map of Russia and Kazakhstan with the location of the study sites.

High quality data for the model development were obtained from the Yershov experimental station (Saratov region, Russia) and the experimental station of the Barayev Grain Research Institute at Shortandy (Akmola region, Kazakhstan). Data for both stations include a comprehensive weather record, a record of annual yields, ancillary data regarding sowing dates and management and field data, as well as a limited amount of phenological dates. Note that the latter are not sufficient to allow a full calibration and verification of the description of phenology in the model.

The data for Yershov cover the period 1951–2002. Data for 1951–1976 were used for the model calibration, whereas data for 1977–2002 was used for the model verification and application. The data for Shortandy cover the period 1986–2009.

The two experimental stations are situated in the dry steppe area. Soils in Yershov are black soils, whereas in Shortandy they can be considered as belonging to the southern type of black soil. According to the standard Russian classification they can be classified in both cases as Chernozems (Sommer and de Pauw, 2011, p. 278).

To test the model ability to simulate yield representative for the regional scale, additional weather and yield data were obtained for the Tselinograd and Atbasar districts in the Akmola region, Kazakhstan. The weather data are those from the weather stations at Astana (Tselinograd) and Atbasar. They were provided by the national weather services, and cover the period 1986–2009. Productivity data for the same period were collected from the regional offices of statistics and represent average yields at the district level. The time series were tested for the presence of a time trend (Conradt et al., 2012). A third degree polynomial trend was found in the yields series for Tselinograd. No statistically significant trend could be detected in the time series from Atbasar.

Farming in Tselinograd and Atbasar is specialized on grain production, primarily spring wheat (Sommer et al., 2013). The average grain sown area during 2005–2009 was 238′200 ha in Tselinograd and 355′900 ha in Atbasar, which correspond to 3.0%, respectively 3.3% of the total district territory. Agricultural landscapes in both districts can be described as medium dry steppe on Chernozems and Kastanizems of medium salinity (Bayekenova and Lebed, 2006).

2.2. Model description

A full description of the model is given in Appendix A, but an overview of the model structure and model components is presented here (Fig. 2).