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The expansion of wheat thermal suitability of Russia in response to climate change

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ABSTRACT

The emergence of Russia as a major grain exporter is not only crucial for the world commercial agriculture and food security, but also for the country's economy. Here we examine the past-to-future thermal suitability for winter wheat (*Triticum aestivum*, L. 1753) cultivation over Russia and compare it with the recent trends of wheat yields and harvested area. The analyses use a multi-model ensemble median of the most updated bias-corrected outputs from five CMIP5 Earth System Models (1950–2099) under two representative concentration pathways (RCP 4.5 and RCP 8.5) and the Era-Interim dataset (1979–2016).

Our results show that the thermal suitability has increased by ~10 Mha per decade since 1980. Consistently, winter wheat yields and harvested area have also increased over the last decade by ~0.5 t/ha and ~4 Mha, respectively. Moreover, a potential for the Russian wheat sector may still be exploited if we consider the abandoned land (~27 Mha) after the collapse of the Soviet Union. Our results also show that the increase in heat availability and the reduction of the frost constraint will likely move the thermal suitability toward the north-western and the Far East regions. Conversely, increases of extreme heat events are projected in the southern regions of Russia, which currently represent the most productive and intensively managed wheat cultivation area. Our findings imply both opportunities and risks for the Russian wheat sector that calls for sustainable and farsighted land management strategies to comprehensively face the consequences of global warming.

1. Introduction

Wheat currently represents the most valuable crop for Russia which ranks among the world's first producers (~60 Mt per year averaged over the period 2013–2016, source: (FAO, 2017)).

During the Soviet time, Russia was a net wheat importer, despite wheat production being higher than the current level, and grain was used mainly to feed livestock (Liefert et al., 2013). After the dissolution of the Soviet Union, the economy of Russia moved toward a more market-oriented system, and the substantial government subsidies to agriculture (which had favored the livestock sector) mostly ended. This severely reduced the livestock sector, as well as domestic demand for and production of feed grains, but which in turn freed up grain output for exports (Liefert et al., 2013). Moreover, plentiful investments from a new class of large, vertically integrated enterprises (i.e. that combine primary agriculture, processing, distribution and sometimes retail sale) have increased the average wheat yields (Liefert and Liefert, 2015a). As a consequence, after 2000 the country's wheat production and exports have started to rise considerably (Fig. 1) up to reach the world's top records. According to the Foreign Agricultural Service of the U.S. Department of Agriculture (USDA, 2018) and the International Grains Council expectations (IGC, 2017), in 2016 Russia exported ~30 Mt of wheat, becoming the world's leading wheat exporter. The emergence of Russia as a major grain exporter is not only crucial for the world commercial agriculture and food security, but also for the country's economy, recently aimed to improve the domestic agriculture as a response to the Western economic sanctions (Liefert and Liefert, 2015b; Bond et al., 2015).

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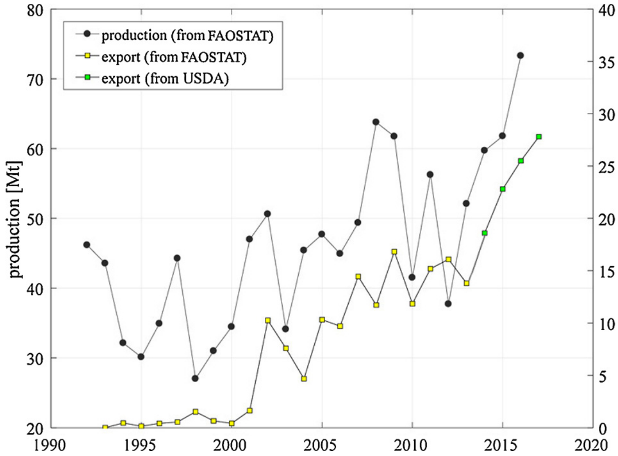

Fig. 1. Wheat production and export since 1992.

Russian agriculture is also likely affected by global warming, which is shifting the agricultural suitability toward the northern latitudes (Zabel et al., 2014; Ramankutty et al., 2002) while increasing the frequency of warm spells in the southern regions (Perkins et al., 2012) where currently most of the grain production takes place (Asseng et al., 2015; Teixeira et al., 2013).

Indeed, projected land suitability over Russian Federation has already been evaluated both by global assessments (Zabel et al., 2014; Zhang and Cai, 2011; Ramankutty et al., 2002) and by regional studies but accounting only for European Russia (Schierhorn et al., 2014), or not accounting for extreme events (Sirotenko et al., 2007). However, an updated evaluation embracing the Ural, Siberia and Far East regions and that considers both the long-term trends and the extreme events is still lacking. Here we present a simple yet informative screening on the past-to-future thermal condition for winter wheat development over the Russian Federation by looking at the fulfilment of wheat heat requirement and the occurrences of stressful heat and frost extreme events. The analyses use a multi-model ensemble approach using the most updated bias-corrected outputs from five CMIP5 Earth System Models (ESMs, Table 1) under two representative concentration pathways (RCP 4.5 and RCP 8.5) and the Era-Interim dataset (Table 1). Overall, in the present article we discuss *i*) the thermal suitability of the recent past (embracing only croplands plus grasslands) with the recent trends of wheat yields and harvested area; *ii*) the projected thermal suitability, heat fulfilment and stressful heat and frost extreme events for two future time frames with respect to a baseline; *iii*) opportunities and risks for the Russian wheat sector emerged from our findings.

Table 1
Climate datasets.

Data source	Institution	Period	Reference
ERA-Interim	European Center for Medium-Range Wheatear Forecast	1979–2016	Dee et al. (2011)
CMIP5-GCMs:		**1950–2099**	
GFDL-ESM3M	Geophysical Fluid Dynamics Laboratory, USA		Donner et al. (2011)
HadGEM2-ES	Met Office Hadley Centre, UK		Jones et al. (2011)
IPSL-CM5A-MR	Institu Pierre-Somni Laplace, France		Dufresne et al. (2013)
MIROC-ESM	AORI, NIES, JAMSTEC, Japan		Watanabe et al. (2011)
NorESM1-M	Norwegian Climate Centre, Norway		Bentsen et al. (2013)

2. Methods

2.1. Wheat heat requirement (growing degree days)

Many crop models predict plant development using the degree days (DD) algorithm (Jamieson et al., 1998; McMaster et al., 1991; Ritchie and Nesmith, 1991; Weir et al., 1984), which gives the timing of crop phenological development. According to its simplest formulation, the DD algorithm totalizes average daily air temperatures above a given temperature threshold (hereinafter *base temperature,* T_0), until a phase is completed (Ritchie and Nesmith, 1991; Wang, 1960). The totalized amount, expressed as growing degree days (GDD), is assumed as an intrinsic characteristic of the crop phase (Davidson and Campbell, 1983; Wang, 1960). The underlying assumption of the DD algorithm is that the rate of crop development (i.e. the reciprocal of the time to mature a given phase, d^{-1}) is a linear function of daily air temperature (Davidson and Campbell, 1983), formally expressed as:

$$Dr = a + b\cdot T \tag{1}$$

Where Dr is the developmental rate [d^{-1}], a and b are empirical coefficients of the linear function, and T is the daily average air temperature [°C]. The intercept of the linear regression with the axis of temperature ($-a/b$) provides the best estimate for the base temperature ($T_{0,}$ °C), while the reciprocal of the slopes (i.e. $1/b$) equals to the crop heat requirement expressed as growing degree days (GDD, °Cd).

Through phenological observations (a phase time length and related average air temperature experienced during that phase) it is possible to verify whether a developmental phase rate is a linear function of daily air temperature and, if so, estimate reliable values for GDD and $T_{0.}$

For our purposes, we use field observations (Fig. S1) on wheat development and corresponding temperature measurement from the work of Podolsky (1984). Data involve four wheat cultivars (Iroda, Kharkovskaya 46, Surkhak 5688 and Shark) collected in different regions of Russian Federation, Azerbaijan, Kazakhstan and Tajikistan (former USSR).

Observed wheat phenological phases from Podolsky (1984) are: 1) from *sowing* to *full mass sprouting*; 2) from *full mass sprouting* to *the beginning of tillering*, 3) from *beginning of tillering* to *full stalk shooting*, 4) from *full stalk shooting* to *heading*; 5) from *heading* to *wax ripeness*. Although the observations from Podolsky (1984) do not follow any widely-established phenological scale (e.g. Zadoks (Zadoks et al., 1974), Feekes (Large, 1954)), they have the advantage of being well contextualised for the study domain (field stations and crop varieties from Russia Federation or regions close to it). Each phase is marked by a unique identification number (*k*, from 1 to 5, Table 2). For each phase, we regress the linear Developmental Rate function (*Dr*) as shown in Eq. (1) using ordinary least squares technique (Fig. S1). The resulting parameters and basic statistics for the single phases are shown in Table 2.

2.2. Stressful hot and frost extreme events

Stressful extreme events are defined as the occurrence of at least three consecutive days of maximum or minimum air temperature above and below, respectively, thresholds temperatures selected from a literature survey and mainly related to wheat critical physiological damages. Critical physiological damage in response to a selected frost event included seedling death, sterility, and death of formed grains (Barlow et al., 2015; Porter and Gawith, 1999; Bonciarelli and Bonciarelli, 1992). Similarly, critical physiological damage in response to a heat event included sterility and abortion of grains around anthesis and leaf senescence. Selected threshold temperatures, relative reference, and phenological phases are reported in Table 3. Since winter precipitation in most parts of the Russian Federation usually falls as snow with persistent duration (Brown and Mote, 2009; Groisman et al., 1994), the selected thresholds for minimum temperatures hypothesise