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Will climate change benefit or hurt Russian grain production? A statistical evidence from a panel approach

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Abstract Using recent advances in statistical crop yield modelling and a unique dataset consisting of yield time series for Russian regions over the period from 1955 to 2012, the study investigates the potential impact of climate change (CC) on the productivity of the three most important grains. Holding current grain growing areas fixed, the aggregate productivity of the three grains is predicted to decrease by 6.7% in 2046–2065 and increase by 2.6% in 2081–2100 compared to 1971–2000 under the most optimistic representative emission concentration pathway (RCP). Based on the projections for the three other RCPs, the aggregate productivity of the three studied crops is assessed to decrease by 18.0, 7.9 and 26.0% in the medium term and by 31.2, 25.9 and 55.4% by the end of the century. Our results indicate that CC might have a positive effect on winter wheat, spring wheat and spring barley productivity in a number of regions in the Northern and Siberian parts of Russia. However, due to the highly damaging CC impact on grain production in the most productive regions located in the South of the country, the overall impact tends to be negative. Therefore, a shift of agricultural production to the Northern regions of the country could reduce the negative impact of CC on grain production only to a limited extent. More vigorous adaptation measures are required to maintain current grain production volumes in Russia under CC.

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1 Introduction

Accumulating evidence suggests that increases in greenhouse gas concentrations will change the world climate and increase the frequency and severity of extreme weather events (IPCC 2013). Climate change (CC) is expected to fundamentally alter the average level and variability of temperature during seasons. Due to its direct connection with weather, agriculture is one of the economic activities expected to be most likely and significantly affected by CC (Schlenker and Roberts 2009; Fisher et al. 2012).

Studies on the impacts of CC on agriculture have been based on two major approaches (Ortiz-Bobea and Just 2012). The first approach captures CC impacts by applying processed-based crop simulation models developed and calibrated for specific sites using historical crop yield and climate observations (Mearns et al. 1992; Semenov et al. 1996; Sirotenko et al. 1997; Jones and Thornton 2003; Alcamo et al. 2007). An important advantage of process-based models is their ability to simulate crop yields considering different technology choices, such as crop mix, fertiliser-use intensity, adjustments in sowing dates or use of irrigation and to study the effect of CO_2 fertilisation on crop productivity. While, in general, processed-based models represent a valuable tool for assessing the likely impacts of CC, a few aspects might affect the accuracy and reliability of projections obtained on their basis. First, most processed-based crop simulation models exhibit a high degree of complexity, which may lead to considerable model prediction uncertainties (Schlenker and Roberts 2009) and represent a constraint for applying processed-based models to a sufficiently large number of representative locations. Second, applying crop simulation models to locations/regions at high aggregation levels is often associated with a loss in the precision of how crop growth processes are modelled and an increase in the number of uncertain parameters (Lobell and Burke 2010).

The second approach relies on econometric models estimated using observational data and therefore better captures producers' actual behaviour and ability to adapt to changing environment. Mendelsohn et al. (1994) were the first to leverage econometric approaches to estimate the impact of CC on agricultural productivity. Exploiting cross-sectional variation in climate and land values across US counties while controlling for potentially confounding factors such as soil types, they provided Ricardian estimates of the impact of CC on agricultural profitability. Deschênes and Greenstone (2007) drew attention to a serious limitation of the Ricardian approach, namely its vulnerability to the omitted variable problem. To overcome this concern, they applied a panel approach to US census data on agricultural profits with county and state-by-year fixed effects. A number of studies have followed the work by Deschênes and Greenstone (2007) developed and applied the panel approach to estimate reduced-form statistical crop yield models. Most studies in this line of research have been done in a US context (Schlenker and Roberts 2009; Ortiz-Bobea and Just 2012; Roberts et al. 2012). A careful analysis of CC impacts using the panel approach is still largely lacking for a number of European countries, and thus, relatively little is known about the relationship between climate and agricultural productivity in Europe. Some exceptions include studies by Moore and Lobell (2014) for selected regions in the European Union and an application of the Ricardian approach in the context of European agriculture by Chatzopoulos and Lippert (2015) and Van Passel et al. (2016).

The overall impact of climate change in statistical approaches is derived by multiplying projected changes in weather variables used in the analyses by respective model coefficients estimated on the basis of historical data. This procedure implicitly assumes that no further adaptations to climate change will be done by farmers in future periods. This aspect highlights a major disadvantage of statistical approaches, which cannot do projections considering a broader set or/and a larger extent of adaptations, which may be available/used in future periods. They are incapable to account for a potential CO_2 fertilisation effect.

To the best of our knowledge, there are only two studies that assess the impact of CC on Russian grain production using a statistical approach. Interestingly, they arrive at contradictory results. In their study of CC impacts on global crop production, Lobell et al. (2011) found that Russia experienced the largest negative overall impact of CC worldwide during the period 1980–2008. According to these authors, recent climate trends have depressed Russian wheat yields by almost 15%. At the same time, as reported by Sirotenko and Pavlova (2012), winter wheat yields have grown at rates varying from 0.4% per decade in the Central economic region to 2.8% per decade in the Volga region over the period 1975–2010. Both studies estimated reduced-form yield models and used analogue model specifications with average seasonal temperatures and rainfall as dependent variables. Lobell et al. (2011) used a fixed-effect panel model at the global scale with country-specific quadratic technology trends, whereas Sirotenko and Pavlova (2012) applied an econometric approach based on the first difference time series of yields and weather variables. However, while Lobell et al. (2011) used the country-level crop yield panels and accordingly aggregate the weather data up to the national levels, Sirotenko and Pavlova (2012) estimated weather-yield relationships separately for single economic regions[1] in Russia.

In this study, we aim to update projections of CC impacts on Russian grain production using the most recent yield and weather data for single subjects of the Russian Federation and employing a panel fixed-effect modelling approach. We build upon recent advances in the modelling of the yield-weather relationship by accounting for the potentially damaging effects of extreme temperatures (Schlenker and Roberts 2009). To capture smooth technical change, we specify and test economic region-specific time trends. According to our predictions, grain productivity should increase in most of the Northern regions, whereas it is predicted to drop in a number of most important grain-producing regions located in the South of the country, thus causing an overall negative CC impact on Russian grain production in most cases.

2 Methodology

We base our analysis on panel fixed-effects regressions of crop yields on a set of crop-specific weather indicators, controlling for smooth technological progress. In particular, we elaborate on the following basic form of the crop yield model:

$$\ln y_{it} = \mathbf{w}_{it}^{'}\beta_w + u_i + f_g(t) + \epsilon_{it}, \tag{1}$$

where y_{it} is the yield in observation unit i (in our case oblast[2]) and year t, $\mathbf{w}_{it}$ is the vector of relevant weather variables and β is the vector of model parameters. Unit-fixed effects (u_i) are used to account for oblast heterogeneity, and economic region-specific time trends $f_g(t)$ capture

[1] Economic regions represent federal subjects, grouped according to certain common characteristics, such as geographic location, availability of natural resources and similar climate conditions, and level of development.

[2] Oblast and krai are territorial units that can correspond to province, just as autonomous republic, but with a lower level of independence from the federal government. For simplicity, in the text, we use the term oblast for all three different types of federal subjects and refer to economic regions as regions.

the effect of technological progress with g indicating the economic region. This specification allows us to identify the weather effect parameters from unit-level weather deviations about the unit average while controlling for region-specific trends. We conduct our analysis using the data for 62 subjects of the Russian Federation (autonomous republics, krais and oblasts[3]) actively engaged in grain production and group them into 12 larger regions with similar economic and natural conditions. We use agricultural data for three major grain crops in Russia—winter wheat, spring wheat and spring barley—over the period 1955–2012, as reported by the Russian Federation Federal Statistics Service (Rosstat 1992–2014; TsSU 1956–1991).[4]

Taking into account the methodological improvements proposed by recent studies (see, e.g. Schlenker and Roberts 2009; Roberts et al. 2012; Burke and Emerick 2013; Tack et al. 2015), we include the following indicators in the vector of weather variables $\mathbf{w}_{it}$: vegetative period growing degree days (GDD), extreme heat degree days (HDD), growing season total precipitation and its square (P and P^2, respectively) measured for the main vegetative growth period of a crop. To compute GDD and HDD, we approximate the distribution of daily temperatures (T_i) within each day using a trigonometric sine curve connecting daily minimum and maximum temperature records (Snyder 1985). Following Stöckle (2013), we set the baseline temperature for all three grain crops to 3 °C and the upper bound temperature to 25 °C. Then, the model in (1) is specified as

$$\ln y_{it} = \beta_1 GDD_{it} + \beta_2 HDD_{it} + \beta_3 P_{it} + \beta_4 P_{it}^2 + \beta_5 HDD_{it} P_{it} + u_i + f_g(t) + \epsilon_{it}, \tag{2}$$

and estimated as a regression with standard error adjusted for spatial correlation (Conley 1999; Hsiang 2010). An interaction term between precipitation and HDD is introduced to account for the fact that greater precipitation may mitigate the damaging effects of extremely high temperatures, especially in case of spring grains (Schlenker and Roberts 2009). For winter wheat, we set the summer growing season to the period from March 1 to June 30 and also control for weather in the autumn (September 1–November 30) and winter (December 1–February 28) months. For both spring grains (spring wheat and spring barley), we define a growing season of totally 3 months covering the period from May 1 to July 31. Additionally, we account for the effect of temperature and precipitation on winter wheat vegetative growth over the autumn and winter months, as well as precipitation during autumn and winter periods on spring grain growth, considering that accumulated soil moisture could influence the growth of a plant during spring and summer periods.

Model coefficient estimates are used to predict the impact of CC, I_{CC}, defined as the percentage change in the yields for a projected period against the yields in the baseline period, holding growing areas constant:

$$I_{CC} = \frac{\sum_i^N a_i e^{\mathbf{w}_{i1}'\beta_w + u_i + f_g(t=2012)}}{\sum_i^N a_i e^{\mathbf{w}_{i0}'\beta_w + u_i + f_g(t=2012)}} - \quad \text{with } i \in [1; 62] \tag{3}$$

where a_i denotes the crop sowing area in unit i, $\mathbf{w}_{i1}$ is the vector of weather variables for the

[3] For a graphical description of Russian territorial division, see Fig. S1 in Online Supplementary Material.

[4] See Online Supplement Material for the descriptive statistics

projected period and $\mathbf{w}_{i0}$ is the vector of weather variables for the baseline period (1971–2000). We apply Eq. (3) to obtain estimates of the CC impact on grain production for two projected periods, 2046–2065 and 2081–2100.

We use predictions of CC from the Fifth Assessment Report of the IPCC (IPCC 2014). Using the HadGEM2-ES model, we obtain monthly model output for four representative concentration pathways (RCPs) which rely on different assumptions of future development paths, such as economic, technological or demographical changes, which, in turn, result in different levels of GHG emissions in the atmosphere.[5] For all four pathways and both time horizons, we compute 20-year averages of monthly average minimum temperature, monthly average maximum temperature and monthly total precipitation and use these data to derive weather variables for the projected periods.

Available climate projections provide estimates of average minimum and maximum daily temperatures for each month. Using changes in average monthly maximum and average monthly minimum temperatures relative to the baseline period, we reconstruct the course of daily temperatures employing the same procedure as when using historical data and successively derive two degree day measures. Total seasonal precipitation values are constructed using projections of daily precipitation.[6]

3 Results and discussion

3.1 Past yield outcomes

The model estimation results are presented in Table 1. Our estimates indicate a positive response of grain yields to *GDD*. The respective coefficient estimates are of about the same magnitude for all three crops and indicate that an additional growing degree day increases the yield by 0.12% for winter wheat, 0.09% for spring wheat and 0.11% for barley.

We find a negative impact of extreme temperatures on grain yields in Russia. Additionally, the *HDD* coefficient is higher for both spring grains than for winter wheat. Each additional heat degree day (e.g. exposure to temperatures above 25 °C for one additional day) reduces the yield of winter wheat by 0.8%, spring barley by 1% and spring wheat by 1.44%. The probability of daily temperatures exceeding the 25 °C threshold is considerably higher for spring wheat and spring barley than for winter wheat, since a larger part of their vegetative period (phenology phases such as tillering, heading, anthesis and grain formation) takes place in June and July. This explains a higher elasticity of yields in *HDD* for these two crops.

In addition to accumulated temperatures during the warm season, the model for winter wheat includes average daily temperatures and total precipitation for the autumn and winter months. The model estimates suggest an inverse U-shaped response of winter wheat yields on both average temperature and total precipitation in autumn with the optimal seasonal temperature of 12.6 °C and the optimal precipitation in the autumn months of 261 mm. Considering that the average daily temperature for the crop areas under grains was 4.8 °C in the 1955–2012 period, an increase in autumn temperatures should positively influence productivity of winter grains. The average total precipitation in September–November varied between 21.8 and 365.8

[5] Please see Online Supporting Material for a description of RCP scenarios used in this study.
[6] Please see Online Supporting Material for a descriptive statistics for the baseline and projected periods for each of the pathways.

Table 1 Crop yield model estimation results, 1955–2012

Variable	Winter wheat	Spring wheat	Spring barley
GDD	0.123***	0.0853***	0.112***
	(0.012)	(0.010)	(0.010)
HDD	− 0.791***	− 1.375***	− 0.951***
	(0.181)	(0.199)	(0.178)
T^{autumn}	7.891***	–	–
	(1.812)		
T^{autumn^2}	− 0.312**	–	–
	(0.130)		
T^{winter}	− 1.952*	–	–
	(1.076)		
T^{winter^2}	− 0.057	–	–
	(0.061)		
P^{summer}	0.274***	1.099***	0.977***
	(0.077)	(0.093)	(0.088)
P^{summer^2}	0.0001	− 0.002***	− 0.002***
	(0.000)	(0.000)	(0.000)
P^{autumn}	0.523***	–	–
	(0.069)		
P^{autumn^2}	− 0.001***	–	–
	(0.000)		
P^{winter}	− 0.037	–	–
	(0.110)		
P^{winter^2}	− 0.001	–	–
	(0.001)		
$P^{autumn-winter}$	–	0.249**	0.087
		(0.087)	(0.089)
$P^{autumn-winter^2}$	–	− 0.001***	0.000
		(0.000)	(0.000)
$HDD \cdot P^{summer}$	–	0.004**	0.001
		(0.001)	(0.001)
R^2	0.985	0.973	0.972
Observations	2790	3218	3422

Standard errors are presented in parentheses; *, ** and *** denote statistical significance at the 10, 5 and 1% significance level, respectively. Coefficients and corresponding standard errors are multiplied by 100. Source: own calculations

across regions and years covered by the study and follows a gamma-like distribution with a substantial part of probability mass below 261 mm. This fact implies that winter wheat was often not optimally supplied with water in autumn months. Although a reduced specification of the model for winter wheat excluding average daily temperatures and total precipitation in the winter months and their squares was rejected, the majority of corresponding parameter estimates did not receive statistically significant estimates. Spring wheat had a positive response to autumn and winter precipitation, indicating that moisture, accumulated during those periods, later results in higher yields.

We also find a positive response of grain yields to summer precipitation. The coefficient estimates for spring grains suggest that spring wheat requires more precipitation from May to July than barley: the optimum amount of rainfall is estimated to be 274 mm for spring wheat and 224 mm for barley.

The coefficient estimates of the interaction terms ($HDD \cdot P^{summer}$) were found to be not statistically significant for winter wheat and spring barley. However, our results suggest that a similar phenomenon to that found by Schlenker and Roberts (2009) in the context of US agriculture is observed for spring wheat in Russia: the interaction term of *HDD* and the summer precipitation are positive and statistically significant, indicating that summer precipitation helps to reduce heat stress on spring wheat.

Finally, the estimates of economic region-specific time trends suggest an only moderate technological change in Russian grain production. The country's aggregate yield increasing by 8.7, 11.6 and 10.5 kg/ha, on average, annually for the observed period (1955–2012) for winter wheat, string wheat and barley, respectively. This finding is in line with empirical evidence that suggests that compared to developed countries, yields grew at a lower rate, especially during the Soviet time, resulting in stagnation in the early transition period (Trueblood and Arnade 2001).

3.2 Projected yield changes

Climate change impacts on the productivity of the three studied grain crops for each of four RCPs are presented in Table 2. Our estimates project the overall country-wide effect of CC on grain yields to be negative for practically all RCPs and projections' time frames. In case of the least harmful representative concentration pathway—RCP2.6—the crop area-weighted average yield of the three studied grains is predicted to reduce by 6.7% in the medium term. The estimate of the long-term aggregate impact on productivity of the three studied grains projects a statistically significant increase of 2.6% compared to the 1971–2000 period. An increase in productivity in the long term can be explained by decreases in emission concentrations projected to take place according to this RCP in the middle of the century. This is expected to slow down upwards shifts in temperatures and soften the effect of global warming on agriculture in the long term.

For RCP4.5, the estimates are significant for both projected periods and predict the production of the three grains to decrease by 18.1% and by 31.2% in the medium and long terms, respectively. In case of RCP6.0, the CC impact on the aggregate productivity of the

Table 2 Predicted climate change impact under HadGEM2-ES for four selected representative concentration pathways (RCP2.6, RCP4.5, RCP6.0 and RCP8.5)

Pathway	Period	Total	Winter wheat	Spring wheat	Spring barley
RCP2.6	2046–2065	−0.0665**	−0.0427	0.0007	−0.2008***
		(0.0287)	(0.0394)	(0.0185)	(0.0234)
	2081–2100	0.0255	0.0217	0.1168***	−0.0871***
		(0.0345)	(0.0349)	(0.0372)	(0.0328)
RCP4.5	2046–2065	−0.1808***	−0.1245**	−0.1499***	−0.3295***
		(0.0460)	(0.0552)	(0.0397)	(0.0400)
	2081–2100	−0.3116***	−0.2416***	−0.2836***	−0.4830***
		(0.0575)	(0.0723)	(0.0475)	(0.0429)
RCP6.0	2046–2065	−0.0794*	−0.0503	−0.0211	−0.0796***
		(0.0417)	(0.0483)	(0.0341)	(0.0147)
	2081–2100	−0.2587***	−0.1551**	−0.2915***	−0.2121***
		(0.0554)	(0.0647)	(0.0541)	(0.0405)
RCP8.5	2046–2065	−0.2517***	−0.1955***	−0.2093***	−0.4157***
		(0.0526)	(0.0603)	(0.0522)	(0.0397)
	2081–2100	−0.5538***	−0.4431***	−0.5966***	−0.7107***
		(0.0774)	(0.1038)	(0.0597)	(0.0485)

Standard errors are presented in parentheses; *, ** and *** denote statistical significance at the 10, 5 and 1% significance level, respectively. Source: own calculations three studied grains is expected to cause a decline in yields by 7.9% in the medium term. However, with a statistically significant estimate predicting a 25.9% decrease in yields, the long-term effect of global warming is expected to be close to that of RCP4.5. The difference between the two medium RCPs expresses itself in the relatively low number of heat waves that are projected in the medium term in RCP6.0. Fewer heat waves result in a lower number of heat degree days, thus creating more favourable conditions for crop production. However, in the long run, RCP6.0 almost aligns with RCP4.5 in terms of emissions, resulting in significant productivity decline (− 7.9 and − 25.9% for the medium term and long term, respectively).

In the business-as-usual pathway RCP8.5, which assumes a complete absence of measures to mitigate CC and consequently growing surface temperatures, grain yields are projected to show a significant decrease of 25.2 and 55.4% in the medium and long terms, respectively.

Our estimation results suggest that winter wheat is likely to benefit from increasing temperatures in the autumn and winter months as well as from increasing growing degree days. However, by causing a rise in the number of days with extreme temperatures and substantially reducing precipitation levels in the summer months in the most important winter wheat-producing regions in South Russia, CC should be expected to have a mainly damaging effect on winter wheat productivity in Russia. No significant changes were estimated under RCP2.6 for winter wheat. For all other projections, which were found to be statistically significant, the production of winter wheat is projected to reduce in both the medium and long terms: from 12.5% (RCP4.5) to 19.6% (RCP8.5) in the medium term and from 15.5% (RCP6.0) to 44.3% (RCP8.5) in the long term, compared to the baseline period.

Spring wheat productivity is expected to increase under RCP2.6 by 11.7% in the long term. This positive CC impact on spring wheat productivity is a result of the spatial distribution of spring wheat production in Russia: spring wheat is predominantly concentrated in the Northern regions of the country where CC is projected to result in an increase in growing degree days and a limited rise in heat degree days. Currently, spring wheat in major producing regions have not yet reached its full production potential because the growing season is not sufficiently long for the development of the plant in these regions. Therefore, a moderate increase in summer temperatures can improve conditions for spring wheat production in these regions. However, for higher rises in summer temperatures, the CC impact on spring wheat productivity is predicted to be negative. Our results for RCP4.5 indicate that spring wheat yields might decline significantly (by 28.4%) in the long term. According to the RCP8.5, spring wheat yields could decline by 20.9% in the medium term and by 59.7% in the long term compared to the 1971–2000 period.

Spring barley—unlike spring wheat—is not expected to benefit from CC in any projection. For all RCPs and time horizons, the productivity of spring barley is projected to decline substantially given no serious adjustments in production practices on Russian farms. Our study identifies a statistically significant reduction by 20.1% in the medium term and by 8.7% in the long run for RCP2.6. For RCP4.5, we predict a statistically significant fall in barley productivity due to CC—by 33.0 and 48.3% in the medium and long terms, respectively. Given a development as captured by RCP6.0, barley production can potentially decrease by 8.0% in the medium term and 21.2% in the long term. The impact under RCP8.5 would be the most damaging by reducing barley yields by 41.6 and 71.1% in the medium and long terms, respectively. This drastic fall in barley yields is associated with the joint effect of an increased number of heat degree days and a lower level of precipitation, projected for the main barley-producing regions located predominantly in the Southern regions of the country, which already have a relatively high probability of heat waves and dry weather periods in the current climate.

Our study predicts serious differences in the CC impact across individual oblasts. Figures 1, 2 and 3 show the spatial distribution of the projected CC impacts for two selected RCPs at the oblast level in the medium and long terms for three examined crops. Although the magnitude of productivity changes varies across RCPs, trends in productivity for individual oblasts indicate similar developments in both RCPs (the only exception is RCP2.6, which projects a predominantly positive CC impact in the long term).

The CC impact on winter wheat productivity (Fig. 1) is predicted to be positive for most regions. In fact, winters in the Northern and Siberian parts become warmer, creating better conditions for germination and tillering. However, the share of these regions in the country's overall wheat production is very small. As mentioned above, the most important winter wheat-producing regions are located in the South of the country. In these regions, winter wheat production is projected to shrink from rising temperatures in summer and spring.

The CC impact on spring wheat (Fig. 2) is assessed to be negative for most regions in the South of the European part of the country. Spring wheat productivity is expected to decline partly due to a higher number of heat degree days and partly due to a lack of precipitation in the summer period. According to RCP8.5, most regions in South Siberia are expected to experience an increase in spring wheat productivity, while the same regions under RCP2.6 are projected to show a significant reduction in the productivity of this crop. This difference in our assessments is due to the fact that RCP2.6 projects higher levels of precipitation for Russia than any other RCP and a modest increase in temperatures. This change should worsen conditions for growing spring grains in these regions. A substantially greater increase in growing degree days would be necessary to improve spring grain productivity given high levels of precipitation. This increase in *GDD* is expected to happen under RCP8.5. It can

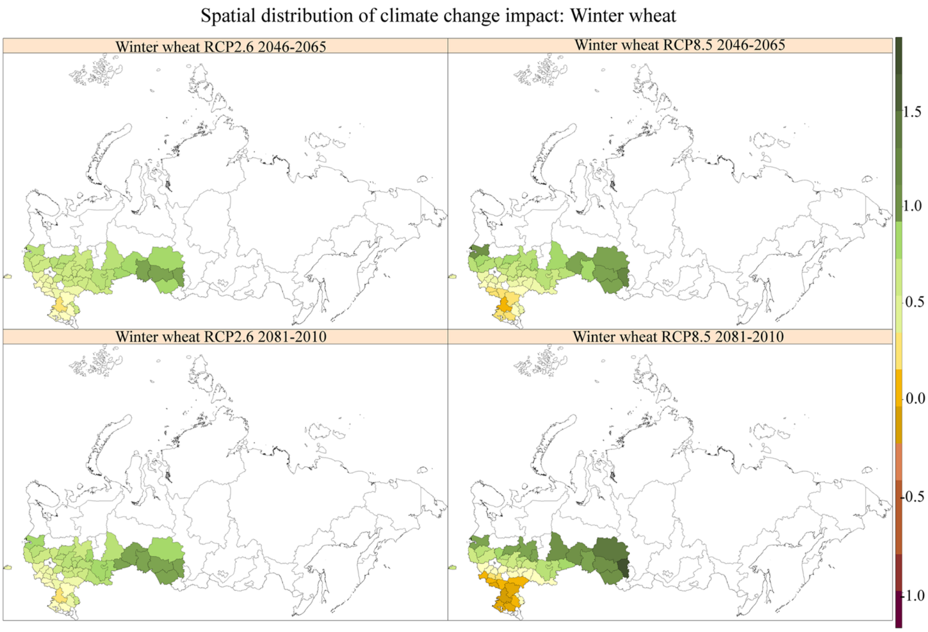

Fig. 1 Predicted climate change impact under HadGEM2-ES for winter wheat at the oblast level for two selected representative concentration pathways: RCP2.6 and RCP8.5. Vertical axis represents percentage change in yields relative to the baseline period. Source: own calculations

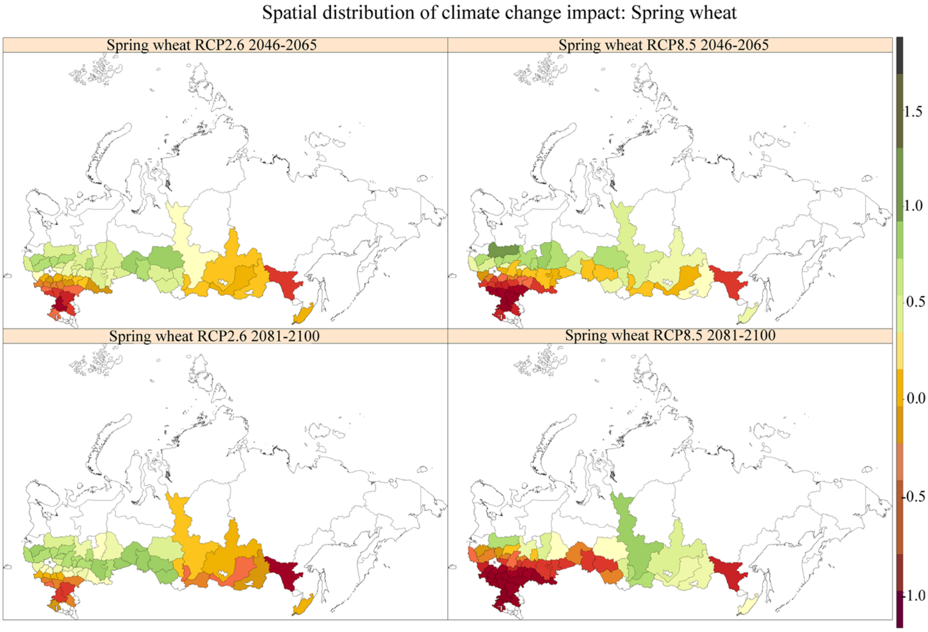

Fig. 2 Predicted climate change impact under HadGEM2-ES for spring wheat at the oblast level for two selected representative concentration pathways: RCP2.6 and RCP8.5. Vertical axis represents percentage change in yields relative to the baseline period. Source: own calculations

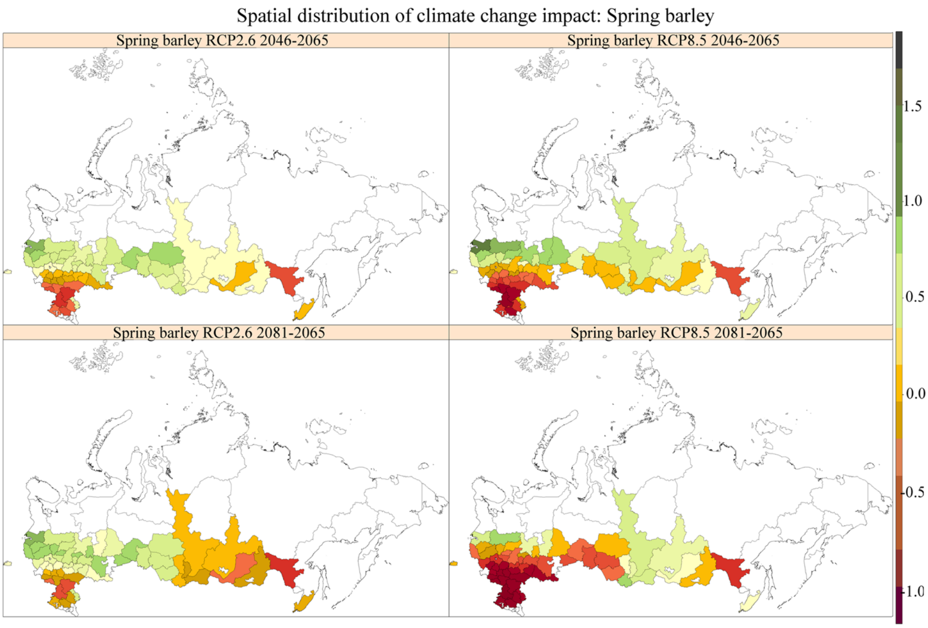

Fig. 3 Predicted climate change impact under HadGEM2-ES for spring barley at the oblast level for two selected representative concentration pathways: RCP2.6 and RCP8.5. Vertical axis represents percentage change in yields relative to the baseline period. Source: own calculations

positively affect spring wheat yields in a number of grain-producing regions in Siberia. Northern regions of Russia will mainly benefit from global warming according to our study results for both RCPs in the medium term, but might be negatively affected in the long term. A prolonged growing period as indicated by a higher number of growing degree days and higher levels of precipitation projected for the summer period under RCP2.6 are expected to considerably increase the productivity of spring wheat in these regions in both the medium and long terms. Given these regions' high share in national spring wheat production, this is expected to increase the aggregate country's yield of spring wheat under RCP2.6. However, greater rises in temperatures projected by RCP8.5 would lead to a considerable increase in *HDD* which would damage spring wheat yields in these regions as well. This explains a negative CC effect on the aggregate spring yield in RCP8.5 (Table 2).

Spring barley is traditionally considered as the grain crop that is least vulnerable to heat waves or sudden frosts and is therefore planted country-wide, including Southern regions of the country which are often exposed to temperature extremes in the summer months. In these regions, barley yields are expected to decline greatly due to high exposure to heat degree days in the summer period (Fig. 3). In regions where conditions are expected to become more favourable (predominantly in the North of the country and some regions in Siberia), the share of cropland allocated to spring barley is relatively low at the moment to have any significant impact on the aggregate productivity of this crop.

A more detailed examination of the oblasts-level CC effects on grain yields shows that, in the absence of new adaptation measures, agricultural productivity in Russia might experience a dramatic decline. In the long term, winter grain productivity is expected to experience a decline of up to 50% in the most productive and important grain-producing regions of the country with highly fertile black soils—Krasnodar, Rostov and Stavropol. An option to mitigate the negative CC impact on agricultural production in Russia would be a shift of grain production to the Northern and Siberian parts of the country. A warmer and milder climate in autumn and early spring in Central and Northern Russia and Siberia might have a beneficial effect on the development of winter wheat, while warmer summers will create favourable conditions for spring grains. However, several recent studies (Prishchepov et al. 2013; Schierhorn et al. 2014) draw attention to the process of land abandonment, which took place in Russia during the 1990s and resulted in a substantial shrinkage in agricultural land in these regions. Therefore, extensive investments would be required to restore agricultural production in such areas. Moreover, given a relatively low soil fertility in the majority of Northern and Siberian regions, this option is not likely to offset production losses caused by CC in the most productive regions in South Russia (Schierhorn et al. 2014; Liefert and Liefert 2015).

Obtained results represent one of the possible outcomes of a changing climate; hence, it is important to take into account uncertainty of climate modelling. The general circulation model, HadGEM2-ES, used for the experiment in this research, tends to project slower increases in mean temperatures than other models and was found to overestimate spring precipitation and underestimate summer precipitation (Müller and Robertson 2014). Another uncertainty that arises from the climate change modelling exercise is the resolution mismatch between weather datasets and information about the distribution of crop areas. More research is needed to analyse climate change under different general circulation models and their ensembles to better qualify the impact of CC on grain production in Russia and account for different sources of model and prediction uncertainties.

4 Conclusions

Using recent advances in statistical crop yield modelling, the study investigates the potential CC impact on the productivity of the three most important grains in Russia. Our study results indicate that in the medium term, CC might have a substantial positive effect on winter wheat, spring wheat and spring barley productivity in a number of regions in the North and the Siberian parts of Russia. In contrast, the most productive regions located in the South of the country are predicted to experience considerable decreases in the productivity of all three crops. Holding current grain growing areas fixed, the aggregate productivity of the three grains is predicted to decrease by 6.7% in the medium term and increase by 2.6% in the long term under the most optimistic pathway, RCP2.6. Based on the projections for the three other representative emission concentration pathways, the aggregate productivity of the three studied crops is assessed to decrease by 18.0, 7.9 and 26.0% in the medium term and by 31.2, 25.9 and 55.4% by the end of the century. However, we have to draw attention to the fact that our historical climate-yield relationship is identified from year-to-year variation in weather about a smooth time trend used to capture the effect of technological adjustments. Hence, our estimates control only for short-run adaptations of the kind that were present in the historical period and do not take into account any serious changes in production practices and adaptation strategies that can be implemented in the future. Accordingly, more research is required to evaluate the effect of different adaptation measures and their effectiveness in reducing the negative impact of CC on Russian agriculture in the long run.

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