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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

We conduct an examination of the climate effect to analyze the historical dependence of grain production on temperatures and precipitation levels, and project this dependence to estimate the productivity of different grain types in the mid- and long-terms, given four greenhouse gas concentration pathways. We find that altering temperatures have an equivocal effect on agriculture. The most productive zones of the southern black soil belt is projected to face considerable declines in yields, due to insufficient precipitation levels and high probability of heat waves during the summer vegetation period. The northern part, on the contrary, can experience increases in productivity as a result of milder and drier winters and warmer springs.

JEL: Q12, Q16, Q54, P32

Keywords: Russia, grain production, climate change.

ZUSAMMENFASSUNG

WIRD DER KLIMAWANDEL DER RUSSISCHEN GETREIDEPRODUKTION NUTZEN ODER SCHADEN?
STATISTISCHE EVIDENZ AUF DER GRUNDLAGE EINES PANEL-ANSATZES

Wir untersuchen den Klimaeffekt, um die zeitliche Abhängigkeit der Getreideproduktion von Temperatur und Niederschlagsmengen zu bestimmen. Darauf aufbauend prognostizieren wir die mittel- und langfristige Entwicklung der Produktivität verschiedener Getreidearten für vier unterscheidliche Entwicklungspfade der Treibhausgaskonzentration. Wir finden, dass sich verändernde Temperaturen keinen einheitlichen Einfluss auf die Landwirtschaft haben. Die produktivsten Zonen im südlichen Schwarzerdegürtel werden einen deutlichen Rückgang der Erträge infolge von unzureichenden Niederschlagsmengen und einer hohen Wahrscheinlichkeit von Hitzewellen während der Vegetationsperiode im Sommer erfahren. Im Unterschied dazu ist in den nördlichen Regionen ein Anstieg der Produktivität zu erwarten als Folge eines milderen und trockeneren Klimas im Winter und höheren Temperaturen im Frühjahr.

JEL: Q12, Q16, Q54, P32

Schlüsselwörter: Russland, Getreideproduktion, Klimawandel.

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). Projected 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 affectted by CC (SCHLENKER and ROBERTS, 2009; FISHER et al., 2012). Successful and effective adaptation to CC requires knowledge of the mechanism and the magnitude of its impacts, as well as information about the ability and potential capacity of economic agents to adjust to changes in their environment (BURKE and EMERICK, 2013).

Studies on the impacts of climate change 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, ROSENZWEIG and GOLDBERG, 1992; SEMENOV et al., 1996; SIROTENKO, ABASHINA and PAVLOVA, 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. 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 level 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 revealed preferences. MENDELSOHN, NORDHAUS and SHAW (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 U.S. 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 U.S. 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) 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 U.S. context (SCHLENKER and ROBERTS, 2009; ORTIZ-BOBEA and JUST, 2012; ROBERTS et al., 2012). A careful analysis of climate change 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. A few exceptions are studies by MOORE and LOBELL (2014) for selected regions in the European Union countries and an application of the Ricardian approach in the context of German agriculture by CHATZOPOULOS and LIPPERT (2015).

In this study, we examine the potential impact of CC on Russian agricultural production. Russia is one of the most important grain producing nations and since 2000 has evolved into a major grain exporter. During 2011-2013, Russia exported annually on average 23 million metric tons of grain (LIEFERT and LIEFERT, 2015). Considering the country's nontrivial role in world food production, climate-induced changes in agricultural productivity in Russia could have serious consequences for global food supply and world food prices. From 1976 to 2013, Russia's average annual temperature has increased at a rate of 0.43°C per decade, that is, twice as much as the global rate (ROSHYDROMET, 2014). These temperature increases might have been beneficial for areas in Northern Russia that exhibit a poor suitability for agricultural production under current climate, but at the same time might have had a damaging effect on agricultural productivity in more important grain-producing regions located in the South of the country. Therefore, on many levels Russia represents an interesting case study for analysing not only the magnitude but also the sign of CC impacts on agricultural productivity.

There have been only a few assessments of potential CC impacts on agricultural productivity in Russia. Most of the existing studies have applied crop simulation models to compute the average country-level impact of climate change on the productivity of selected crops, mainly wheat and barley. Based on projections obtained using a process-based crop simulation model, SIROTENKO et al. (1997) find that average grain production in Russia might decline by 15 % by the year 2030. ALCAMO et al. (2007) derive similar estimates of CC impacts on national production. However, when extending their analysis to the regional level, the latter study recognises that potential gains in agricultural productivity due to CC can outweigh potential damages. ALCAMO et al. (2007) indicate that the range of CC impacts is very broad – varying from -9 % to +12 % of the country average grain production. These findings suggest that a number of regions in Russia could actually benefit from future changes in climate.

PAVLOVA et al. (2014) develop and apply a crop simulation model for the steppe zones in Russia and Kazakhstan. The results of this study suggest that water scarcity during the growing season represent a major stress factor in the steppe zone of Russia. Given that the steppe zones of Russia are expected to become more arid in the future, PAVLOVA et al. (2014) conclude that seasonal water shortages will be a key factor influencing grain productivity in this area.

SAFONOV and SAFONOVA (2013), analysing results presented by the Russian Research Institute of Agricultural Meteorology, indicate a potential decrease in grain crop yields by 9 % and 17 % by 2030 and 2050, respectively. In addition, the authors point out that North-western regions are more likely to benefit from increasing temperatures and are expected to experience grain yield increases by 8-9 %. In contrast, DRONIN and KIRILENKO (2007) predict a rather pessimistic future for Russian agriculture. They argue that potential damages to agricultural production in the South-European regions of Russia possessing best soils, most suitable for crop production (chernozem soils[1]) is unlikely to be compensated by shifting agricultural production to areas up to the boreal forest zone due to poor soil quality and hard terrain

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, SCHLENKER and COSTA-ROBERTS (2011) find that Russia has 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) who conducted their analysis based on a winter wheat time series aggregated at the level of the country's economic regions[2], 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

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[1] Black fertile soil that is conductive to high agricultural yield.

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

yield models and used analogue model specifications with average seasonal temperatures and rainfall and their squares as dependent variables. The main difference in the modelling approaches between two studies is that Lobell, Schlenker and Costa-Roberts (2011) use a fixed-effect panel model at the global scale with country-specific quadratic technology trends, whereas Sirotenko and Pavlova (2012), similar to Lobell and Field (2007), apply an econometric approach based on the first-difference time series of yields and weather variables. Moreover, while Lobell, Schlenker and Costa-Roberts (2011) used the country-level crop yield panels and accordingly had to aggregate the weather data up to the national levels, Sirotenko and Pavlova (2012) estimated weather-yield relationships separately for single economic regions in Russia.

In the current 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. Additionally, we include economic region-specific time trends to capture smooth technical change. Finally and most importantly, 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). Our results suggest that CC will have an equivocal impact on grain production in Russia. Overall, conditions for efficient production of grains have been deteriorating, resulting in considerable shrinkages of yields. Holding current grain growing areas fixed at the 2012 level, production of all three studied grain crops is expected to decrease by by 6.1 % in the long term (2081-2100) for the pathway with the lowest rates of greenhouse gases concentrations (RCP2.6), and decrease by 50.6 %in the long term for pathway with the highest projected concentration of greenhouse gases in the atmosphere (RCP8.5). However, the observation of the spatial distribution of climate effect indicates advantageous conditions in most of the northern regions, resulting in higher productivities of all three examined types of grain. Because our historical climate-yield relationship is identified from year-to-year variation in weather about a smooth trend, these estimates should be interpreted as inclusive short-run of an adaptation of the kind already present in the historical period.

The paper is organised as follows. The next section briefly describes our methodology. The third section provides an overview of the data and climate projections used. It is followed by the presentation and discussion of the main empirical results. Concluding remarks are presented in the last section.

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:

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

where y_{it} is the yield in observation unit i (in our case oblast[3]) 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

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[3] 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, further in the text we use the term oblast for all 3 different types of the subjects of the Russian Federation, and refer to economic regions as regions.

$f_s(t)$ capture the effect of technological progress. 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.

Taking into account the methodological improvements suggested by recent studies (see e.g. SCHLENKER and ROBERTS, 2009; ROBERTS et al., 2012; BURKE and EMERICK, 2013; TACK et al., 2015), we include in the vector of weather variables $\mathbf{w}_{it}$ the following indicators: vegetation 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 vegetation period of a crop, i.e. March-June for winter grains and May-July for spring grains. Then, the model in (1) is specified as

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

and estimated as a regression with standard error adjusted for spatial correlation (CONLEY, 1999; HSIANG, 2010). An interaction term between precipitation and HDD are introduced to account for the fact that greater precipitation may mitigate the damaging effects of extremely high temperatures (SCHLENKER and ROBERTS, 2009).

Additionally, to account for the effect of temperature and precipitation on winter wheat vegetation over the autumn and winter months, we apply the following extension of the model in (2):

$$\begin{aligned} \ln y_{it} = \quad & \beta_1 GDD_{it} + \beta_2 HDD_{it} + \beta_3 P_{it}^{March-June} + \beta_4 P_{it}^{March-June^2} \\ & + \beta_7 T_{it}^{Sept-Nov} + \beta_8 T_{it}^{Sept-Nov^2} + \beta_9 T_{it}^{Dec-Feb} + \beta_{10} T_{it}^{Dec-Feb^2} \\ & + \beta_{11} P_{it}^{Sept-Nov} + \beta_{12} P_{it}^{Sept-Nov^2} + \beta_{13} P_{it}^{Dec-Feb} + \beta_{14} P_{it}^{Dec-Feb^2} \\ & + u_i + f_s(t) + \epsilon_{it}, \end{aligned} \tag{3}$$

where T_{it} denotes average daily temperatures in the corresponding period. We test the model in (3) against model in (2) for winter wheat to verify if weather in the autumn and winter months can explain a significant part of the variation in winter wheat yields.

Model coefficient estimates are used to predict the impact of climate change, 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:

$$I_{CC} = \frac{\sum_{i=1}^{N} a_i e^{\mathbf{w}_{t1}' \beta_w + u_i + f_s(t=2012)}}{\sum_{i=1}^{N} a_i e^{\mathbf{w}_{t0}' \beta_w + u_i + f_s(t=2012)}} - 1, \tag{4}$$

where a_i denotes the crop sowing area in unit i, $\mathbf{w}_{t1}$ is the vector of climate variables for the projected period, $\mathbf{w}_{t0}$ is the vector of climate variables for the baseline period (1971-2000). We apply equation (4) to obtain estimates of the CC impact on grain production for two projected periods, 2046-2065, and 2081-2100.[4]

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[4] In our assessments, we hold the effect of technological progress at the average over the reference period.

DATA

We conduct our analysis at the level of 77 subjects of the Russian Federation (autonomous republics, krais, and oblasts) actively engaged in grain production, and group them into 12 economic regions with similar economic, social 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). Descriptive statistics for agricultural data is presented in Table 1. After validating reported data and excluding yield time series for regions with an extremely low number of observations, our final sample reduces to 69 oblasts.

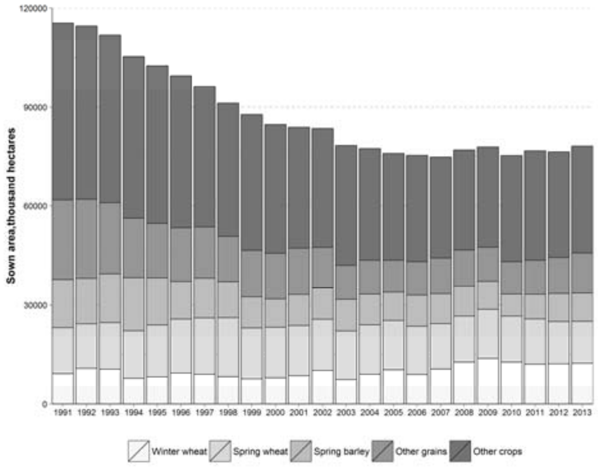
Table 1: Descriptive statistics

		Unit	Mean	Median	Min	Max	Std. dev
			Agricultural data				
Winter wheat							
	Yield	tonnes/ha	1.87	1.77	0.17	5.54	0.79
	Sown area	thousand ha	174.83	46.7	0.01	2071.50	337.71
Spring wheat							
	Yield	tonnes/ha	1.19	1.13	0.01	4.33	0.53
	Sown area	thousand ha	356.77	91.3	0.10	5150.50	646.11
Barley							
	Yield	tonnes/ha	1.29	1.20	0.05	4.17	0.61
	Sown area	thousand ha	181.82	86.40	0.03	2425.60	262.18
			Weather data				
Winter wheat							
	GDD	units	837.89	816.38	187.48	1504.59	216.01
	HDD	units	8.76	4.68	0.00	111.55	11.30
	Average temperatures Sept-Nov	°C	4.83	4.92	-6.53	14.47	3.70
	Average temperatures Dec-Feb	°C	-10.02	-9.09	-30.41	5.47	6.31
	Total precipitation March-June	mm	241.22	235.74	56.12	568.30	72.14
	Total precipitation Sept-Nov	mm	135.69	129.31	21.81	365.78	50.22
	Total precipitation Dec-Feb	mm	97.47	97.33	6.78	342.95	43.26
Spring grains							
	GDD	units	1189.21	1189.77	591.55	1753.70	189.60
	HDD	units	21.34	12.85	0.04	189.53	24.19
Total precipitation		mm	177.27	176.64	27.37	422.32	56.03

Source: ROSSTAT 1992-2014; TSSU 1956-1991; SHEFFIELD et al. (2006).

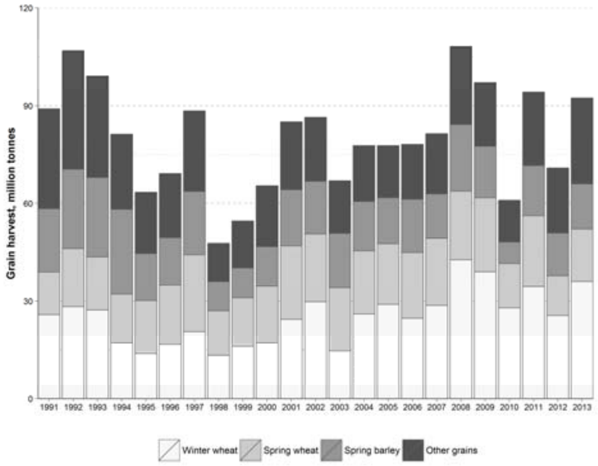
Crop production is an important branch of Russian agriculture. It accounted for 50.4 % of the country's gross agricultural product in the last decade (ROSSTAT, 2015). A major share of crop production comes from grain crops, which cover over 57.8 % of the country's total sown area (Figure 1). Winter wheat is the most important grain crop in Russian agriculture. During the period 2001-2013 it accounted for 13.9 % of the total sown area and 24.1 % of the grain sown area. Its average share in the country's total grain production was 35.7 % over the same period (Figure 2). The shares of areas sown in spring wheat and spring barley were 31.9 and 19.6 % from 2001 to 2013. During this period these two crops contributed 22.8 and 18.0 % of total grain production, respectively.

Figure 1: Sown area, Russian Federation, 1991-2013



Source: ROSSTAT 1992-2014.

Figure 2: Structure of grain production, Russian Federation, 1991-2013



Source: ROSSTAT 1992-2014.

The weather variables were conducted using the Global meteorological forcing dataset of 1.0° grid resolution by SHEFFIELD, GOTETI, and WOOD (2006). Using information on the distribution of areas under grains within each oblast (BONTEMPS et al., 2010), we derived spatially weighted average, maximum, and minimum daily temperatures and precipitation levels for crop-specific growing seasons. For winter wheat the growing season spans the period from March 1 to June 30, while for spring grains we define a shorter growing season lasting from May 1 to July 31. For winter wheat, we also compute weather variables for the autumn (September-November) and winter (December-February) months. We use these data to calculate weather variables for the models described in Table 1 and specified in Equations (2) and (3).

The two previous studies applying statistical crop yield models to assess the impact of CC on Russian agriculture use average monthly or seasonal temperatures. However, this procedure is not in line with agronomic information as it does not account for the effect of extreme temperatures during the plant's life cycle (TACK et al., 2015). In our research we account for the effect of extreme temperatures by distinguishing between *GDD* and *HDD* temperature measures.

To compute *GDD* and *HDD* measures, 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 (T_b) and the upper bound temperature to 25°C (T_u), and calculate *GDD* and *HDD* as follows:

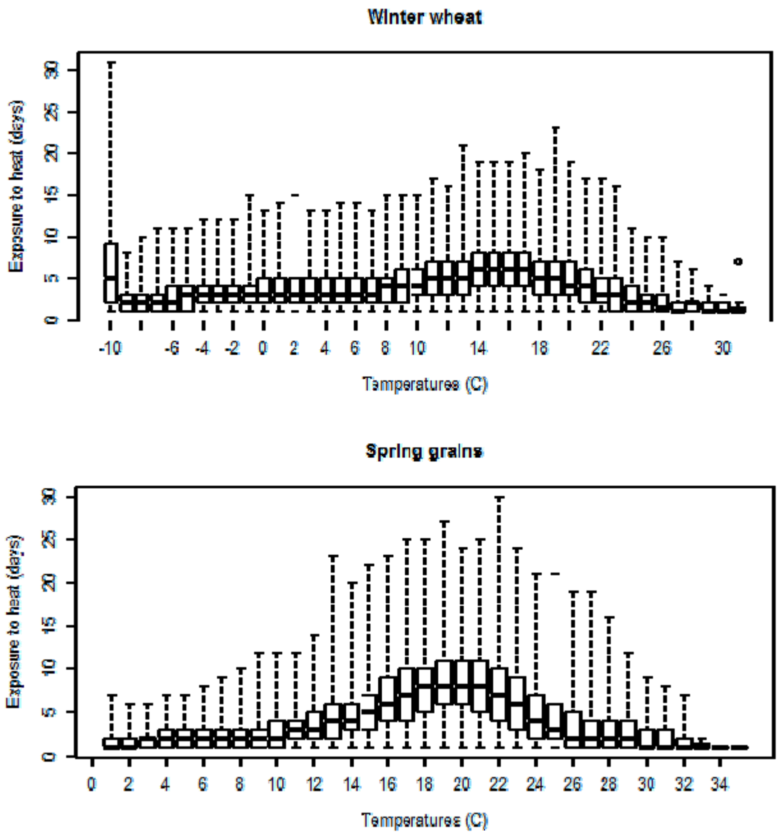
$$GDD = \begin{cases} T_b & if\ T_i \leq 0 \\ T_i - T_b & if\ T_b < T_i < T_u \\ T_u & if\ T_i \geq T_u \end{cases} \tag{3}$$

and

$$HDD = \begin{cases} 0 & if\ T_i \leq T_u \\ T_i - T_u & if\ T_i > T_u \end{cases} \tag{4}$$

Figure 3 shows the distribution of days when winter and spring grains were exposed to each 1°C temperature interval during the growing season across all observation years and oblasts. This figure demonstrates that spring grains are more likely to be exposed to extreme heat events than winter grains. This finding suggests that the former might be more vulnerable to potential increases in summer temperatures. In contrast, winter wheat is more likely to avoid exposure to extreme temperatures because its vegetation starts earlier in the spring and it is harvested earlier.

Figure 3: Descriptive weather statistics: Growing season temperatures, 1955-2012



Source: Own representation of data by SHEFFIELD, GOTETI and WOOD (2006).

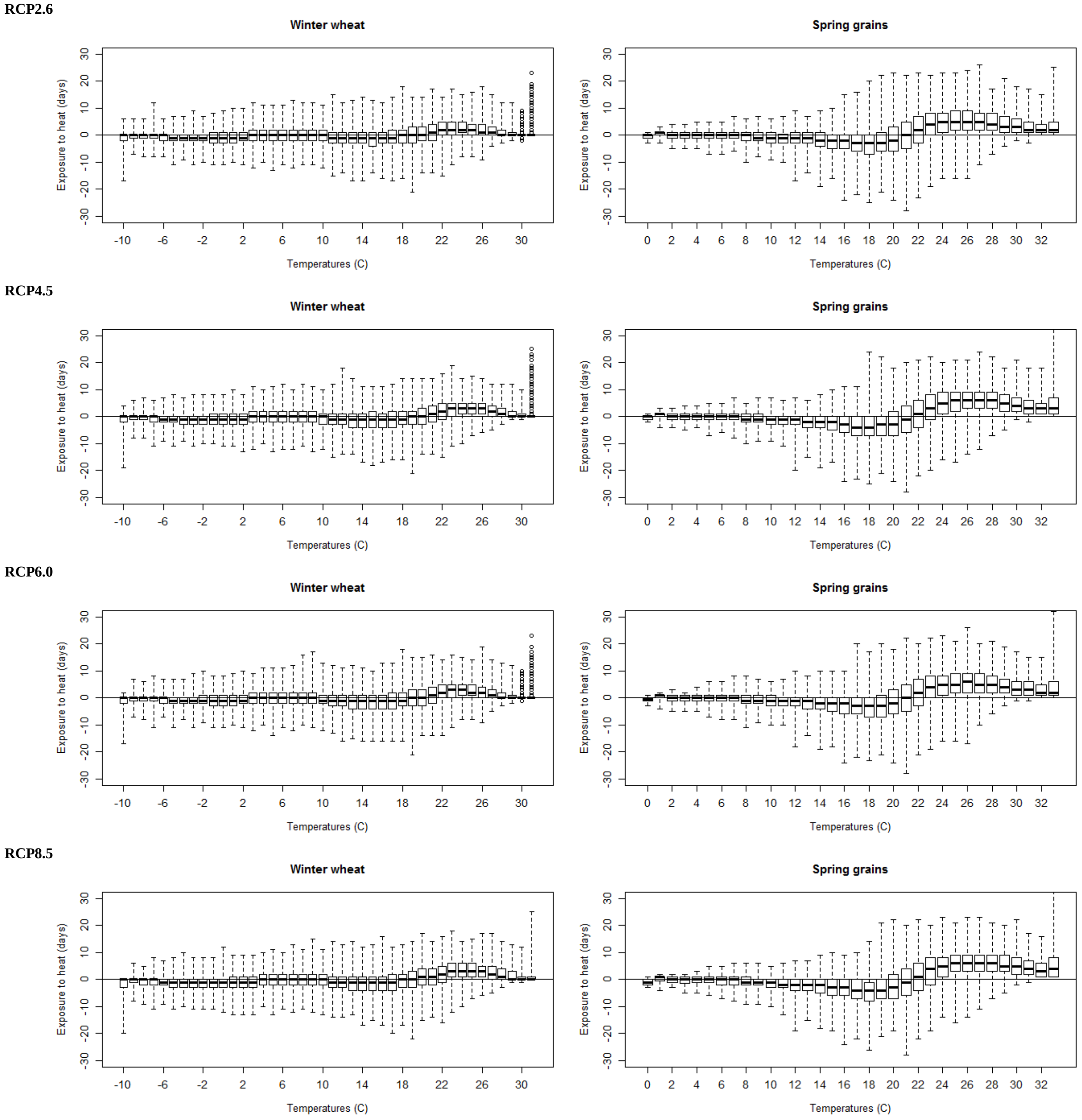
Note: Graphs show the distribution of temperatures during the growing season (March-June for winter wheat, and May-July for spring wheat and spring barley). Whiskers show the maximum and minimum exposure to the selected temperature range. Box marks observations that fall into the 25-75 % percentile range, and the bold line indicates the sample median.

CC predictions of climate change were derived from the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014). We use the climate model developed by the Hadley Centre for Climate Prediction and Research (HadGEM2-ES), and obtain monthly model output for four representative concentration pathways (RCP) – RCP2.6, RCP4.5, RCP6.0 and RCP8.5 – relying on different assumptions of development paths, such as economic, technological or demographical changes, which, in turn, result in different levels of greenhouse gas emissions in the atmosphere (IPCC, 2014). Pathway 2.6 assumes a rapid economic growth, moderate increase of global population until the middle of the century and declining afterwards, with balanced use of different energy sources aggressive climate change mitigation strategies that result in peak emissions in the short run, and their further decline until the end of the century. This storyline projects an increase in average global temperatures by 0.3 - 1.7°C in the long run relative to 1986-2005. Pathways 4.5 (medium-low) and 6.0 (medium-high) adopt a fast economic growth, related to changes in economic structure and the switch to information technology with clean and energy-saving technologies in order to stabilise emission levels by the end of the 21 century. In contrast to RCP2.6 emissions are expected to reach their peak 2070-2100 and decrease afterwards. The resulting change in temperatures according to medium-low emissions concentrations pathway is 1.1 - 2.6°C and 1.4 - 3.1°C for medium-high emissions concentrations pathways, RCP4.5 and RCP6.0, respectively. RCP8.5 implies that the global economy continues business-as-usual development, resulting in a very heterogeneous and fragmented world with temperature changes varying between 2.6 and 4.8°C. For each scenario we compute the 20-year average values of temperatures and total monthly precipitation for the medium term (2046-2065) and long term (2081-2100) based on daily temperature extremes and precipitation.

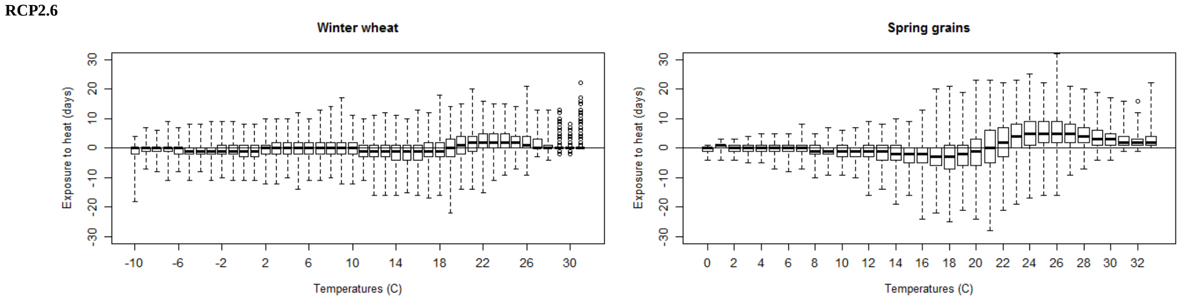
Figure 4 presents the differences distribution in projected and baseline temperatures for the growing seasons of winter and spring grains for both above-mentioned periods. Following IPCC recommendations, we derive average climate for the baseline period using average absolute daily temperatures and temperature anomalies for the historical dataset. There is no pronounced and significant divergence in the temperature differences between scenarios, but the number of days with extreme temperatures is expected to increase according to all four scenarios.

Figure 4: Differences in baseline temperatures and climate change projections (HadGEM2-ES) for 4 selected representative concentration pathways (RCP2.6, RCP4.5, RCP6.0 and RCP8.5)

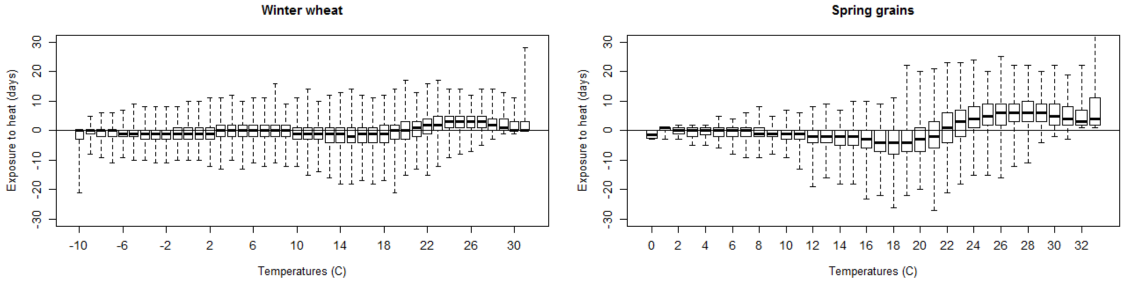
Medium term (2046-2065)



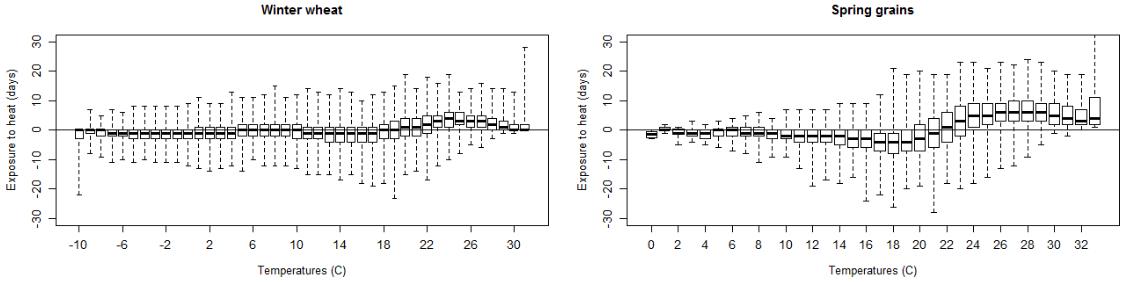
Long term (2081-2100)



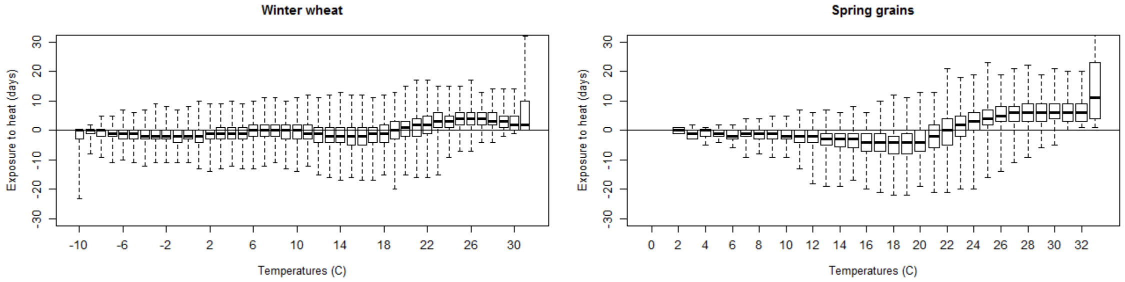
RCP4.5



RCP6.0



RCP8.5



Source: Own calculation based on IPCC (2014) and SHEFFIELD, GOTETI and WOOD (2006).

Note: Graphs show the changes in the distribution of temperatures during the growing season (March-June for winter wheat, and May-July for spring wheat and spring barley). Whiskers show the maximum and minimum exposure to the selected temperature range. Box marks observations that fall into the 25-75 % percentile range, and the bold line indicates the sample median.

Available climate projections provide estimates of average monthly temperatures. However, to calculate in *GDD* and *HDD* under counterfactual climates we need the information regarding exposure to temperature intervals. To derive values of degree days for the two projection periods we obtain the climate differences between mean projected values and mean values during the baseline period (SCHLENKER and ROBERTS, 2009). We then obtain projectted minimum and maximum temperatures by adding the climate difference to actual daily extremes for the baseline time frame. We then reconstruct the since curve of the degree days measures based on the 20-year average projected temperatures. Descriptive statistics for projected climate variables for all pathways and time horizons, including indicators of degree days and precipitation, is presented in Table 2.

Table 2: Descriptive statistics: Projected climate variables

Crop	Pathay	Period	Variable	Mean	Median	Min	Max	St.dev
Winter' wheat	RCP2.6	2046-2065	GDD	1109.45	1100.91	765.04	1493.84	196.67
			HDD	34.42	27.85	2.47	102.31	23.78
			Average daily temperatures Sept-Nov	8.56	7.64	2.58	15.56	3.52
			Average daily temperatures Dec-Feb	-5.72	-6.28	-17.35	5.57	5.93
			Total precipitation March-June	228.00	214.75	83.01	454.39	68.77
			Total precipitation Sept-Nov	158.67	155.96	107.72	216.30	27.70
			Total precipitation Dec-Feb	161.22	163.18	86.24	330.01	39.67
	RCP2.6	2081-2100	GDD	1103.58	1097.13	763.38	1471.55	184.01
			HDD	32.54	27.02	2.83	96.98	22.86
			Average daily temperatures Sept-Nov	8.18	7.20	2.44	15.31	3.51
			Average daily temperatures Dec-Feb	-6.29	-6.59	-17.45	4.96	5.92
			Total precipitation March-June	240.91	236.47	90.68	450.92	65.80
			Total precipitation Sept-Nov	174.44	175.49	107.77	254.58	29.30
			Total precipitation Dec-Feb	154.90	158.55	85.88	297.30	34.57
	RCP4.5	2046-2065	GDD	1173.99	1168.94	808.36	1536.05	184.71
			HDD	47.49	41.35	4.87	116.85	26.91
			Average daily temperatures Sept-Nov	8.99	8.01	2.85	16.41	3.61
			Average daily temperatures Dec-Feb	-4.86	-4.85	-16.06	5.62	5.69
			Total precipitation March-June	234.04	227.23	88.05	441.65	64.35
			Total precipitation Sept-Nov	146.19	141.56	92.40	218.77	28.59
			Total precipitation Dec-Feb	161.41	166.22	86.41	316.10	39.44
	RCP4.5	2081-2100	GDD	1214.45	1218.78	848.03	1563.04	174.09
			HDD	61.62	57.24	5.12	137.18	33.01
			Average daily temperatures Sept-Nov	9.85	8.85	4.59	16.81	3.39
			Average daily temperatures Dec-Feb	-4.84	-5.30	-15.13	5.72	5.48
			Total precipitation March-June	224.62	212.99	78.98	429.47	65.42
			Total precipitation Sept-Nov	163.87	168.00	105.87	237.58	27.70
			Total precipitation Dec-Feb	159.32	162.01	92.14	325.63	37.92
	RCP6.0	2046-2065	GDD	885.42	856.97	614.03	1243.92	171.51
			HDD	4.49	3.16	0.15	18.41	4.33
			Average daily temperatures Sept-Nov	8.57	7.58	2.98	15.85	3.56
			Average daily temperatures Dec-Feb	-5.46	-5.79	-15.71	4.94	5.59
			Total precipitation March-June	234.69	234.44	87.57	428.11	61.81
			Total precipitation Sept-Nov	165.29	162.97	110.13	256.00	30.52
			Total precipitation Dec-Feb	159.74	161.36	90.15	326.48	39.29
	RCP6.0	2081-2100	GDD	1292.58	1304.97	917.06	1636.44	184.72
			HDD	64.34	55.46	10.68	151.82	35.23
			Average daily temperatures Sept-Nov	10.66	9.85	5.08	17.46	3.36
			Average daily temperatures Dec-Feb	-3.17	-3.37	-13.13	6.91	5.30
			Total precipitation March-June	219.22	206.39	77.53	405.85	64.24
			Total precipitation Sept-Nov	147.99	148.10	97.09	221.14	26.14
			Total precipitation Dec-Feb	167.77	171.89	92.91	312.41	38.27
	RCP8.5	2046-2065	GDD	1218.64	1218.53	876.91	1548.76	175.11
			HDD	52.79	48.01	5.26	129.47	29.60

Crop	Pathay	Period	Variable	Mean	Median	Min	Max	St.dev
			Average daily temperatures Sept-Nov	9.44	8.44	4.08	16.61	3.45
			Average daily temperatures Dec-Feb	-4.20	-4.68	-14.34	5.82	5.31
			Total precipitation March-June	214.71	201.37	74.94	427.30	68.19
			Total precipitation Sept-Nov	151.20	147.99	99.66	240.10	28.70
			Total precipitation Dec-Feb	165.99	169.64	87.63	331.64	40.19
	RCP8.5	2081-2100	GDD	1394.86	1405.59	1065.44	1729.23	147.46
			HDD	93.87	92.16	23.59	173.75	37.38
			Average daily temperatures Sept-Nov	12.99	12.15	7.94	19.61	3.23
			Average daily temperatures Dec-Feb	-1.36	-1.61	-10.98	8.05	5.03
			Total precipitation March-June	224.88	221.94	81.30	403.35	59.29
			Total precipitation Sept-Nov	164.08	160.01	106.39	236.35	35.14
			Total precipitation Dec-Feb	188.88	192.85	103.42	366.77	43.42
Spring grains	RCP2.6	2046-2065	GDD	1373.39	1414.10	455.59	1698.27	209.98
			HDD	67.06	57.36	0.00	224.62	53.41
			Total precipitation	191.31	172.33	41.25	427.27	81.07
	RCP2.6	2081-2100	GDD	1383.14	1422.98	483.39	1698.16	207.45
			HDD	63.18	52.06	0.00	209.11	49.59
			Total precipitation	229.51	216.82	54.42	474.00	87.91
	RCP4.5	2046-2065	GDD	1437.91	1500.68	523.10	1672.20	201.51
			HDD	92.57	87.33	0.00	246.84	61.54
			Total precipitation	187.97	166.32	43.45	453.46	82.12
	RCP4.5	2081-2100	GDD	1479.79	1532.88	631.83	1681.13	183.84
			HDD	114.20	120.07	0.00	274.67	72.94
			Total precipitation	179.85	155.67	36.65	443.44	83.06
	RCP6.0	2046-2065	GDD	1189.83	1217.87	405.94	1522.23	208.64
			HDD	10.30	6.34	0.00	50.92	11.67
			Total precipitation	198.01	191.50	54.62	420.30	73.95
	RCP6.0	2081-2100	GDD	1513.31	1559.92	721.25	1687.07	169.08
			HDD	118.62	119.57	0.01	278.60	71.56
			Total precipitation	170.42	143.28	33.63	440.00	87.32
	RCP8.5	2046-2065	GDD	1484.74	1534.00	597.51	1689.80	184.64
			HDD	106.33	101.74	0.00	265.44	67.82
			Total precipitation	181.51	159.39	37.25	437.05	86.96
	RCP8.5	2081-2100	GDD	1523.62	1570.81	884.08	1740.39	144.42
			HDD	163.81	167.37	0.04	261.31	70.91
			Total precipitation	169.03	144.25	36.28	486.48	85.32

Source: Own calculations based on IPCC (2014).

RESULTS AND DISCUSSION

1. Past yield outcomes

The estimation results for the models are presented in Table 3. Our estimates indicate a positive response of grain yields to growing degree days. The coefficient estimates are of about the same magnitude for all three crops, namely 0.12 % increase in winter wheat yields, 0.1 % increase in spring wheat and barley yields.

Similar to the results obtained by SCHLENKER and ROBERTS (2009) we find a negative impact of heat degree days on grain yields in Russia. This result implies that significant yield losses are likely to occur when daily temperatures exceed 25°C. The *HDD* coefficient estimates for the two spring grains are higher than that for winter wheat, suggesting that spring grains might be more strongly affected by extreme temperatures. Each additional heat degree day (eg. being exposed to 25°C for one additional day) reduced winter wheat yield by 0.8 %, spring barley yield by 0.9 %, and spring wheat yield by 1.3 %. This finding can be explained by the fact that yield growth is completed to a larger extent by the end of June for winter wheat, which makes it both less exposed and less susceptible to extreme temperatures in the mid-summer. The probability of daily temperatures exceeding the 25°C threshold is considerably higher for spring wheat and spring barley since a larger part of their vegetation period (phenology phases such as tillering, heading, earing and grain formation) takes place in June and July.

Table 3: Model estimation results, 1955-2012

Variable	Winter wheat	Spring wheat	Spring barley
GDD	0.123***	0.098***	0.113***
	(0.012)	(0.009)	(0.009)
HDD	-0.791***	-1.285***	-0.918***
	(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***	1.134***	1.013***
	(0.077)	(0.085)	(0.079)
P^{summer^2}	0.0001	-0.003***	-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)		
$HDD \cdot P^{summer}$	-	0.003***	0.001
		(0.001)	(0.001)
R^2	0.985	0.972	0.972
Observations	2790	3218	3422

Source: Own calculations.

Note: 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.

In addition to accumulated temperatures during the warm season, our econometric model for winter wheat includes average daily temperatures during autumn and winter months. Warmer climate during the sowing period might have a beneficial effect on winter wheat yield. However, extremely warm autumns are likely to negatively affect the development of this crop and thus reduce its yields. Similar holds for winter temperatures – warmer winters do not necessarily lead to better growing conditions for winter wheat, and potentially may result in yield losses.

We find a positive response of grain yields to summer precipitation. This is a reasonable result as most of the grain production in Russia is rainfed. The magnitude of the summer precipitation coefficient is the highest for spring wheat, indicating that it is the most sensitive plant. The effects of autumn and winter precipitation on winter wheat yields are similar to that in the summer. Interestingly, the rainfall during the autumn months seems to play a more decisive role for the winter wheat productivity than the summer rainfall.

Finally, the summer precipitation does not help to reduce damaging effect of extreme heat on spring wheat yields. According to our estimates, the coefficient estimates of the interaction terms ($HDD \cdot P^{summer}$) were found to be not statistically significant for these two crops., However, our result suggest that a similar phenomenon as found by SCHLENKER and ROBERTS (2009) is observed for spring wheat in Russia: the interaction term of *HDD* and the summer precipitation is positive and statistically significant indicating that summer precipitation helps to reduce heat stress in the case of spring wheat.

2. Projected yield changes under Hadley climate scenarios

Climate change impacts on the productivity of the 3 studied grain crops under Hadley models for 4 selected representative pathways are presented in Table 4. Previous studies projected significant yield reductions for spring grains in both the medium and long terms in Russia. Our estimates go in line with previous studies and project the overall country-wide effect of climate change to be negative. In case of the least harmful representative concentration pathway (2.6), grain yields are predicted to reduce by 14.8 % in the medium term and by 7.4 % in the long term. An increase in productivity in the long run relative to the medium run is explained by decreases in emissions concentrations, projected to decrease by the middle of the century according to this concentration pathway, thus slowing down the increase in temperatures and softening the effect of global warming on agriculture. According to our calculations, representative pathway 4.5 that implies the stabilisation of emissions in the atmosphere by the end of the century projects a decrease in yields by 24.7 % and by 34.6 % in the medium and long terms, respectively. It is interesting to note that pathway 6.0, that just as well assumes the stabilisation of emissions concentrations by the end of the century, projects a small increase of yields by 9.8 % in the medium-run and a decrease in the long term, similar to the of RCP4.5, 36.5 %. The difference between pathways expresses itself in relatively low number of heat waves that are projected in the medium term in RCP6.0. Less heat waves results in lower number of heat degree days, creating more favourable conditions for crop production. However, in the long run it aligns with similar in terms of emissions concentration pathway, RCP4.5. In the business-as-usual pathway (RCP8.5), which assumes complete absence of measures to mitigate climate change, grain yields are forecasted to decrease by 30.6 % and 50.5 % in the medium and long terms respectively.

Our assessment suggests that in many horizons the country production of spring wheat will not be as damaged by climate change as other crops. For example, in RCP2.6 yields are expected to decrease only 6.9 % and further increase by 5 %, while according to RCP6.0 we might observe an increase of 22 % in the medium run. This process takes place as a result of the spatial distribution of spring wheat production: predominantly concentred in the European regions with mild climate as well as in some parts of South Siberia, spring wheat, planted in spring and harvested in early autumn, does not face extreme heat and drought, typically observed in the southern part of the country. On the contrary, major spring wheat producing zones have not yet reached high yields level because the growing season is still not long enough for fast and efficient development on the plant. In case higher concentrations of emissions result in higher temperatures, springs and summers will have favourable conditions for spring wheat. However, the warmer the climate is projected to be, the more dangerous this increase of temperatures becomes even for those areas where temperatures currently are not high enough. As presented in Table 3, emission stabilization pathway 4.5 projects a decrease by 21.8 % and 31.8 % in the medium and long terms, respectively. Similarly, business-as-usual pathway suggests that yields could plummet down by 25.5 % in the medium term and by 52.4 % in the long run.

Spring barley is expected to benefit from climate change only in case the development follows the pathway 6.0: in the medium run spring barley yields could increase by 22.1 % in the medium run. In all other scenarios and horizons spring barley is expected to considerably suffer from climate change. Our study identifies a reduction of up to 28.7 and 18.5 % in the medium and long runs according to RCP2.6. Concentration pathway 4.5 suggests a fall in yields up to 39.8 and 51.4 % in the medium and short runs, respectively. Similar holds for RCP8.5: production could potentially decrease by 46.9 and 66 %. This is a drastic fall in yields that results from the increased number of heat degree days and absence of precipitation, projected for main barley producing regions located predominantly in the south of the country, where conditions are already not very suitable for agricultural production. Spring barley traditionally was planted there because it was resistant to heat and dry periods that were common for that part of the country. However, apparently projected climate change will increase temperatures up to a level when its impact on barley production becomes negative.

Table 4: Predicted climate change impact under HadGEM2-ES for 4 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	-0.14776	-0.1300	-0.0690	-0.2868
		(0.0404)	(0.0490)	(0.0354)	(0.0323)
	2081-2100	-0.06094	-0.0736	0.0504	-0.1851
		(0.0512)	(0.0466)	(0.0631)	(0.0470)
RCP4.5	2046-2065	-0.24679	-0.1882	-0.2177	-0.3980
		(0.0554)	(0.0621)	(0.0534)	(0.0456)
	2081-2100	-0.34556	-0.2771	-0.3180	-0.5139
		(0.0626)	(0.0744)	(0.0571)	(0.0475)
RCP6.0	2046-2065	0.097558	0.0059	0.2213	0.1088
		(0.0082)	(0.0185)	(0.0016)	(0.0002)
	2081-2100	-0.36524	-0.2988	-0.3413	-0.5248
		(0.0657)	(0.0790)	(0.0609)	(0.0469)
RCP8.5	2046-2065	-0.30617	-0.2572	-0.2549	-0.4687
		(0.0608)	(0.0656)	(0.0654)	(0.0465)
	2081-2100	-0.50545	-0.4121	-0.5239	-0.6601
		(0.0763)	(0.0988)	(0.0622)	(0.0511)

Source: Own calculations.

Note: Standard error in brackets.

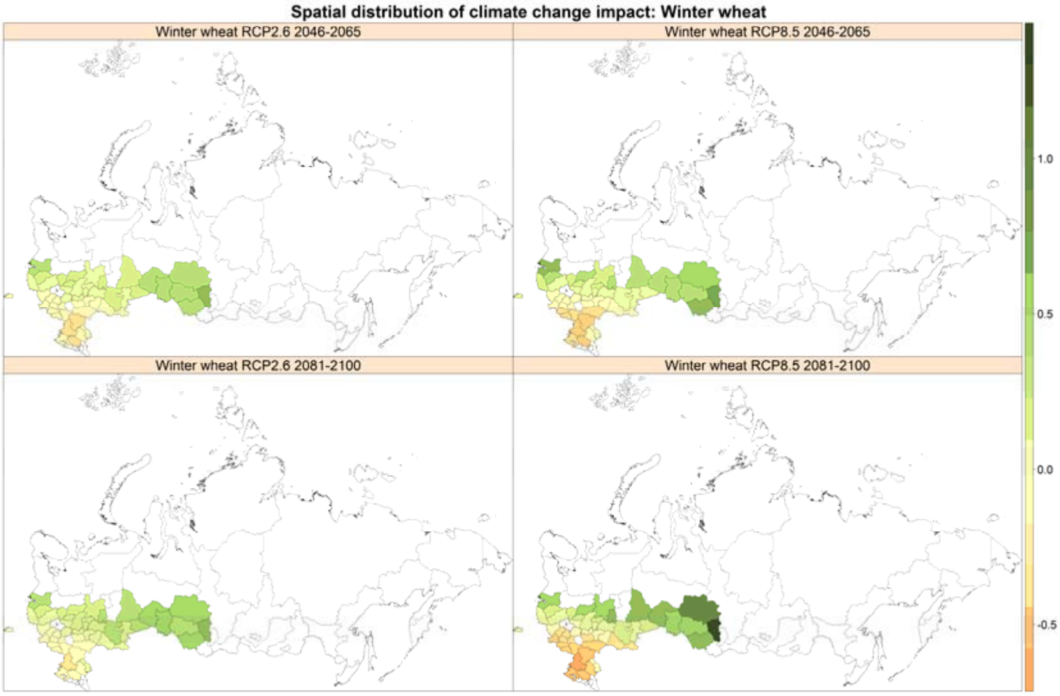
We find similar to spring wheat medium and long-run impacts of global warming on winter wheat yields. Although our estimation results suggest that winter wheat is likely to benefit from increasing temperatures in the autumn and winter months as well as from increasing growing degree days, our analysis indicates that winter wheat yields increases in summer temperatures in most cases would have a damaging effect, resulting in higher number of heat degree days, that could decrease yields by 13 and 25.7 % in the medium term and by 7.4

and 41.2 % in the long run for concentration pathways 2.6 and 8.5, respectively. This finding contradicts our initial expectation that increasing temperatures would have created favourable conditions in winter and early spring for a better development of crop during the vegetation period. It indeed holds for northern parts of the country, while southern regions that have the largest share of cropland under winter wheat would severely suffer from rising temperatures in summer and spring, thus increasing the number of heat degree days. These results become clearer once we observe the spatial distribution of climate change effect.

The projected impacts are not only crop specific; in addition, they vary across oblasts providing further insights into the effect of climate change on agricultural productivity in the country. Figure 5, Figure 6 and Figure 7 show the spatial distribution of the projected CC impacts at the oblast level for two selected concentration pathways[5] in the medium and long terms for three examined crops. Although the magnitude of productivity changes varies across scenarios, the tendency for increasing or decreasing productivity for oblasts remains the same for all projections, with the exception that climate change effect becomes softer in the long run for RCP2.6 because of decreasing emission concentrations and slower than in the medium term rising temperatures.

At first glance it seems that the effect on winter wheat (Figure 5) will be rather positive than negative. In fact, winters in the Northern and Siberian parts become warmer, creating better conditions for the germination and tillering. However, the share of these regions in the country's wheat production is very small, while southern regions have long established tradition of winter wheat growing. There temperatures in the early summer become already too high for efficient development of crops, resulting in the potential decreases of yields.

Figure 5: Predicted climate change impact under HadGEM2-ES for winter wheat at the oblast level for 2 selected representative concentration pathways (RCP2.6 and RCP8.5)



Source: Own calculations.

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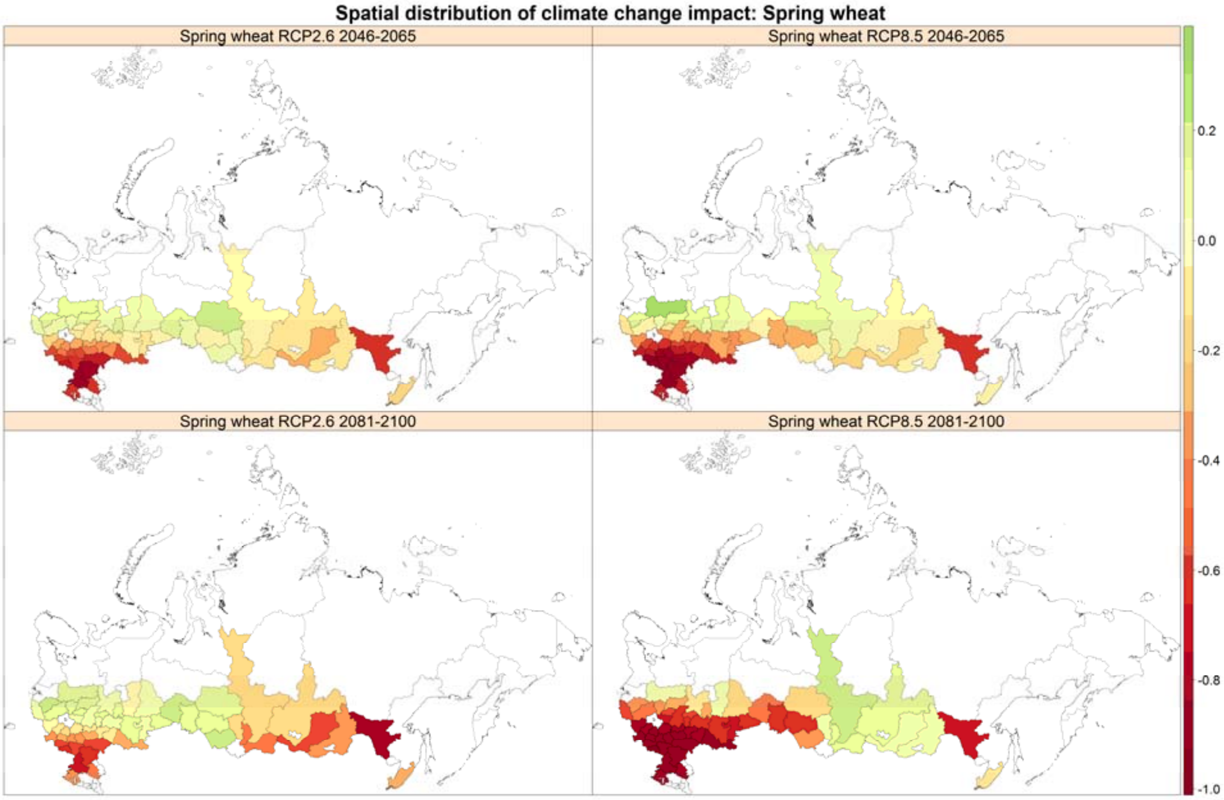
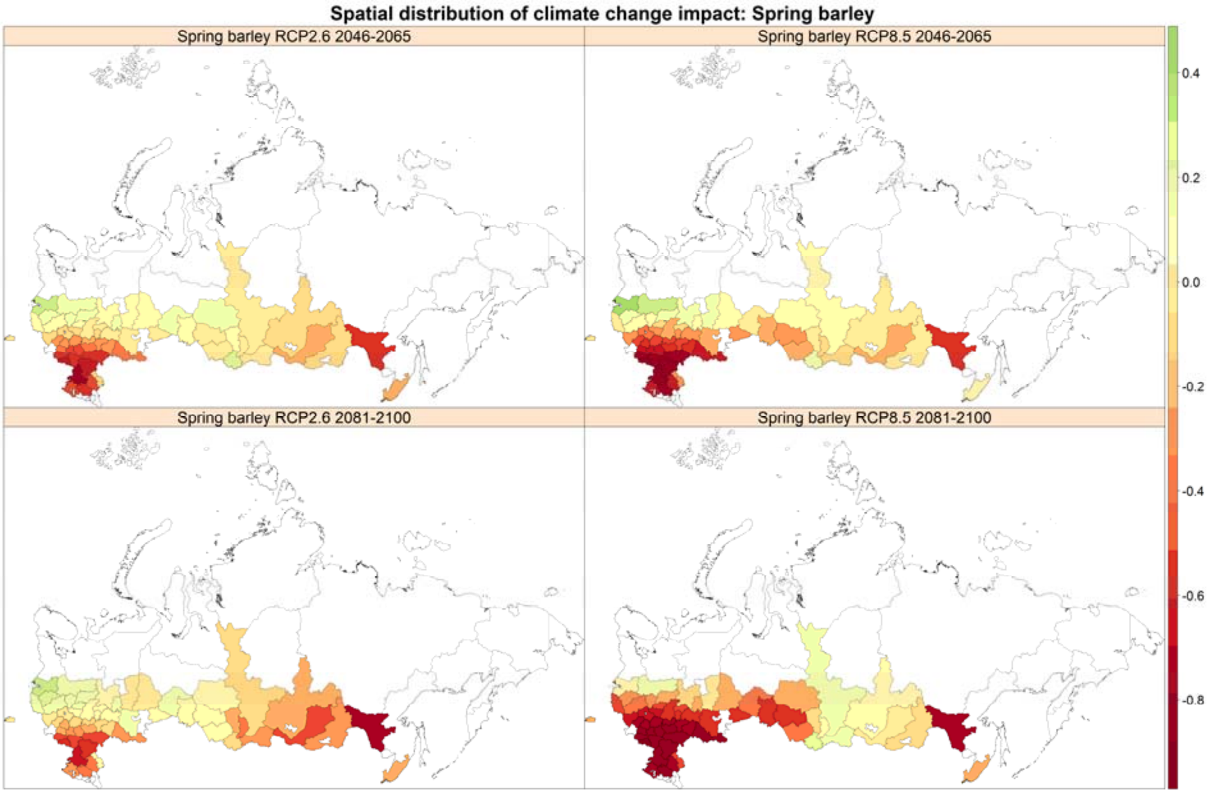
[5] To show contrasting results we select the most optimistic pathway (RCP2.6) and compare it to the business-as-usual pathway (RCP8.5).

Figure 6: Predicted climate change impact under HadGEM2-ES for spring wheat at the oblast level for 2 selected representative concentration pathways (RCP2.6 and RCP8.5)



The effect of spring wheat, presented in Figure 6, seems to be extremely negative, given very high temperatures in the South of the country during the spring grains vegetation period, May-July. In fact, in these regions productivity declines partly due to higher number of heat degree days and partly as a result of lack of precipitation, according to existing projections. In Northern regions productivity increases vary from 0.1 % to 40 %. This process takes place because of prolonged growing period and higher levels of precipitation projected for summer period in that parts of Russia. These regions already produce the biggest share of spring wheat, and therefore, the overall effect of climate change on the country's weighted average productivity is softer than expected.

Figure 7: Predicted climate change impact under HadGEM2-ES for spring barley at the oblast level for 2 selected representative concentration pathways (RCP2.6 and RCP8.5)



Spring barley (Figure 7) is traditionally considered as crop, the least vulnerable to heat waves or sudden frosts, and therefore it is planted country-wide, including southern regions with the least productive conditions. Similarly to winter and spring wheat, it is expected to suffer from increasing temperatures during the summer period and lower precipitation levels. In regions where condition become more favourable (predominantly North and some zones in Siberia) the share of cropland allocated for spring barley is too low at the moment to have any significant impact on the overall effect of climate change on productivity.

A detailed examination of the oblasts level CC effects on grain yields shows that in the absence of new adaptation measures not observed in the historical period agricultural productivity in Russia might show a dramatic decline. Winter grain productivity is expected to show a decline of up to 50 % in the most productive and important grain producers of Russia, rich with black soils Krasnodar, Rostov and Stavropol. A key solution to mitigate the effect of climate change on agricultural production for most Russian regions would be extending croplands for both spring and winter grain to the Northern and Siberian parts of Russia. Warmer and milder climate in autumn and early springs in the Central and Northern Russia, and Siberia, might have a beneficial effect for 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., 2013) have showed that the process of land abandonment that took place in Russia during the 1990s and resulting in considerable shrinkage of agricultural lands, happened as a result of lower crop yields and lack of infrastructure in the proximity of cropland. Accordingly, technological improvements and efficient uses of fertilisers would be required to reduce the magnitude of the damaging effect of temperature increases on grain production in these regions.

CONCLUSIONS

Changing climate and the increasing frequency of extreme weather events may result in bad harvests, which in turn may translate into food stress and price fluctuations. Effective adaptation to CC requires knowledge of the mechanisms and the magnitudes of its impacts, as well as information about the ability and capacity of economic agents to adjust to changes in their environment. This knowledge should provide a valuable basis for elaborating and implementing policies aimed at reducing adverse CC effects. Our study investigates the potential impacts of climate change on agricultural productivity in Russia – now one of the major grain producers in the world.

Our results suggest that increasing temperatures might have a positive effect on winter wheat, spring wheat and spring barley productivity in Northern and Siberian regions of Russia. In contrast, Southern regions might experience considerable decreases in productivity of all three crops. Holding current grain growing areas fixed, the productivity of grain in general is projectted to decrease by the end of the century by 6.1 % for the pathway with the lowest level of emissions concentrations, and by 50.6 % for the business-as-usual development pathway, which assume faster rates of global warming, given no new adaptation measures will be introduced. The impact of climate change on Russian grain production in the medium term is expected to be more moderate.

Our research suggests that in the mid- and long-terms, Russia can effectively mitigate the negative effect of climate change on its grain production by extending the production of winter and spring grains to the North of Russia. Milder autumns and earlier springs due to global warming can considerable improve growing conditions for winter grains in most grain producing regions and lead to an increase in the share of winter grains in the total growing area under grains. At the same time, warmer summers will result in longer vegetation periods for spring grains, increasing their productivity. However, the lack of infrastructure, lower productivity of land, and absence of investments to safely reintroduce the abandoned lands into the agricultural process creates obstacles for increases in production in the North of the country. Similarly, more efforts are required to reduce the negative impact of climate change on grain production in the Russia's most productive regions of the Southern and Northern Caucasian areas. Water scarcity in combination with increased spring and summer temperatures might considerably affect productivity of both winter and spring grain crops in these regions. Accordingly, adaptation measures should focus probably on breeding new – more drought-resistant – grain varieties and adopting soil moisture accumulating and presserving technologies.

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