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ORIGINAL ARTICLE

Climate change, food stress, and security in Russia

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Abstract Farming in higher latitudes is generally believed to benefit from a warmer climate due to extended growing season, reduced risk of frost, availability of more productive cultivars, and an opening potential of farming in northern locations. We analyzed the impact of climate change on production of cereals in Russia and found that this general perception of beneficiary effect of a warmer climate is unlikely to hold, primarily due to increasing risk of droughts in the most important agricultural areas of the country. Past impacts of droughts on food security throughout the twentieth century suggest that a number of adaptation options are available to mitigate the increasing risks of crop failure. We analyze the effectiveness of these measures in connection with a set of climate change projections, under two contrasting scenarios of interregional grain trade: "Fortress Market" and "Open Market."

Keywords Climate change · Russia · Agriculture · Food security · Droughts

Introduction

Is climate change universally beneficial for the agriculture of the northern countries? The Russian public seems to believe so, although it is largely uninformed and uninterested in issue at all (BBC World Service Poll 2007). Similarly, the Russian National Communications to the UN Framework Convention on Climate Change have mostly focused on benefits of climate change to agriculture, such as the projection of a climate-related yield increase of cereals by 14% in the 2050s when compared to the current yield (Interagency Commission of the Russian Federation on Climate Change Problems 2006). Indeed, the results from general circulation models (GCMs) universally project the most profound warming at higher latitudes. This warmer climate should expand growing season length and allow the use of more productive crop varieties with higher growth degree-days requirement. Observations from the 1990s indicate reduced risk for frost damage to crops in all Russian regions, especially near their northern border of cultivation (Interagency Commission of the Russian Federation on Climate Change Problems 2006). Higher temperatures can shift bioclimatically suitable areas for intensive agriculture in Russia as much as 600 km to the North, with significant increase in agricultural output. Pegov et al. (2000) have estimated a 50–100% potential increase in production, mainly due to increased availability of land suitable for agriculture.

Although higher temperatures are beneficial for agriculture, there are other factors that negatively impact yields. Limited land availability and lower soil fertility outside of *Chernozem* (Black Earth) belt, located in Russian steppes (Stolbovoi and McCallum 2002), make it unlikely that the shift of agriculture to the boreal forest zone will bring significant production increase. The benefits of declining frost damage are already being reduced by increasing crop damage from ice and longer wet periods in spring (Interagency Commission of the Russian Federation on Climate Change Problems 2006). But the principal limiting factor for crop yield in the major agricultural areas in South European Russia is summer precipitation (Field 1968).

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During the twentieth century, at least 27 droughts have occurred in this region (Meshcherskaya and Blazhevich 1990). For the twenty-first century, our own and other studies indicate increasing risk of reoccurring severe droughts in the zone with the most fertile soil (Alcamo et al. 2007; Interagency Commission of the Russian Federation on Climate Change Problems 2006). Under current climate, only a relatively small area in Lower Volga River basin (presently one of the driest parts of the Russian grain belt) has a high frequency of severe droughts. In the future, the area of frequent severe droughts will likely extend to a considerable part of South European Russia (Fig. 1).

Most extreme weather events translate into reduced crop yields. While the crop failures can often be compensated locally through interregional trade and grain reserves, they are much harder to deal with when droughts spread to multiple regions. During the twentieth century, cereal crop failures in the production regions of Russia have several times escalated into serious food crises throughout the country—on a few occasions they even turned into famines where millions of people perished. However, even the worst repetitive droughts did not necessarily trigger a widespread famine or an extensive food shortage in the past. For example, in 1906, the worst year for agriculture of Russian Empire in the decades preceding World War I, a 33% decrease in marketable grain resulted in 30% increase in prices on domestic market. Two-third of the losses was carried by consumers, and one-third by producers. There nevertheless was no interruption in grain flow from productive to consumption regions and no food crisis in any region of Russia (Zak 1925). Under administrative control of the grain market, similar crop failures would have likely lead to more dramatic consequences. For example, the weather pattern in 1916 was more favorable for agriculture in Russia than in 1906, but many cities of Central European Russia suffered the following winter and spring from food crises, mainly due to the tight administrative control of grain market, such as the introduction of a system of fixed prices for government purchases (Gatrell 1999).

The barriers to interregional food exchange have always played a major role in the emergence of a food crisis. In this paper, we examine the role of the administrative system for food security under climate change. For that, we first analyze the historical pattern of cereal production in Russia, interregional grain trade, and the incidents of emerging food crises, and formulate a scenario of administrative barriers to grain trade. Then we extend our analysis into the twenty-first century by computing the risks to food security under altered grain yields, as simulated by Alcamo et al. (2007) under several scenarios of climate change. Finally, we compare the results of our simulations under restricted food market with the results of model runs without regional trade barriers.

A system of the administratively controlled interregional food exchange in Russia was introduced in the beginning of 1990s and held for over a decade. This system is characterized by restricted food trade across region borders inside the country, especially, in years of poor harvests. It was established by regional authorities in order to protect the local agriculture business from competitors and to secure the internal food reserve and/or low prices. We show that this administrative control over food production and trade leads to elevated risk of food stresses in the new climate. Further, elevated danger of food stress, mainly in non-productive regions, can potentially escalate separatist tendencies in production regions as they try to secure their own consumption by making the barriers even higher. At the same time, the risk of frequent future food stresses can be mitigated if Russia successfully develops free market relationships between regions.

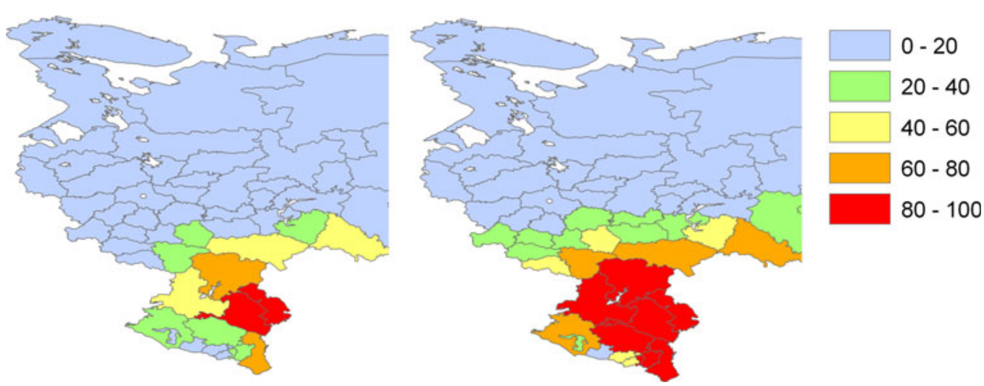

Fig. 1 Frequency of extremely dry years (years per century) in the most productive agricultural areas of the European part of Russia. An extremely dry year is defined as a year when the Hydrothermal Coefficient (see explanations in the text) falls below 0.7 during the growing period. *Left pane* presents current climate, *right pane* presents the climate of the 2070s, based on the HadCM3 A2 scenario. Map polygons correspond to existing top-level administrative divisions

Interregional food exchange in Russia

The border between boreal forests and forest-steppe zones of Russia also separates food-consuming industrial North from the food-producing agricultural South. These two zones differ both geographically and historically, and this division was used for many administrative purposes from the late nineteenth century (Statisticheskii ezhegodnik Rossii (Statistical yearbook of Russia) 1916, 1902), e.g., for census data collection or railway network construction to allow fast grain transporting (Voeikov 1963). The localization of cereal production (mainly winter wheat) in steppe and forest-steppe zones of European Russia with the best soils and warmer climate was completed during the nineteenth century, resulting in a clear-cut division of the country into production and consumption zones. As a result, over half of the cereals in Russia are currently produced in a contiguous territory spreading through just 5.5% of the country. Other regions primarily grow cereals for their own consumption (including grain for feed, e.g., for meet and poultry production), or, especially the industrial regions of the North, almost entirely rely on imports from other regions (Fig. 2). This concentration of agricultural production in a small region brings an advantage normally acquired with specialization—while requiring a highly functional regional integration of the agricultural economy.

The distance between the most important agricultural zones in the South (there are also a few important areas of agriculture in the Asian part of the country) and the major consumption zones in the European Center and North, high yield variability, and historically low transportation cost when compared to production expenses result in an unusually high importance of interregional trade for food security. This is especially true for grain production. Throughout the twentieth century, the regulations imposed on interregional grain flows fluctuated greatly, as the regions tried to protect their own consumption and the central government tried to distribute the limited resources to whatever regions they deemed to be more important. The history of food crises in Russia shows that during the poor harvest years, the production regions typically had an advantage over consumption regions in both the caloric consumption and the prices. For example, in the beginning of the twentieth century, grain price in the production regions would typically be 5–8% lower than the price in consumption regions during an average year (Zak 1925). However, after the disruption of interregional food trade and excessive procurement of grain from devastated collective farms in late 1920s–1930s, imposed by the Stalin regime, it was the producing part of Russia that suffered the worst food crises, followed by mass famines. For example, during the Ukrainian famine (*Holodomor*) in 1932–1933, the death toll has probably been between six and seven million people. At the same time, the industrialized consumption regions received a clear advantage through food rationing and other government-controlled relief measures. Later, since the middle of 1960s and through the "developed socialism" period of 1970s–1980s, the production regions were once again granted some limited advantage, being allowed to keep larger amounts of locally produced food for regional consumption, while the food deficit in consumption regions was covered in part by the state reserve and in part by grain imports from abroad (Dronin and Bellinger 2005).

Since the beginning of the 1990s, Russian agriculture was experiencing a deep crisis. Livestock has declined by more than 40%, which is comparable to the World War II period. There is no fodder resource in many regions of Russia, while growing or importing forage has become unprofitable due to slow livestock weight gain and low meat purchase prices. Even though grain production stayed low, a significant volume of grain (12×10^6 t in 2002, or 14% of the total harvest) was being exported from the country due to falling domestic purchasing power and reduction of livestock inventories; at the same time, food import reached 24–28% of the total import of the Russian

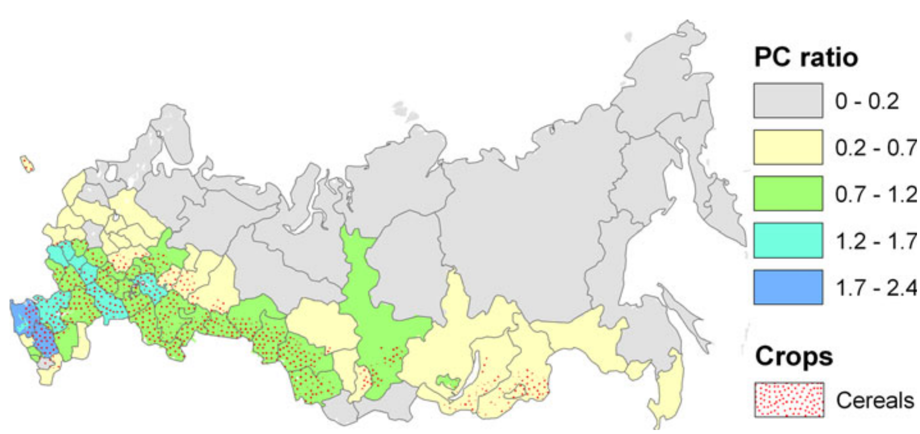

Fig. 2 A ratio of region grain production to region grain consumption (1990s, National Committee on Statistics Goscomstat data). The dots outline the main cereal production area (data from Stolbovoi and McCallum 2002). A relatively small territory in SW Russia is a principal producer of cereals for other regions; this is also a territory where an increase of drought frequency is projected by GCMs

Federation, a proportion similar to the one observed 20 years prior (Goscomstat 2000; Nefedova 2003).

Modern Russia is a country with a transitional economy, which comprises the elements of both free market and administrative control inherited from developed socialism. On the national level, the wholesale and retail prices for agricultural produce are generally governed by supply and demand. However, strong administrative control over agricultural activity and wholesale prices on regional level still exists in many regions of Russia. The chronic crisis of Russian agriculture was frequently accompanied by regional separatism. In dry 1998, nearly half of the regions most affected by the drought adopted regional regulations banning or restricting export of grain to other regions of Russia (Kalmanov 1999). These regulations combined the control over interregional food trade with intraregional price regulations. Some regions instituted a compulsory grain purchase for regional emergency reserve and consumption with prices much lower than free market. Others licensed the wholesalers to sell grain to other regions of Russia only after their obligations inside the regions are met. In a few cases, compulsory grain procurement methods were reported (Nefedova 2003). The amount of grain procured via these compulsory programs has been as high as 20% of the total average national grain production (Nefedova 2003).

An unusually low level of crop specialization between the producing regions (as opposed to the climatically explained difference in agriculture of producing and consuming regions) has been both the result and an explanation of these trade restrictions. Many regions still preferred self-sufficiency to economic advantage of free market. However, it is not true that all the regions followed the same administratively controlled production—consumption strategy. First, many consumption regions depended on grain imports from other regions; it is highly unlikely that those regions will ever be able to become agriculturally self-sufficient due to poor soils and unfavorable climate. Second, some production regions still preferred exporting the surplus grain, while the others forced their wholesalers to keep a considerable part of their grain purchase inside the region (e.g., increasing the amount of grain used as livestock feed). As a result, grain consumption per capita varies widely in regions. We distinguish five major groups of Russian regions according to their production-consumption strategies (Table 1):

Production regions, which sell their grain surplus on a free market (Central Black Earth, and Northern Caucasus);

Production regions, which use a considerable part of their grain surplus locally (usually for feed) rather than sell it to other regions (Lower Volga, South of Western Siberia, and Middle Volga);

Consumption regions, managing to produce and import enough grain to keep their consumption above the national average (Volga-Vyatka, South of Eastern Siberia, and Baikal region);

Consumption regions with low local production, which import enough grain to support normal consumption (some North Caucasus' republics);

Table 1 Grouping of the regions according to their geographic location and trade strategies

Production group		Geographic group	
No.	Description	No.	Name
1	Production regions, preferring to sell all grain surplus on a free market	4	Central Chernozem
		6	Northern Caucasus
2	Production regions, preferring to consume much grain surplus inside the regions rather then to other regions	7	Lower Volga
		9	South-western Sibeia
		17	Middle Volga
3	Consumption regions, managing to produce and import enough grain to keep their consumption above the national average	8	Volga-Vyatka
		12	South of eastern Siberia
		14	Baikal region
4	Consumption regions, consuming grain at about the average level	5	North Caucasus' republics
5	Consumption regions, consuming much below the national average	1	North
		2	North-West
		3	Central
		10	Western Siberia
		13	Eastern Siberia
		15	Far East
		16	North East
		18	Urals

For indices see legend to Fig. 3

Consumption regions with low local production, which consume well below the national average (North, North-West, Central, Western Siberia, Eastern Siberia, Far East, North East, and Urals).

Data and methods

Climate change scenarios

To estimate the impacts of future climate change on Russian grain production, we mainly use results from the UKMO general circulation model (GCM) HadCM3 (Pope et al. 2000), for the IPCC socioeconomic scenarios A2 and B2 (the latter corresponding to somewhat lower global temperature increase). To test our findings for consistency, we compare results against simulations made on the basis of scenarios made by ECHAM4/OPYC3 (Roeckner et al. 1996). From the GCMs, we use decadal mean climate parameters to emulate cumulative climate change for the 2020s and 2070s. For temperature, the difference between these time slices and the present was measured by subtraction of the values; for precipitation, the difference is expressed by division. All results were rescaled into 0.5×0.5 degree grid. To account for daily and annual weather variability, we have used the climate and daily weather generator WGEN (Richardson and Wright 1984; Friend 1998). This procedure generated two sets of scenarios, for the climate of the 2020s and 2070s, as ensembles of the values for maximum and minimum temperatures, precipitation, solar radiation, etc.

The climate change scenarios show a significant increase in temperature and a moderate increase in precipitation for agricultural zones of the country (Table 2). For the 2020s, both HadCM3 and ECHAM4 show greater temperature increase for the B2 emissions than for A2. However, by 2070s, temperatures under A2 are about 1°C higher than those for B2 (for both HadCM3 and ECHAM4, the HadCM3 increase being somewhat less). For HadCM3, 2070s mean annual temperatures warm, compared to current climate, by 4.8°C under A2, and 3.9°C under B2 scenario. For ECHAM4, temperatures increase by 6.1°C and 5.3°C, correspondingly.

For precipitation, both A2 and B2 scenarios show similar increases for the 2020s, but for the 2070s the A2 scenario has a stronger increase in precipitation. Both HadCM3 and ECHAM4 project almost universally identical increase of precipitation under the same scenarios. However, the additional precipitation is not distributed evenly. The main part of Russian territory experiences moderate precipitation increase; on the other hand, the most intensively used agriculture areas in the south of the European part of the country experience precipitation decline under both HadCM3 and ECHAM4 and both A2 and B2. Also, for a significant part of the grain belt, precipitation increases on the annual basis, but decreases during the summer months.

Even when higher amount of precipitation is projected for a region, the region can become drier under warmer temperatures. We used the Summer Hydro Thermal Coefficient (HTC) by Seljaninov (1966), accepted in Russia, to quantify the effect of changing temperature and precipitation on climate aridity. The HTC is computed as a sum of precipitation from the beginning of the growing period, multiplied by 10 and divided by a sum of effective temperatures. Growing period is defined as a period with average daily temperatures above 10°C. HTC values usually fall between 0.4 and 2, with lower values corresponding to drier conditions. HTC below 0.7 is considered typical for droughts, while HTC from 0.7 to 1 indicates moderately dry summers, and HTC around 1.2 usually coincides with optimum conditions for agriculture balance between thermal and water recourses.

We computed HTC for current climate and for the two future time slices (2020s and 2070s), across all climate change scenarios. Results indicate that the majority of the principal agriculture regions of Russia will be drier in the future than they are now, especially during the summer

Table 2 Climate change scenarios for agricultural zones of Russia

			Annual temperature	Summer temperature	Annual precipitation	Summer precipitation
Current climate			−5.2	12.9	457	187
2020s	A2	HadCM3	−3.4	14.4	486	196
		ECHAM4	−3.	14.1	497	192
	B2	HadCM3	−3.1	14.9	497	198
		ECHAM4	−2.4	14.7	497	186
2070s	A2	HadCM3	−0.4	12.5	546	211
		ECHAM4	0.9	17.4	540	194
	B2	HadCM3	−1.3	16.4	519	206
		ECHAM4	0.1	16.7	527	192

months. For the most important producing regions of the European part of Russia, temperatures will increase by 1–2°C by 2020 and by 3–4°C by 2070, while precipitation will stay the same or decrease. For a few regions with intensive agricultural production in the Asian part of the country, the temperature increase will be matched by an increase in precipitation; however, the more favorable climate here is unlikely to compensate for drier climate in the majority of agricultural regions.

Drought frequency and severity are likely to increase in the drought-prone main grain growing areas of Russia under both A2 and B2 scenarios (Fig. 1). For example, under current climate Stavropolsky kray (Northern Caucasus) experiences 28 dry years in a century, increasing in the 2020s to 64, and in the 2070s to 89 (HadCM3; for ECHAM4, 32 and 70 years, correspondingly). In current climate, in Krasnodarsky kray (Northern Caucasus) the frequency of dry years is 21 per century, increasing in the 2020s to 51, and in the 2070s to 67 per century (HadCM3; for ECHAM4, 32 and 57 pre century, correspondingly). The severity of droughts also increases: mean HTC drops from 1 to 0.65 for Krasnodarsky kray and from 0.9 to 0.5 for Stavropolsky kray (HadCM3, A2). Under the B2 scenario, changes are similar.

In contrast, the northern regions of European Russia as well as the Far East experience no significant change in occurrence of dry summers. For example, Leningradskaya oblast (North-West) has one dry summer per century and Khabarovsky kray (Far East) has five. In these conditions, longer growing period and higher growing degree-days may indeed benefit local agriculture. However, other features such as land availability and soil fertility are at least equally important as the bioclimatic factors.

Impacts of climate change on agricultural production

We have adapted the model of global agroecological zones GAEZ (Fischer et al. 2000) to estimate climate change impact on agricultural crops. In the GAEZ model, the entire territory of Russia is separated into a half by half degree cells. Each of the cells is characterized by the soil, relief, and 6 parameters of climate: precipitation, temperature (monthly average and monthly variability), relative air humidity, incoming solar radiation, and wind speed. The climate parameters were synthesized for each month of 1901–1995 period using the CRU climate database (New et al. 2000). For the synthesized future climate (2020s and 2070s), we assumed that monthly temperature variation, air humidity, solar radiation, and wind speed were characterized by 1961–1990 data. For those years, we also adopted synthesized monthly precipitation and average temperature ensembles, described above. An analysis of simulation results for 1961–1995 climate when compared with the reports from Russian National Committee on Statistics (Goscomstat 2000) and from the Central Statistical Committee of the Russian Empire (Statisticheskii ezhegodnik Rossii (Statistical yearbook of Russia) 1902, 1916) demonstrated adequate performance of the model during the years with limited amount of precipitation (Kirilenko et al. 2004). Since dry summers seem to be the main risk factor for food security, we considered the modified GAEZ suitable for the study.

The GAEZ model simulates the production of 154 crop species and varieties for the whole world. We have adapted GAEZ for the simulation of Russian agriculture. While the base model simulates agriculture of different countries, we adopted the existing subdivision of Russia into 89 administrative regions. We limited the list of crops to the three most important cereals: wheat (including 4 spring and 4 winter varieties), rye (including 4 spring and 4 winter varieties), and corn (including 6 varieties). More details are provided by Alcamo et al. (2007). In the ‘Fortress Market’ scenario, we considered only the two most important food crops for each administrative region. For the ‘Open Market’ scenario, we considered only the most productive food crops. In this way, we emulate regional crop specialization under a free market, since the regions aim for producing the crops best suited for climate and soils, as opposed to self-sustaining policies of the ‘Fortress Market’. Our simulations estimate the potential production for each of the administrative units during 2020s and 2070s. It is worth noticing that under frequent droughts, the main agricultural areas of Russia experience decreased mean yield. At the same time, the northern regions are able to compensate by increased yield, however, restricted by low soil fertility and limited land availability (Fig. 3).

A model of interregional grain exchange

We developed a simple model of interregional grain exchange to compare the impact of climate change on food consumption in different market scenarios. In the model, 89 top-level administrative units (oblasts, krays, republics, autonomous oblasts, autonomous republics, and two municipalities) of Russia were integrated into 17 geographic regions (in the following named ‘georegions’). Each georegion consists of contiguous and agriculturally similar administrative units, such as North Caucasus, Lower Volga, Middle Volga, etc. For the georegions, the amount of grain available for consumption depends on their own local production, the part of the harvest available for export from the major agriculture production regions, and the purchasing power of consumption regions, computed as mean income per capita.

We consider two scenarios, named ‘Fortress Market’ and ‘Open Market’. The scenarios determine a share of

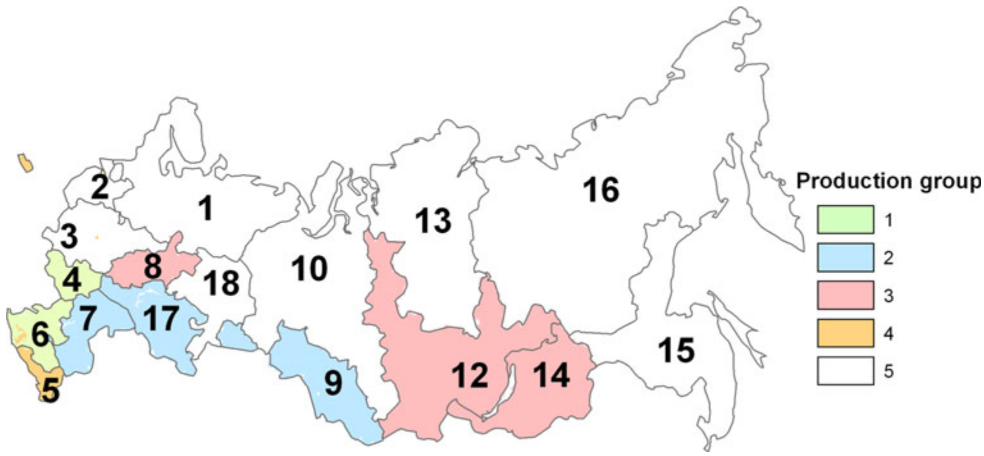

Fig. 3 Impact of changing climate on wheat yield in European Russia. The difference between GAEZ simulations for 2070s under HadCM3 A2 scenario and GAEZ simulations for current climate is shown. Sharp decrease corresponds to yield reduction of at least 1 t ha^{-1}; moderate decrease corresponds to yield reduction of 0.1–1 t ha^{-1}; no change corresponds to yield increase or reduction by less than 0.1 t ha^{-1}. Areas with little current grain production are not shown

harvested grain available for sale and the accessibility to grain markets. The 'Fortress Market' scenario suggests that a number of production regions tend to restrict their sales, holding a considerable amount of grain surplus for their internal consumption, while the 'Open Market' scenario assumes that the production regions are able to sell the available harvested grain without administrative restrictions.

The 'Fortress Market' scenario approximates the administrative market regulations, similar to those in 1990s - mid-2000s. We compute mean georegion production $\bar{p}_i : \sum \bar{p}_i = 1$ as a ratio of mean regions' production (computed as detailed above) and Russia's total mean grain production. The mean georegion consumption $\bar{c}_i : \sum \bar{c}_i \approx 0.9$ is computed as a ratio of the mean consumption of that region and Russia's mean grain production. During a year t, we compute the grain balance of a georegion i as $\beta_i(t) = p_i(t) - \bar{c}_i$. If $\beta_i(t) > 0$, the extra grain is sold on the market. If $\beta_i(t) < 0$, the necessary grain is purchased. During the year t, the supply is computed as

$$\Theta(t) = \sum_{1}^{N_g} \max(\beta_i, 0),$$

and demand as

$$D(t) = \sum_{1}^{N_g} \max(-\beta_i, 0),$$

where N_g- the number of georegions.

A certain volume of grain $S(t)$ is stored from previous years, e.g., in federal reserves, estimated as 10% of the mean yield. The stored grain can be added to the market in a poor harvest year and purchased in good years. We conservatively estimated the maximum volume of grain reserves at 10% of mean harvest.

If $\Theta(t) - D(t) > 0$, then there is enough grain on the market, and each georegion will be able to purchase the grain it needs. Grain purchased per capita will be equal to mean consumption per capita: $a_i(t) = \bar{c}_i$. If, in contrast, $S(t) + \Theta(t) - D(t) < 0$, then grain shortage occurs: $a_i(t) < \bar{c}_i$. In this case, we assume that grain wholesalers of the regions will not be able to purchase the necessary volume of grain. As grain price will follow the increasing demand, the georegions with higher income per capita levels and lower food price (e.g., due to shorter transportation requirements) will be able to purchase a larger share of grain:

$$a_i(t) = w_i \Theta(t),$$

where the weight is computed as:

$$w_i = \max(-\beta_i, 0)\ \mathrm{Income}_i / D(t),$$

and normalized as

$$\sum w_i = 1.$$

Income_i denotes income per capita in the region.

Finally, we compute stress is a ratio of available and required grain:

$$\sigma_i(t) = a_i(t)/\bar{c}_i$$

Table 2 shows the expected number of high-stress events, defined as a 30% grain shortage, in 100 years: $100 * E(\sigma_i(t) < 0.7)$

In the "Fortress Market" model, the producing regions get an advantage, as they sell the grain only after they satisfy their own internal purchase. However, this advantage will be reduced in high-stress years, as all producing regions, except perhaps the best agricultural regions, will be hit by extensive droughts. The wealthy regions such as the Center or oil-producing West Siberia are also able to cope with higher prices. Other regions cannot compete for the diminishing resources and have to lower the consumption, e.g., by converting to subsistence agriculture.

In the 'Open Market' scenario, all produced grain is eventually sold in a national-wide market, regardless of

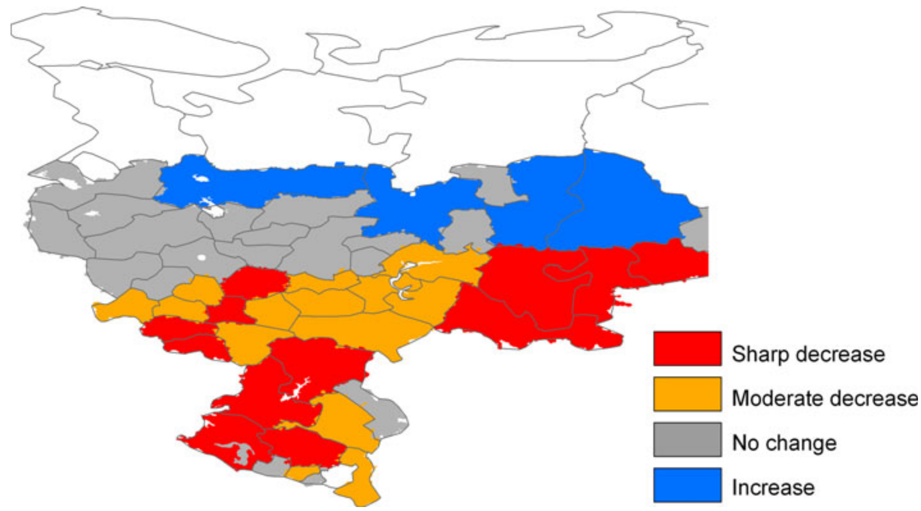

Fig. 4 Impact of changing climate on wheat yield in European Russia. The difference between GAEZ simulations for 2070s and 1961–1990 climates under HadCM3 A2 integrations. "Sharp decrease" corresponds to a decrease of at least 1 t ha^{-1}; "moderate" to a decrease of 0.1–1 t ha^{-1}; "no change" to yield variations of less than 1 t ha^{-1}. Regions with insignificant grain production are not shaded

where it has been produced: $\beta_i(t) = p_i(t)$. The volume of grain available for purchase is obviously larger than in the 'Fortress Market' scenario; grain purchase follows the same principle. This additional grain available in a market can be estimated on the basis of country average consumption per capita, as in this scenario we suggest that no regions try to hold their surplus grain (Fig. 4).

Results

Similar to other simulation-based assessments of Russian agriculture for changing climate (e.g., Sirotenko et al. 1997; Parry et al. 2004), we find that, in absence of adaptation, the currently most productive part of Russia is likely to suffer from decreasing yield of cereals. Although agricultural production increases in some regions, overall the mean yield decreases considerably due to more frequent droughts in the most production regions, including North Caucasus. The worst yield decrease is observed in Stavropolsky kray, where the production of cereals decreases by 23% in the 2020s and by 56% in the 2070s (under HadCM3 A2 scenario). In contrast, cereal yields in the Central geographic region and in the north of the country increase only moderately (Fig. 3). However, this yield increase contributes little to the total grain production of the country. Climate change also benefits grain production in East Siberia, where the climate becomes milder with higher temperatures and increasing precipitation (Alcamo et al. 2007).

The increasing frequency of bad harvest events translates into food stress; however, this process is influenced by interregional food exchange. We quantify food stress as the number of events when the amount of available grain (i.e. the grain locally grown or purchased from other regions) in an administrative region drops to 70% of the current level per century. This rather arbitrary level was set under the assumption that current food stress is relatively low and should roughly correspond to the frequency the regions have to appeal for food relief. For each time period, model simulations return a set of alternative crop yield projections; we further extrapolate these projections to generate the number of stress events per 100 model simulations and then interpret the results as projected number of food stress years per century in specific climate conditions of the 2020s and 2070s.

Our results (Table 3) show that for current climate and under the 'Fortress Market' scenario, the producing regions from production group 1 (those preferring to sell their grain surplus) have very low food stress (three events of grain shortage per century). The producing regions from group 2 (those mainly consuming their surplus grain internally) have slightly higher food stress level. The highest stress is in the extremely dry Lower Volga region with ten grain shortage events per century. The majority of consumption regions have low to moderate level of food stress (typically ten events per century). Overall, we can conclude that the current administrative system controlling interregional food exchange works well and provides adequate level of food security.

Under the scenarios of future climate, the 'Fortress Market' performs much worse for many regions. Despite an acute drop in yield, the producing regions (shaded in Table 3 with gray) continue to perform relatively well in the 2020s. Indeed, the majority of the regions suffer food shortages only sporadically, similar to current conditions. The only exception to this pattern is the Lower Volga region, which is very susceptible to droughts. The consuming regions suffer the most from the increasing drought frequency. Consequently, these regions demonstrate elevated food security risks: thirty grain shortage years per century in the 2020s and every other year in 2070s. Rich

Table 3 Future change in food stress frequency (events per century) for current interregional food exchange scenario, 'Fortress Market'

Region	Groups	Current climate	A2		B2	
			2020s	2070s	2020s	2070s
C. Black Earth	1	3	3	0	0	10
N. Caucasus	1	0	0	3	0	0
Lower Volga	2	10	20	23	20	40
S–W Siberia	2	3	0	0	0	10
Middle Volga	2	3	3	13	13	20
Volga-Vyatka	3	10	17	20	13	27
S–E Siberia	3	13	3	0	10	0
Baikal region	4	3	0	17	7	17
N. Caucasus Republics	5	10	3	20	23	33
North	5	10	30	47	37	60
North–West	5	3	10	17	10	23
Central	5	0	0	0	3	0
Western Siberia	5	13	33	50	43	60
Eastern Siberia	5	20	37	50	57	60
Far East	5	10	27	47	33	60
North East	5	10	30	47	37	60
Urals	5	7	0	7	10	17

industrial or oil-producing regions, e.g., West Siberia, manage to purchase enough grain on the market to meet their needs, but poor regions or those with already strained resources do much worse (Table 3).

In the 2020s, the list of territories that cannot cope with decreasing grain production is restricted to the poorest regions of the country, European North-West, Eastern Siberia, Baikal and Far East. By the 2070s, the same regions continue to have low food security level, but the number of grain shortage years per century increases from approximately ten per century to once in three years in the 2020s, and to every other year in 2070s.

Discussion

Our major reason for comparison of two extreme scenarios of grain exchange was that it evidently approximated the food market in Russia for considerable time extent during the twentieth century. One might argue that, with improved management, better yields, and increasing grain exports, this scenario has become obsolete. Indeed, a visible improvement in grain production in the second half of this decade has been frequently viewed as an evidence of agricultural recovery due to increased investments and more regulations from the federal government. However, the unprecedented 2010 heat wave, which affected 23 provinces of European Russia forced the leaders of affected regions to return to what P. Goble (2010) describes as "the rebirth of the supply-based regional separatism" Russia experienced in the 1990s. On federal level, a ban on grain exports was introduced to last from August 15th to December 31st, 2010. Counteracting the separatist tendencies, 35 billion rubles ($\sim$\$1.2 billion) in federal aid was pledged; however, it is not clear if the funds are adequate to help the producers absorb the losses: in absence of crop insurance practice (according to Swiss Re, only 25% of crops are insured in Russia, as compared to 80% in the US—Anonymous 2010), the growers rely on federal aid if crops fail. Further, federal agricultural subsidies are set to be significantly reduced as the federal government strives to comply with WTO rules. Altogether, these developments demonstrate that current attempts to reduce the separatism in food trade in the country might prove to be short-lived, as regional authorities are gaining more control over agriculture.

Even if the 'Fortress Market' scenario is more feasible for the near future than it seems, there are some simple measures that can mitigate negative impact of droughts on food production in the country. For Russia, adaptation measures to climate change include those that take advantage of increasing area with favorable climate conditions, which could easily double the yield when climate alone is considered (Pegov et al. 2000). However, our simulations show that an increase in area under agriculture can only partially alleviate the negative consequences of climate change (Table 4). In producing regions, there is little land suitable for agriculture which is not already converted into arable. In consuming regions of the north, land reserve is also not very significant, as large areas are unsuitable for agriculture due to inferior soils, existing land use or prohibitive terrain. Current trends in the latter

Table 4 Future change in food stresses (events per century, mean between A2 and B2) under various mitigation scenarios for the 'Fortress Market' when compared with the 'Open Market' scenario

Region		'Fortress Market'								'Open Market'		
		No mitigation			Reserves			Shift				
P	G	CC	2020	2070	Cur.	2020	2070	2020	2070	CC	2020	2070
1	CBE	3	2	5	0	0	5	0	5	3	3	10
1	NC	0	0	2	0	0	2	0	0	0	0	7
2	LW	10	20	32	10	17	28	20	28	10	13	17
2	SWS	3	0	5	3	0	5	0	3	10	20	20
2	MV	3	8	17	0	7	15	7	13	0	0	5
3	VV	10	15	23	7	5	20	12	15	10	28	38
3	SES	13	7	0	10	7	0	5	0	10	7	12
3	B	20	47	55	10	42	48	38	48	20	40	53
4	NCR	3	3	17	3	3	15	2	13	17	38	50
5	N	10	13	27	3	13	27	10	18	0	0	0
5	NW	10	33	53	7	18	48	25	50	10	5	12
5	C	3	10	20	0	3	15	5	8	7	3	12
5	WS	0	2	0	0	2	0	0	0	0	0	0
5	ES	13	38	55	10	22	50	28	50	10	7	12
5	FE	10	30	53	10	17	48	23	45	10	7	12
5	NE	10	33	53	10	20	48	27	50	3	3	10
5	UR	7	5	12	3	5	10	3	10	3	3	10
Mean		7	13	22	4	9	20	10	17	6	8	14

The column with production groups is marked with "P", geographic regions "G" are presented in the same order as in the Table 2, "CC" means current climate

regions also render these optimistic projections of land use shift unrealistic. The territories newly becoming available for grain production due to increasing temperatures are subject to rural depopulation and widespread abandonment of agricultural lands (up to 40% of agriculture lands in the 1980s are now vacant—Ioffe and Nefedova 2004).

Adaptation can also be achieved through increased federal food reserves. In the past, this was the most effective instrument to overcome grain shortage during a poor year. Indeed, doubling food reserves can keep the frequency of food stress years below ten per century for all regions, almost entirely eliminating the negative consequences of current climate variability (Table 4). In the 2020s, the same mitigation strategy provides only a moderate relief in stressed regions, and increasing state reserves is a totally unacceptable strategy for more drastic change of climate, such as in 2070s.

Our simulations show that the 'Open Market' scenario could provide a more effective mechanism for coping with food crises than any combination of mitigation measures under the 'Fortress Market'. Under the 'Open Market' scenario, food stresses is distributed quite differently from conditions under the 'Fortress Market' scenario. Under the 'Open Market' scenario, the rich regions can afford a high consumption level, so they have a lesser stress capacity. Yet many of less fortunate regions also benefit from the relaxed interregional exchange. Even though a few regions (North Caucasus, Volga-Vyatka, Baikal) become marginal, primary due to their low income per capita, but in general the frequency of food stress years decreases.

Decreasing frequency of years with a high food stress due to a better working system of interregional grain transportation is not the only benefit of this scenario. Under the 'Open Market' scenario, the regions tend to lean toward agricultural specialization, becoming better adjusted to the local climate, landscape, and soils. As a result, it will be easier for the profit-oriented regional agriculture to adapt to changing climate via shifting to better suited crop varieties and management, while the adaptation under the 'Fortress Market' scenario is limited, as the regions prefer to keep all main crop varieties even at the expense of lower yields.

It is worth noticing that we estimate the worst consequences of persistent droughts in North Caucasus, even though in the past this region was one of the most sustainable in terms of food production. North Caucasus is the key region for stability of Russian agricultural market, and the loss of its consistently superior grain yields because of frequent droughts can result in complete disruption of the existing interregional grain transportation in the country and further enhance administrative barriers between the

Russian regions. In the 'Fortress Market' scenario, North Caucasus traditionally plays a major role of the principal agricultural donor, as its three oblasts (compared to 22 production regions and a total of 89 regions in Russia) provide half of the total grain surplus sold to other regions, often at an expense of their own consumption, which is lower than the country's average. As North Caucasus seems to be the most affected by future droughts, its poorer performance severely limits the amount of grain available for the consumption regions. Any other agricultural region brings lesser impact on grain availability, when affected by severe droughts.

There are many adaptation options outside of the scope of this paper. First, improved management and higher input levels would increase the yield, even though the application of fertilizers has shrunk dramatically from 1980s, mainly due to price concerns. In the hydrologic and climatic conditions of the best agricultural areas of European Russia, irrigation could be a very promising way of dealing with negative impact of increased frequency of droughts, especially in the Lower Volga and North Caucasus. However, limited water availability already limits irrigation extent. Simulations for the region that were carried out using the WaterGap model (Alcamo and Henrichs 2002) also suggest that the grain belt area has low irrigation potential and that water availability for irrigation is likely to decrease in the future. The complicating factor is an abundance of saline soils. These soils require intensive and economically prohibitive management, including washing-out and building water collectors for drain waters (Gaponenko 2005). Indeed, after the irrigated area in Russia peaked at 2.75% of the total agricultural area in 1980s, it decreased gradually during the following two decades, mainly due to overirrigation-related loss of soil fertility, poor water quality, and monetary constraints (Novikova 2006). Additionally, abstraction of the water resources of Volga and Don rivers for irrigation purposes competes against the industrial and residential water needs, and reduces the environmental services, such as rehabilitation of water ecosystem of the Don and Taganrog Gulf of the Azov Sea (Gaponenko 2005).

Another effective adaptation measure would be to improve management practices. This could bring multiple additional benefits, including an increased soil carbon sink (Romanenko et al. 2007). Finally, the carbon fertilization effect, i.e. the positive impact of increased atmospheric CO_2 on plant growth, and the associated increased water use efficiency of the plants may significantly modify the outputs of the agriculture models. Overall, accepted in the production models CO_2 fertilization effect on yield for the major crops averages 24% for C3 species and 27% for maize, when CO_2 concentration is increased to 550 μmol mol^{-1} (Long et al. 2006). However, little is known about CO_2 growth enhancement at a regional level, and even less about the effects on pests, weeds, and interactions with increasing O_3 level. Free air carbon dioxide enrichment (FACE) studies indicate that the impact of elevated CO_2 level on yield should be reconsidered toward significantly lower values (Long et al. 2006), which seems to be consistent with recent non-FACE studies (Tubiello et al. 2007).

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