

Grain Crops Productivity in the European Part of Russia under Recent Climate Change

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Abstract—Trends in agro-climatic resources and wheat yields in the main grain regions of European Russia are considered. The analysis is based on the results of calculations performed with the Climate–Soil–Yield simulation system. The results reveal a relative decline in climate-driven yields of 10 to 30% over two decades for both winter and spring wheat. Multiple regression equations linking yield trends with indicators characterizing the state of agro-climatic resources are determined. They show differences in climate driven yield trends between spring and winter wheat. However, differences are only marginally significant suggesting that switching from spring wheat varieties to winter wheat would not completely neutralize the negative impact of climate trends. The probability of occurrence of drought in the grain regions of the European part of Russia is calculated for 1998–2017. The areas where the probability of occurrence of severe droughts during May–August equals or exceeds 50% are determined.

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1. INTRODUCTION

Studies dealing with climate variability and change clearly indicate the increasing importance of hydro-meteorological factors for the sustainable development of agricultural production. It is expected that over the coming decades Russia will remain one of the leading exporters of grains on the world market, providing a significant contribution to meeting the expected demand for grain commodities [26, 38]. From this point of view, the question of changes in humidity and thermal conditions in the main grain production regions of Russia and neighboring countries, and the impact of extreme climatic conditions on their grain productivity remains of great actuality [5, 19, 23].

Regarding the territory of Russia, changes in the frequency and intensity of extreme weather events (floods, hurricanes, droughts, etc.) induced by current warming are likely [3, 28]. Over most of European Russia, there is already an increase in the number of days with abnormally high rainfall during winter, but a decrease in summer. There is also an increase in aridity in most agricultural regions, in particular in the main grain production areas.

This sensitivity of grain production to adverse weather conditions makes the country's agricultural production unstable [17, 24, 31]. It is noted in [32] that recent trends in annual and seasonal average temperatures already had a negative impact on the gross harvest.

The first goal of this work is to assess trends in indicators characterizing agro-climatic resources and changes in grain productivity in the main wheat production areas of the European part of Russia—the Central Black soil Regions (CBR)—the part of the Central Federal District (FD), the Volga Federal District (Volga FD) and Southern Federal District (Southern FD). The second goal is to estimate the frequency of occurrence of hazardous hydrometeorological phenomena (HP) over the past decades in this area. We recall that about 75% of wheat acreage of Russia is concentrated here [13, 36].

2. MATERIALS AND METHODS

Hydrometeorological data. Two sources of meteorological and agrometeorological data were used. Firstly, the archives of the average air temperature and precipitation for each month from 1951 to 2017, compiled by the Institute of Global Climate and Ecology of Roshydromet [4], for a total of 54 stations evenly distributed throughout the study area.

Secondly, the data for 1992–2017 included in the 10-day telegrams received from the regional offices of Roshydromet on the 1st, 11th and 21st day of each month. These data are available for a total of 327 stations in the Central FD, Volga FD and Southern FD and contain both meteorological parameters (in particular, air temperature, precipitation, humidity, solar radiation) and agrometeorological data.

Statistics of yield and acreage. Yield statistics at the level of subjects of the Russian Federation for 1996–2015 were extracted along with the corresponding data on acreage from the yearbooks published by the Federal State Statistics Service of Russia (Rosstat) [13]. The average yield at the Federal District level was estimated as the weighted average of the regional yields, with weights proportional to the cultivated area. To analyze the dynamics of yield and repeatability of poor yield years, data on the yield of spring and winter wheat as well as spring barley were used.

The Climate–Soil–Yield (CSY) simulation system. The CSY simulation system implements a mechanistic description of the production process and of the water-thermal regime of the agrocenosis [14, 17]. The input information for the system are data from the network of meteorological and agrometeorological observations, as well as data on water-physical properties of the soil and the level of its fertility. CSY simulates crop phytomass and grain accumulation, as well as of the main components of soil water balance and soil moisture reserves at the daily time step throughout the growing season.

The CSY simulation system has been used for operational purposes since 1985, and has been extensively tested in the past.

Tasks tackled with CSY include the preparation of bulletins of current agrometeorological conditions, the assessment of climatic resources, the monitoring of the state of grain crops in all major production areas of the Russian Federation, and the provision of short- and medium-term yield forecasts.

These tasks are comparable to those undertaken at the European level by the European Commission Joint Research Centre (JRC) in the framework of the Monitoring Agricultural ResourceS (MARS) program with the Crop Growth and Monitoring System (CGMS) [29, 39]. The CSY is also used as main computational tool for the preparation of climate change impact assessments [8, 10, 11, 33, 37].

Visualization of the results. For visualization of the results, maps were produced with the geographic information system QGIS (Quantum GIS). Spatial interpolation of hydrometeorological and yield data was based on kriging, as implemented in Surfer (Golden Software).

3. RESULTS AND DISCUSSION

3.1. Assessment of Agro-climatic Resources

A number of agro-climatic indices are calculated by the CSY system [16] and are then used for the further analysis [11, 17]. Updated information on meteorological anomalies and trends calculated according to the method for monitoring changes in the current climate in Russia [18], is published annually [9]. Below we present the corresponding estimates of trends and indicators of anomalies of agro-climatic resources calculated for the entire period of global warming (since 1976) and for the last 20 years (1998–2017).

Thermal regime. Over the recent decades, the availability of thermal resources has continued to increase throughout the entire agricultural zone of Russia. The exceptions are some regions in Eastern Siberia and the Far East of Russia.

Over the past twenty years, the rate of increase in January temperature (important for assessing the conditions of overwintering crops) has slowed down, albeit slightly.

Table 1 presents estimates of changes in the thermal regime for the last two decades as compared to the baseline period 1961–1990, their 95% confidence intervals and mean errors. Across the territory of European Russia, the maximum increase in the sum of temperatures above 10 °C and 5 °C, respectively, was significant, about 300–320 °C. Estimates of these indicators in the Volga FD are close to the average for Russia (~200 °C).

The vegetation period ($T > 5$ °C) increased on average by 10 days in the regions under consideration (Table 1). According to the estimates given in [22], an increase in the sum of temperatures in the range of 200 to 300 °C allows a switch from early-ripening varieties of cereals (barley, wheat, oats) to late-ripening

Table 1. Deviations and their 95% confidence intervals of the average values of indicators of heat supply to agricultural crops for the period 1998–2017 from the average values for the period 1961–1990

Region	Sum of air temperatures, C		Transition date in spring over temperature (days)		Duration of the period (days)		Duration of the wheat vegetational season, days	
	>10 C	>5 C	10 C	5 C	$T > 10 C$	$T > 5 C$	spring	winter
CBR	239 17 (8.2)	248 19 (8.9)	-4 0.5 (0.2)	-5 0.6 (0.3)	8 0.6 (0.3)	10 0.7 (0.4)	-4 1.0 (0.4)	-3 0.5 (0.3)
Volga FD	202 14 (6.6)	219 16 (7.6)	-2 0.9 (0.4)	-3 0.5 (0.2)	6 0.9 (0.4)	9 1.4 (0.3)	-6 2.2 (1.1)	-4 1.4 (0.6)
Southern FD	287 41 (19.2)	317 41 (18.8)	-2 0.7 (0.4)	-9 2.0 (1.0)	7 1.5 (0.7)	10 2.7 (0.3)	4 1.8 (0.8)	4 1.4 (0.6)

Note: Statistical errors of the average values are in parentheses.

Table 2. Estimates of the linear trend (units/10 years) in seasonal precipitation amounts and indices of moisture conditions for the periods 1998–2017 and 1976–2017

Area	The amount of precipitation, mm/10 years						DI, units/10 years	N, days/10 years
	winter	spring	summer	autumn	during the growing season of wheat			
					spring	winter		
1998–2017								
CBR	3	9	-9	-0.2	0.4	8	0.05	1
Volga FD	-6	2	-2	3	-3	5	0.07	3
Southern FD	-5	13	-24	-18	8	8	0.13	3
Russia	1	5	2	-1	4	6	0.04	1
1976–2017								
CBR	0	3	-8	-2	-13	-10	0.05	4
Volga FD	2	5	-8	-1	-12	-8	0.05	4
Southern FD	-4	7	-7	4	7	8	0.04	1
Russia	3	6	-0.4	0.1	-5	-3	0.02	2

Note: DI is the dryness index of M.I. Budyko; N is number of days with moisture reserve ≥ 10 mm in the soil layer 0–20 cm.

varieties, which are, as a rule, more productive. In CBR, for example, compared to 1961–1990, it has recently become possible to grow corn for grain, early-ripening beans, late-ripening sunflower, millet, late-ripening varieties of spring wheat and spring barley.

The moisture regime. A positive trend in spring precipitation amounts was observed almost throughout the entire agricultural area of Russia. Summer precipitation trends were negative in all Federal Districts of European Russia, except for the North-Western Federal District, but positive in the Asian part of Russia (APR), i.e., in the Ural, Siberian and Far Eastern Federal Districts. In these latter areas, the corresponding trends were of 1.0, 3.0 and 8.0 mm/10 years, respectively [9].

Trends in seasonal amounts of precipitation and indicators of moisture regime are presented in Table 2. Analysis of the simulation results for 1998–2017 shows that the degree of aridity increased in all seasons, except spring, over most of the agricultural areas.

In this context, it is important to emphasize the positive trends in the number of days during the growing season ($T > 5 C$) with moisture reserves in the arable layer of the soil (0–20 cm) that are less than or equal to 10 mm, which was the case throughout the territory under consideration (the 10 mm threshold defines the HP “soil drought”). This confirms the current trend of increasing aridity.

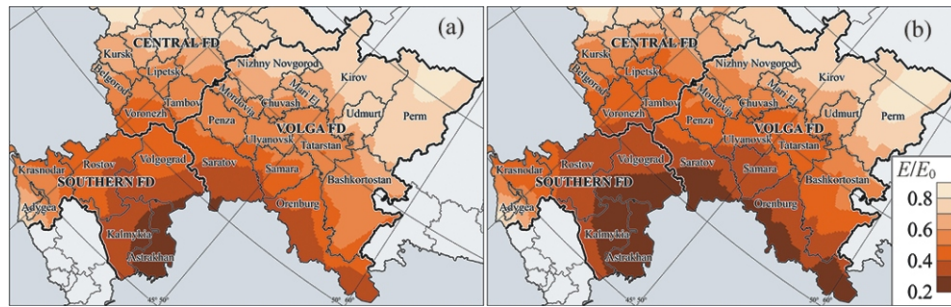


Fig. 1. Average values of the moisture sufficiency coefficient (E/E_0) over the growing season of spring wheat in (a) 1996–2005 and (b) 2006–2015.

Due to the large variability of the precipitation records, series of observations over a twenty-year period do not always allow to obtain statistically significant estimates of linear trends. Thus, estimates of autumn precipitation trends for 1998–2017 and 1976–2017 differ both in magnitude and sign (Table 2). The homogeneous distribution of decadal amounts of precipitation is consistent with the data in [21].

With the minimum amount of hydrometeorological information (average monthly values of air temperature and precipitation) the CSY system can calculate the hydrothermal coefficient of G.T. Selyaninov (HTC), the dryness index of M.I. Budyko (DI), and the other indicators of soil moisture.

According to A.I. Budagovsky [1], one of the best criteria for assessing and monitoring drought is the evaporation deficit E :

$$E = E_0 - E \quad (1)$$

where E_0 is the so called evaporation (the maximum possible evaporation) and E is actual evaporation.

The CSY system calculates a similar indicator, i.e., the ratio of these values (E/E_0). The local correlation of this moisture index with the yield of spring and winter wheat is estimated at 0.70–0.80 (with HTC in the range 0.30 to 0.50). The maps in Fig. 1 present the results of the evaluation of this indicator for the growing season of spring wheat during 1996–2005 and 2006–2015. On top of meridional and longitudinal gradients, there is a marked tendency for an increase in HTC, that is, an increase in the degree of aridity over most of the territory under consideration. Moisture deficiency did not increase between these two decades in the northern part of Central FD and Volga FD.

3.2. Assessment of Actual Yield Trends

Decrease in growth rate of wheat yield was found in many areas around the world [25, 35]. Recognizing the existence of a complex of factors associated with the introduction of new varieties, changes in agronomic practices, or even changes in agricultural policy, Peltonen-Sainio et al. [34], Finger [27], and Brisson et al. [25] concluded that in France the absence of a positive yield trend in the recent past was partly due to more unfavorable climatic conditions.

This is consistent with the findings of Lobell et al. [32] who analyzed the possible effects of warming and changes in precipitation patterns on the yield trends of major crops on the national scale. The conclusion, however, is opposite to that of Licker et al. [30] for the Rostov region, who found that climate variables displaying the most pronounced trends had only a minor impact on yield trends.

Over the past decade, the spatial organization of grain production in Russia was significantly changed. Production became increasingly concentrated in regions with more favorable environmental and climatic conditions. In 2016, 58% of grain was harvested in the southern part of European Russia, with another 21% in the southern regions of the Volga FD and the Urals FD, despite the fact that these two macro regions together occupy only 10% of the territory of Russia [7].

Let us consider how the yield of grain crops changed during the period of global warming (since 1976) in the main cultivation areas of European Russia. Table 3 presents the statistical characteristics of the yield series of spring wheat, winter wheat, spring barley as well as grain and leguminous crops as a whole for the periods of 1998–2017 and 1976–2017.

The data show high positive trends (b) in spring wheat yield over 1998–2017 in CBR and Southern FD, amounting to 7.9 and 6.5 (centner/ha)/10 years, respectively (Table 3). The coefficient of determination (D)

Table 3. Statistics of yield time series for 1998–2017 and 1976–2017 (calculations based on Rosstat data)

Area	1998–2017					1976–2017				
	<i>m</i>		<i>V</i>	<i>b</i>	<i>D</i>	<i>m</i>		<i>V</i>	<i>b</i>	<i>D</i>
Spring wheat										
CBR	18.0	5.9	33	7.9	63	15.8	5.0	32	2.5	38
Volga FD	14.1	4.0	28	3.2	22	13.6	3.4	25	0.8	8
Southern FD	13.4	5.4	40	6.5	51	11.8	4.6	39	1.8	25
Russia	15.4	4.3	28	5.3	51	13.5	4.2	31	1.9	30
Winter wheat										
CBR	23.9	6.0	25	8.2	66	20.7	5.8	28	3.3	47
Volga FD	18.9	5.3	28	3.1	12	18.1	5.2	29	1.2	8
Southern FD	27.5	6.5	24	7.7	49	25.4	5.8	23	2.1	20
Russia	21.7	5.7	27	6.3	44	20.0	5.3	28	1.9	21
Spring barley										
CBR	19.8	5.7	29	7.6	61	17.5	5.3	30	2.6	37
Volga FD	15.6	4.4	28	3.1	18	15.1	3.9	26	0.8	7
Southern FD	15.4	5.1	33	6.0	47	15.1	4.3	29	0.8	5
Russia	16.3	4.2	26	4.8	44	15.0	4.0	27	1.4	23
Grains and legumes										
CBR	19.8	5.8	30	8.6	75	17.2	5.2	30	2.9	48
Volga FD	15.4	4.0	26	3.5	27	14.4	3.5	24	1.2	19
Southern FD	24.8	6.5	26	9.2	70	22.4	5.6	25	2.6	31
Russia	18.9	5.1	27	7.1	60	17.0	4.5	26	2.1	32

Note: *m* is average, centner/ha; *s* is mean square deviation, centner/ha; *V* is coefficient of variation, %; *b* is coefficient of the linear trend, (centner/ha)/10 years; *D* is coefficient of determination, %. Here and in the Table 4 boldface means “statistical significant at 5%.”

explained by the linear trend is quite high and ranges from 51 to 63%. In regions with a large spring wedge (in the Volga FD) the trend was also positive, but smaller in magnitude (3.2 centner/ha for 10 years).

Winter wheat is the main grain crop in many regions, and more than 80% of its acreage is concentrated in Southern FD, in the CBR and in the lower Volga regions. Since 1976 and for a shorter period (since 1998) there has been a significant positive trend in winter wheat yield in the main cultivation areas of European Russia. Large positive trends in winter wheat yields (*b*) over 1998–2017 are observed in the CBR and the Southern FD, being of 8.2 and 7.7 (centner/ha)/10 years, respectively. Positive, but less significant yield trends (*b*), namely, ~3.1 (centner/ha)/10 years, were obtained for the Volga FD (Table 3).

Across the European part of Russia, in CBR, Volga FD and Southern FD, where 75% of spring barley acreage is concentrated, the interannual variability (*V*) of its yield over the past twenty years was relatively high, ranging from 28 to 33% according to calculations for 1998–2017. Estimated yield trends for spring barley and spring wheat are close in values (Table 3) and present similar spatial patterns.

Time series of the actual yield of spring and winter wheat and their linear trends, as well as the dynamics of the respective acreage for the period of 1996–2015 in the CBR, Volga FD and Southern FD (Fig. 2) confirm the main findings, as presented above. Minor differences in trend estimates could be due to a shift in the beginning and end of the estimated period.

In addition to differences in the overall level of productivity of winter and spring wheat between Federal Districts, Figure 2 illustrates the overall increase in yields since 1995. Trend analysis revealed that in the Volga FD and Southern FD, spring wheat yield levels stabilized after 2010. There is a sharp rise in spring wheat yield in the CBR. The yield of winter wheat was increasing in the entire territory under consideration in 2011–2015.

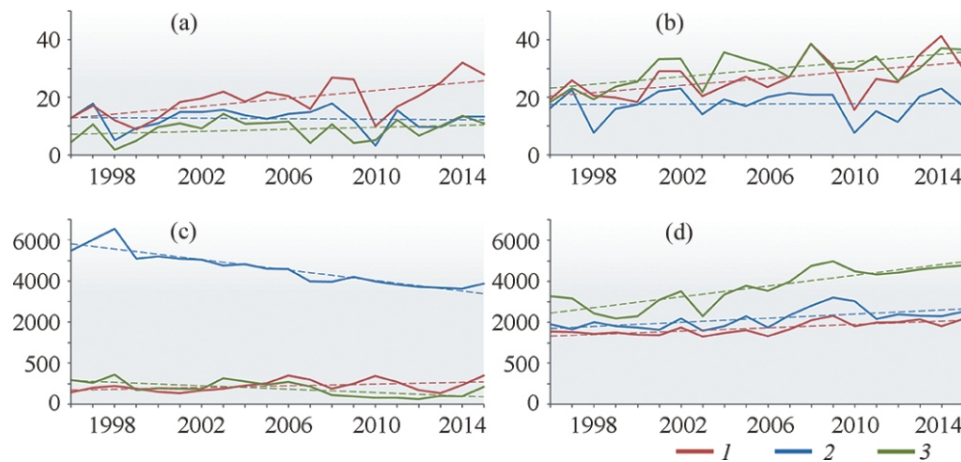


Fig. 2. (a, b) Evolution of yield (centner/ha) and (c, d) acreage (1000 ha) for (a, c) spring and (b, d) winter wheat during 1996–2015 in the CBR (1), Volga (2) and Southern (3) Federal Districts. Yields were aggregated taking into account acreage as given by Rosstat.

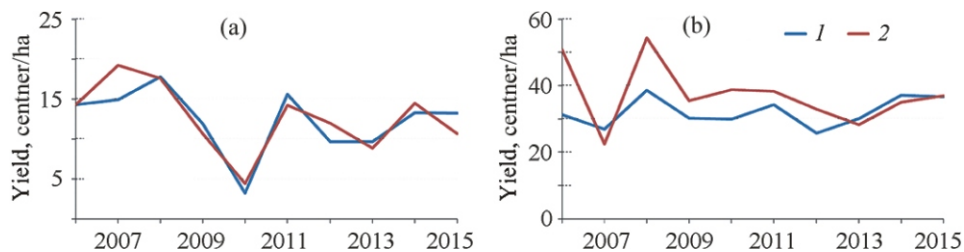


Fig. 3. Evolution of (1) actual (Rosstat data) and (2) simulated (the CSY system) yields of spring wheat in the (a) Volga FD and (b) winter wheat in the Southern FD for the period 2006–2015. Yields were aggregated taking into account acreage as given by Rosstat.

Spring wheat acreage in Volga FD has decreased significantly over the past two decades, by about 2000 thousand hectares. Since 2007, there has been a relative stabilization at 4000 thousand hectares. In CBR and Southern FD, where the area under spring crop cultivation is small, such drastic changes have not been observed. Nevertheless, one should note the reduction of acreage in the Southern FD for the period of 2007–2014. The area occupied by winter wheat increased in the territory of all three Federal Districts and stabilized over the last five years (Fig. 2).

3.3. Climate-driven Yield (Simulation with the CSY System)

To assess the impact of climate change in recent decades on wheat yields, we made a retrospective analysis (from 1996 to 2015) with the help of the simulation system CSY [15, 33, 37]. The CSY system has been in use for agro-climatic monitoring and medium- and long-term forecasting for more than 30 years.

In order to reveal the climate component of yields, for all simulations the parameters associated with agronomic practices and land use management were kept fixed and adjusted in accordance with the current levels of agricultural technology. Plant parameters for grain crops (spring and winter wheat), initial and boundary conditions were taken from the operational version of the CSY system.

The dynamics of the actual and calculated yield of spring wheat in the Volga FD and winter wheat in the Southern FD for the period of 2006–2015 is presented in Fig. 3. The average values of the actual and simulated yield of spring wheat in the Volga FD for the period from 2006 to 2015 are close to each other, and are of 12.4 and 12.6 centner/ha, respectively. CSY simulations reproduce well the low yield levels experienced in 2010 as a consequence of extreme aridity, 5 centner/ha. Simulated and actual data on winter wheat yield in the Southern FD for the last five years are consistent, although the average actual yield (32.1 centner/ha) is lower than the simulated value (37.4 centner/ha). The most likely reason for this is that the CSY system

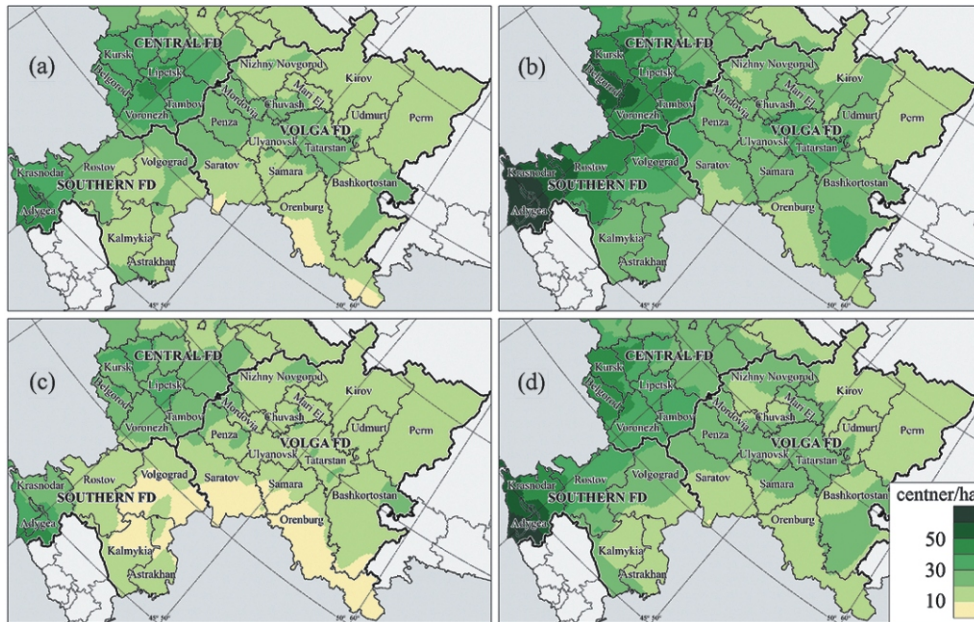


Fig. 4. Average yield of (a, c) spring and (b, d) winter wheat for the periods of (a, b) 1996–2005 and (c, d) 2006–2015 as simulated with the CSY system.

does not consider the agrometeorological conditions of the autumn-winter period which may introduce a certain error in the simulations.

The spatial distribution of the average climate-driven yields of spring and winter wheat for the periods 1996–2005 and 2006–2015 reflects, firstly, the higher productivity of winter wheat (~25 centner/ha) than of spring wheat (~15 centner/ha) and, secondly, the difference in yields between the southern and southwestern, as well as between the eastern and southeastern regions of European Russia (Fig. 4). Average yields range from ~40 to 50 centner/ha for winter wheat on the eastern border of the Southern FD and CBR to less than 15 centner/ha for spring wheat in the Orenburg and the Perm regions. This marked difference mirrors not only the agro-climatic background but also regional differences in the level of soil fertility (the most fertile soils being located in the Krasnodar region and CBR).

Simulations show that in 2006–2015 the climate-related yield of both spring and winter wheat decreased in comparison with 1996–2005, but to a greater extent for spring than for winter wheat (Fig. 4). This is typical for the most vulnerable areas in relation to HP events of drought: the Volgograd region, the south of the Saratov and Samara regions and the Orenburg region. The decline in winter wheat yields for the past decade in comparison to the previous one is also visible, although less significant (Fig. 4).

The results of CSY reveal that differences between spring and winter wheat trends calculated from actual yields almost disappear when considering simulated climate-driven yields. With a few exceptions (spring wheat in the Republic of Mari El, Nizhny Novgorod and Kirov regions and in the north of the Perm region), it is possible to infer a negative trend equivalent to a relative decrease of ~15–20% over 20 years. This is quite significant but generally consistent with the trends in heat and moisture indicators characterizing agro-climatic resources for the same period.

Taking into account the share of acreage, the climate-driven long-term decline in winter wheat yields was approximately equivalent to –12, –28, and –8% in CBR, Southern FD, and Volga FD, respectively. The corresponding statistical estimates for spring wheat were –11, –30, and –17% in CBR, Southern FD, and Volga FD, respectively. Spring wheat was more susceptible to the effects of increasing temperature and reduced precipitation during the growing season than winter wheat, primarily due to the later onset of the main phases of development around germination-maturation. Hence, differences in responses to recent climate trends are evident, but statistically not sufficiently significant to justify neutralizing the negative impact of climate trends through switching from spring wheat varieties to winter wheat.

Table 4. Correlation coefficients, coefficients of the multiple regression equation, (1) and their normalized estimate (-coefficient) for 1996–2015

Federal District	Correlation coefficient		Coefficient of the regression equation (-coefficient)					
	R^2	R_{adj}	N	T_5	T_6	R_6	R_{VEG}	W_{100}
Spring wheat								
Central	0.67	0.42	0.62 (0.50)		-3.48 (-0.34)			
Volga FD, north part	0.79	0.62	-0.08 (-0.43)		-3.19 (-0.53)		0.03 (0.36)	
Volga FD, south part	0.78	0.61	-0.10 (-0.14)		-3.01 (-0.58)		0.07 (0.46)	
Southern FD	0.56	0.31			-2.01 (-0.30)			0.12 (0.37)
Winter wheat								
Central	0.74	0.51	0.55 (0.48)		-5.12 (-0.48)	-0.03 (-0.14)		
Volga FD, north part	0.86	0.74		-0.89 (-0.26)	-1.52 (-0.38)		0.029 (0.50)	
Volga FD, south part	0.67	0.46	0.14 (0.16)		-2.19 (-0.40)	0.11 (0.42)		
Southern FD	0.68	0.42		-3.82 (-0.50)				0.10 (0.30)

Note: R^2 is correlation coefficient; R_{adj} is adjusted correlation coefficient; N is duration of the wheat growing season; T_5 , T_6 are average air temperatures for May and June, respectively; R_6 , R_{VEG} are the amounts of precipitation for June and the growing season of wheat, respectively, mm; W_{100} is moisture reserves in the soil layer 0–100 cm at the time of germination.

The question arises which of the trends in observed agro-climatic indicators (predictors) affect in first place the trends of climate-driven wheat yield (predictand). The set of predictors chosen for the analysis included only instrumentally observed parameters, such as air temperature and precipitation for a particular vegetation period, soil moisture reserves or certain functions of these indicators (HTC, DI, etc.) in the northern and southern parts of Volga FD, Southern FD and in CBR.

Based on the identified interrelations we constructed multiple regression equations describing trends of climate-driven productivity of spring and winter wheat as a function of trends in agro-climatic indicators for four regions. Predictors, equation coefficients, and multiple correlation coefficients are presented in Table 4. For example, the trend in the climate-driven yield of spring wheat in the Volga FD can be described by the regression equation:

$$Y = -3.01 T_6 + 0.07 R_{VEG} + 0.10 N + C \quad (2)$$

where Y is the climate-driven yield trend, T_6 is the trend in June temperature, R_{VEG} is the trend in total precipitation, and N is the trend in the growing season length, C is intercept.

The coefficient of determination for the multiple regression equation (2) is quite high, amounting to 78% ($R^2 = 0.78$).

Thus, it can be stated that in the south of the Volga FD the main contribution to the trend in climate-driven spring wheat yield was related to the trend in June temperature T_6 (normalized estimate = -0.58) and the trend in growing-season total precipitation R_{VEG} (= 0.46). At the same time, in the Southern FD, trends in climate-driven winter wheat yield were significantly influenced by the trends in May temperature T_5 (= -0.50) and soil moisture on the date of vegetation renewal in spring, W_{100} (= 0.30) (Table 4).

Table 5. Assessment of average drought-induced losses (%) in spring wheat yield in 1995–2015 relative to 2008 in the Central, Volga and Southern Federal Districts (results of simulations with the CSY system)

Area	Yield losses, %							
	1995	1998	2010	2011	2012	2013	2014	2015
CBR	–26	–34	–50	–44	–20	–35	–8	–14
Volga FD	–29	–60	–62	–27	–28	–39	–11	–36
Southern FD	–33	–44	–54	–34	–54	–61	–36	–30

Overall, the results of the present study indicate that the negative trends in climate-driven yields across the main grain areas of European Russia from 1998 to 2017 were caused by increasing aridity and changes in the thermal regime over the growing season of grain crops. This suggests that the positive trends in actual yields in this area over the past 20 years were largely due to the adaptation of land use systems to climate change.

4. HAZARDOUS HYDROMETEOROLOGICAL PHENOMENA

4.1. Assessment of Losses from Adverse Hydrometeorological Conditions

The degree of damage caused to agriculture by drought depends on the area under drought as well as on the intensity and duration of anomalous dryness. In the case of localized drought, the grain economy of the country, as a rule, does not suffer from big losses. In the case of intense drought over large areas, the damage caused by drought increases dramatically, making it necessary to monitor drought evolution according to certain indicators or criteria [20].

For a comparative assessment of the intensity of drought and its damage, years characterized by local yield minima in the time window 1995–2015 were selected (Table 5). Simulations performed with the CSY system revealed that for European Russia the 2010 drought was the most significant event of the past 60 years in terms of yield losses relative to 2008, the year characterized by the highest yield levels. In 2010, the shortfall in spring wheat productivity was of 62% in the Volga FD, 54% in the Southern FD and 50% in the CBR. In the Volga FD comparable losses were obtained for 1998, when the decline in spring wheat harvest was 60%. In the Southern FD in 2010, 2012, and 2013 the decline in spring wheat yield exceeded 50%.

Thus, on the large scale, the drought of 2010 led to a significant decrease in the yield of spring crops over almost the entire territory of European Russia, in particular in the southeast. In 2010, the estimated climatic yield of spring grain crops was lower than the corresponding yield in 2008 by more than 80% in the Samara, Orenburg, Penza, and Saratov regions as well as in the Republic of Tatarstan. Significant losses of grain yield that exceed 60–70% compared with 2008, were observed in the Voronezh, Lipetsk, Tambov, and Volgograd regions, in the republics of Bashkortostan, Mordovia, Chuvashia and Kalmykia, as well as in the Krasnodar region (Fig. 5). The spatial patterns of drought in 2012, also shown in Fig. 5, indicate a weaker intensity of drought in that year.

4.2. Assessment of Territories Unfavorable for the Production of Agricultural Crops

The territories of the Russian Federation subjects unfavorable for crop grains were assessed in relation to two factors, drought and waterlogging. The choice of climatic indicators for the assessment is determined by the “Rules of attribution of the territories adverse for the production of agricultural products” approved by the Government of the Russian Federation. The results of simulations are transferred to the Ministry of Agriculture of the Russian Federation in the context of operational activities.

The approach adopted for the assessment comprised two steps. First, the collection, processing, and control of observations for temperature and precipitation at stations through collecting 10-day agrometeorological telegrams KN-21 (since 1995). Second, the simulation of the crop development and evaluation of the HTC based on observations from ~900 meteorological and watch stations of the Hydrometeorological Agency located within eight Federal Districts and 85 Subjects of the Russian Federation. Calculations were carried out for running 20-year periods: 1995–2014 and 1998–2017. The maps locating

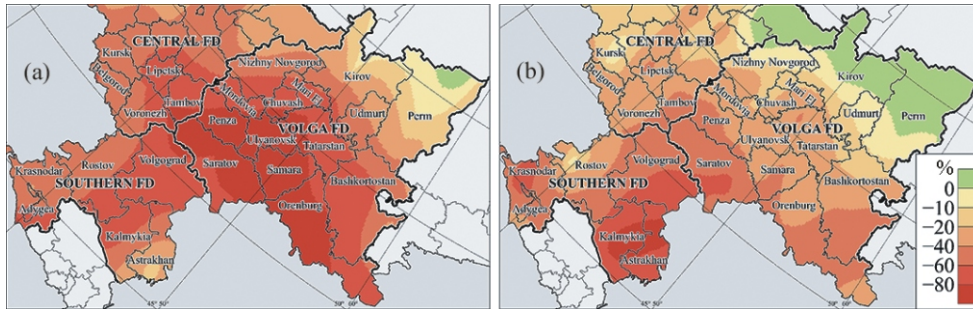


Fig. 5. Deviation relative to 2008 (%) of climate-driven spring wheat yield in 2010 (a) and 2012 (b), as simulated with the CSY system.

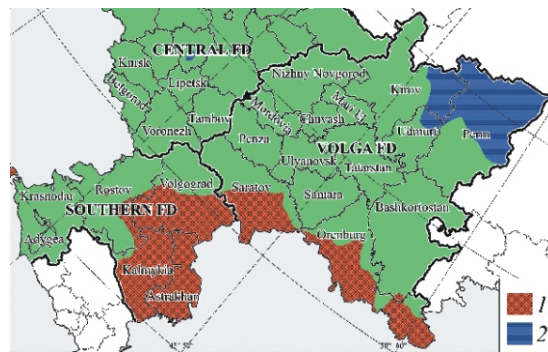


Fig. 6. Map of the areas facing severe drought with a probability of 50% in the period May–August (1) and waterlogging with a probability of 30% in the period August–September (2), according to data for 1998–2017.

the territories where the specified criteria of aridity and waterlogging are met, were produced using the geographic information system QGIS.

Figure 6 presents the spatial patterns of severe drought ($HTC = 0.6$) during May–August and the probability of waterlogging ($HTC = 2.0$) during August–September, for the period of 1998–2017 in the CBR, Volga FD and Southern FD.

On request, tables and maps showing the boundaries of areas with the probability of severe droughts in 50% or more of the considered years and waterlogging in 30% or more of the years can be provided.

The calculations make it possible to identify the regions and municipal districts of the Federal Districts vulnerable to severe droughts (Table 6). For example, the probability of severe drought during May–August in the Saratov region ranged from 10% in the Petrovsky district to 90% in the Alexandrovo-Gaisky district. The probability of droughts in the Novouzensky (85%), Krasnokutsky (75%), Ershovsky and Ozinsky (70%) areas was high. The data of Table 6 show that the high degree of exposure to drought is typical for the entire Saratov region: in 51% of the years considered about 46% of the area was under drought.

The approach allows identifying areas prone to one or the other HP events according to the established criteria at the scale of municipalities, regions, and republics for the purpose of taking strategic decisions in relation to agricultural production, agricultural insurance, and other types of support to farmers, as carried out by central and local authorities.

5. CONCLUSIONS

The increase in grain production has brought Russia to a leading position in the world grain trade, and maintaining the current level of production is a priority. Along with the solution of socio-economic and agronomic problems, it is also important to assess in time trends in agro-climatic resources.

Table 6. Subjects of Russia in which exposure to severe droughts (HTC = 0.60) during May–August occurred with a probability of 50% or more

Republic, region	Probability of severe drought, %	Fraction of area (%) in which severe drought occurred with probability $\geq 50\%$
Volga FD		
Orenburg	53	57
Saratov	51	46
Southern FD		
Kalmykia	56	90
Crimea	53	50
Astrakhan	90	100
Volgograd	51	63

Note: The probability of occurrence of drought is calculated for 1998–2017.

The simulation system CSY, implemented based on a modern generation of dynamic models of the production process and instrumental observations of climate, soils and crops, accurately reproduces the current state and variability of agro-climatic resources across the agricultural land of Russia at different scales (Federal Districts, regions, Municipal Districts).

Changes in resources across the agricultural areas of Russia are associated with the warming tendency observed in the last quarter of the 20th–early 21st century. Most sensitive areas to climate change are the main grain-producing regions of European Russia, that is, the CBR, Volga FD, and Southern FD. There a decrease in climate-driven yields of wheat is observed.

The lack of positive trends in climate-driven yields of spring and winter wheat in these regions over 1998–2017 was caused by increasing aridity and changes in growing-season thermal regime of grain crops. Positive trends in actual yield over the same period are therefore likely due to the improvement of agricultural technologies for grain crops cultivation and achievements of domestic breeding, i.e., the introduction of high-yielding varieties and hybrids.

Negative trends in climate-driven yields revealed for some regions of southern Russia are not yet dramatic, but may become so if adaptation measures are not taken to counteract the effects of observed climate change in the production of grain crops.

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