

Assessment of Agroclimatic Resources and Spring Wheat Yields in Tatarstan

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Abstract—Climate trends for the recent decades and a potential influence of agricultural technologies on spring wheat yields in the Republic of Tatarstan are analyzed. The authors used data on spring wheat yields (Federal State Statistics Service) and observations from 18 meteorological stations during 1961–2020. Climate-driven yields were calculated using the Climate–Soil–Yield simulation system. Yields at a fixed agronomic level were calculated for the periods of 1961–1990 and 1991–2020. It was established that there are differences in the trends in actual and climate-driven yields for these periods. Average actual yields for the second period are almost twice as high as those for the first period, but the rate of their increase does not grow. Average climate-driven yields in 1991–2020 were lower than in 1961–1990 (Mann–Whitney test, $p = 0.05$). An analysis of agroclimatic resources for individual decades shows that the downward trend in climate-driven yields is linked to a substantial temperature rise during the growing season and a harsher precipitation regime. The rate of a possible decrease in climate-driven yields of spring wheat in Tatarstan makes up ~2% per decade during 1991–2020.

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1. INTRODUCTION

The issues of developing the scientific and methodological basis for the agroclimatic monitoring of regional agricultural systems during climate change based on the Climate–Soil–Yield simulation system were discussed in [7, 8, 15]. According to the forecast based on climate models, it is expected that the rate of future warming will be similar to the modern one, and the frequency and intensity of severe weather events will increase [1, 19, 21]. In these conditions, an important problem is to provide the reasonable assessment of trends in agroclimatic conditions and crops productivity in the main grain cropping regions. Such assessment should be a base for the informational and analytic adaptation of the Russian agriculture to observed and projected climate change in accordance with the National Adaptation Plan [3, 5, 6].

According to the Ministry of Agriculture and Food of Tatarstan, about 52% of arable land is allocated in the structure of crop areas for the cultivation of grain crops, such as winter and spring wheat, pea, oat, and barley [13]. Spring wheat yields in Tatarstan over the period of 2001–2020 were the highest (~29.0 centner/ha) among the subjects of the Russian Federation. At the same time, the republic ranks fifth in the gross yield of spring wheat in Russia and ninth in the crop areas.

Taking into account a leading role of Tatarstan in the grain production and a growing demand for it both at the internal and external market, the monitoring of the growth and development of crops under observed climate change is necessary both in the operational practice of services for agricultural producers and management structures and for developing a regional plan of adaptation to climate change.

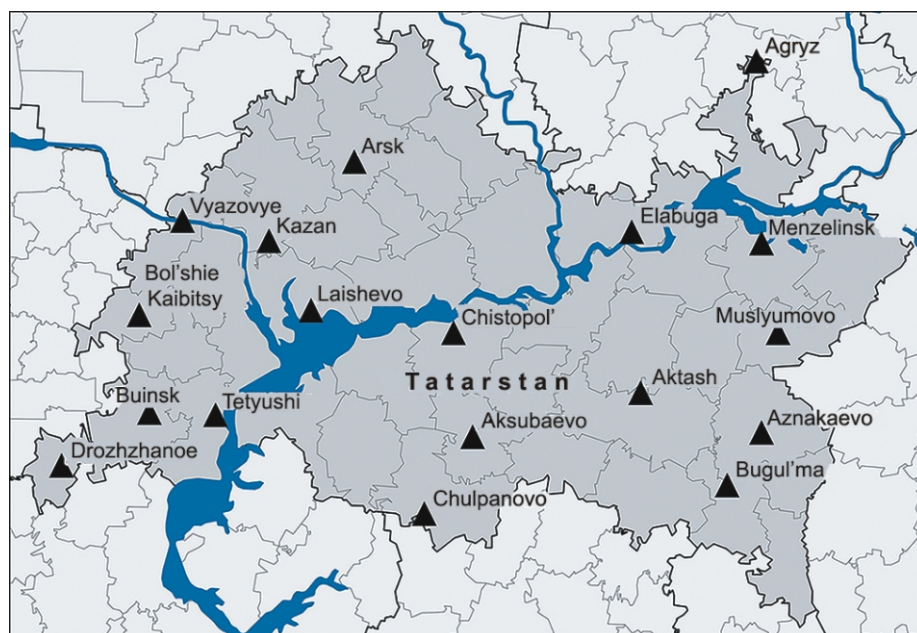


Fig. 1. The schematic map of location of meteorological stations on the territory of the Republic of Tatarstan.

The objective of the present study is the regional agroclimatic monitoring and the assessment of climate change impacts on agroclimatic resources in the Republic of Tatarstan for the wheat, which is the main grain crop. The problem is solved on the basis of the modern technology: the Climate–Soil–Yield simulation system, which allows obtaining detailed (in time and space) quantitative estimates of climate change impacts over a rather long period from 1961 to 2020.

2. DATA AND METHODS

Information database. Monthly data for the period from 1961 to 2020 from the subset of the Climate database (Israel Institute of Global Climate and Ecology (IGCE)) were used. The agrometeorological monitoring was carried out using the observations of air temperature and monthly precipitation at 18 meteorological stations on the territory of Tatarstan from 1995 to 2020. The observational data were received in the Roshydromet PROMETEI software package for hydrometeorological data processing. The schematic map of the location of the stations is presented in Fig. 1.

Climate–Soil–Yield simulation system. The Climate–Soil–Yield simulation system [20] combines the Weather–Yield dynamic model, the information database, and the technology for its processing and analysis. The identification and verification of the system were performed using the data of retrospective and agrometeorological observations, including soil moisture observations.

The data processing technique and various visualization schemes (tables, graphs, schematic maps) in the Climate–Soil–Yield system allow the retrospective, operational, and predictive analysis of agrometeorological conditions on the territory of individual subjects of the Russian Federation. The full list of output agroclimatic indices and productivity indicators, as well as of extreme weather conditions for the climate change monitoring with the Climate–Soil–Yield system was given in [9].

Climate-driven yields as an indicator of crops productivity were calculated in the simulation system based on actual meteorological and agrometeorological data (observations) at an average (over some years) agronomic level fixed by the model parameters.

Calibration and verification of the Climate–Soil–Yield system. Soil moisture. In most of the central regions of the European part of Russia, the observed changes in agroclimatic resources against a background of ongoing warming are linked to a trend toward the soil drying [10, 11, 17]. The most informative and practically demanded indicator of the moisture regime of agricultural fields is the observations of soil moisture carried out at Roshydromet meteorological stations. Due to an insufficient density of the observa-

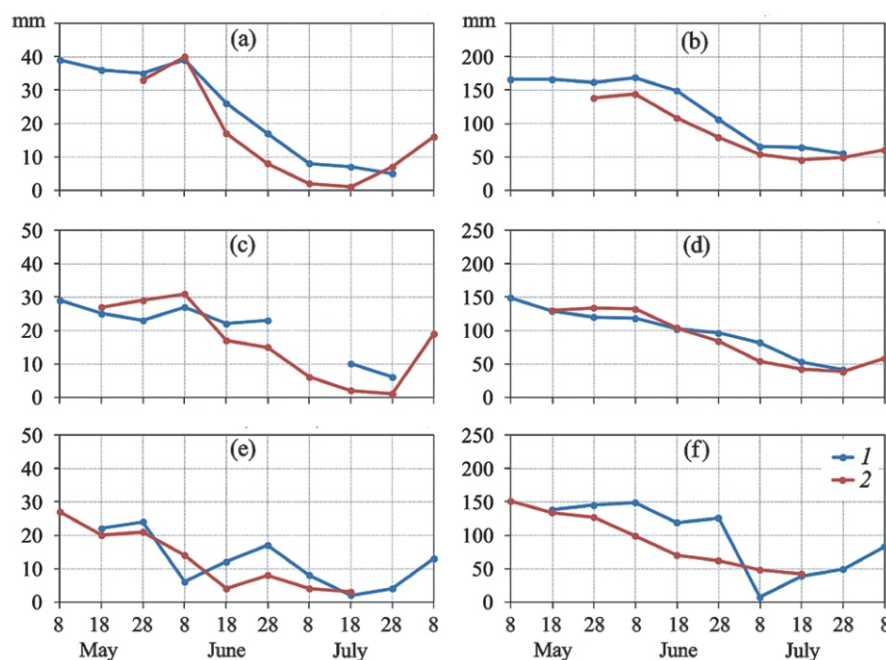


Fig. 2. (1) Observed and (2) calculated productive soil moisture on the 8th, 18th, and 28th days of the month in (a, c, e) the arable (0–20 cm) and (b, d, f) one-meter (0–100 cm) layers in 2020 at three observation stations: (a, b) Bol'shie Kaibitsy, (c, d) Drozhzhanoe, and (e, f) Aznakaevo.

tion network, the computational methods are important in terms of assessing observed and projected climate change.

In the Climate–Soil–Yield system, productive soil moisture during the growing season is a result of simulating the infiltration, evaporation, transpiration, and root absorption of moisture [14]. The correction and verification of the model were based on the observations of soil moisture under spring grain crops (spring wheat or spring barley) at individual meteorological stations. Figure 2 presents the calculated and observed soil moisture in the arable and one-meter layers at Bol'shie Kaibitsy, Drozhzhanoe, and Aznakaevo stations in 2020. A relative error of calculations is 10–20%, which may be considered as a quite good result, taking into account an accuracy of determination of actual soil moisture at meteorological stations.

Climate-driven yields. Based on the data of field experiments and literature data, the model constants were determined at the stage of the model construction: the general constants that do not depend on crops (the factor of conversion of integral radiation into photosynthetically active radiation, gas exchange coefficients, cardinal temperature of respiration, etc.) and the specific constants for different crops (the sum of effective temperatures during interphase periods, the factors of conversion of reproductive organs into the economic yield, the parameters for calculating biological functions, etc.).

It is obvious that the model whose parameters were identified from experimental data cannot be used for predicting spatially averaged yields. When passing to the calculation for individual regions, it is necessary to limit the model “empiricism,” which is achieved by selecting a small number of parameters for optimization [14].

Climate-driven yields calculated in the Climate–Soil–Yield system primarily indicate the effects of climatic factors on the crops productivity. An agronomic level or a level of agricultural efficiency is indirectly determined by the model parameters that remain constant during one or another time period. If there is a dramatic jump in the level of the land use system and yields increase, the corresponding parameters are corrected with account of observed trends.

The model parameters were configured for the territory of Tatarstan using the Rosstat (Federal State Statistics Service) data on yields [12]. The target function was minimized by the least-squares method:

$$F(\dots, r_c, a_r) = \sum_{j=1, N} (Y_m - Y_a)^2$$

Table 1. The statistical characteristics of spring wheat yields (centner/ha) in the Republic of Tatarstan during 1961–2020 (according to Rosstat)

Period	Mean	<i>SD</i>	C_v , %	Max	Min	Amp
1961–1970	12.3	3.5	28	17.3	9.0	8.3
1971–1980	14.3	2.4	17	18.1	9.9	8.2
1981–1990	14.3	5.1	36	21.8	7.8	14.0
1991–2000	20.1	7.9	39	36.9	10.4	26.5
2001–2010	25.8	8.6	33	33.2	3.3	29.9
2011–2020	22.9	5.9	26	30.6	11.0	19.6

Here and in Table 2, *SD* is the standard deviation; $C_v = SD/\text{Mean}$ 100% is the coefficient of variation; Max is the maximum value; Min is the minimum value; Amp = Max – Min.

where Y_m is the climate-driven yield modeled in the Climate–Soil–Yield model; Y_a is the observed yield (Rosstat); N is the length of observation series; r_c , a_r are the parameters of the model growth and development module.

3. RESULTS AND DISCUSSION

3.1. Observed Yields

The time series of actual spring wheat yields over the period from 1961 to 2020 was considered. The analysis revealed that spring wheat yields in Tatarstan in the recent three decades have dramatically increased starting from the late 1990s–early 2000s. During 1961–1990, decadal mean spring wheat yields varied within a quite narrow range and were equal to 12.3, 14.3, and 14.3 centner/ha, respectively. During 1991–2020, the decadal mean yield exceeded 20 centner/ha, with a maximum in 2001–2010 equal to 25.8 centner/ha, even taking into account the abnormal low yield in 2010. Maximum yields increased almost twice: from ~17–22 centner/ha in 1961–1990 to ~31–37 centner/ha during 1991–2020 (Table 1).

It should be noted that the level of spring wheat yields in Tatarstan did not decrease during the reformation period in the 1990s, when the crops productivity decline was observed almost everywhere. For example, in 1993 and 1994, the mean yield in the republic was 20.5 and 23.9 centner/ha, respectively, with the mean wheat (spring and winter) yields of 14 centner/ha for entire Russia.

Figure 3 presents the series of actual and climate-driven spring wheat yields from 1961 to 2020 (with the model configuration for the agronomic level observed in 1961–1990). It also allows tracing trends in crop areas expressed in percent relative to the mean values for the first decade (1961–1970).

It is clear that the technological component in the yield series became a key one in 1991–2020, while the series of climate-driven yields had no dramatic jump after 1990. On the contrary, a negative trend was obvious during 1961–2020 (Fig. 3).

It is known that modern agronomic technologies include diverse components: fertilization, use of drought-resistant and stress-tolerant varieties, various tillage systems, selection of optimum sowing dates, crop rotation system, moisture-saving technologies, etc.

The studies have shown that scientifically grounded technologies for applying mineral and organic fertilizers with account of weather conditions have become a dominant factor in crops production [16]. During 2000–2018, according to the Rosstat data, the volume of mineral fertilizers applied to grain and leguminous crops increased by three times: from 20.5 kg/ha in 2000 to 60.5 kg/ha in 2018. The volume of organic fertilizers applied to grain and leguminous crops increased since 2000 by 48% up to 1.2 t/ha in 2018 [2].

Having no similar estimates for individual regions, it may be argued with a high probability that the corresponding volume of fertilizers can only be greater for such economically developed region as Tatarstan.

Another important factor is selection work. In Russia, the contribution of selection to the yield growth in the recent decades is estimated at the level of 30–70%, and its role is expected to increase as negative climate trends strengthen [2].

The yield growth may be associated with another factor indirectly affecting the productivity. As clear from Fig. 3, the areas sown with spring wheat in the republic decreased from ~780000 ha in 1961–1970 to ~520000 ha in 2011–2020. It is well known that the yields grow if crop areas are reduced and nonpro-

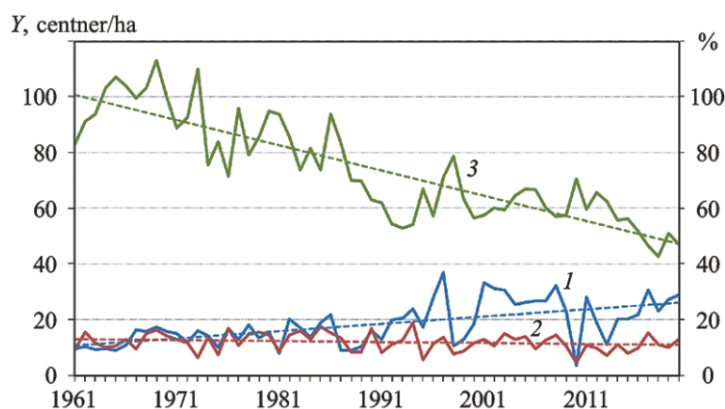


Fig. 3. The time series of (1) actual Y_a and (2) calculated Y_m yields and (3) relative areas sown with spring wheat (percentage of the mean values for 1961–1970; the right scale) in Tatarstan. The straight lines are linear trends, the respective linear trend coefficients b are: (1) 2.6 centner/ha per decade; (2) –0.4 centner/ha per decade; (3) –9% per decade.

Table 2. The statistical characteristics and the correlation matrix for observed (Y_a , centner/ha) and climate-driven (Y_m , centner/ha) yields and sown areas (S , 10^3 ha) of spring wheat for 1961–1990 and 1991–2020

Parameter	Mean	SD	C_v , %	Correlation matrix		
				Y_a	Y_m	S
1961–1990						
Y_a	13.6	3.8	27.9	1.00	0.60	−0.06
Y_m	12.6	3.1	24.6		1.00	−0.23
S	781	116	14.9		−0.23	1.00
1991–2020						
Y_a	22.9	7.7	33.6	1.00	0.68	−0.34
Y_m	19.6	5.6	28.6		1.00	−0.38
S	520	69	13.3			1.00

The values with the significance level $p = 0.05$ are bolded.

ductive land is removed from agricultural use. In this case, the coefficient of correlation between the observed yields and sown areas for 1991–2020 is –0.38, and the contribution of the trend in the sown areas to the total variance of the yield series reaches 12%.

3.2. Climate-driven Yields

With the evident growth in the technological component of yields, it is methodologically reasonable to configure the model parameters characterizing the agronomic level and to provide the further agroclimatic analysis for two periods: 1961–1990 and 1991–2020, or the “early” and “late” periods. The continuous series of years (from 3 to 5) was chosen to identify these model parameters. It included good, medium, and bad years and was close enough to the beginning of the “early” and “late” periods.

The results of the system verification indicate a statistically significant correlation ($p = 0.05$) between the model Y_m and actual Y_a yields (Table 2). The relative error of calculations is 6.7 and 10.0%, and the correlation coefficients are equal to 0.60 and 0.68 for 1961–1990 and 1991–2020, respectively.

The high interannual variability of yields was registered in both the first and the last three decades of the analyzed period. This means that despite the yield growth in the recent decades, the sustainability of grain production from spring wheat remains at the level of 65–70% (calculated as an extension of the coefficient of variation to 100%).

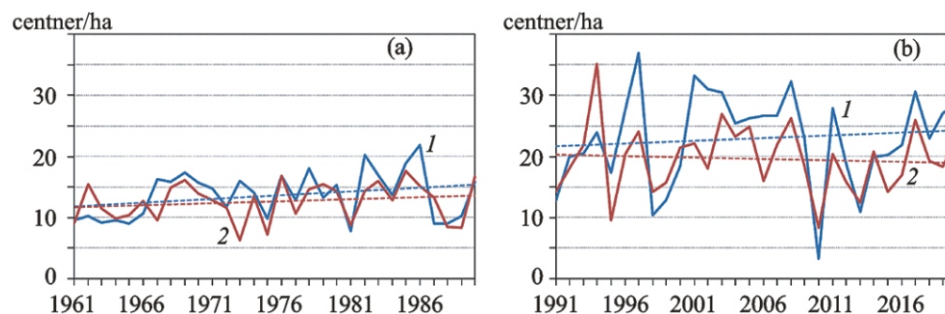


Fig. 4. The variations in (1) actual Y_a and (2) calculated Y_m yields of spring wheat in Tatarstan for the periods of (a) 1961–1990 and (b) 1991–2020. The respective estimates of linear trend coefficients (b) and the correlation coefficient (r) for 1961–1990: (1) $b = 1.2$ centner/ha per decade, (2) $b = 0.5$ centner/ha per decade; $r = 0.60$; for 1991–2020: (1) $b = 0.9$ centner/ha per decade, (2) $b = -0.4$ centner/ha per decade; $r = 0.68$.

3.3. Analysis of Trends in Climate-driven and Observed Yields

The trends in actual and climate-driven yields were analyzed separately for the “early” and “late” periods.

The linear trend coefficients for observed and climate-driven yields during 1961–1990 were positive and equal to 1.2 and 0.5 centner/ha per decade or 9.0 and 3.9% per decade (relative to the mean yield). The respective coefficients for the series of Y_a and Y_m for 1991–2020 had opposite signs and were equal to 0.9 and -0.4 centner/ha per decade or 3.9 and -2.0% per decade (Fig. 4). Thus, against a background of the almost two-fold increase in observed yields in the recent three decades, the rate of their growth decreases. It is noteworthy that the trends toward the yield growth slowdown are also observed in Western Europe [18].

Since the analysis of the yield series does not reveal linear, statistically significant estimates of the linear trend coefficients using the t -test, its nonparametric analog, the Wilcoxon (or Mann–Whitney) test, was applied to compare the independent yield samples for 1961–1990 and 1991–2020.

The results allow supposing the presence of a statistically significant difference in the level of actual and climate-driven yields from the “early” period to the “late” one: an increase in observed yields is statistically significant at the 1% level ($p = 0.01$), and a decrease in climate-driven yields is significant at the 5% level ($p = 0.05$).

As for revealing the presence or absence of the statistical difference in the average yields from decade to decade, the statistically significant difference was found only from 1981–1990 to 1991–2000 in the series of observed yields. Thus, the 1990s are the break point of the period.

3.4. Variations in the Parameters of Agroclimatic Resources

The analysis of the trends in the parameters of agroclimatic resources was based on observational data from Kazan meteorological station.

The estimated trends for the thermal parameters over the warming period since 1976 for the whole agricultural zone were presented in [4]. It was shown that the trends in the parameters of the thermal regime remain positive in the entire European part of Russia.

The estimates of thermal parameters for Kazan station presented in Table 3 also indicate positive dynamics of heat resources on the territory of Tatarstan. Average air temperature for the growing season of spring wheat in the recent decade has increased by 1.2°C as compared to the base period. This was a reason for its shortening and is most often associated with the shortfall of yield. The growing season of spring wheat became shorter approximately by 10 days, and phenological dates are observed earlier: at the beginning of May.

The data on total precipitation, Selyaninov’s hydrothermal coefficient (HTC), and moisture coefficient presented in Table 3 show that the most favorable moisture conditions were observed during the decade from 1971 to 1980, when more than 200 mm of precipitation was registered during the growing season of spring wheat, and the HTC varied within 1.1–1.5. During the “late” period, the amount of precipitation was smaller than during the base period by 40–50 mm or 22–28%, which is significant for the zone of moderate wetting.

Table 3. The variations in the indices of agroclimatic resources for the growing season of spring wheat during 1961–2020 according to Kazan meteorological station

Period	Y_m , %	D_{beg}	D_{end}	N , day	T , °C	T_{max} , °C	R , mm	HTC	E/E_0	$W20$, mm	$W20_6$, mm
1961–1990 (base)	100	May 9	August 8	92	17.0	20.1	180	1.14	0.55	33	17
1961–1970	100	May 11	August 10	92	16.9	18.6	151	0.97	0.50	31	14
1971–1980	97	May 7	August 8	94	16.8	18.1	202	1.27	0.57	35	20
1981–1990	104	May 8	August 6	91	17.5	20.1	188	1.19	0.58	33	18
1991–2000	86	May 5	July 31	88	17.3	21.1	131	0.86	0.48	34	12
2001–2010	91	May 3	July 30	89	17.5	19.8	169	1.08	0.53	31	12
2011–2020	83	May 5	July 28	84	18.2	19.1	138	0.89	0.49	36	12

The calculations were performed in the Climate–Soil–Yield simulation system. Y_m is the estimated climate-driven yield relative to the mean for 1961–1990; D_{beg} is the date of seedling; D_{end} is the date of yellowing; N is the length of the growing season; T is average air temperature over the growing season; T_{max} is maximum air temperature over the growing season; R is total precipitation over the growing season, mm; HTC is the Selyaninov's hydrothermal coefficient over the growing season; E/E_0 is the moisture coefficient over the growing season; E is evapotranspiration over the growing season, mm; E_0 is evaporation over the growing season, mm; $W20$ is soil moisture in the arable layer (0–20 cm) at the moment of vegetation renewal; $W20_6$ is soil moisture in the arable layer (0–20 cm) in June.

There are also negative decadal trends in the HTC and moisture coefficient (E/E_0) dynamics. For example, the mean HTC for the last decade was 0.89 or 78% of the mean value for the base period, which is above the limit of the criterion for the severe event “drought” ($\text{HTC} < 0.6$), but indicates insufficient moisture.

The variations in moisture reserves in spring at the beginning of vegetation from decade to decade in both the “early” and “late” periods do not point out any worsening of moisture conditions. Moisture reserves are maintained at a rather high level in the arable soil layer (31–36 mm). This result is consistent with the previous estimates of trends toward the spring precipitation growth [4]. At the same time, in summer, starting from the second 10 days of June, when spring wheat can be in the critical phase (“blossoming–earring”) for the growth and development, soil moisture decreases ($W20_6 = 12$ mm). In some years, moisture in the arable layer can decrease to the critical level (<10 mm).

Thus, it can be stated that in the last three decades, when growing spring wheat, agricultural producers of grain in Tatarstan faced the shortage of soil moisture more often than before the 1990s.

Table 4 presents the estimates of the agroclimatic indices for the period from 2011 to 2020, which illustrate a wide range of their variations. Among the years with large shortfall of grain (~40% relative to the mean level), 2013 and 2015 stand out. The thermal stress in these years was the highest: the average temperature over the growing season was 18.8 and 19.1 °C, with the normal equal to 17.0 °C. In 2013, the amount of precipitation was almost twice smaller than the normal, and soil moisture was completely exhausted already by mid-June. The growing season lasted only 80 days and ended at the earliest time: at the beginning of the third 10 days of July. The crop loss made up 43% (2013) and 38% (2015).

4. CONCLUSIONS

The Ministry of Agriculture of the Russian Federation worked out a long-term strategy for the development of the grain complex of the country until 2035. Its implementation will make it possible to maintain the food security of the country at a high level and to hold its position on the international grain market. The resulting estimates of the trends in agroclimatic resources and productivity of spring wheat in the Republic

Table 4. The variations in the indices of agroclimatic resources of the spring wheat growing season during 2011–2020 according to Kazan meteorological station

Year	Y_m , %	D_{beg}	D_{end}	N , day	T , °C	R , mm	HTC	E/E_0	W_{20} , mm	W_{20_6} , mm
2011	85	May 5	July 31	84	18.9	239	1.51	0.64	29	29
2012	76	April 24	July 15	83	18.1	108	0.72	0.47	42	7
2013	57	May 4	July 22	80	18.8	104	0.69	0.38	27	3
2014	87	May 10	July 30	82	18.5	108	1.71	0.41	26	13
2015	62	May 10	July 28	80	19.1	121	0.79	0.42	38	6
2016	77	April 30	July 21	83	18.0	64	0.43	0.37	33	5
2017	119	May 9	August 10	94	16.7	182	1.16	0.60	43	18
2018	87	May 9	July 29	82	18.0	105	0.71	0.49	44	9
2019	79	May 3	July 28	87	17.8	153	0.99	0.48	33	8
2020	100	May 6	August 1	88	17.8	191	1.22	0.65	47	19

The designations are the same as in Table 3. The calculations were performed in the Climate–Soil–Yield simulation system.

of Tatarstan over the recent decades can be considered in the context of informational and analytical support of this strategy.

The temperature rise during the growing season in combination with the observed positive trends in the degree of aridity of the territory causes a decrease in the climate-driven yields of spring wheat from 1991 to 2020. A statistically significant decrease in climate-driven yields was revealed from 1961–1990 to 1991–2020, i.e., positive trends in climate-driven yields in 1961–1990 changed into negative ones in 1991–2020. No significant fluctuations in the climate-driven yield were found on the decadal scale, and they remain at the level of its interannual variability.

The resulting estimate of the rate of the decrease in climate-driven yields at the level of –2.0% per decade during 1991–2020 cannot be considered insignificant, taking into account that it is comparable in absolute value with the rate of the increase in observed yields (3.9% per decade).

The analysis of changes in the agroclimatic indices and the assessment of a measure of their impact on productivity demonstrated that the Climate–Soil–Yield system as a modern technology based on which current climate change in Tatarstan is simulated can also be used for an adequate assessment of future changes in the agricultural sphere of the republic.

Another essential component of the developed technology for evaluating the productivity variations is the planned operational 10-day agroclimatic monitoring on the territory of Tatarstan for updating and detailing the resulting estimates for different agroclimatic zones and separate administrative areas.

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