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REVIEW

Climate-Driven Dynamics of Grain Production in Russia in XX–XXI Centuries: A Review of Statistical Models in Historical Studies

Nikolai Dronin[1] · Andrey Kirilenko[2]

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Abstract Multiple changes in centralized agricultural policies over the past 100 years have influenced crop production in Russia. The differential contributions of political and climatic factors in the performance of Russian agriculture have been widely examined in many historical and economic contexts. Besides traditional descriptive analysis statistical models proved their usefulness due to the quantitation of the role of both factors. We review the results of the statistical models of climate-driven dynamics of grain production in Russia in different historical periods. The modeling approach also proves its actuality today when Russia surprisingly emerges as a major net exporter of grain. Many experts attribute this success to a warmer climate, extending the growing season. Yet climate-yield modes are unable to fully explain this unprecedented yield increase with climate change alone. We propose that projecting climate change's impact on yields under climate change in countries with transition economies needs to account more for the political factor in grain production.

Keywords Russian agriculture · Climate change · Agricultural policy · Modeling · Grain production

Introduction

Differential contributions of political and climatic factors to crop yields in Russian agriculture have been widely examined in many historical and economic contexts [7, 12, 13, 21, 28, 29, 35, 41, and 46]. Two examples illustrate the importance of such work. Gatrell [13] suggested that favorable weather conditions were the main drivers of the upward dynamic of grain production in Russia in 1909–1913 rather than the 1906 agrarian reforms of Prime Minister of the Russian Empire Pyotr Arkadevich Stolypin aimed at creating a moderately wealthy class of independent farmers by dissolving peasants' communes. Thus, Gatrell took issue with many historians who claimed that the Stolypin reforms had resulted in considerable progress in Russian agriculture in the pre-WWI period.

Similarly, the period of high upward trend in grain production in 1965–1975 was attributed by Severin and Carey [35] and many other authors to an unusually favorable weather pattern rather than Kosygin-Liberman's economic liberalization reforms. The authors then proposed that this trend would be reversed in 1976–1980 and that the Soviet Union, which had increased its livestock inventory in a favorable decade, would suffer from acute feed grain shortage. Notably, the agricultural weather in 1965–1975 was only suboptimal and included two episodes of widespread drought (in 1972 and 1975) and several smaller droughts (in 1967, 1968, and 1969). Meanwhile, the harvests of 1976 and 1977 were good, while 1978 was marked by an absolute historical record in grain production with 127.4 million tons harvested [33], hence contradicting Severin and Carey's [35] projections based on a popular climate cycles theory [18]. It was not until 1979 that the deep food crisis in the Soviet Union started, triggered by spells of an unfavorable weather pattern that continued until the mid-1980s. This illustrates the problem of analysis

✉ Nikolai Dronin
ndronin@gmail.com

Andrey Kirilenko
andrei.kirilenko@ufl.edu

1 Moscow State University, Moscow, Russian Federation

2 University of Florida, Gainesville, USA

of agricultural production in the Soviet Union in relation to climate the earlier researchers had to deal with: both grain production and meteorological data have been incomplete and imperfect. Note, that the weather conditions of banner year 1978 were then described as being too cold in summer and excessively rainy in autumn [8].

The "weather-yields" models help in the historical analysis of agriculture performance. The yield-weather models work best when farmers (peasants, *kolkhozniks*) are motivated to avoid unreasonable yield losses promoting optimal timing for planting, better seeding materials, better pest control, fertilization, replanting of damaged crops, shortening harvesting period, etc. Conversely, periods of poor performance of climate-yield models ("climatic yield" deviates from observations by a large margin) hint at the effect of suboptimal agricultural policies. During 1909–1913, climatic yield is close to observations thus supporting the effectiveness of Stolypin's agricultural reforms [16]. Likewise, during 1965–1978 climatic yield matches the observations indicating that Kosygin-Liberman's reforms were effective in minimizing unreasonable losses. Conversely, the stagnation of agricultural production from 1979 until the mid-1980s coincides with a negative divergence between climatic and observed yields.

Furthermore, the subject is increasingly thought-provoking because of the recent success of Russia in grain production. In the 2010s Russia has become a major net exporter of grain. Looking back at the routinely poor performance of Russian agriculture in the twentieth century, this growth of grain production is exceptional. Undeniably, a major factor in that was the climate, including short growing seasons, cold spells, and periodic droughts. Nevertheless, there were important political (non-climatic) factors, which mainly manifested themselves during the years of turmoil. We are thus led to look closely at the contribution of both factors in the recent advance of Russian agriculture.

We applied statistical modeling to investigate the role of climate and policies in the performance of Russian agriculture. Statistical models often have advantages over dynamic processed-based models when it comes to accounting for agricultural statistics [19, 38, and 42]. Interpreting the implication of dynamic models for agricultural statistics is not a straightforward task [40]. This is particularly true for Russia, where interpretation of a dynamic model requires manipulation of official agricultural statistics, for example, to take account of the differential impact of years with either favorable or detrimental impact on yields in years of political turmoil. In practical terms to reach satisfactory matching between simulated values and official statistics one must filter data for years of political instability [1, 9, and 16]. Moreover, for Russia, in particular, an additional adjustment is required to reflect losses in boom years because of a shortage of machines or other facilities [8]. On the contrary, with historical statistical models, such as ours, built on extended historical intervals, all such peculiarities of Russian (Soviet) agricultural practice are to some extent "inside" the statistical models.

In this publication, we review the history of the application of statistical models to investigate the climatic and political factors in the dynamics of grain production in Russia during the last hundred years.

Pioneering Statistical Models of Grain Production in Russia before WWI

Even though the effect of weather on yields has been known for millennia, it was only in the nineteenth century that quantitative forecasting started. In Russia, this work was initiated by a new Bureau of Agricultural Meteorology within the Department of Agriculture founded in 1897. The Bureau has organized a systematic collection of plant development records together with weather data through a dedicated network of 81 stations. Notably, a similar system of collection and analysis of meteorological data, phenological characteristics, and yields of various crops appeared in Great Britain only in 1924, and in the USA in 1937 [45]. In 1913, the first results of data analysis published by Russian climatologist P.I. Brounov showed a strong correlation ($R = 0.86$) between cereals' yields and soil moisture content in May—beginning of June [2, 5]. Even though the period of data collection was short and statistical methods primitive, this and similar research were able to demonstrate the capabilities of agricultural models to predict future yield based on just a few weather parameters, at least in the regions sensitive to moisture deficit [32].

V. M. Obukhov [23], director of the Institute of Experimental Statistics and Statistical Methodology of the Central Statistical Office, was the first to analyze the long-term performance of key grain crops and reported a yield increase from 0.57 t/ha in 1883 to 0.82 t/ha in 1914. The apparent 1.1% annual yield increase was termed the "agrotechnological trend", and its low value was attributed to slow progress in technological and management practices. Thus, Obukhov for the first time introduced into agroclimatic science the concept of "agrotechnical trend", or "yield norms", which is the most important parameter of long-term yield dynamics associated with the gradual improvement of farming practices [30]. The difference between the "yield norm" and the actual yield was attributed to the weather. Among different yield norm approximations of the long-term yield trend, Obukhov [23] recommended a simple linear approximation, concluding:

> "When constructing yield norms according to the least-square method, we proceed from the hypothesis of a uniform increase in yield over the study period. This hypothesis was tested by me in detail regarding the evolution of rye yields and turned out to be satisfactory not only on the all-Russian, but also on a district scale. In this article, it is checked on a nationwide scale in relation to the collection of all grain bread and the harvest of the most important spring grains: oats, spring wheat, and barley, and also withstood the test. As you can see ... the hypothesis of the evolution of yield over time according to the second-order parabola gave almost identical yield rates for each year, as well as the hypothesis of yield growth in a straight line, so there is no reason to abandon the hypothesis of a uniform increase in yield in the period 1883–1915" [23, p.52].

In 1928, a statistical collection of harvests in the regions of Russia for the period 1883–1915 was published, and the preface to the collection stated that the main purpose of the publication was to study the relationship between yields and weather conditions [39]. However, these studies were discontinued.

Interruption in Modeling of Weather-Dependent Agricultural Production in the 1930–1940s

The primary role of the weather factor began to be questioned with the establishment of the kolkhoz system as central authorities regarded any reference to weather conditions as an attempt to an excuse for plan failure. The concept of the "socialist reorganization" of farming into a system of large state farms ("sovkhozes") was incorporated into a law as early as 1919 (The Law of Socialist Land Tenure). The large-scale "heroic period" reorganization of agriculture however started only in 1928, when the development of large sovkhozes was approved by the Party Politburo. Naum Jasny [14] describes the socialized agriculture of the USSR of the first half of the twentieth century in detail, documenting how "more and more ambitious plans calling for huge, ever-expanding increases in sovkhoz production replaced one another in succession" during that time. The perception of weather ("nature") rather than careful government planning controlling agriculture contradicted the doctrine of central planning. The first issue of the Economy of Agriculture journal wrote:

> "We must, as before, be staunch fighters for the general line of the party—for the Marxist-Leninist theory and methodology and give a merciless rebuff to any wrecking "theories" of the Kondratyevites, the Chayanovites,[1] who imposed on us the pre-revolutionary slave rates of agricultural development and an increase in harvest. A similar merciless rebuff must also be given to all "fashionable" bourgeois "theories" of Moore and Jevons[2]borrowed from the West that are searching for explanations of crop failures in the celestial secrets of cosmogony, in the periodicity of solar influences, and similar mysteries, incomprehensible and not subjected to the will and reason of mankind … trying to undermine the energy and the will of the proletariat." [36, p.66].

The ideological pressure on agricultural science however has started earlier. In 1926, Professor A.V. Chayanov was advised by his publisher: "It would be superficial and even naïve to look at meteorology and to sunspots for the causes of an increase or a fall in grain harvests… "Comrade" yield [is] the object of the planned action of the productive forces of the Socialist state" [cit.45, p.12]. One victim of those views was the above-mentioned dedicated network of agrometeorological stations, which was transferred to the USSR Weather Bureau rather than the Ministry of Agriculture.

Thus, agrometeorological researches in Russia were practically suspended in the 1930s and 1940s due to political reasons. It was only in 1949 when the USSR State Planning Committee (Gosplan) published a selected Obukhov scholarship [24] in a book edited by S.G. Strumilin.

Restoration of Climate-Yield Research

The network of agrometeorological stations was re-established after the end of WWII, yet the calculation of agrotechnical trends of different crops was resumed only in the 1970s. During this period, many scientific works appeared that aimed to predict the yield of crops based on various empirical statistical patterns between the state of crops and weather and other factors. These are the works of F.N. Kogan, S.A. Verigo, M.S. Kulik, A.V. Protserov, A.M. Alpatiev, L.A. Razumov, N.B. Meshchaninov, E.S. Ulanova, and Yu.I. Chirkov, V.M. Pasov, A.N. Polevoy and others. A detailed review of these works was made by F.N. Kogan [18]. The purpose of most studies was to develop short-term forecasts of yields of various crops in the regions of the country, depending on meteorological parameters. The important role of the agrotechnical factor

[1] Professors N.D. Kondrat'ev (1892–1938) and A.V. Chayanov (1888–1937) are renowned for their research in agricultural statistics, economics, and sociology. Both of them were accused of fabricated political crimes, trialed, and executed.

[2] H.L. Moore and W.S. Jevons suggested a link between astronomical events and weather, on one side, and between weather and economy, on the other [6].

for the forecast of yield for a period of 5–10 years was recognized. According to many researchers, this factor should be taken into account when determining the trend dynamics of yields in connection with the expected growth of the culture of agriculture, capital investments in agriculture, equipping it with machines and equipment, etc. [25]. The main method of calculating the trend was an extrapolation of the parameters of the trend change in yield for the previous period based on linear or other mathematical functions.

In the 1970s, trend calculations were made by the hydrometeorological service for yield forecasts for five-year plan periods. The yield forecasts for a five-year period were calculated based on an assessment of the contribution of certain agrotechnical factors (the use of fertilizers, the expansion of mechanization, the emergence of new varieties, etc.) to the yield trend of previous five-year plans [18, 22]. Calculations of the agrotechnical trend were also used for short-term forecasts. To do this, four trends in yield growth were calculated, depending on the degree of favorable weather conditions each year: very good, good, satisfactory, and bad. The assessment of the favorableness of the current weather situation was carried out from winter precipitation, considering the correlation between them and summer precipitation (since the connection of atmospheric processes between different seasons was assumed). If rainfall-unfavorable summers were projected, the yield was estimated according to a trend that applied only to the "bad" years between 1946 and 1975 [18]. All these works were practically oriented and none of them investigated the climate dependence of Russian agriculture in a historical context.

Modeling of Weather-Depended Grain Production in Russia for the Period before WWII

The early agrometeorological research in Russia was rediscovered by Wheatcroft [45], who extended their methodology to analyze climate effect on the production of cereals in Moscow, Kyiv, Odesa, Kazan, Saratov, and Orenburg *oblasts* of USSR from 1885 to 1940. Following Obukhov [23], Wheatcroft [45] hypothesized that the observed long-term linear yield trend of 0.9% annually is an effect of persistent percolation of new technologies into agriculture (agro-technological progress). The difference between the observed yield and the trend was fitted to the weather patterns, specifically, with rainfall and temperature. Finally, the residuals of this second model were elucidated as the political factor. In favorable political situations, climatic and actual yields demonstrated strong correlations, while in years of political instability correlations were weaker, and actual yields were found well below the climatic ones: Pearson's correlation of climatic yields with actual data was 0.91 ($P = 0.01$) for the first two decades of twentieth century and 0.37 (not significant at $P < 0.05$) for most unstable decade of 1917–1928. Wheatcroft [45] found that rather than Stolypin's reform, the high pre-WWI yields in Russia can be explained by a pattern of favorable weather. On the other hand, a large grain yield decline (by 20–25%) in the 1930s should be attributed to the political factor of collectivization of agriculture rather than climate [46].

Seemingly viable, this approach attributed any negative deviation of actual production from climatic (simulated) one to the "political factor". This however assumes that there are no positive contributions of state policies to agriculture. Our study [16] showed that the correlation during a specified period between the harvest and computed production can be used as an indicator of favorable or unfavorable agricultural politics in Russia: weak correlation hints at bad politics while a strong correlation is likely to be associated with state support of agriculture and market liberalization.

Modeling of Weather-Explained Grain Production in Russia for the Period after the WWII

Dronin and Kirilenko [9] applied the model suggested by [45] and two models of their own to analyze 1958–2010 grain yields in 51 *oblasts* of Russia, reporting a 1.15% yield trend, very much in line with Obukhov's analysis. They found good correspondence between model results and the observed yields in the main grain-producing belt of Russia, generally located in forest-steppe and steppe geographical zones [9]: Pearson's $P = 0.75$.

We advanced Wheatcroft's approach by specifying "political factor" as the concrete agricultural campaigns that had been specially designed and implemented (sometimes forcibly) by the government. As a matter of fact, it is rather difficult to name a single extended period in the XX century when Russian agriculture was left for a relatively free ride; the history of Russian agriculture in the XX century could be regarded as a sequence of changes in agricultural campaigns. Russian peasants reacted quickly to political changes, increasing in more favorable circumstances or curtailing (sabotaging) production with too strict administrative regulation of their activity. The influence of the political factor on the dynamics of yields can be identified by some increase or decrease in yields, during certain agrarian political campaigns that lasted (in the active phase) for 5–8 years. In contrast to the agrarian political programs, the weather changed greatly from year to year, causing an annual random fluctuation in yields. Let a particular campaign start e.g. in 1958 with a certain Party

Table 1 Mean wheat yields (tons per ha): observed, "climatic yield" projected based on the weather, and the difference between observation and projection

Period	Observed	Projected	Observed − Projected
1960–1964	0.94	0.95	− 0.01
1965–1969	1.23	1.16	0.07
1970–1974	1.44	1.29	0.15
1975–1979	1.41	1.36	0.04
1980–1984	1.35	1.48	− 0.13
1985–1989	1.68	1.53	0.15
1990–1994	1.61	1.69	− 0.08
1995–1999	1.23	1.65	− 0.42
2000–2004	1.57	1.85	− 0.28
2005–2009	1.86	2.01	− 0.15
2010–2014	1.93	2.01	− 0.08
2015–2019	2.55	2.36	0.19
2020–2023	3.00	2.49	0.50

decree and end in 1965 with another decree. During this period the yields of cereal crops permanently went below the trend. The attribution question is, can weather alone explain the observed dynamic of yields? As it is hardly possible to explain the decline of yields with weather alone, one can conclude that other factors such as the agricultural policies were at fault.

Names of some these campaigns are well known: the Stolypin reforms in 1909–1913; War Communism in 1918–1921, New Economic Policy (NEP) in 1922–1928, Stalin collectivization in 1929–1953, Khrushchev's "virgin land campaign" in 1954–1964; Kosygin-Liberman's reform in 1965–1975; Brezhnev's stagnation (emasculation of the reforms) in 1976–1985; Gorbachev's "Perestroika" in 1986–1991; liberalization and privatization of agriculture in 1991–2000; restoration of state support of agriculture from 2000. We estimated, for example, that Khrushchev's "Virgin Lands" campaign (1954–1964) brought 15% losses of trend yields of grain. While, the declined yields can be partially attributed to severe droughts in the newly cultivated areas, the decline was too steep to be attributed to climate alone without considering failed agricultural policies: manpower and machinery shortage, undeveloped infrastructure, and poor cultivation practices contributed to decline grain production equally. Similarly, both climate and policy contributed to the large 20% increase in grain production during the "intensification" period of 1965–1975. However, the next attempt at economic (including agriculture) reforms in the 1990s led to a 15% reduction in grain production. It was only in the early 2000s that agricultural production started to grow, which Uzin [43] and Serova [34] attributed to increasing government support of the farmers. However, this period also coincides with an episode of favorable weather, which contracted against unfavorable factors of policy. It was not until after 2005 that the political factor started playing a significant positive role in raising agricultural production.

In general, the climate in Russia was rather good for grain production from 1958 to 2010 but a considerable number of these favorable years were lost due to bad agricultural policy, which is especially clear for the 1990s (Table 1).

Our approach assumes that the difference between simulated climatic and real yields is due to the influence of a political factor, by which we mean specific agricultural development programs. This assumption can be confirmed by the following test. Based on the historical analysis, we assigned each year either a positive (+ 1) or a negative (− 1) agrarian policy index. In the same way, deviations of the real yield from the calculated climatic for all regions were ranked. Despite the simplistic nature of this test, a relatively high correlation (Spearman rank correlation) was obtained between two series of values equal to 0.53 ($p < 0.01$), which confirms the strong influence of agrarian policy on the dynamics of grain yields in Russia in 1958–2010 [9].

Note that agricultural performance cannot be considered separate from the entire spectrum of societal, economic, and environmental transformations. As such, even when changes in government policies are being considered together with climate to explain variations in grain yields, one would not be able to explain the observation perfectly. Still, they help in discerning at least partially the positive and negative societal factors affecting agriculture while helping in the attribution of the observed changes to climate.

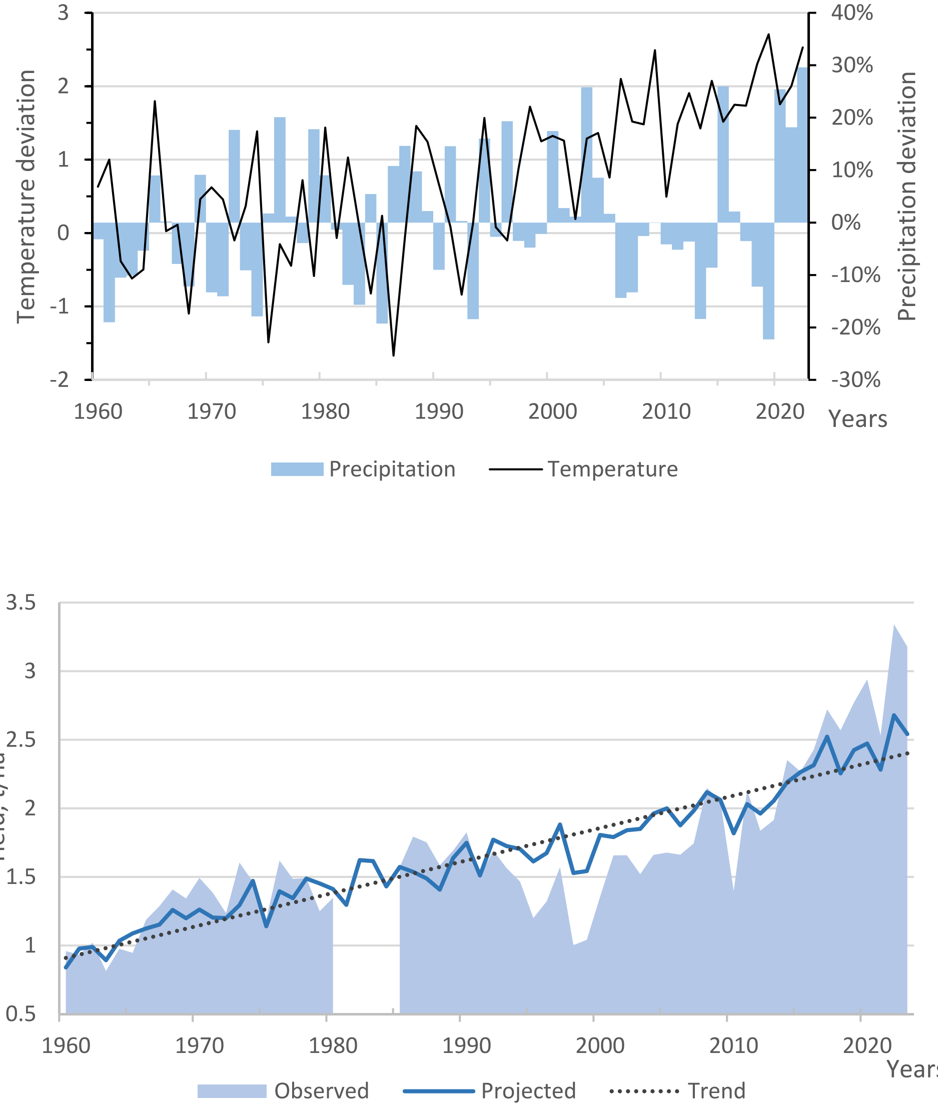

Fig. 1 **A**: mean temperature and precipitation in the top five wheat-producing oblasts of Russia; **B**: observed and projected wheat yield, averaged over the wheat-producing regions. The projection is obtained as a mean of three statistical yield-weather models. Note that for the period 1980-1985 regional yield data were not available in Soviet statistical reports

The 2010s: A Break from the Century-Old Agricultural Practices?

The majority of studies on the history of Russian agriculture postulate a strong dependence on the dynamic of agricultural production from the weather. However, something has changed in the last decade. While in the year 2000, Russia was only the 18th largest net exporter, in 2015–2016 it became the top one, exporting 34.5 million tons of grain including 25.6 million tons of wheat [11]. The year 2017 was a banner year with a new record both for production at 131.1 million tons and sales of 48.8 million tons (or slightly more [10]) including 42 million tons of wheat [37]. Russia targets an even higher goal of harvesting 150 million of grain by 2030. Meanwhile, in 2022, a new record was set for grain harvesting—157.7 million tons, and in 2023, a harvest of 140.2 million tons was obtained. Encouraged by these successes, Russia has set itself the goal of increasing production to 205 million tons by 2050.

However, these projections leave open the question as to the nature of the main driver of recent and anticipated surges. Climate change and agricultural policy are the main suspects.

The deterioration of climatic conditions by the 2020s was predicted by most global circulation models (GCMs), which showed either a decrease or a slight increase in precipitation against the background of an increase in temperature in the south of the European part of Russia [4, 17]. Climate change increases the likelihood of severe droughts in the North Caucasus and Western Siberia [1, 27], as evidenced by more frequent droughts in 1999–2015 [44]. The Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) estimated a possible drop in grain production by 10–20% by 2035 relative to the end of the twentieth

Fig. 2 Cluster analysis of the MLR, RR, and LR (A) weather-yield models. Modified from Kirilenko and Dronin [15]. Group 1 (red) regions include the main grain-producing areas in the European part of Russia. The intermediate categories show disagreement among the predicted clusters. In the Group 1 cluster, the actual yields significantly exceeds predictions based on climate alone despite lower than normal precipitation levels. Group 2 regions (blue) were less productive and showed little divergence between the actual and climatic yields. Other colors designate the areas that are not statistically significant

century due to a growing moisture deficit in the main grain-producing belt [31]. In the model of Alcamo et al. [1] climate-related yields (i.e., free from agrotechnical trends) for the 2020s were projected to be 6–12% lower compared to the period 1960–1990. Lobell et al. [20] showed that climate change had already caused a 3.9%–6.5% decline in climate-driven Russian wheat yields per decade between 1980 and 2008. Pavlova and Karachenkova [26] showed that trends in climate-driven yields of winter and spring wheat are negative in most of the southern part of European Russia, for example, the average climate-related yield of spring wheat in 2006–2015 is 75% of the 1961–1990 level. According to the empirical model of Belyaeva and Bokusheva [3], each additional warm day at a base temperature of 25 °C should cause a decrease in climate-related yields of winter wheat by 0.8%, spring barley by 1% and spring wheat by 1.44%.

Given the recent success of Russia in grain production and dryer climate, we expanded the previous research [15] to include 2010–2023 data. Following the conventional approach, we broke observed grain production into the long-term trend explained by the percolation of new technologies, the short-term trend explained by weather patterns (mean monthly temperature and monthly precipitation), and the factors of policies. Then, we fit crop yields to weather data using three statistical models using different statistical approaches: MLR, Lasso, and Ridge regression. Details of the methodology are shown in [15].

The main results of our models are shown in Fig. 1 and Table 1. There are distinct periods when the observed yield was lower or higher than the yield projected from climate and technological progress; these periods are nearly identical in all three statistical models (Fig. 1). The current period of unprecedented growth of grain production follows an increased government support of agriculture in the 2010s. Interestingly, the weather in the 2010s was not favorable for crop production due to a lower than average precipitations (Fig. 1A), while the observed yields have increased rapidly, exceeding the weather-based predictions by a wide margin (Fig. 1B).

The current period of high yields is also characterized by increasing divergence among the regions. Yield increase (over the climate yield) is mostly concentrated in a contingent group of oblasts with the best *Chernozem* soils, located close to the railway transportation networks and ports (Fig. 2). Notably, these oblasts have been able to attract large agroholdings integrating producers, food processing, and agriculture service providers, which in turn allowed them to secure support at the local and federal levels and to attract monetary and organizational support [15]. Meanwhile, other grain-producing regions have reduced the area of land under agriculture in the 1990s (by 40%) and are yet to restore the losses. Hence, even now the nonclimatic factors continue to exercise a major influence on grain production, albeit in a more regionalized fashion, deepening the gap between the winning and losing regions.

Conclusions

Agricultural agencies such as USDA routinely report that grain harvests in Russia are primarily governed by the weather. This observation is correct, yet incomplete. Indeed, many studies have confirmed a strong dependence on Russian grain production in the last hundred years on climate. Yet, in Russia, the role of the ever-changing government policies towards agriculture is exceedingly strong. During some historical periods, these policies succeeded in stimulating Russian peasants (*kolkhozniks*) to increase yields and reduce grain losses along the technological chain. In these episodes, the harvest approaches the climatic yield or even exceeds it, indicating a rapid pace of technological advance in the Russian agricultural sector. During other periods, the harvests are well below what they should have been based on the observed weather. In the recent period, Russia has demonstrated a high rate of growth in agricultural production despite some deterioration of climate conditions, i.e. lessening dependence on weather. Overall, however, the Russian yields are below the ones in climatically analogous areas of Canada. It has an important global dimension. The global importance of Russia as a grain exporter, however, requires an understanding on its' source: is it indicative of an unusually favorable stretch of agricultural weather or a true unmasked potential of the agricultural sector. Our recent study presents an argument in favor of the latter.

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Data Availability Data can be provided by individual request.

Declarations

Conflicts of interest None.

Ethics Approval The submitted work is original and has not been published elsewhere in any form or language.The results presented are obtained without inappropriate data manipulation. All required information about the methods used is presented in the paper. The research has not involved human and/or animal participation.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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