Recent grain production boom in Russia in historical context

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Recent grain production boom in Russia in historical context

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Abstract. In recent years, Russia has established herself as the leading supplier of grain worldwide and continues to make ambitious plans for raising its grain production in the long-term. Within the context of Russian agricultural history, the recent high growth of grain production is exceptional. This growth however is not fully replicated by the "weather-yield" crop models, which project only moderate yield increase in the 21st century and fail to predict the most recent record growth in grain yields. The difference between the projected climate-dependent yields and observations is especially high in two of the most important agricultural regions, Central Black Earth and Northern Caucasus, while the rest of the agricultural zone is shows good agreement with the regression models. Similar differences were observed in the late 1960s, which we interpret in terms of the fast changes in agricultural technology during the Union of Soviet Socialist Republic (USSR) agricultural reforms followed by periods of reversal. We also interpret the current period of high differentiation between weather-yield model results and collected yield as evidence of a higher than usual contribution of agricultural reforms in yield improvements, which, however, are primarily benefiting the large-scale producers located in the most productive areas of Russia.

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1. Introduction

The explosive growth of Russia's grain export in the 21st century is exceptional. Between 1992 (first year grain export information was reported to the Food and Agricultural Organization [FAO]) and 1996, Russia exported only 0.9 million tons of grains per annum on average (FAOSTAT 2020). From 2000 to 2004, the exports increased to 7.1 million tons, while from 2014 to 2018 (the last year that this information was reported to FAO at the time of writing), it further increased to 38.8 million tons. This increase moved Russia's position between the top world grain exporters from the 25th place to 10th and then to 3rd place globally (after the United States [US] and the Ukraine). The majority of this export was from wheat and wheat products, of which Russia is the top exporter (FAOSTAT 2020). From 2019 to 2020, Russia kept its dominant position in the world market.

The current development of the Russian grain production sector is in full compliance with planned targets of the Russian government, perhaps for the first time in modern history. During the first ten years of FAO reporting (1992–2001), the Russian Federation harvested an average of 74 million tons of grain annually (FAOSTAT). During the next ten years (2002–2011), annual grain production remained at roughly same level (80 million tons). The 2013 Federal Program of Agricultural Development and Regulation of Markets for Agricultural Produce, Raw Materials, and Food for 2013 to 2020 (Ministerstvo 2013) set a target for Russian agriculture to achieve an average annual grain (barley, corn, and wheat) production of 115 million tons, including export potential of an estimated 30 million tons by 2020. A similar projection by the Ministry of Agriculture predicted a production of 120 to 130 million tons of grain by 2020, thus providing enough capacity to export 30 to 40 million tons of grain (Schierhorn et al. 2012). Yet another 2012 projection by the Russian Institute for Agrarian Market Studies predicted production growth to 125 million tons by 2019 with export capacity of 45 to 50 million tons (ibid.). The European Bank for Reconstruction and Development (EBRD) has estimated the maximum potential grain production in Russia at 126 million tons (EBRD–FAO 2008). Russia appears to be on track to meet official targets; on average, from 2013 to 2019, the country produced 110 million tons of grain on average (FAOSTAT). In 2017, a record harvest of 131.1 million ton of grain was collected, of which 48.8 million tons were exported (FAOSTAT). Inspired by this success, the Russian government anticipates annual harvests of 150 million metric tons of grain by 2030 and 205 million tons by 2050.

Within the context of Russian agricultural history, the recent growth of grain production is truly exceptional, especially compared with the last 100 years when Russian agriculture has routinely fallen short of planned targets. This recent growth may ensure the food security for the country (Dronin and Bellinger 2005). Climate is believed to be the most important, highly variable factor in Russian grain production (Dronin and Kirilenko 2013). The 1930s, 1950s, and 1990s were characterized by prevailing poor agricultural weather, such as persistent meteorological droughts, while the 1910s, 1970s, and 1980s were favorable due to moister weather conditions. Meanwhile, climate alone is also unable to explain the entire yield change as different yields could be achieved under similar weather conditions due to changes in technology and management. Technological progress is typically modeled as a slow long-term increase in yield, yet in Russia the political (non-climatic) factor had been strongly affecting agricultural management practices, manifesting itself in the periods of fast technological progress in agriculture after years of stagnation (Kirilenko and Dronin 2005). In the 20th century, few episodes of faster growth of agricultural production in Russia occurred when pro-farmer policies, such as Stolypin's reforms in early 1910s and Kosygin’s reforms in late 1960s, coincided with unusually favorable weather. However, the rate of annual growth of grain production (2.6%) in the last seven years (2003–2017) is approximately double that of any of these other periods.

It seems that climate change together with slow technological progress are unable to explain the historical variability of grain production on a decadal scale and also cannot explain the current upward dynamics of current agricultural production in Russia. Thus, the goal of this paper was to investigate those unrecognized sources that are responsible for the present grain production boom. Specifically, we use weather-yield regression models trained on historical agricultural statistics to demonstrate that climate change is only marginally beneficial for grain production in Russia. We then analyzed the implementation of applied countrywide advanced agrotechnology and management at record pace and suggest that the new elements in agricultural practices rather than climate change are the main factors responsible for the observed fast improvements in grain production. In Chapter 1, we review the history of modeling climate-driven crop yield in Russia over the 20th century. Chapter 2 introduces data and methods used in this study to estimate the trend of yield driven by climate. Furthermore, 1960–2010 yields backcasted by our model are presented in Chapter 3. Finally, the results are discussed in Chapter 4, and the overall findings are summarized in Chapter 5.

2. Application of statistical climatic models to measure climate dependence of Russian agriculture

Numerous papers address the question of estimating the influence of the effect of national agricultural policies on yields. Chand and Raju (2009) estimated variability in agricultural and food production in Indian provinces resulting from the adoption of new technology. The authors analyzed the residual values from de-trended yield time series and found that the residuals' variance had decreased, which was interpreted as an effect resulting from green revolution policies. Similar methods for estimating the patterns of yield variability have been employed by many authors for studies on different regions (see Naylor et al. 1997).

The history of agricultural meteorology in Russia began during the last decade of the 19th century with the pioneering research of climatologists A.I. Voeikov and P.I. Brounov. These innovative studies were based on the analysis of weather records, crop yields, and crop phenology. The data were provided by a dedicated network of agrometeorological stations supervised by the Bureau of Agricultural Meteorology, which was established at the Department of Agriculture by P.I. Brounov in 1897. These very first studies showed a strong correlation between yields and weather in late spring and early summer (Brounov 1913; Alsberg and Griffing 1928). Later, V. M. Obukhov[1] (1927) produced a linear trend of yields for five different crops (winter and spring wheat, rye, barley, and oats) for the years 1883–1914 and found an annual increase of 1.1% (8 kg/ha) in the yield norm from 0.57 t/ha in 1883 to 0.82 t/ha in 1914. He suggested splitting the observed dynamics of yields into the linear part (which he called the "agrotechnological trend" that was explained as slow progress in technological and management practices) and deviations from the trend, which he explained as due to the weather. To approximate this long-term agrotechnological trend, Obukhov explored different mathematical functions but concluded that the linear approximation was the best for this purpose. In spite of the simplicity and the shortage of data, these early statistical methods provided a way to make useful projections of yields in the main agricultural zone of Russia, which incidentally, were sensitive to moisture deficits (Sandersen 1954).

Between the 1930s and the 1940s, agrometeorological research in Russia slowed down for managerial and political reasons. In 1930, the agrometeorological station network was reorganized and its agricultural division was reassigned from Narkomzem (Ministry of Agriculture) to the USSR Weather Bureau. In addition, the idea of yields controlled by weather as opposed to the centralized planning did not sit well with the ideological doctrine. For example, one article in the Economy of Agriculture Journal in issue 1, 1933 stated:

> "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[2], 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[3] 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." (Shumanov 1933: 66).

Even as early as 1926, the publisher of Professor A.V. Chayanov's book advised him: "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

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[1] V.M. Obukhov was a prominent Soviet agricultural statistician. From 1926 to 1933 he served as Director of the Institute of Experimental Statistics and Statistical Meteorology.

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

[3] H.L. Moore and W.S. Jevons tried to establish a link between astronomical events and weather and between weather and economy (Carchedi and Roberts 2018).

harvests… “Comrade” yield [is] the object of the planned action of the productive forces of the Socialist state” (cit. Wheatcroft 1977: 12). It was only after World War II that the USSR Hydrometeorological Service expanded its agrometeorological network and resumed the use of statistical models to forecast grain harvests in Russian regions based on the weather at the beginning of the vegetation period (Kogan 1981). At the same time, a selection of articles on agrometeorology was published by the USSR State Planning Committee (Gosplan) as an edited book (Obukhov 1949).

In 1977, Australian historian S.G. Wheatcroft (1977) reviewed the original agrometeorological studies performed by Russian scientists at the end of the 19th and the beginning of the 20th centuries and concluded that their simple statistical approach would be very successful in Russia. His study covered the climatic factors affecting cereal production in six major agricultural provinces[4] of Russia from 1885 to 1940. Following (and referring to) the Obukhov (1927) approach, he subtracted the long-term linear trend from the reported yields for each of the provinces to remove the effects of slow evolutionary agro-technical progress. Wheatcroft’s estimations of the yield trend were slightly lower than Obukhov’s findings, which showed an approximately a 0.9% annual growth trend (7 kg/ha). For each of the six provinces, a linear regression model was then constructed to explain the detrended yield using monthly rainfall and mean surface air temperature as residuals. The residuals were analyzed for the entire country and then further interpreted as the influence of the political factor. Wheatcroft showed different patterns of residuals for different state agricultural policies; some policies were presumably pro-farmer and were characterized by a high correlation of actual yields and climatic ones, while for periods of policies known for historians as unfavorable or even disastrous for Russian farmers the correlation was low. Notably, during the 20th century years preceding Russian Revolution (1900–1917), the correlation between reported and climate-driven yields was exceptionally high with $R = 0.91$; $p < 0.01$. Comparatively, during the 12-year period following the Revolution (1917–1928), the correlation between the reported and climate-driven yields was low: $R = 0.37$; $p > 0.05$. During the latter period, a series of inconsistent reforms in agriculture starting with compulsory grain procurement (“prodrazverstka”) was replaced with a free market "new economic policy" (NEP), which was in turn replaced with discriminatory market regulations (a practice of “price scissors”, which artificially inflated prices for industrial goods and deflated prices for agricultural products during that period). Finally, a collectivization campaign with a partial return of grain procurement and a policy of “liquidation” of the most successful farmers (“kulaks”) was undertaken. Based on this statistical analysis, Wheatcroft speculated that the above-average yield over the entire five-year period of 1909 to1913, including the record yield 1913, could be explained by a period of good weather rather than by the Stolypin’s reform. In contrast, the decline of grain production by 20% to 25% below the trend in the 1930s was explained by destructive rural policy (forcible collectivization of Soviet peasants) rather than poor weather conditions during this decade (Wheatcroft and Davies 1994a).

Dronin and Kirilenko (2013) advanced Wheatcroft’s approach for the 1958 to 2010 crop years[5] in 51 grain producing Russian provinces and reported a 1.15% annual growth trend (16 kg/ha), which was surprisingly similar to Obukhov’s (1927) analysis for 1883 to 1914 (1.1% annual growth). They found that model residuals can be well explained with the changes in the “political factor”: (1) Khrushchev’s “virgin land campaign” from 1954 to1964; (2) the intensification of Soviet farming from 1965 to 1975, known as the Kosygin’s reforms; Gorbachev’s

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[4] Moscow, Kiev, Odessa, Kazan, Saratov, and Orenburg

[5] The choice of 1958 as the starting year for analysis was determined by very low reliability of the agricultural census data during the Stalinist period and during the immediately ensuing years (Wheatcroft and Davies 1994b; Dronin and Bellinger 2005).

"Perestroika" from 1985 to 1991; (4) liberalization and privatization of agriculture from 1991 to 2000, and (5) the program of state support for agriculture that started in 2000. For example, Khrushchev's "virgin lands" campaign coincided with a 15% grain yield reduction with only half of these losses attributable to adverse climate conditions (Dronin and Kirilenko 2013). Conversely, during the finest period of Soviet agriculture between 1965 and 1975, favorable climate and intensification policies equally contributed to the 20% gain in grain yields (Ibid.). The deep economic crisis of the 1990s resulted in a yield reduction of more than 15% from the trend, mostly due to unsuccessful agricultural reforms (Ibid). While some agricultural experts suggest that the recovery of Russian agriculture began in the early 2000's (Uzin 2004; Serova 2007) with the increase in federal support, the model of Dronin and Kirilenko (2013) showed that most of the observed yield increase was due to a favorable agricultural climate period, and the results of the support became visible only in the second part of the decade.

3. Data and methods

Following the conventional approach described in the previous chapter, the starting point in our analysis was detrending the yield time series to remove long-term improvements in crop production attributed to slow and gradual changes in technology and/or regional climate. Lobell and Ortiz-Monasterio (2007) demonstrated that different detrending techniques return similar results, so we applied the simplest one with a linear trend. The residuals were then used as a dependent variable in a multiple regression model with agro-climatic variables, such as temperature and precipitation that were used as predictors (Nicholls 1997; Lobell and Ortiz-Monasterio 2007; Matiu et al. 2017). For example, Lobell and Ortiz-Monasterio (2007) explained variability in crop yields by minimum and maximum temperatures and precipitation over the growing period. More recent publications frequently use data mining methods, such as random forest (Hoffman et al. 2018), artificial neural networks (Crane-Droesch 2018), Bayesian inference (Shirley et al. 2020), and others. While these techniques improved model fit (Hoffman et al. 2018), the improvement was made at the expense of reduced result interpretability shared by black-box models[6].

To build up result robustness, we used three models: (1) multiple linear ordinary least squares regression (MLR), (2) lasso regression (LR), and (3) ridge regression (RR). Incidentally, all three models have same form:

$$y = \beta_0 + \Sigma\beta_i x_i \quad + \varepsilon$$

in which x_i represents climate variables (monthly or quarterly temperature and precipitation), and y represents observed yield. The MLR followed the earlier weather-yield models discussed in the previous section for finding the values of the best fit parameters, β_i, using the ordinary least squares (OLS) method. Specifically, the OLS finds model parameters that minimize the cost function, $\Sigma(y_j - \hat{y}_j\ )^2$, in which y_j are observations, and $\hat{y}_j$ are respective model predictions. To address overfitting and multicollinearity problems in the model, we applied the variable selection by adhering to the following protocol. First, the model was fitted to all climate variables. Five variables with the best explanatory power for all administrative units were then selected: (1) the temperature for months of June and July, (2) second-quarter precipitation, and (3) the precipitation for months of July and December:

$$\hat{y} = a_0 + a_1 t_6 + a_2 t_7 + a_3(p_4 + p_5 + p_6) + a_4 p_7 + a_5 p_{12}$$

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[6] Black-box models have internal implementation, which is hard or impossible to inspect (is "black" for a researcher). Many (but not all) machine learning algorithms are black-box systems.

in which $\hat{y}$ represents estimated climatic yield, t_i represents monthly temperature, p_i is monthly precipitation, i is the number of the month, and a_j indicates model parameters.

The MLR model still suffered from the uniformity in the variable selection, which did not reflect the multitude of climates in the country and resulted in poor model performance in some regions, such as the Far East section of the country. To address this problem, we used more robust alternatives, namely lasso and ridge regressions. Both models modify the OLS cost function targeting reduction in model complexity. Specifically, the OLS cost function, $\Sigma(y_i - \hat{y}_i\ )^2$, does not discriminate against the number of independent variables and leads to the overfitting problem. That is, the model may demonstrate a very good fit on the training data but a poor fit when new data not used in model training are introduced. Both LR and RR solve this problem by changing the cost function through introduction of a penalty to minimize the coefficients at the independent variable, β.

For instance, in RR the cost function is of a form, $\Sigma(y_i - \hat{y}_i\ )^2 + \lambda\Sigma(\beta_i)^2$, while in LR the cost function is $\Sigma(y_i - \hat{y}_i\ )^2 + \lambda\Sigma|\beta_i|$. Note that when the parameter $\lambda = 0$, both LR and RR become the familiar OLS model. The advantage of LR and RR is that both of these models automatically select the most significant variables for the model either by penalizing or by excluding the least significant variables. A detailed discussion of the LR and RR is provided by Tibshirani (1996).

The selection of the variable in the LR and RR models was individual for each administrative unit. The most frequently selected variables reflecting at least half of the administrative units were the growing period precipitation (April–July with positive coefficients), harvesting period precipitation (August–September with negative coefficients), and February precipitation (with negative coefficients). The time frame of the model was a 62-year period from 1958 to 2019 that encompassed multiple attempts in improving the agricultural sector of the country. For consistency and to accommodate for changes in administrative units in Russian Federation, the model adopted the upper level administrative division of the country at the time of Declaration of State Sovereignty of the Russian SFSR (June 12, 1990). Consequently, the missing data points for yields in newly introduced administrative units were treated in the model as missing data and were excluded. For climate variables, we followed the family of statistical models introduced by Lobell (see Lobell and Ortiz-Monasterio 2007) and used temperature and precipitation as the variables. Yield statistics for provinces are presented in Soviet and Russian official statistical reports related to corresponding years.

The mean monthly air temperature was acquired from the temperature product GISS GISTEMP v4 SBBX.Tsurf250 from the National Aeronautics Space Administration (NASA) Goddard Institute for Space Studies (GISS), gridded at 1 x 1 degrees of geographical latitude and longitude with application of a 250 km smoothing filter (Hansen et al. 1987; Lenssen et al. 2019). For 1958 to 2016 monthly precipitation, we used the Full Data Monthly Product V.2018 (V8) from Global Precipitation Climatology Centre ([GPCC]Schneider et al. 2018). The recent years missing from the fully vetted product (2017–2019) were acquired from the “First Guess” product (Ziese et al. 2011; Schamm et al. 2014). Precipitation amounts from both products were compared for one overlapping year (2016) to ensure data compatibility. All products were interpolated into a standard grid of 0.5 x 0.5 degrees of geographical latitude and longitude.

Following the established practice (see Lobell and Ortiz-Monasterio 2007), the gridded parameters of climate variables were unified at the level of administrative units of the country by using their respective weighted means. The weights represented the 1992 area taken by agriculture in each cell of the grid (Ramankutty and Foley 1998) to match the reference year for administrative division of the country. The administrative units with 10 or more missing years of data and those with little or no grain production were excluded from consideration resulting in 59 remaining units for further analysis.

4. Results

The model residuals were averaged across all administrative units and are presented in Figure 1. Recall that the residuals represent yield variability that is unexplained by the long-term technology trend and climate; we attributed the residuals to the changes in agricultural policies. The results clearly show distinct periods in deviation between the predicted and actual yields that are consistent over all three models (MLR, RR, and LR). The first period of high yields encompassed the mid-1960s to mid-1970s, which we attributed to the success of Kosygin's agricultural reforms, including simplified credits for collective farms, tax reductions, irrigation, reduced central management, and many others. The initial boost from those initiatives eventually regressed; one of the drivers of this regression was the return of rigid and poorly coordinated central management, publicly known at the period as "vedomstvennost", loosely translated as "multiplicity of controlling departments". The second period of high yields spanned from the mid-1980s to the early 1990s following the 1982 "Food program", probably initiated by Gorbachev, who at that time was overseeing agriculture at the Political Bureau (Dronin and Kirilenko 2013). The final period started in late 2000s and is ongoing.

Figure 1.

Notably, starting from circa 2010, the simulated yield based on climate variables alone clearly deviated from the reported yields, similar to the previous periods of agricultural reforms (Figure 2). Interestingly, this period was also characterized with reduced precipitation in the main producing areas (Figure 2B). The first indication of the divergence could be observed in 2009 when actual grain production was well out of our simulation. However, the disastrous drought of 2010 that hit the entire European part of Russia masks the beginning of the divergence. In retrospective, the positive gap between two the projected climatic and observed yields reached its historic maximum in the 2010s (Table 1), making the past decade exceptionally productive for Russian agriculture.

Figure 2.

Table 1.

The variety of climates in grain producing areas of the country affected the dynamics of yield with the possibility of some areas affected by unfavorable weather while the others exhibited beneficial agrometeorological conditions. We attempted a cluster analysis of model residuals aiming at segmentation of the agricultural areas of the country. A grouping algorithm was run for the number of clusters k=2 … 15, and then, the optimal number of clusters was determined based on Calinski-Harabasz pseudo F-statistic. For all three models (MLR, RR, and LR), the optimal number of groups was found to be k = 2. Notably, the obtained clusters were nearly contiguous, clearly following the "Tobler's First Law of Geography", which provided additional support for the validity of the yield model. All three models returned similar clustering with some differences at the edges of the clusters. The proportion agreements were 0.86, 0.92, and 0.95 for MLR–LR, LR–RR, and MLR–RR comparisons, respectively. Figure 3 (A, B, and C) illustrates the grouping for the MLR, RR and LR model.

The residual yield change differs between the groups (Figure 3D). Group 1 consisted of the most productive lands in the Northern Caucasus and Central Black Earth regions of Russia and exhibited somewhat more extreme variations, but the most interesting feature of this group was the high increase in yields in the 2010s[7]. Meanwhile, less productive lands in Group 2 demonstrated smaller variabilities and only moderate yield increases in the 2010s.

Figure 3.

5. Discussion

The climate in the main agricultural regions of Russia is changing. All eight subdivisions[8] of the Central Black Earth province and three subdivisions of Northern Caucasus have reported warmer temperatures with small changes in precipitation resulting in a dryer condition in the vegetation period. For example, between the 1960s and 2010s in Voronezh Oblast (Central Black Earth region), the mean temperature of the April to September growing period has increased by 2.4 ºC while precipitation has increased by 60 mm. Moreover, precipitation pattern has changed with occurrences of heavy rains providing monthly precipitation norm in one day and damaging the crops (Kostebelova and Makhonchenko 2019). These heavy rains are usually followed by hot and dry weather with dry winds ("sukhovey") that lead to high soil evaporation. Despite increasing precipitation the relative humidity of air has decreased by 6% in recent years (Ibid). Local media are especially concerned about water resource depletion in the province. In the summer of 2020, the Dokuchaev groundwater well in Kamennaja Steppe went completely dry for the first time since it was established in 1892 as the water level has continued to fall at least 5 m yearly since 1990 (Yarmolenko 2020). Similar pictures are observed in the Northern Caucasus where winter temperature has increased by 2,1-2.8ºC and summer – 0,8ºC while precipitation has increased by 17% since 1985 (Ivashkov 2017). In Stavropol krai, in the 18 last years, eight catastrophic rainfalls that exceeded 100 mm out of 18 over the entire observation period occurred. At the same time an increase in frequency of very hot days with temperatures exceeding 40ºC were observed at 12 out of 16 meteorological stations. (Vliyanie 2019). During the same timeframe, three large prolonged droughts were observed. Local agronomists have called for shifting crop selection from frost-resistant to drought-tolerant cultivars (Ibid).

While longer vegetation period is favorable for crops, such as winter wheat, higher summer temperatures are damaging, especially when precipitation is limited. Hence, one could expect little change or even a decrease in grain yields following the climate change. Indeed, Russian media routine reports adverse weather conditions faced by the local farmers during the sowing season. Those reports however are not necessarily realizing in poor yields, for example, in the 2010s the main productive areas suffered from a decrease in precipitation and higher than normal temperatures (Figure 2B), yet grain production was noticeably higher than expected based on statistics or predictions according to the weather-yield models (such as our model, see Figure 2C). During those years, the main grain producing regions in the Northern Caucasus and the Black Soil zone of Russia produced exceptional yields. Meanwhile, the yields in the least productive northern provinces of European Russia and in Buryatia (Eastern Siberia) have not improved despite the warmer climate.

The story of the 2017 harvest is representative of this exceptional production. A good harvest was not expected that year, to say nothing of a record one. In spring and early June, numerous alarming weather reports by

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[7] Primorsky kraj in the Far East is included in Group 1 with some reservations. This region is located in the forest zone and is characterized by a capricious monsoon climate, which is rare for Russia. The region specializes in production of technical crops, mainly soybeans, while grain crops occupy only 0.7% of its total area. For comparison. in Krasnodar kraj, grains occupy 48% of the region's land.

[8] We used the term "subdivision" for all federal subjects that are constituent members of the Russian Federation.

the media were broadcast. In June 2017, unstable weather conditions with rains and extreme temperature fluctuations were observed in the Central, North-Western, and Volga regions. The agricultural areas of the Urals underwent cold rainy weather for weeks. In the Northern Caucasus, the weather service reported cold weather with temperatures of 2 to 3 °C below the norm and rains lasting for 2 to 5 days. Russian meteorological service reported that grain crop maturation was lagging due to frequent rains, excessive atmospheric moisture, and waterlogged soil in some regions that led to the spread of strawworms and fungus (Katkova 2017a). The excessive soil moisture destroyed winter crops in some regions, such as Yaroslavl and Orel. The Ministry of Agriculture warned that heavy rains and hail were damaging crops in parts of the Northern Caucasus. In Mordovia Republic, located in the eastern part of the European Plain of Russia, the late May frost killed a variety of crops of up to 150 thousand hectares at which point the local authorities had to declare an emergency (Ibid). Initially, the Ministry of Agriculture forecasted a 110 million tons yield of grains. In early June, the Ministry corrected the forecast down it to 100 to 103 million tons due to unfavorable weather conditions (Burlakova 2017). On 3 July the Minister of Agriculture confirmed the low projection of grain production at 100-103 million tons referring to poor weather (Katkova 2017b). In reality, the 2017 grain harvest hit a historical high of 134.1 million tons, taking the agricultural experts by surprise (see Abramov 2017).

The recent success of Russian agriculture is also challenging results of the standard weather-yield models trained on historical yield data, which have failed to replicate the fast increase in grain yields in the best agricultural areas of Russia. The statistical model reported in this article projected much smaller than observed increase in climatic yield (Figure 2; Table 1). Our own earlier grain production estimates (Luobimtseva et al. 2015) fell considerately below the record 2017 yield. Similarly, a model by Belyaeva and Bokusheva (2018) estimated that each additional heat degree day over the base of 25°C causes a reduction in the yield of winter wheat by 0.8%, spring barley by 1%, and spring wheat by 1.44%. This model also failed to explain the most recent grain production boom (R. Bokusheva, personal communication). Over a longer time period, Lobell et al. (2011) estimated that climate trends have caused a decline in Russian wheat yields by 3.9% to 6.5% per decade during the period from 1980 to 2008, while in fact the trend over that period was close to zero. The model by Sirotenko and Pavlova (2012) found marginal growth of weather explained yields[9] over the 1975 to 2006 period at a rate of 0.4% per decade in the Central economic region to 2.8% per decade in the Volga region.

In contrast to the moderate yield predictions based on the weather-yield models, experts point out the huge untapped agricultural potential in Russia. The official high projections of Russian grain production have been based on estimates of so-called "potential yields" on the assumption that agroclimatic conditions in Russia are similar to those of Canada (EBRD-FAO 2008). Following this logic, Russia should be able to raise its average yields by 65% from 1.86 (2008–2012 yield in Russia) to 3.54 t/ha (in Canada). This projection is in agreement with a much earlier research by Sirotenko et al. (1997) that estimated that Russian grain production could be increased by as much as 120% (relative to 1986–1990) had the soil fertility been improved. Similarly, Deppermann at al. (2018) utilized the Environmental Policy Integrated Model EPIC-IIASA model and found a potential increase in cereal production in 2030 in Russia by 70% (up to 3.0 to 3.2 t/ha) from the basic 2000–2010 level in "the strongest intensification" agricultural scenario; notably, only 9% of the reported additional production was due to recultivation[10], whereas

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[9] Note that this data reflects only winter wheat, while Lobell et al. (2011) data are for winter and spring wheat.

[10] No definite trend in crop area over the last ten years in Russia have been observed. Actually, in this period, crop areas devoted to cereals in Russia has been largely static.

91% was due to better application of fertilizer, pesticides, and other technological improvements. Other experts also reported a potential increase in grain production with improved technologies and recultivation of lands abandoned during the free-market reforms of the 1990s (Deppermann et al. 2018; Meyfroidt et al. 2016; Schierhorn et al. 2014). Notwithstanding those projections, in the record year 2017 Russia has already reported a 2.91 t/ha yield.

The Russian government has been supporting the country's agriculture after the prolonged period of frequently unsuccessful experiments with free market reforms in the agricultural sector of the economy. The goal of improving food independence of the country was set as early as in 2000 (Wegren 2002) when it was exemplified as a primary task in the "Main Directions of the Agricultural Food Policy of the Government of the Russian Federation for 2001 - 2010" (Osnovnye …2000). During the last 20 years, the Russian agricultural strategy, including meat production, is mostly driven by considerations of national food security and self-sufficiency (Wegren 2013). The main tools of this policy are state purchases and commodity interventions in order to limit price volatility to support livestock grain producers in years of poor harvests. To protect consumers and meat producers, the government also resorts to grain export restrictions. The food security doctrine was adopted in 2005 and aimed at achieving self-sufficiency. This goal is yet to be achieved as Russia is still one of the top 15 global importers of food and agricultural products (USDA 2019). Although progress in pork and poultry production is noticeable due to strong protection measures (since 2014 countersanction measures) the number of beef cattle and dairy cows has declined from 19.9 million in 2010 to 18.6 million in 2017 (Wegren 2018).

The current state policies however are under stress. Over the last three years, grain production has grown while the domestic demand has not increased due to a decline in population. In the record year 2017, spring grain prices were lower than in spring 2016 and have continued to decline as a result of large reserves and stagnant domestic and foreign demand (USDA 2017). While the government provides a subsidy that depends on area that was sown, the intensiveness of use of arable land, and soil fertility, this support has also declined following the overall stagnation of the Russian economy. As a result, farmers' financial situation is worsening (USDA 2017). In 2016, the Russian government announced a reduction of 9% in federal support for agriculture from 237 billion rubles in 2016 to 215.9 billion in 2017 together with plans for further reductions to 198 billion in 2018 and 194 billion rubles in 2019 (reductions of 16.5% and 18%, respectively) as described by IKAR (2017).

Russian agriculture is also inadequately supported by machinery. The utilization rates for tractors and harvesters, for example, are double or triple the norm (Alabushev et al. 2010).[11] With the increase in agricultural production and exports, the infrastructure, including the railways, ports, and storage facilities, are becoming over-stressed, especially in Siberian agricultural regions due to their remoteness from the main markets. For example, inadequate storage leads to a loss of at least 10% of harvest.[12] That loss of storage discourages local businesses from investing in the grain producing sector (USDA 2010; Liefert et al 2013). Only recently the government began to address the modernization and expansion of the physical infrastructure, particularly storing and transportation capacities, which is the most serious bottleneck for the grain producing sector in Russia (Wegren 2018).

Another area of concern is fertilization, which is critical for further yield improvement (Schierhorn et al. 2014). The majority of grain crops in Russia still rely on low-cost agrotechnologies with a minimum use of

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[11] In a 2016 interview, Pavel Skurikhin, the head of the National Union of Grain Producers, estimated a 15% to 20% loss of grain associated with harvesting delays resulting from a shortage of harvesters. Instead of a normal 5–6 days, the harvesting lasted up to 30 days (Samofalova 2016).

[12] Ibid.

agrochemicals (USDA 2017). The fertilizer application remains low: circa 22 kg/ha compared with 134 kg/ha in the United States and 199 kg/ha in Germany (Dyatlovskaya 2018). The depreciation of the national currency resulted in a rapid increase in the prices of imported chemicals[13]. Currently, the central government compensates farmers for some fertilizer costs, while the majority of provincial budgets cannot afford the required support (Kiselev et al. 2013). The government did not simulate higher fertilizer application until 2014 when the government mandated the fertilizer industry to sell a certain share of their product domestically by lowering prices (Dyatlovskaya 2018).

Seed quality is yet another area of potential improvement with up to 20% of seeds being of low quality leading to an estimated up to 3 million tons of potential harvest loss (Samofalova 2016). The single exception is corn production, which constitutes 6.2% of the overall grains. In the last six years, corn production has more than doubled as a result of an increase in cultivation area and improvement in yields (up to 30%), largely due to better quality seeds. Notably, 50%–55% of corn seeds are imported. The reason behind low quality seeds in Russia is underdevelopment of the seed industry in the country because an average farmer household cannot afford to purchase imported seeds (USDA 2017).

The inadequate support of the agricultural sector combined with the necessary improvements in fertilization rates, machinery, seeds, and operating personnel have led to geographical divergence in agricultural development rates. Specifically, we found that the current boom in grain production is mostly driven by a compact group of provinces in the Central Black Earth and Northern Caucasus regions (Figure 3A–C). This area boasts prime soils and relatively mild agricultural climate, which however, has an elevated risk for the occurrence of droughts. This area also has the highest in the percentage of croplands managed by the large-scale business groups frequently operating over 1 million hectares of land (agroholdings) in Russia. Accordingly, in the fertile Central Black Earth, agroholdings operate 45% of the arable lands, whereas in Northern Caucasus, it is –21%, in the Volga region 17%, in the South Ural 9%, and in Western Siberia only 7% (Rylko 2011; Grouiez 2012). The percentage of land operated by agroholdings generally decrease along with yields. Between the top 100 grain producers in Russia, 88 are located in the Central Black Earth and Northern Caucasus regions, two in the Volga region, two in Tatarstan, and four in Siberia (VIAPI 2009).

Few experts have reviewed the economic efficiency and productivity of Russian agroholdings (Visser et al. 2017) as they are not considered separately in statistical data by Russia's statistical agency RosStat (Uzin et al. 2020)[14]. However, sparse data show that the fertilizer use in agroholdings is 260% higher than in other agricultural companies (Uzun et al. 2012). In 2009, the average grain yield in Russia was 1.79 tons per ha compared with 3.56 tons per ha in the top 100 largest grain producers (VIAPI 2009). Therefore, it seems that in times of limited monetary and logistical support from the state, those large-scale operators are the main drivers of productivity and efficiency in the grain sector since they are capable of gaining the most advantage from state support, attracting investments, obtain better seeds, purchase fertilizers, improve infrastructure and storage capacity, and increase grain exports due to their proximity to sea ports (Liefert et al 2013).

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[13] Thus, with approximately the same level of chemical application in 2015 and 2016 when compared with 2014, costs of chemicals rose by 112% and 175% in 2015 and 2016, respectively (IKAR 2017).

[14] This paper is the first study that presents a full list of more than 1000 agroholdings (about 30% working in grain production sector) in Russia and analyzes the corresponding data from the two agricultural surveys (2006 and 2016) in addition to other official sources.

The apparent divergence in Russian agricultural sector has created uncertainly in projections of the impact of future climate change on grain production. The global circulation model (GCM) projections for the mid-21st century show a somewhat poorer climate in the majority of today's principal agricultural lands affected by droughts. This model reveals a decrease or slight increase in precipitation against a background of increasing temperature (Alcamo et al. 2007; Bobylev et al. 2012; Safonov and Safonova 2013; Monier et al. 2017; Pavlova et al. 2018), which is especially unfavourable for agricultural areas in the Northern Caucasus and Western Siberia. Following this trend of increasing moisture deficit in the main grain producing belt, the Russian hydrometeorological service has estimated grain production to fall by 10% to 20% by 2035, relative to the end of the 20th century (Roshydromet 2014). Note that climate change benefits grain production in the secondary grain production areas in East Siberia in which the climate becomes warmer and milder. Some weather-yield models project that the negative impact of climate change will be compensated by a significant increase in grain production driven by a warmer and longer growing season in the currently least productive northern regions of the forest zone. This projection, however, is somewhat curtailed as other natural (such as land availability and fertility)[15] and social (such as sparse population and lack of infrastructure) factors should be considered (Alcamo et al. 2007).

6. Conclusion

Russian grain production is booming. Recently, Russia became the third largest country in grain exports and top in wheat export. This success is mainly achieved through improved yields in two regions: (1) The Central Black Earth and (2) North Caucasus. Meanwhile, climate favorability for agriculture in those regions is not improving but rather bringing new problems for farmers. Hence, we showed that both regions have significant differences between the yield projected by weather-yield models and actual yield amounts. We explain this difference as a substantial increase in the importance of non-climatic factors in recent dynamics of grain production in these regions.

Our analysis suggests that the observed agricultural boom in both regions reflects large structural improvements, including subsidies, state control over price volatility, modernization and expansion of the physical infrastructure. These improvements are mainly recuperations from the long-term deficiencies in the agricultural policies, first suggested in research dating back to 1990s. The regions with the best soils and access to sea ports are the main beneficiaries of these policies, which are reflected in the development of large agroholdings leading the agricultural sector. The regions with the highest percentage of land in agroholding ownership also demonstrates the highest yields and the highest discrepancy between the climate-related and observed yields. Although not recognized in the official statistics, agroholdings attract a considerable portion of state financial support and play a crucial role in unlocking the untapped agricultural potential in Russia. At the same time, smaller operators and less advantageous regions are trailing with respect to this major agricultural improvement.

In the future, GCM projections suggest deterioration of the agricultural climate in the main grain producing areas, mainly due to the increase in water deficit. The fast increase in agricultural production apparently runs against this dynamic, suggesting significant potential for adaptation to climate change in the agricultural sector, including a

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[15] The dominant type of soil in Russia is Podzols, which occupies 22% of the land area. Due to the low fertility of Podzols, the agricultural lands in Central Russia require 4.7 times higher fertilization per hectare as compared to the Chernozem steppes of the Volga region. In addition, smaller field sizes and remoteness from settlements has caused elevated labor and fuel costs (1.8 and 1.4 time, respectively) as compared to those in the steppe zone (Kruchkov and Rakovetskaya 1990).

shift to drought tolerant cultivars and crops, such as corn (including winter corn) and sunflower, a shift in sowing time, expansion of the area under winter crops and thermophilic spring crops (Dronin and Kirilenko 2011), and many other changes. The resilience of the agricultural sector is however limited with the apparent difference in adaptation capacity among the large producers located in the most productive areas close to population centers and sea ports.

Figures

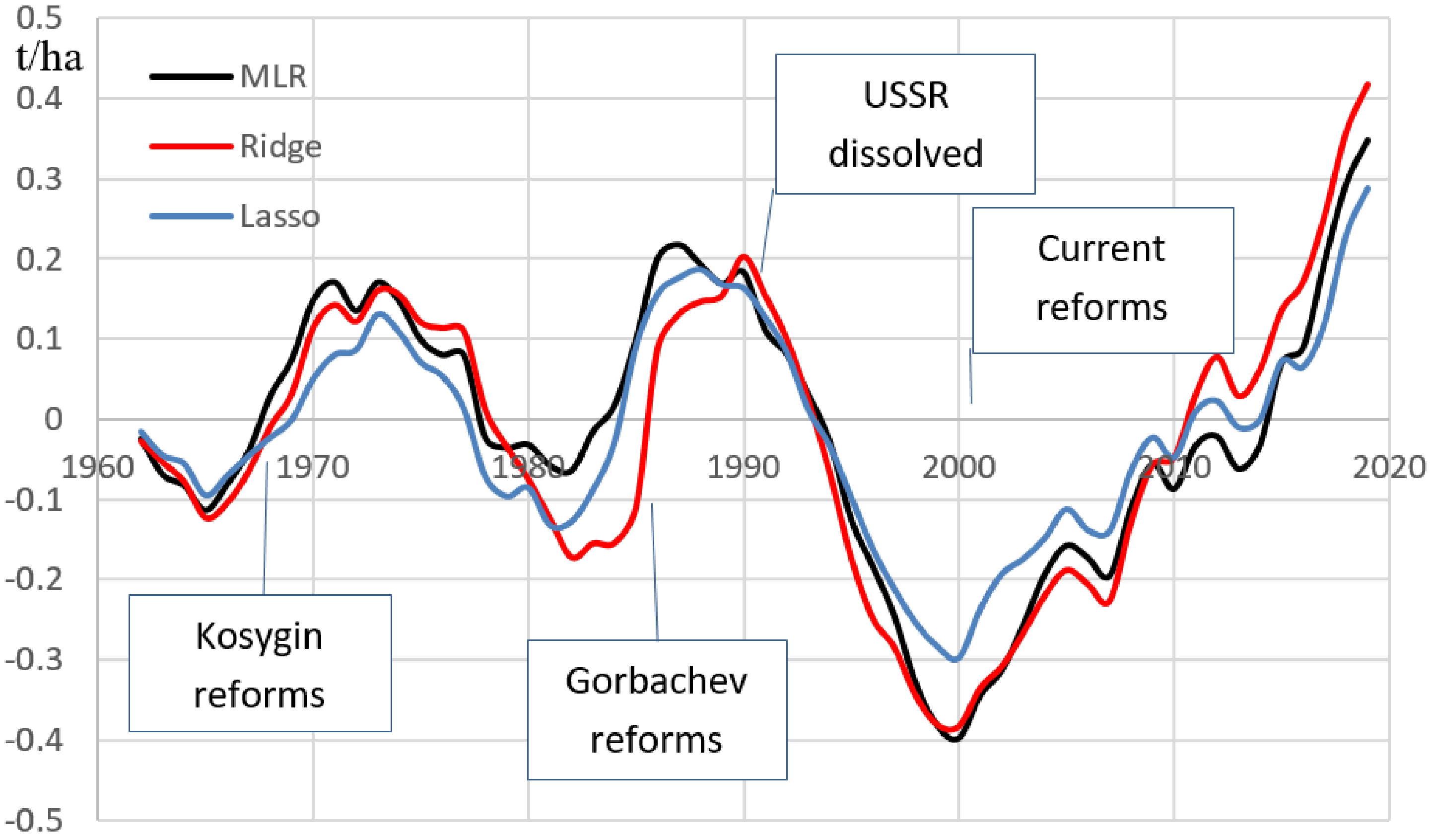

Figure 1

Residuals of the multiple linear, lasso, and ridge regression (MLR, RR, and LR, respectively) weather-yield models over time, averaged across all administrative units and smoothed with a 5-year running mean. The lines represent yield variability (t/ha) that was not explained by the long-term technology trend and climate variability and was attributed to the changes in agricultural policies.

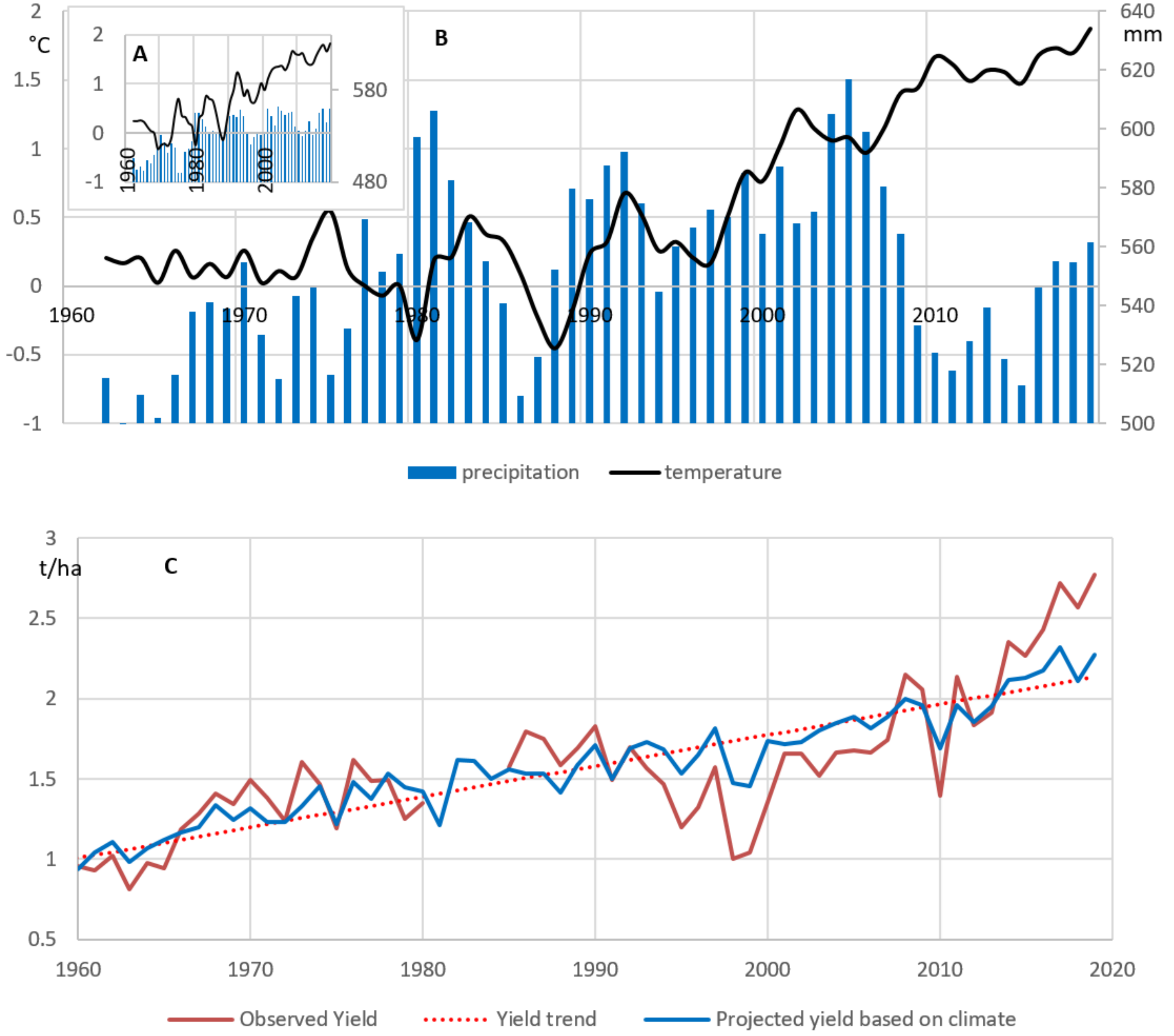

Figure 2

A, B: Five-year running mean for the mean annual temperature and annual precipitation for the wheat producing areas of Russia (A) and for the top five wheat producing areas in the European part of Russia (Krasnodar, Rostov, Stavropol, Voronezh, and Kursk) (B). C: Observed and projected yield with projections (the mean over the MLR, LR, and RR models) based on climate alone.

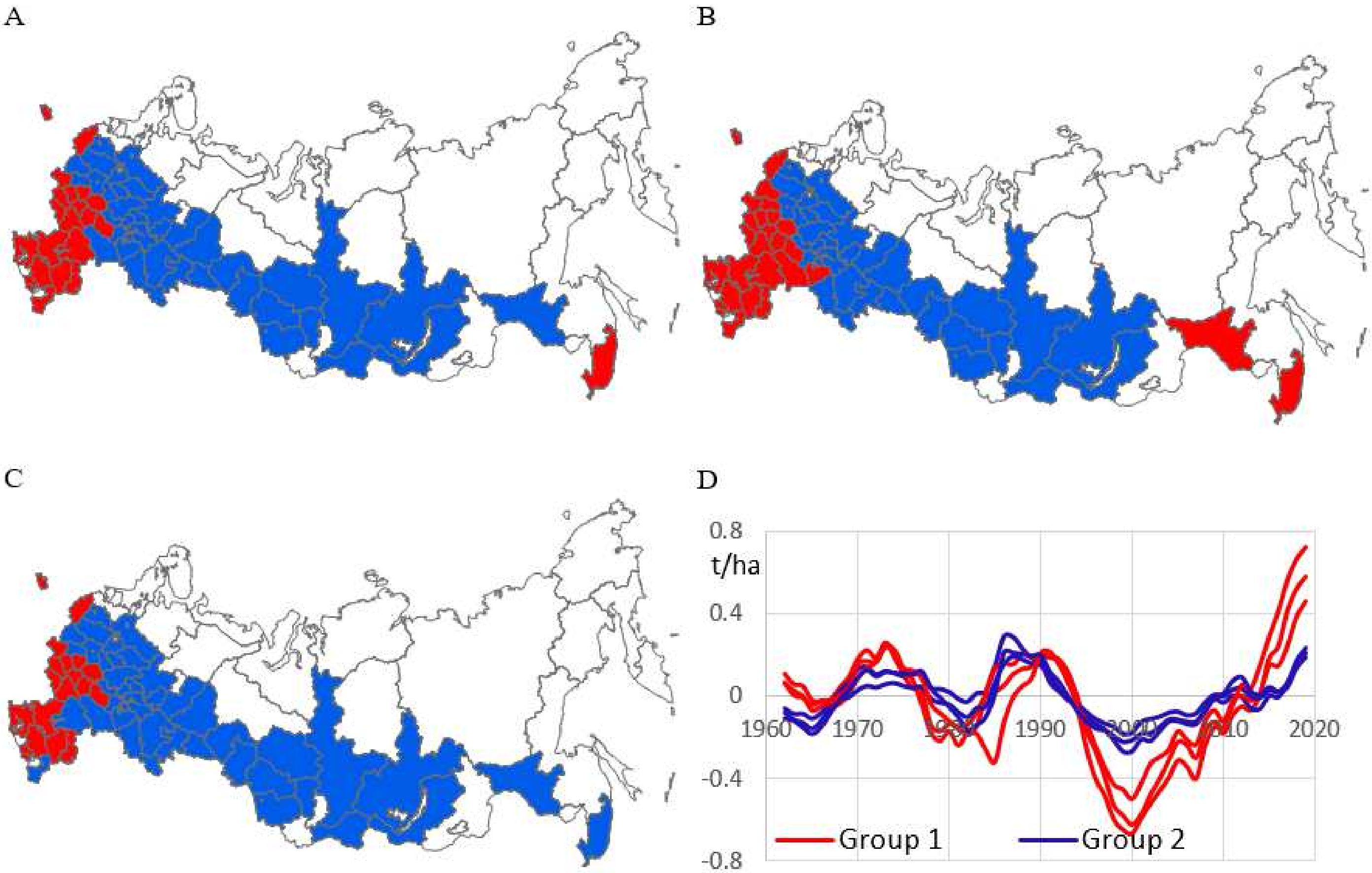

Figure 3

Cluster analysis of the MLR (A), RR (B), and LR (C) weather-yield models. Group 1 (red) regions include the main grain producing areas in the European part of Russia. D: Residuals of the MLR, LR, and RR weather-yield models over time, averaged for clustered administrative units. In the Group 1 cluster, the actual yields significantly exeeded predictions based on climate alone despite lower than normal precipitation levels in the 2010s (Figure 2B). Group 2 regions (blue) were less productive and showed little divergence between the actual and climatic yields.