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# The Relationship Between Grain Crops Yield and Climate in the Urals

**Shary P.A[1,2*], Sharaya L.S[2] and Rukhovich O.V[2]**

[1]Institute of Physicochemical and Biological Problems in Soil Science RAS, 142290, Pushchino, Russia

[2]All-Russian Research Institute of Agrochemistry named after D.N. Pryanishnikov, 127550, Moscow, Russia

[*]**Corresponding Author:** Shary P.A, Institute of Physicochemical and Biological Problems in Soil Science RAS, 142290, Pushchino, Russia, E-mail: p_shary@mail.ru

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## Abstract

The relationship between the yield of spring wheat, spring barley and oats with climatic characteristics in the Urals region, which includes the Kurgan, Chelyabinsk, Sverdlovsk and Tyumen regions, is considered. Yield values are averaged over the last 12 years and represent mean regional values: 89 regions for wheat, 70 for barley, and 84 for oats. Climatic indicators used include the nighttime temperature (Tmin), daytime temperature (Tmax), diurnal temperature range (DTR) and precipitation (Prec) for each month averaged over 50 years (1950–2000). It is shown that in July Tmin and Tmax in the region are independent, while literature considers night and day temperatures dependent across the entire territory of Russia. The strongest correlation between yield for all three crops is observed with the summer DTR: $r = -0.545$ for wheat, −0.521 for barley, and −0.425 for oats. Maps of the average monthly temperature, the temperature range in summer, as well as the spatial gradients of crop yields, which are calculated from these maps, show noticeable differences. Therefore, using these temperature indicators in modeling can lead to varied results. As the summer Tmin decreases, and the summer Tmax increases with the rising altitude of the earth's surface, the yield correspondingly diminishes with elevation.

**Keywords:** Yield; Correlation with Climate; Spring Wheat; Spring Barley; Oats

## Introduction

The analysis of the relationship between agricultural crop yields and environmental factors, such as climate (weather) and topography, is carried out either using simulation models or statistical methods [1]. An advantage of the latter is the explicit estimation of the explained variance, expressed by the coefficient of determination. Although such an estimation is theoretically possible for simulation models such as CERES (Crop Environment Resource Synthesis) [2], this is rarely done in practice. A disadvantage of the statistical approach is that yield is usually not very closely related to environmental climatic factors [3], which requires a significant number of observation sites, around 100, to obtain statistically significant results. Therefore, it is important to understand which climatic factors are especially important in a given region, that is, most closely related to its yield. A further difficulty with statistical models is also the often-encountered dependence between climatic factors [4].

In this regard, the day-time temperature Tmax and the night-time temperature Tmin, as well as the average temperature Tmean (equal to (Tmin+Tmax)/2), draw attention. Although it has been shown that at the resolution of 50 km, the annual average Tmax and Tmin are closely related for most of the land [5], their individual impact on crop yield differs. Therefore, sometimes the diurnal temperature range (DTR) is used, defined as the difference between them. For future forecasts, it is important that on the global average, Tmin rises twice as fast as Tmax [5], meaning that DTR decreases with warming. However, the role of DTR as an environmental factor is not yet well understood.

Yields depend on climate, so this relationship has been studied in many works, which usually used average temperature Tmean and precipitation P [6-12]. However, it has been noted that yields can also be affected by the diurnal temperature range DTR [13], which does not depend on Tmean and is decreasing globally due to climate change [14], since Tmin at global warming is growing faster than Tmax [5]. This has sparked interest in studying the relationship between yields and DTR, but such studies are still few [13,15-17], especially since Tmin and Tmax over most of the Earth's drylands are usually closely related [5].

Greenhouse gases and humidity reduce incident long-wave radiation, causing Tmin to increase more rapidly than Tmax. Albedo influences DTR through the fraction of solar energy absorbed, and soil moisture can reduce DTR through evaporative cooling; both of these processes mainly affect Tmax. Snow at near-freezing temperatures can also reduce DTR by giving up energy when it freezes and taking it away when it melts. Turbulent heat mixing in the boundary layer can reduce DTR by decreasing daytime temperatures and increasing nighttime temperatures, which is influenced by wind. Surface water vapor influences Tmin and Tmax, leading to a minor effect on DTR [14]. Thus, the physical nature of DTR is complex, which leads to a significant discrepancy in its values in climate models [14]. However, most models predict a significant decrease in DTR at high latitudes and a relatively small decrease in Europe [14]. Various characteristics of climate and topography are considered in the literature [18,19], but DTR is absent among them.

The original study [13] found that rice and maize yields were negatively associated with DTR in a few cases, but the association was not significant in most cases due to small sample sizes. In Spain, winter DTR was one of the best predictors for wheat yields, with these yields being negatively associated mainly due to an increase in Tmin with increasing DTR [16]. In India, the association of wheat yield with DTR was negative and significant in the south of the country where yields are lower [17]. This information is clearly not enough to form a clear picture of the relationship between yields and DTR. Therefore, and because there are not enough effective climatic predictors in agriculture, we undertook this study in the Ural region of the Russian Federation, using three crops.

The purpose of this work is to study the relationships between the yield of spring wheat, spring barley and oats with environmental climatic factors, including DTR, as well as with the land surface elevation in the Urals.

## Materials and Methods

We investigate the relationship between the yield of spring wheat, spring barley, and oats with the climate in the Trans-Ural region, which uncludes the Kurgan, Chelyabinsk, Sverdlovsk and Tyumen regions (Fig. 1). The area of the region is 511 000 km$^2$. Rain-fed agriculture is practiced in the region. We use the 12-year average (2011–2022) yield data for each district: 89 districts for wheat, 70 districts for barley, and 84 districts for oats. Climate data are sourced from the World Climate database [20], where the temperature and precipitation of each month are averaged over 50 years (1950–2000) and are presented as 30 resolution grids (about 1 km). We used WorldClim data because of its high resolution and small size of districts. Although time frames do not coincide, we interested in mean values of climate or climatic norms. These data include night-time (Tmin), day-time (Tmax) and average (Tmean=(Tmin+Tmax)/2) temperatures, as well as monthly precipitation (Prec). For each month, we also calculated diurnal temperature range (DTR), defined as the difference DTR = Tmax–Tmin [5]. The dependency of these climatic factors on the season is shown in Figure 2.

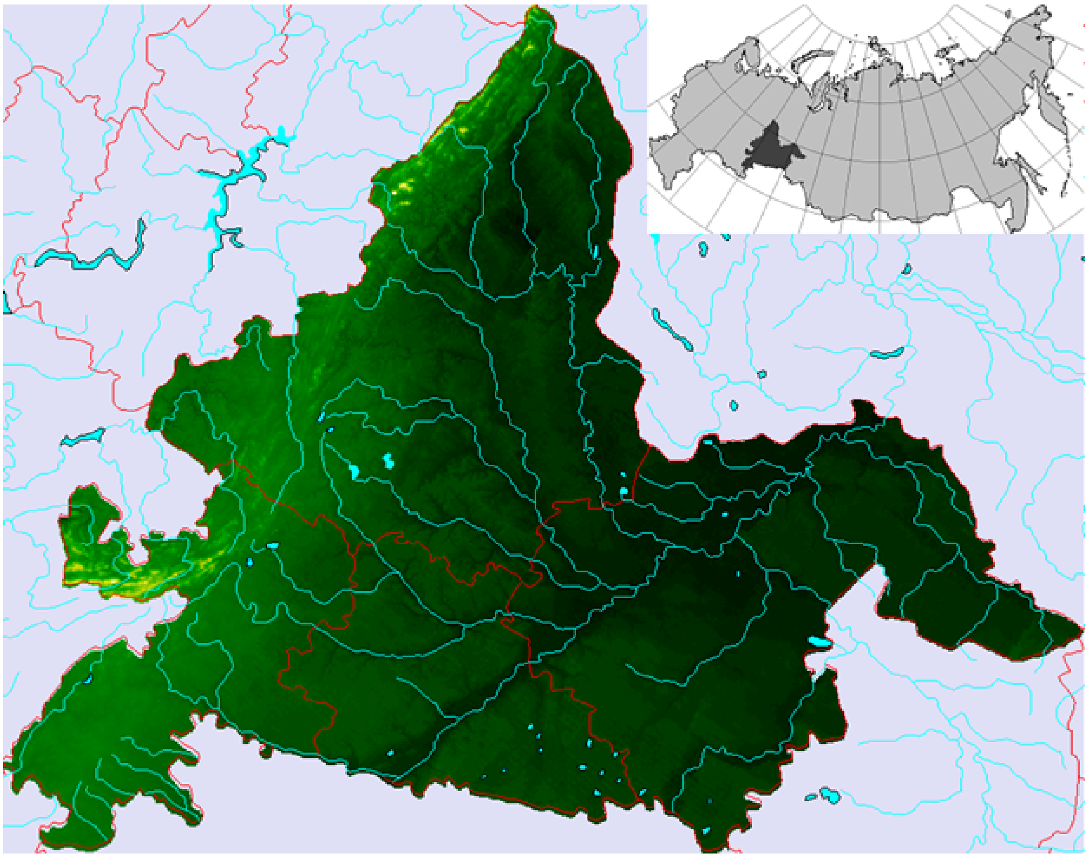

**Figure 1:** The region under study is located east of the Ural Mountains

For each district, we identified the point of the corresponding centroid ("center of gravity"), and for this point, we read the values of climate variables from the respective grids. Given the smooth gradual changes in these variables in space and the small size of the districts compared to the study region, we considered this approach acceptable, although it would be more correct to use the averages for the districts. It should be noted that warming in the study region mainly occurs in the winter period (by 2.3–3.0°C for 1966–2018), and least of all – in summer (by 1.3–1.5°C for the same time) [21].

The earth's surface elevation data are taken from the SRTM30 database [22] where they are presented with a resolution of 30 (about 1 km). We use SRTM30 because of its resolution and small size of districts. In the region, the elevation varied from 50 to 528 meters with an average of 179 meters.

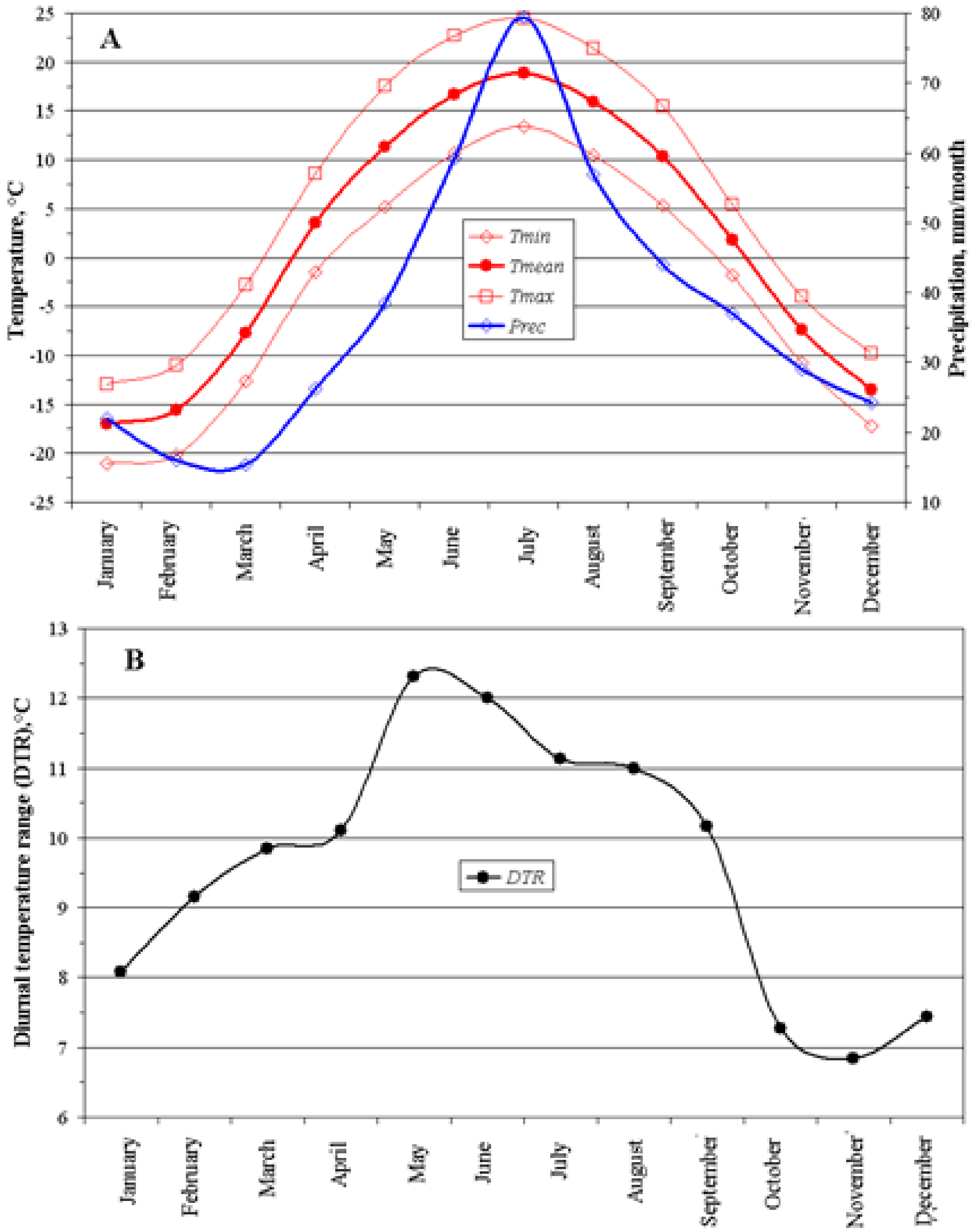


**Figure 2:** The dependence of regional average temperatures and precipitation (A) and diurnal temperature range DTR (B) on months.

## Results and Discussion

To assess whether monthly Tmin and Tmax are dependent, we calculated the correlation coefficients between them for the region of study, Figure 3.

Thus, in July, the relationship between Tmin and Tmax is insignificant, that is, July night and day temperatures can be used as independent variables. They are relatively weakly related in summer ($r = 0.264$, $P < 0.05$), and they are most closely related in winter ($r = 0.857$, $P < 10^{-6}$). The summer DTR and Tmean are also very close to independent.

The analysis shows that the strongest correlation between wheat yield and temperature-dependent environmental factors in the study region is observed with the diurnal temperature range DTR, and not with the temperatures themselves (Tmin, Tmean, Tmax), Figure 4.

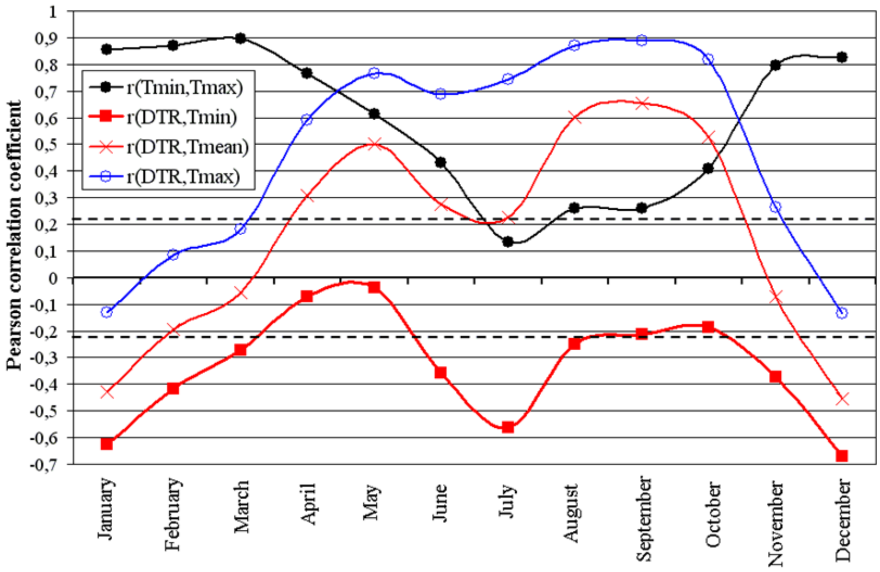


**Figure 3:** Correlation between temperatures and DTR as a function of month. The point between the dotted lines corresponds to a non-significant relationship at $P < 0.05$

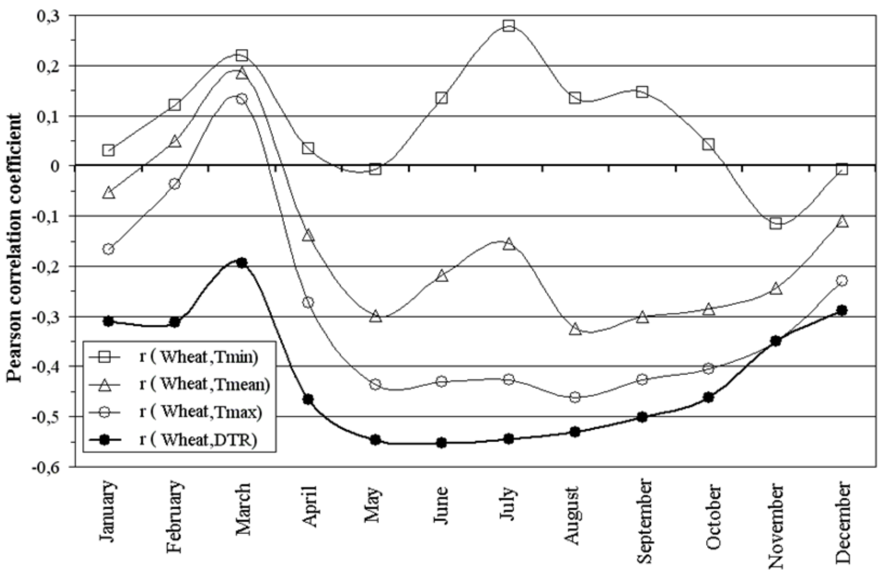


**Figure 4:** Dependence of the correlation coefficient between the yield of spring wheat and Tmin, Tmean, Tmax, DTR on months. The points located between the dotted lines correspond to a non-significant relationship at $P < 0.05$

The positive correlation between wheat yield and July night temperature is appears to be due to the fact that cold nights negatively affect the yield of this crop [5]. It should be noted that the correlation between barley and oats yields and July Tmin is also negative, but statistically insignificant (not shown). The negative correlation between wheat yield and day-time temperature in the summer months is caused by the known negative effect of high temperature on wheat yield [2,7]. These two circumstances lead to the observed stronger (negative) correlation between wheat yield and DTR.

A similar dependence for all three crops is shown in Figure 5.

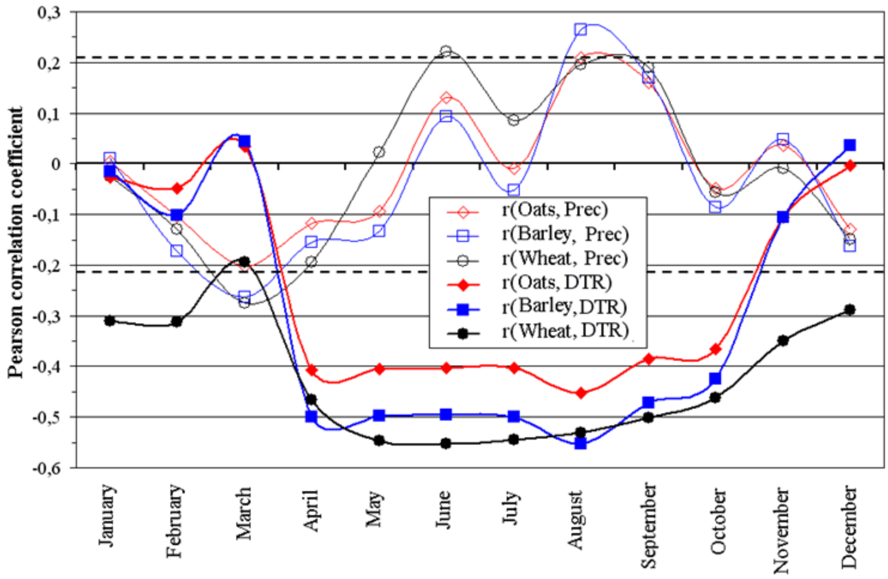


**Figure 5:** Dependence of correlation coefficient between the yield of wheat, barley and oats and DTR and precipitation Prec on months. Points lying between the dotted lines correspond to non-significant links at $P < 0.05$

It is evident from the study that crop yield correlations with precipitation are weak in the region, and the strongest (negative) correlation with DTR is observed in the warm season. In July, the connection becomes weaker than in June and August, possibly due to some soaking of crops resulting from significantly increased precipitation in July (see Figure 2).

To consolidate the findings into a single illustration, we use seasonal averages instead of individual months, Figure 6.

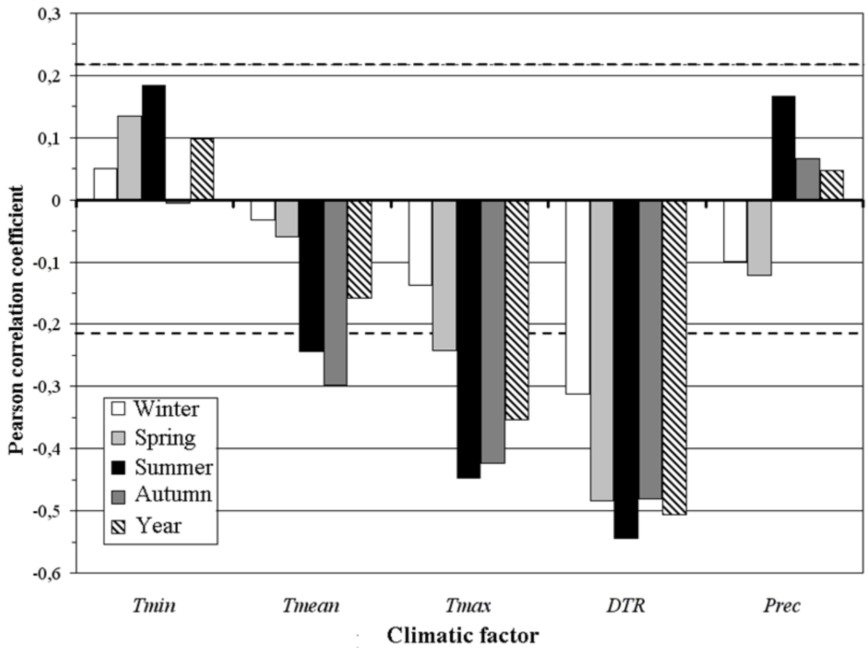


**Figure 6:** Dependence of the correlation coefficient between the yield of spring wheat and climatic factors on the time of year. The bars placed between the dotted lines correspond to a non-significant relationship at $P < 0.05$

The histogram of Figure 6 clearly shows that in the region of study, the strongest correlation with spring wheat yield is observed for the diurnal temperature range DTR in the summer. During this period, the relationship between wheat yield and the day-time temperature Tmax is negative, while with night-time temperature Tmin is positive, which causes a stronger correlation with DTR. The correlation between wheat yield and summer DTR is quite strong and significant ($r = -0.545$, $P < 10^{-6}$). The results are similar for spring barley ($r = -0.521$, $P < 10^{-5}$) and oats ($r = -0.425$, $P < 10^{-4}$). Note that in the region, the spatial changes – a mosaic of average daily temperature and temperature changes in summer – are noticeably different, as depicted on Figure 6. Such differences can lead to different modeling results and construction of yield maps if one or the other factor is used. The spatial gradients of yields for these two temperature indicators are also different. An assessment based on a linear trend shows that an increase in the summer Tmean space by 1 degree corresponds to a decrease in the yield of wheat by 0.216 t/ha, barley by 0.361 t/ha and oats by 0.221 t/ha. A spatial increase in summer DTR by 1 degree C leads to other indicators: a decrease in the yield of wheat by 0.240 t/ha, barley by 0.220 t/ha and oats by 0.197 t/ha. These facts also influence the simulation results.

Let us also note the important, in our opinion, connection between climatic factors and altitude as illustrated in Figure 7.

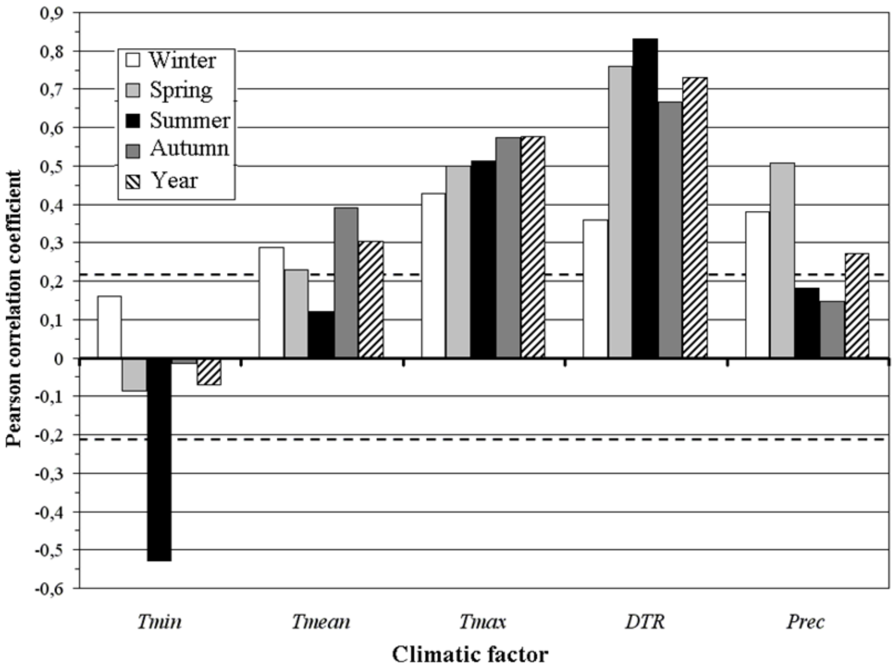


**Figure 7:** Relationship between climatic factors and altitude in the region. The bars located between the dotted lines correspond to a non-significant relationship at $P < 0.05$

Thus, it is evident that the night-time temperature Tmin decreases in summer, while Tmax and DTR at any season increase with elevation. This is somewhat unusual, since, according to the “barometric law”, temperature usually decreases with altitude [23], a phenomenon that in the study region is observed only for the summer night-time temperature Tmin ($r = -0.530$, $P < 10^{-6}$). Note that the “barometric law” is just a rule, exceptions to which are not so rare. According to Fig. 6, the summer diurnal temperature range DTR increases most strongly with altitude ($r = 0.831$, $P < 10^{-6}$). Given the negative relationship between wheat yield and summer DTR (see Fig. 5), this yield decreases with altitude ($r = -0.418$, $P < 10^{-4}$). A similar pattern is also evident for barley ($r = -0.523$, $P < 10^{-5}$) and oats ($r = -0.414$, $P < 10^{-3}$). The gradients of crop yields with respect to elevation, estimated by linear trends, are as follows: an increase in elevation by 10 m can lead to a decrease in the yield of wheat by 17.3 kg/ha, barley by 21.0 kg/ha and oats by 18.4 kg/ha.

Different links of yields with Tmean and DTR are related to different patterns of maps of these variables, Figure 8.

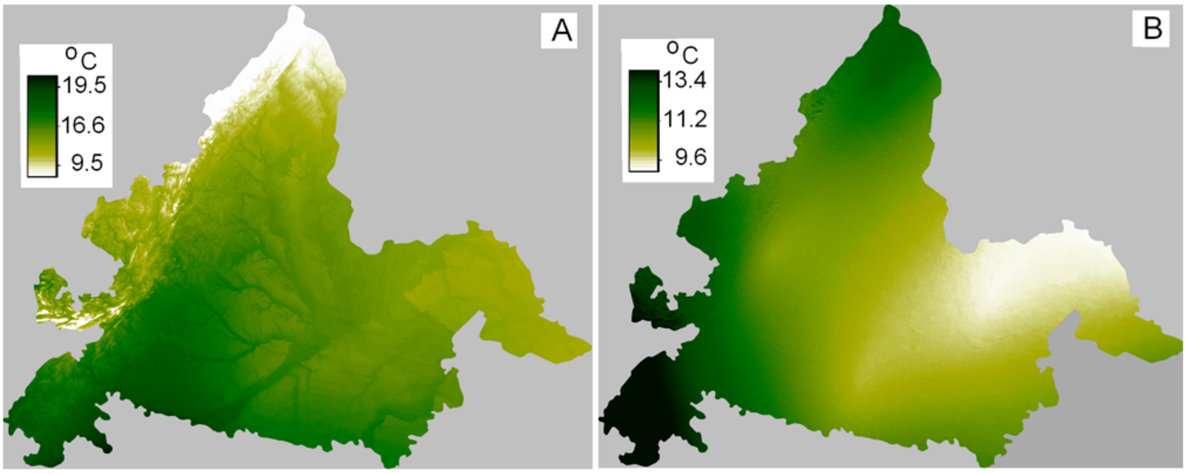


**Figure 8:** Maps of summer Tmean (A) and summer DTR (B).

For statistical comparisons with 12-year averaged (2011–2022) yields, we used 50-year averaged (1950–2000) WorldClim data close to climate norms (1961–1990). This is a limitation of our approach, however, we note that in our opinion, spatial patterns of changes in the hydrothermal status of soils, including moisture reserves in the upper meters, are formed not over 10 years, but rather over a longer period of time. The same time frame is required for their significant change. Therefore, it seemed important to us to study the relationship of harvests not with weather (average for 2011–2022), but with climate (average for 1950–2000). The results obtained show the significance of such connections for the study area, especially in the summer.

## Conclusions

The correlation analysis presented above reveals that the most influential climate factor for estimating the yield relationships of spring wheat, spring barley and oats with climatic factors in the Urals research region is the summer diurnal temperature range (DTR), which has the strongest correlation with the yield. The relations with the average daily temperature, which is typically used to build spatial and temporal models, are noticeably weaker. It is also demonstrated that variations in the regional Tmean and DTR mosaics differ, potentially leading to diverging outcomes in predictive modeling. In the region, this is due to the negative relationship between yields and summer day-time temperatures and a positive relationship with summer night-time temperatures.

Since Tmin and Tmax in July are independent, they can be used as independent environmental factors, for example, when constructing predictive yield maps.

It is noteworthy that the specific nature of the studied region is such that the summer day-time temperature Tmax increases, and the summer night-time temperature Tmin decreases with altitude. Given that the yields of all the crops studied here increased with higher night-time temperature Tmin and decreased with higher day-time temperature Tmax, an increase in altitude led to reduced yields of these crops.

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