Changes in regional climatic characteristics in
the Non-Chernozem zone of the Russian
Federation and their impact on soybean yields

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Abstract. The work analyzes agroclimatic resources in the Non-Chernozem zone of Russia for the period from 1981 to 2023. As a result of studying the data array, it was established that the values of the sum of active temperatures in the agroclimatic subzones of the Non-Black Earth Region increased by 200-250°C, the amount of precipitation falling during the growing season decreased by 20-40 mm, the hydrothermal humidification coefficient (HTC) of Selyaninov decreased by 0.1-0.3 p. The changes led to a shift of the isotherm of the sum of active temperatures by 150-200 km towards high latitudes. A grouping of years of research was carried out according to the hydrothermal coefficient, the yield and growing season of soybean variety Georgia were determined. As a result of the research, it was revealed that the highest average seed yield for the group of years (moistening conditions) was obtained in the year with sufficient moisture and amounted to 2.47 t/ha, and the lowest - 1.18 t/ha per year with insufficient moisture. A significant relationship has been established between seed yield, the weight of 1000 seeds and the HTC of the growing season: the variation in soybean yield during the years of research is 63% associated with the influence of factors: the weight of 1000 seeds and the HTC of May-August ($R^2 = 0.63$). Thus, the recorded upward trend in the sum of active temperatures in the region for the crop is positive and contributes to the expansion of soybean crops in the Non-Chernozem zone of the Russian Federation.

1 Introduction

Over the past few years, Russia has seen a significant increase in the area under soybeans
(Glycine max (L.) Merr.). This was facilitated by a number of factors, the leading of which are favorable price conditions on world markets and high purchasing prices on the domestic market, a significant need for complete and high-quality feed from the rapidly developing poultry and livestock industries [1-2]. According to the theory of N.I. Vavilov about the centers of origin of cultivated plants, the homeland of cultivated soybeans is Southeast Asia, including Mountainous China, Japan, Nepal and adjacent areas. Consequently,

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cultivated soybean was formed in a humid monsoon climate with elevated air temperatures. This determines its high need for heat and moisture throughout the growing season [3].

The large spatial heterogeneity of agricultural land and soil types determines the strong dependence of the agricultural sector on regional fluctuations and climate change. There are many different climate change scenarios, but without exception, all modern climate models give a warming of the Russian climate in the 21st century, significantly exceeding the average global warming. One of the climate change forecasts is aimed at studying the increase in average annual temperatures, the sum of active temperatures and an increase in precipitation [4-8].

The central region of the Non-Chernozem Zone is considered risky for sowing. The climatic conditions of this region satisfy the requirements of ultra-early and early ripening soybean varieties. The expansion of soybean acreage in the Central region for a long time was hampered by the weather and climatic conditions of the region. However, the process of climate warming observed in recent decades makes significant amendments to established ideas [9-10].

In this regard, the goal of our research is to study the fluctuations in average values of climatic characteristics caused by climate change in the Non-Black Earth zone of Russia, and to establish their impact on soybean yields in the Ryazan region.

2 Materials and methods

The parameters of changes in agroclimatic conditions of the Non-Black Earth Region were analyzed for the period 1981-2023. Field experiments were carried out in 2009-2023. at the Institute of Seed Production and Agricultural Technologies, located in the second agroclimatic region of the Ryazan region, on dark gray forest soil, heavy loamy in granulometric composition with a humus content of 5.3%. The object of research is an early ripening soybean variety of the northern ecotype, Georgia. The research was carried out using standard methods, and agricultural technology was generally accepted for the growing area [12].

The heat and moisture supply of the region was taken as the main indicators for calculation. The average monthly air temperature and the amount of precipitation by month and for the growing season as a whole, as well as the sum of active temperatures, were calculated. To analyze the growing season, the Selyaninov hydrothermal coefficient (hereinafter referred to as HTC) indicator was used.

3 Results

As a result of studying the above parameters for the period from 1981 to 2023, the Non-Chernozem region of the Russian Federation is divided into 3 agroclimatic subzones: northern, central and southern (Table 1).

Analysis of agroclimatic parameters in the regions of the Central Non-Black Earth Region showed a widespread increase in the sum of active temperatures with a decrease in the HTC during the growing season (Table 2).
Table 1. Characteristics of agroclimatic subzones of the Non-Chernozem zone of Russia (1981-2023).

<table>
<thead>
<tr>
<th>Agroclimatic subzone</th>
<th>Region</th>
<th>Average air temperatures for May-August, °C</th>
<th>( \sum T \geq 10 , ^\circ C )</th>
<th>Total precipitation, mm</th>
<th>HTC for the growing season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>Tverskaya, Yaroslavl, Kostroma</td>
<td>16.0-18.0</td>
<td>2000-2200</td>
<td>285-295</td>
<td>1.4-1.7</td>
</tr>
<tr>
<td>Central</td>
<td>Smolenskaya, Moscow, Kaluga, Vladimirskaya, Ivanovskaya</td>
<td>18.0-19.0</td>
<td>2200-2400</td>
<td>265-285</td>
<td>1.1-1.4</td>
</tr>
<tr>
<td>South</td>
<td>Bryansk, Oryol, Ryazan, Tula</td>
<td>19.0-21.0</td>
<td>2400-2600</td>
<td>255-265</td>
<td>0.7-1.1</td>
</tr>
</tbody>
</table>

Table 2. Average values of sums of active temperatures and HTC for agroclimatic subzones for the period from 1981 to 2010. and from 2011 to 2023.

<table>
<thead>
<tr>
<th>Agroclimatic subzone</th>
<th>( \sum T ) effect., °C</th>
<th>HTC for the growing season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>1850</td>
<td>1965</td>
</tr>
<tr>
<td>Central</td>
<td>1890</td>
<td>2020</td>
</tr>
<tr>
<td>South</td>
<td>2000</td>
<td>2250</td>
</tr>
</tbody>
</table>

The values of the sum of active temperatures during the growing season increased in all agroclimatic subzones, but the most significant increase was in the south and amounted to an average of 250°C for the regions included in it - rising from 2000°C to 2250°C. At the same time, there are leading regions in terms of temperature growth during the growing season. Thus, in the Ryazan region, the values of the sum of active temperatures increased over a 40-year period by 495°C and currently amount to 2475°C; in the dry year 2010, the value of the sum of active temperatures during the growing season in the region was 2919°C. In the northern agroclimatic subzone, the values of the sums of active temperatures increased on average by region by 115°C - from 1850°C for the period 1981–2010 to 1965°C for the period 2011–2023, the largest increase was noted in the Tver region. In the central agroclimatic subzone, the increase in the sums of active temperatures was 130°C - from 1890°C to 2020°C; the largest increase was recorded in the Moscow region and amounted to 213°C. The HTC value throughout the growing season decreased by an average of 0.1–0.3 points. The largest decrease was recorded in the southern agroclimatic subzone of the Central region of the Non-Chernozem zone - by 0.3 points. Thus, the hypothesis about the gradual aridization of the climate and the increasing likelihood of drought occurrence is confirmed. Along with an increase in the sum of active temperatures and a decrease in the amount of precipitation, a widespread increase in the values of average monthly temperatures was revealed (Table 3). It should be noted that the most significant average monthly temperatures in all agroclimatic subzones increased in May and August: in the northern agroclimatic subzone – by 0.9°C and 1.2°C, in the central – 1.8°C and 1.4°C and in the south – by 2.0°C and 2.3°C, respectively. The most significant increase in values began in 2001 and continues to the present day.
Table 3. Changes in average air temperatures by month in agroclimatic subzones of the Central region of the Non-Chernozem zone for the period from 1981 to 2023.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Precipitation, mm</th>
<th>HTC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>∑T act., °C</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>June</td>
<td>July</td>
</tr>
<tr>
<td>Northern agroclimatic subzone</td>
<td>+0.9</td>
<td>+0.8</td>
</tr>
<tr>
<td>Central agroclimatic subzone</td>
<td>+1.8</td>
<td>+0.7</td>
</tr>
<tr>
<td>Southern agroclimatic subzone</td>
<td>+2.0</td>
<td>+1.8</td>
</tr>
</tbody>
</table>

Monitoring of average monthly precipitation, one of the main factors influencing soybean productivity, showed that the greatest amount in all agroclimatic subzones occurs in July and August and averages from 70 to 90 mm for each month. In August, there is a dynamic decrease in the amount of precipitation, while in May there is a relative increase. Such dynamics for soybeans are positive and contribute to the expansion of its crops in the Central region of the Non-Chernozem Zone.

As a result of comparison of one of the most important climate indicators - the sum of active temperatures, a widespread increase in temperature throughout the entire territory of European Russia and a shift in the boundaries of agroclimatic zones by several degrees to the north were revealed. Sum of active temperatures in different agroclimatic subzones for decades from 2011 to 2023, exceeded the values of the decade from 1981 to 1990. Thus, in the northern agroclimatic subzone the increase was 130–140 °C, in the central – 170–180 °C and in the southern agroclimatic subzone – 280–290 °C. Since the middle of the last century, the average annual temperature in Russia has increased by an average of 1.5 °C and currently one can observe a shift of agroclimatic zones to the north throughout the country, including in its European part, which is consistent with the data of D. E. Mingalev [13].

The Ryazan region found itself in a zone with the sum of active temperatures from 2400 to 2600 °C during the growing season, while a few decades ago the maximum sum of active temperatures in the region reached only 2150-2350 °C. The hydrothermal coefficient decreased from 1.0-1.3 to 0.7-1.1. In the Central region of the Non-Chernozem Zone, local climate warming led to a shift of the isotherm of the sum of active temperatures by 150–200 km towards high latitudes: if in 1981 the isotherm passed through the northern part of the Bryansk and Oryol regions, including a small fragment of the Kaluga region and the Ryazan region, then Currently it passes through the northern part of the Moscow region, partially affecting the territory of the Tver region, includes the Vladimir region and the southern part of the Kostroma region.

To study the impact of climate change on soybean yields, meteorological data for 2009-2023 were analyzed. The sources of weather information were data from a weather station located on the territory of the Institute of Seed Production and Agricultural Technologies (Ryazan region). The meteorological conditions of the growing seasons had significant differences in temperature and humidity regimes. Over 15 years of observations, average temperature values exceeded the long-term average by 2–6 degrees, which also indicates a gradual warming of the climate in the region. Grouping the years of testing by HTC during the growing season over the years of research shows that the hydrothermal coefficient is subject to significant fluctuations over the years of research: the minimum value of HTC was noted in 2011 (HTC = 0.28), the maximum value was observed in 2012 (HTC = 1.65). Based on the analysis, the years were divided into 3 groups according to the HTC value: 1) HTC > 1.5 – “excessive moisture”; 2) HTC 1.0…1.5 – “sufficient moisture”; 3) HTC < 1.0 – “insufficient humidification”.

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Table 4. Grouping of years by hydrothermal coefficient during the soybean growing season (May–August, 2009-2023).

<table>
<thead>
<tr>
<th>Characteristics of the growing season</th>
<th>Growing season, days</th>
<th>Years</th>
<th>Number of years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excessive moisture &gt; 1.5</td>
<td>103</td>
<td>2012</td>
<td>1</td>
</tr>
</tbody>
</table>

An analysis of Table 4 shows that in recent decades there has been a tendency for the number of dry years to increase. So, if in the period 2010-2020 there were 4 of them, then in the second decade we have already observed drought conditions for three years in a row. The duration of the growing season of soybeans increased as the hydrothermal coefficient increased, this was mainly due to an increase in the generative period of soybeans.

![Fig. 1. Dependence of soybean seed yield on the HTC of the growing season, 2009-2023.](image)

The highest average yield of soybean seeds of the Georgia variety by moisture group was obtained in 2014 (year with sufficient moisture, HTC-1.24) and amounted to 2.47 t/ha, and the lowest (1.18 t/ha) in 2011 (year with insufficient moisture, HTC-0.28). The yield of soybean seeds in years with excess moisture was 2.34 t/ha (2012, HTC-1.65), which is slightly (6%) lower than in the year with sufficient moisture (Figure 1). There were years with low HTC during the growing season, but the yield was quite high. This is due to the fact that during the period of formation of reproductive organs there was sufficient rainfall, due to which the potential for future high productivity was laid down. An example of such a year would be 2021, when the yield was 1.89 t/ha, while the HTC was 0.68.

4 Discussion

As a result of the analysis of agroclimatic conditions for the period from 1981 to 2023, a trend was established for an increase in air temperature against the background of a
decrease in the amount of precipitation falling during the growing season throughout the Non-Black Earth Region. The sum of active temperatures increased by an average of 200-250 °C and amounted to 2000-2200 °C in the northern subzone, 2200-2400 °C in the central, 2400-2600 °C in the southern agroclimatic subzone. The amount of precipitation during the growing season has decreased by an average of 20-40 mm and currently amounts to 285-295 mm in the northern agroclimatic subzone, 265-285 mm in the central, 255-265 mm in the southern agroclimatic subzone. The HTC value decreased on average by 0.1-0.3 p. and is 1.4-1.7 in the northern agroclimatic subzone, 1.1-1.4 in the central subzone, 0.7-1.1 in the southern agroclimatic subzone. The northern border of the joint crop in the Central Non-Black Earth Region runs through the northern regions of the Moscow region, affecting the territory of the Tver and Vladimir regions, as well as the southern part of the Kostroma region.

5 Conclusion

As regional climatic parameters change, the importance of the adaptation approach in relation to the selection of varieties adapted to local conditions increases. Analysis of weather data in the Ryazan region (village of Podvyazye, weather station of the Institute of Seed Production and Agricultural Technologies) for May-August 2009-2023, shows that in 46.6% of years there is insufficient moisture, in 46.6% of years there is sufficient moisture, in 6.8% of years there is excessive moisture. At the same time, over this period we observe a tendency to increase the number of years with insufficient moisture. Changes in the climatic conditions of the cultivation region affect the yield of agricultural crops, in particular soybeans. The highest average for the group of years (moistening conditions) soybean seed yield of the Georgia variety was obtained in 2014 (sufficient moisture) and amounted to 2.47 t/ha, and the lowest (1.18 t/ha) in 2011 (insufficient moisture). The yield of soybean seeds in years with excess moisture was 2.34 t/ha, which is 6% lower than in the optimal year. There are years with a low HTC during the growing season, but with a fairly high yield. An example of such a year could be 2021, when the yield was formed at the level of 1.89 t/ha, with the HTC - 0.68. A significant relationship has been established between seed yield, the weight of 1000 seeds and the HTC of the growing season: the variation in soybean yield during the years of research is 63% associated with the influence of factors: the weight of 1000 seeds and the HTC of May-August ($R^2 = 0.63$).

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