The study of the dependence of spring crops yield on the abiotic environmental factors using nonlinear interpolation

S V Morozova¹, E A Polyanskaya¹, N K Kononova², K E Denisov³ and I S Poletaev³

¹Saratov State University named after N G Chernyshevskiy, Russia, Saratov
²Institute of Geography RAS, Russia, Moscow
³Saratov State Agrarian University named after N I Vavilov, Russia, Saratov

E-mail: swetwl@yandex.ru

Abstract. The article discusses the effect of abiotic environmental factors on crop yields. Abiotic factors cannot be changed by human activity; therefore, considering their impact on yield is very important for predicting crop yields. The article analyzes the dependence of spring wheat yield on such abiotic environmental factors as average ten-day air temperatures during the growing season, ten-day amounts of precipitation during the growing season and the Selyaninov hydrothermal coefficient during the growing season. To identify dependencies, the authors applied a non-linear approximation method using a third-degree polynomial dependence with one variable. The study was conducted during the most important growing season of spring wheat, in May and June. The authors show the equations of the third-degree polynomial dependences and graphs, as well as their graphic interpretation. Based on the obtained graphs, the authors have analyzed favorable intervals of abiotic factors for the formation of high yields of spring wheat. The authors indicate the most optimal temperature and humidity conditions for each ten days of May and June. These dependences are suitable not only for spring wheat but also for other spring grain crops, such as oats and barley.

1. Introduction
Agriculture is in close connection with natural and climatic conditions. Growth, development and yields of the crop are largely dependent on sunlight, heat and moisture, changes in weather conditions, and the climate of the area.

With the improvement of agricultural equipment, the application of fertilizers, the introduction of new more productive varieties, their protection from diseases and pests, the improvement of lands and their fertility, the link between agriculture and climate as well as weather increases. Therefore, the intensification of agriculture presupposes complete, accurate and differentiated account of the weather and climate conditions in each natural region.

The purpose of this study is to identify the relationship between the yield of spring crops and temperature and humidity conditions in individual phases of plant development on the example of spring wheat. The region of research was Saratov Oblast, which is an important agrarian region of Russia belonging to the zone of risky farming.

2. Objects, data and methods
The baseline data for the studies were average daily air temperatures and daily precipitation for the
Saratov weather station over 2009–2014 and in May, June and July, according to the website http://www.pogodaiklimat.ru/, as well as data on the yield of spring wheat, barley and oats from 2009 to 2017.

A regression analysis method is applied to the source data. The authors deliberately avoided linear regression and used polynomial one since excess in precipitation and higher temperatures above critical ones, especially in the initial phases of plant development, not only contribute to lower yields but can also cause plant death. Excessive precipitation in those development phases, when ripening occurs, also does not contribute to an increase in yield and the grain quality.

Spring wheat, barley, oats were selected for analysis. The use of polynomial regression allows determining the optimal values of temperature and humidity, as well as their combination for guaranteed (maximum) yields of these spring crops.

The use of polynomial regression models in agrometeorology has been carried out for a long time. E.S. Ulanova and V.N. Zabelin [3] describe second-degree polynomial regression models.

A general view of a polynomial dependence with one variable is as follows [3]:

\[ y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3, \]  

where \( \beta \) is the equation coefficient, \( x \) is the variable (considered factor).

Third-degree polynomials with one variable were selected for the analysis. The authors believe that third-degree polynomials describe the yield dependence on abiotic environmental factors in more detail.

The average temperatures, total precipitation, and the Selyaninov hydrothermal coefficient were considered as abiotic factors [2]. The most important periods for plant development and the formation of productivity elements are May and June. This article presents the results for May. Averaging was performed with a ten-day resolution. Average ten-day temperatures, total precipitation per ten days and hydrothermal coefficient calculated with ten-day values were used.

### 3. Results and discussion

Tables 1–3 present the correlation coefficients between the yield of the studied crops and the temperature and humidity conditions of the first two months of the growing season.

**Table 1. Dependence of spring wheat yield on temperature and humidity conditions in May and June.**

| Factor             | Ten-day period          | May 1-10 | May 11-20 | May 21-31 | June 1-20 | June 21-30 |
|--------------------|-------------------------|----------|-----------|-----------|-----------|------------|
| Temperature        |                         | -0.185   | -0.846    | 0.427     | 0.209     | 0.268      |
| Precipitation      |                         | 0.729    | 0.378     | 0.854     | -0.743    | -0.466     |
| Hydrothermal coeff. |                       | 0.653    | 0.427     | 0.862     | -0.623    | -0.487     |

**Table 2. Dependence of oats yield on temperature and humidity conditions in May and June.**

| Factor             | Ten-day period          | May 1-10 | May 11-20 | May 21-31 | June 1-20 | June 21-30 |
|--------------------|-------------------------|----------|-----------|-----------|-----------|------------|
| Temperature        |                         | -0.641   | 0.109     | 0.866     | -0.955    | -0.827     |
| Precipitation      |                         | 0.330    | -0.658    | -0.149    | 0.897     | 0.575      |
| Hydrothermal coeff. |                       | 0.330    | -0.632    | -0.226    | 0.968     | 0.578      |

**Table 3. Dependence of barley yield on temperature and humidity conditions in May and June.**

| Factor             | Ten-day period          | May 1-10 | May 11-20 | May 21-31 | June 1-20 | June 21-30 |
|--------------------|-------------------------|----------|-----------|-----------|-----------|------------|
| Temperature        |                         | -0.562   | -0.547    | 0.279     | -0.817    | -0.413     |
| Precipitation      |                         | 0.074    | -0.167    | -0.256    | 0.345     | -0.068     |
| Hydrothermal coeff. |                       | 0.117    | -0.134    | -0.239    | 0.524     | -0.068     |
Tables 1–3 indicate that the linear relationship between the dependence of yield and abiotic environmental factors does not appear in all phases of plant development. The most significant linear relationship between the yield and temperature as well as precipitation in spring wheat is in the first ten-day period of May (seedlings) and between precipitation and the hydrothermal coefficient – the third ten-day period of May (1–3 leaves). In the second ten-day period of May, the correlation coefficient between yield and temperature was negative; therefore, high temperatures can have a negative impact on the yield in this period.

For oats, a linear relationship between yield and temperature is in the third ten-day period of May. In the next two phases of development (from June 1–20 and from June 21–30), a rise in temperature contributes to lower yields as indicated by negative correlation coefficients. The correlation coefficient of yield and precipitation has shown that the most significant impact of the precipitation and hydrothermal coefficient on the yield is from June 1-20. Very high temperatures can cause a significant reduction in the barley yield from June 1-20.

The authors attempted to identify the optimal ranges of temperature and precipitation, as well as their combinations (according to the hydrothermal coefficient), which are necessary for certain phases of plant development for the highest yield. Calculations were carried out for each crop and ten-day period of the considered month. The article presents selective results.

The dependence of spring wheat yield on temperature in each ten-day period of May is as follows:

\[ y = 1323.1 - 23.09x + 0.134x^2 - 0.0003x^3 \] (first ten-day period); \hspace{1cm} (2)
\[ y = -219.1 + 3.64x - 0.02x^2 + 0.00004x^3 \] (second ten-day period); \hspace{1cm} (3)
\[ y = 1430.5 - 21.607x + 0.108x^2 - 0.0002x^3 \] (third ten-day period). \hspace{1cm} (4)

A graphic representation of the solution of equation (2) has shown that in the first decade of May, the optimum temperatures for the development of this crop should be lower than 19 °C. If the average ten-day temperatures are higher, the yield reduces sharply. Notably, the average ten-day temperature of the first ten-day period of May in Saratov Oblast is 14-15 °C, which is optimal for the beginning of the growing season of this crop. From 2009 to 2013, such temperature limits were in 2009 and 2011. The yield during these years was 1.1 and 2.64 t/ha, respectively. An adverse combination of temperature and humidity conditions likely contributed to the yield decrease in 2009.

The equation of the third-degree polynomial (3), expressing the dependence of yield on average temperatures of the second ten-day period of May, has shown that the influence of the temperature of this ten-day period on the yield is not as great as the influence of temperature conditions of the first and third ten-day periods. The growth of spring wheat is not so sensitive to temperature fluctuations during this ten-day period, but with increasing temperatures in the second ten-day period of May, the yield also slightly decreases (figure 1).

**Figure 1.** Dependence of spring wheat yield on average ten-day temperatures in May.
A graphical representation of the solution of equation (4), expressing the dependence of yield on the temperature of the third ten-day period of May, has shown that the optimal temperature is 20-22 °C. If during this ten-day period temperatures decrease to 18.5 °C and lower, it will lead to a sharp decrease in yield (figure 1). The growth of average ten-day temperatures above 23-24 °C is also unfavorable. According to the long-term data of the third ten-day period of May, the average ten-day temperature is 18.0 °C, while 19-21 °C is the optimal temperature for the highest yields.

Precipitation is another important abiotic environmental factor affecting yield. The dependence of yield on precipitation in May is as follows:

\[
\begin{align*}
    y &= -2.7 + 2.88x - 0.46x^2 + 0.021x^3 \text{(first ten-day period);} \\
    y &= 1.6 + 0.62x - 0.33x^2 + 0.025x^3 \text{(second ten-day period);} \\
    y &= -0.4 + 0.79x - 0.04x^2 + 0.001x^3 \text{(third ten-day period).}
\end{align*}
\]

**Figure 2.** Dependence of spring wheat yield on the ten-day precipitation in May

In the dry steppe conditions of Saratov Oblast, precipitation is a limiting factor; however, from the equations (5-7), it follows that with an increase in the amount of precipitation above a certain value, the yield drops sharply (figure 2). It is typical of the first and third ten-day periods of May.

According to figure 2, the precipitation of the first and third ten-day periods of May is the most significant factor for stable yields. In the first ten-day period, the amount of precipitation for the plant development must be at least 5 mm; in the second and third ten-day periods – at least 10 mm. Interestingly, in the second ten-day period, the precipitation has a very small influence on the yield. In the first and third ten-day periods, a significant increase in ten-day sums affects negatively the yield.

It is interesting to consider the combined effect of temperature and humidity conditions. The concept of their combination describes the Selyaninov hydrothermal coefficient. The type of analytical dependencies is as follows:

\[
\begin{align*}
    y &= -3.9 + 75.5x - 214.72x^2 + 167.63x^3 \text{(first ten-day period);} \\
    y &= 1.6 + 11.45x - 95.85x^2 + 127.833x^3 \text{(second ten-day period);}
\end{align*}
\]
\[ y = 0.9 + 7.64x - 9.45x^2 + 2.731x^3 \] (third ten-day period). 

Graphic representation of dependences is reflected by the lines in figure 3. Analysis of the graphs indicates that the values of hydrothermal coefficient influence greatly on the yield only in the third ten-day period of May. In the first and second ten-day periods, the complex effect of temperature and humidity conditions does not develop. Thus, we may conclude that in the first two ten-day periods of May, the limiting factors affecting yield are different. In the first ten-day period, the effect of temperature is the most significant since in the initial phase of development the plant uses spring moisture reserves. Subsequently, during the soil drying, precipitation becomes the limiting factor.

Figure 3. Dependence of spring wheat yield on the hydrothermal coefficient in May.

A similar analytical graphical study of polynomial dependencies in June has indicated that for the maximum yield the temperatures of the first two ten-day periods of June should not exceed 24°C, and in the third ten-day period it should be lower than 28 °C. Considering precipitation in June, it can be concluded that in the first and second ten-day periods of June, an increase in precipitation leads to a significant increase in yield, while in the third ten-day period it reduces the yield. Such a critical threshold is the ten-day amount of precipitation, greater than 40 mm. It should be noted that in Saratov Oblast the monthly norm of precipitation in June ranges from 35 to 45 mm.

The dependencies shown for the studied spring crops are also identical for other spring crops (oats and barley).

4. Conclusion
Therefore, the productivity of spring crops depends on the temperature and humidity conditions of each ten-day period of the growing season.

Polynomial regression allows for a more flexible analysis of the yield dependence on the temperature and humidity conditions of the environment than a linear one.

Approximation of the yield dependence on abiotic environmental factors by non-linear dependencies contributes to a more differentiated analysis of the temperature–yield and precipitation–yield relationship.

The yield dependence on abiotic environmental factors is identical for all studied spring crops.
References

[1] Vainovsky P A and Malinin V N 1991 Methods of Processing and Analyzing Oceanological Information, One-Dimensional Analysis (Leningrad: LGMI) p 136

[2] Selyaninov G T 1928 About agricultural climate assessment Works on Agricultural Meteorology 20 165-77

[3] Ulanova E S and Zabelin V N 1990 Methods of Correlation and Regression Analysis in Agrometeorology (Leningrad: Gidrometizdat) p 208

[4] Ostapenco N V, Dzhambirze R R and Chinchenko N N 2016 Correlation of traits determining yield of rice varieties with abiotic environmental factors Works of Kuban State Agrarian University 60 204-10

[5] Shyurova N A, Morozova S V, Denisov K E and Molchanova N P 2016 Model of the influence of abiotic environmental factors on the yield of spring wheat Modern Problems of Preserving the Fertility of Black Soil 277-83

[6] Chetverikov F P, Denisov E P, Solodovnikov A P and Panasov M N 2012 The influence of abiotic factors on the yield of winter wheat in the dry steppe zone of the Trans-Volga region Grain Economy of Russia 6 24

[7] Sandakova G N and Eliseev I 2017 Assessment of influence of weather conditions and mineral nutrition on the yields of strong varieties of spring wheat in Orenburg News of Orenburg. State Agrarian University 3(65) 19-22

[8] Denisov E P, Solodovnikov A P, Chetverikov F P and Panasov M N 2013 Changes in the productivity of spring wheat in the dry-steppe zone of the Trans-Volga region under the influence of abiotic factors Bulletin of the Saratov State Agrarian University Named after N I Vavilov 7 23-6

[9] Moiseev K G, Pyschyk V N and Khomyakov Yu V 2013 Abiotic and biotic factors affecting the productivity of spring wheat Agrophysics 3 6-13