Influence of meteorological conditions on Festulolium seed yield formation

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Abstract. The authors assess the influence of meteorological factors on the yield of Festulolium seeds. The analysis of weather conditions over 12 years shows that precipitation during the growing season of Festulolium in the second year of vegetation closely correlates with seed yield \( r = 0.85 \). The relationship between the yield and the amount of precipitation over the growing season is expressed by the regression equation: 
\[
Y = 190.52 + 3.2894x_1
\]

The yield was closely correlated with the HTC \( r = 0.80 \). This relationship can be expressed by the following equation:
\[
Y = 189.91 + 562.8x_2
\]
It is found that the optimal conditions for Festulolium seed yield formation arise when at least 147 mm of precipitation falls within the growing season (mostly during the period from aftergrowth to flowering), the hydrothermal coefficient is 0.8-1.7, the average daily temperature is within 17-19°C in the flowering phase and 18-21°C during the period of seed formation-ripening, and the proportion of days without precipitation in the flowering phase is at least 57%.

1. Introduction

It is known that the yield of any crop is largely associated with changes in weather conditions and depends on its biological characteristics, soil fertility, and the level of applied agricultural technology. Various combinations and ratios of these factors can create different conditions for yield formation, while their variability determines the year-to-year yield variability. Successful development of agricultural production requires new insights to the level of crop productivity and the processes of yield formation [4, 6, 11].

Potential productivity of an individual plant is determined by the genetic information embedded in the cell nucleus, chloroplasts and mitochondria, and at the level of a particular crop it is defined by the totality of all genes of the given variety-population. In order to reveal the genetic potential of a plant it is necessary to provide every factor of life within the ecological minimum and maximum. At the same time, in order to achieve the maximum productivity it is necessary to quite clearly define not only the general boundaries for each factor, but also its optimal parameters, which correspond to the biological requirements of normal growth of the agricultural crop [21].

In agriculture, with its clear assignment and sequence of all performed works, the knowledge and consideration of weather conditions at different periods of growth and development of agricultural crops constitute a necessary link in obtaining high and stable yields. At the same time, it is necessary to know the biological properties of crops, their need for light, heat, moisture and nutrition, and to take into account the changes in the reaction of crops and varieties to external conditions in different phases.
of the growing season. The same weather factors, such as frost or high temperatures, can be either hazardous for plants or relatively easy for them to tolerate. At the same time, the presence of critical periods in the life of plants does not exclude the fact that a weather situation unfavorable for the growth and development of crops can arise in any phase and affect the subsequent stages of yield formation leading to its decline [5].

The environmental conditions that are necessary for growing *Festulolium* for fodder purposes differ significantly from the conditions that contribute to the formation of high yield of its seeds. According to most researchers, who studied the seed productivity of *Festulolium* [1-2, 9-10, 12, 18, 20, 22], ecological factors play a significant role in creating the generative potential of this hybrid. Among these ecological factors weather conditions have the greatest influence on the growth and development of Festulolium [3, 8, 13, 16]. In some years the meteorological conditions can fluctuate sharply in comparison with both the preceding years and average long-term data. This especially concerns the dynamics of temperature, the total amount of precipitation, and their distribution over time. That is why weather changes in each agricultural year within the same climatic zone have a decisive effect on the stability of yields and quality of plant products [5].

Grasses are more demanding of moisture than legumes. Due to their shallow rooting they use moisture only from the upper soil layers that dry quickly in the absence of precipitation, whereas leguminous grasses have tap roots that can penetrate into deep soil layers [4, 17]. Moreover, moisture supply in the soil is of great importance for sowing perennial grasses, since they have very small seeds (absolute weight of 0.1-4.5 g) that are planted to the depth of 0.5-2.0 cm.

There have been insufficient long-term studies on the changes in yield depending on weather conditions.

In this regard, our research was aimed at studying and in-depth analysis of weather conditions that develop in a particular phase of *Festulolium* vegetation, as well as establishing their correlation with the yield and finding ways to control them.

2. Materials and methods

Experimental part of the study was performed in 2005-2016 in field trials of the Department of Soil Management, Crop Science and Plant Protection, Voronezh State Agrarian University on the plots of ‘Agrotechnology’ Training, Research and Technological Center (N51.7140416 E39.21545371). The soil in the experimental plot was leached medium loamy chernozem containing 4.56-5.50% of humus, 78-129 g·kg⁻¹ of labile phosphorus (P₂O₅), 109-118 mg·kg⁻¹ of exchangeable potassium (according to Chirikov), pH₅₀ was from 4.9 to 5.1, the total absorbed bases was from 21.3 to 22.2 mg·eq. per 100 g of soil, and the degree of base saturation was of 74-86%.

The preceding crop for *Festulolium* was the vetch-oat mixture harvested for green fodder.

The preparation of soil for sowing was conventional for creating seed herbages of perennial grasses in the Central Chernozem Region.

The object of research was the tetraploid VIK-90 *Festulolium* variety (meadow fescue × Italian ryegrass), which belongs to the ryegrass morphotype according to its biological features. This variety was created in the Federal Williams Research Center of Forage Production and Agroecology (FWRC FPA), included into the State Register of the Russian Federation, and admitted for cultivation in the Central Chernozem Region.

The seeding rate was 8.0 kg per hectare with the skip-row planting system (at 30 cm). *Festulolium* seed plantings were harvested by the Sampo-130 harvester at the seed moisture of 40-45% with yield accounting of each registration plot and its subsequent recalculation on the basis of 12% moisture and 100% seed purity.

The experiment was laid in 4 replicates with the randomized location of the plots. The area of the registration plot was 20 m². Experiments, relevant records and observations were carried out according to standard Methodological Instructive Regulations (1986) for perennial grasses seed production. Mathematical processing of experimental data was performed in Microsoft Excel 2010 and Statistica 10.
3. Results
In field conditions the process of creating yield potential depends on how efficiently the plants use light, heat, moisture, and nutrients. The yield of any crop, including *Festulolium*, is formed as a result of photosynthesis, the intensity and productivity of which is influenced by the inflow of photosynthetically active radiation (PAR). With constant PAR inflow the potential yield depends on the coefficient of performance of PAR that changes depending on the biological characteristics of the crop (variety) and prevailing agrotechnical and meteorological conditions [6-7]. According to Federal State Budgetary Institution ‘Central Chernozem Service for Hydrometeorology and Environmental Monitoring’, the territory of the Central Chernozem Region has significant radiation resources ranging from 2.2 to 3.5 billion kcal/ha. In the research site the total inflow of solar radiation (direct and scattered) over the growing season of *Festulolium* was 67.1 kcal/cm². Data on solar radiation inflow during the growing season of *Festulolium* is presented in Table 1.

| Table 1. Inflow and distribution of solar radiation during the thermoperiod (average for the 2005-2016 period). |
|---|---|---|---|---|---|---|---|
| Observation point | April | May | June | July | August | September | October |
| Nizhnedevitsk Weather station, Voronezh Oblast | 38.5 | 56.5 | 62.0 | 59.0 | 47.3 | 32.6 | 17.6 |
| | | | Total solar radiation, kcal/cm² | | | | |
| | 9.2 | 13.5 | 14.8 | 14.1 | 11.3 | 7.79 | 4.2 |
| | | | Total solar radiation, kcal/cm² | | | | |
| | 4.1 | 6.1 | 6.7 | 6.4 | 5.1 | 3.5 | 1.9 |
| | | | PAR inflow, kcal/cm² | | | | |

Not all incoming PAR is used by crops and is absorbed during photosynthesis. In conventional agricultural practices crops use the incoming PAR energy with the coefficient of performance (COP) of 0.5-1.0%. COP of PAR of sowings depends on the biological characteristics of the crop, soil fertility, mineral nutrition level, weather conditions, and applied agricultural technology. The highest level of PAR use is observed in the complex regulation of water, air and nutrition regimes [6, 15].

Based on the data of PAR inflow during the growing season the authors have calculated the potential yield of *Festulolium* seeds at different COPs of PAR (see Table 2).

| Table 2. Potential seed productivity of *Festulolium* at various PAR use, kg/ha. |
|---|---|---|---|---|---|---|---|
| PAR inflow per vegetation, billion kcal/ha | COP of PAR, % |
| 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 |
| 2,605 | 336 | 672 | 1,008 | 1,344 | 1,680 | 2,016 | 2,352 | 2,689 | 3,025 | 3,361 |

Calculations show that in the conditions of the Central Chernozem Region the PAR inflow of 2.61 billion kcal/ha during the growing season and 2.0% COP of PAR can provide the yield of *Festulolium* seeds of 1,344 kg/ha, or 2,016 kg/ha if COP of PAR is 3.0%. However, the actual productivity of *Festulolium* is lower. The reason for the decrease in COP of PAR is the insufficient leaf surface area at the beginning of the growing season and the presence of photosynthetically inactive leaves in the crops due to their physiological age.

Therefore, the radiation regime of the Central Chernozem Region allows obtaining high yields of *Festulolium* seeds (1.3-2.0 t/ha), but the formation of such yield in the crops requires creating a favorable ecological regime.
The main limiting factor in the conditions of the Central Chernozem Region is the moisture supply of crops. The amount of productive moisture that *Festulolium* uses for yield formation is determined by the moisture reserve in the 1-meter layer of soil at the time the growing season resumes, as well as by the amount and efficiency of use of precipitation that fell during the growing season when the yield was being formed.

The results of research for the 2005-2016 period on seed productivity of the VIK-90 zoned variety of *Festulolium* show a large amplitude of fluctuations in seed yield over the years. For instance, in the second-year crops the yield of *Festulolium* varied from 396 to 1,154 kg/ha over the years, i.e. the difference between the best and the worst years was 291% (Figure 1). Such strong variation (V = 29%) is largely due to the effect of weather conditions.

*Festulolium* yield is determined to a large extent by the amount of precipitation and its distribution during the growing season. According to the results of research performed by the authors, the highest yields of *Festulolium* seeds (877-1,154 kg/ha) were obtained in wet years (2005, 2008, 2012, and 2016). In these years the total precipitation over the growing season was 192-285 mm, and most of it fell during the period of aftergrowth-flowering of *Festulolium* (Table 3).

**Table 3.** Seed yield of the VIK-90 *Festulolium* variety depending on precipitation, 2nd year of vegetation.

| Years of research | Amount of precipitation, mm | Seed yield, kg/ha |
|------------------|-----------------------------|------------------|
|                  | over the growing season     | from aftergrowth to flowering | from flowering to ripening |
| 2005             | 285.6                       | 196.7            | 88.9  |
| 2006             | 156.3                       | 67.4             | 88.9  | 587   |
Relatively high seed (646–831 kg/ha) were obtained in 2007, 2009, 2011, and 2014, when the total amount of precipitation over the growing season of *Festulolium* amounted to 116–156 mm. Low *Festulolium* seed yields (396–587 kg/ha) were obtained in dry years (2010 and 2013), as well as in 2006 and 2015, when most of precipitation fell during the period of flowering-ripening, which caused lodging of grass stand.

The analysis of weather conditions over 12 years shows that precipitation during the growing season of *Festulolium* in the second year of vegetation closely correlates with seed yield \((r = 0.85)\). The relationship between the yield and the amount of precipitation over the growing season is expressed by the regression equation:

\[
Y = 190.52 + 3.2894x_1, \tag{1}
\]

where \(Y\) is seed yield (kg/ha) and \(x\) is the total precipitation over the growing season (mm).

Precipitation during the flowering phase of *Festulolium* only insignificantly contributed to the increase in yield \((r = 0.27)\) and had no significant effect on the yield in the period from flowering to ripening \((r = 0.04)\). Late precipitation, especially during the period of crop ripening, had a negative effect on the yield \((r = -0.03)\).

In order to characterize the moisture conditions in a particular territory the hydrothermal coefficient (HTC) is used. Its value allows classifying the years as follows: excessively wet (more than 1.6), wet (from 1.6 to 1.3), insufficiently moist (from 1.3 to 1.0), and dry (less than 1.0) [19].

The highest yields of *Festulolium* seeds (1.123–1.154 kg/ha) were obtained in wet years with the HTC of 1.3–1.7 over the growing season, and the lowest yields (396–877 kg/ha) were observed in dry years with the HTC equal to 0.53–1.01 (Table 4).

**Table 4.** Productivity of the VIK-90 *Festulolium* variety depending on air temperature and HTC during the growing season, 2nd year of vegetation.

| Years of research | HTC  | Average daily temperature, °C | Yield, kg/ha |
|-------------------|------|------------------------------|--------------|
| 2005              | 1.30 | 16.5                         | 1.154        |
| 2006              | 0.98 | 16.8                         | 587          |
| 2007              | 0.95 | 17.4                         | 729          |
| 2008              | 1.00 | 15.8                         | 877          |
| 2009              | 0.70 | 15.1                         | 831          |
| 2010              | 0.53 | 18.8                         | 396          |
| 2011              | 0.85 | 16.3                         | 704          |
| 2012              | 1.31 | 16.6                         | 889          |
| 2013              | 1.01 | 17.5                         | 584          |
The yield was closely correlated with the HTC \( r = 0.80 \). This relationship can be expressed by the following equation (Table 5):

\[
Y = 189.91 + 562.8x_2. \tag{2}
\]

Table 5. Correlation relationships between the productivity of *Festulolium* and weather conditions during the growing season (the VIK-90 variety).

| Meteorological factors                        | Correlation coefficient | Regression equation       |
|----------------------------------------------|-------------------------|---------------------------|
| Precipitation over the growing season        | \( r = 0.85 \)          | \( Y = 190.52 + 3.2894x_1 \) |
| Hydrothermal coefficient                     | \( r = 0.80 \)          | \( Y = 189.91 + 562.8x_2 \) |
| Average daily temperature over the growing season | \( r = -0.61 \)        | \( Y = 3.226.4 - 146.48x_3 \) |
| Precipitation during the period of aftergrowth-flowering | \( r = 0.81 \)          | \( Y = 447.4 + 3.0968x_4 \) |
| Average daily temperature during the period of aftergrowth-flowering | \( r = -0.34 \)        | \( Y = 1.658.1 - 60.982x_5 \) |
| Precipitation during the period of flowering-ripening | \( r = 0.04 \)          | \( Y = 735.04 + 0.2543x_6 \) |
| Average daily temperature during the period of flowering-ripening | \( r = -0.40 \)        | \( Y = 2.072.8 - 64.836x_7 \) |
| Precipitation in the phase of flowering      | \( r = 0.27 \)          | \( Y = 678.37 + 5.5695x_8 \) |
| Average daily temperature in the phase of flowering | \( r = -0.27 \)        | \( Y = 1.427.8 - 36.322x_9 \) |
| Precipitation in the phase of ripening       | \( r = -0.03 \)         | \( Y = 764.15 - 0.1826x_10 \) |
| Average daily temperature in the phase of ripening | \( r = -0.42 \)        | \( Y = 1.994.1 - 59.987x_11 \) |

High temperature generally had a negative effect on the formation of *Festulolium* yield. The relationship between the yield and temperature is negative in all phases of plant development: \( r = -0.34 \) for aftergrowth-flowering; \( r = -0.40 \) for flowering; \( r = -0.42 \) for flowering-ripening; and \( r = -0.61 \) for the entire growing season. The relationship between air temperature over the entire growing season and yield is expressed by the following regression equation:

\[
Y = 3.226.4 - 146.48x_3. \tag{3}
\]

It is known that already at the fifth stage of organogenesis of perennial grasses flowers are formed in the spikelets. This stage is of great importance for further seed productivity, since during this period the potentially possible number of flowers in spikelets is finally determined with no possibility of being increased afterwards. Therefore, the authors studied the dependence of *Festulolium* seeds yield on weather conditions starting from the beginning of spring aftergrowth and not only in the flowering phase.

The highest yield of *Festulolium* seeds is formed when the maximum amount of precipitation falls during the period from aftergrowth to earing. For instance, favorable conditions for the VIC-90 variety arose in 2005, when 196.7 mm of precipitation (68.8% of the total amount) fell from the phase of seedling to earing. In the flowering phase precipitation was 22.3 mm (7.8%), while in the period of seed formation-ripening it was 88.9 mm (31.1%) (Table 6). That year the number of seeds set on
generative shoots of *Festulolium* was the largest (945.6 million pcs/ha), and the seed yield was 1,154 kg/ha.

**Table 6.** Seed yield of the VIC-90 *Festulolium* variety depending on weather conditions.

| №  | Indicators                                                                 | 2010   | 2005   |
|----|-----------------------------------------------------------------------------|--------|--------|
| 1  | Seed yield, kg/ha                                                           | 396    | 1,154  |
| 2  | Precipitation (mm) from aftergrowth to seed ripening, including:            | 115.8  | 285.6  |
| 2.1| - over the period from aftergrowth to earing                                | 83.6   | 196.7  |
| 2.2| - in the phase of earing                                                   | 6.5    | 39.1   |
| 2.3| - over the period from earing to flowering                                 | 6.5    | 61.4   |
| 2.4| - in the phase of flowering                                                 | 0      | 22.3   |
| 2.5| - over the period from flowering to ripening                               | 32.2   | 88.9   |
| 2.6| - in the phase of complete ripeness                                        | 0      | 0      |
| 3  | Average daily temperature (°C) from aftergrowth to seed ripening, including:|        |        |
| 3.1| - over the period from aftergrowth to earing                                | 12.8   | 14.6   |
| 3.2| - in the phase of earing                                                   | 16.1   | 15.7   |
| 3.3| - over the period from earing to flowering                                 | 17.1   | 16.3   |
| 3.4| - in the phase of flowering                                                 | 21.2   | 18.1   |
| 3.5| - over the period from flowering to ripening                               | 21.9   | 17.8   |
| 3.6| - in the phase of complete ripeness                                        | 27.5   | 18.4   |
| 4  | Days without precipitation in the phase of flowering, %                     | 100    | 67     |

Compared to 2005, in the dry year of 2010 the opposite data was obtained. The year of 2010 was characterized by small amount of precipitation during the growing season (115.8 mm), as well as high average daily temperature during the flowering-ripening period (21.9°C) and in the ripening phase (27.5°C). Lack of moisture and high temperature in the beginning of flowering phase had a negative impact on the formation of seeds on generative shoots of *Festulolium*. That year there were only 5.6 million generative shoots per 1 hectare of *Festulolium* grass stand, and the seed yield was 396 kg/ha.

Thus, the lack of moisture and high temperature during the formation of generative organs sharply reduce the seed productivity of *Festulolium*, and it is very difficult to compensate for these losses afterwards.

Data on the correlation between the yield and weather conditions during the growing season of *Festulolium* were shown in Table 5. The combined effect of precipitation and temperature on the productivity of *Festulolium* by vegetation phases can be expressed by the following multiple regression equation (see Table 5 for the “x” value):

\[
Y = 1,468.36 + 177.05x_2 - 130.30x_3 + 2.26x_4 + 29.20x_5 + 4.57x_6 + 116.96x_7 + 6.22x_9 - 3.93x_{10} - 94.01x_{11}
\]

A significant effect on the yield of *Festulolium* seeds is primarily exerted by precipitation that falls during the entire growing season (especially during the period of aftergrowth-flowering), as well as by the average daily temperature, which is confirmed by the data of long-term studies conducted by the authors.

Research results show that weather conditions influence the length of growing season and the terms of individual phases of *Festulolium* development (Table 7).
Table 7. Dependence of onset of full blossom of the VIK-90 Festulolium variety from temperature and precipitation.

| Years of research | Average daily temperature from aftergrowth to flowering, °C | Total effective temperatures (> 5°C) | Precipitation from aftergrowth to flowering, mm | Days from aftergrowth to flowering |
|-------------------|-----------------------------------------------------------|-------------------------------------|-----------------------------------------------|----------------------------------|
| 2005              | 14.9                                                      | 938                                 | 197                                           | 65                              |
| 2006              | 13.5                                                      | 903                                 | 67                                            | 66                              |
| 2007              | 15.3                                                      | 975                                 | 74                                            | 62                              |
| 2008              | 13.7                                                      | 905                                 | 156                                           | 67                              |
| 2009              | 13.1                                                      | 912                                 | 62                                            | 66                              |
| 2010              | 16.7                                                      | 1.075                               | 84                                            | 59                              |
| 2011              | 16.2                                                      | 1.012                               | 55                                            | 62                              |
| 2012              | 16.2                                                      | 1.099                               | 90                                            | 60                              |
| 2013              | 15.3                                                      | 965                                 | 76                                            | 62                              |
| 2014              | 16.5                                                      | 1.052                               | 84                                            | 60                              |
| 2015              | 13.8                                                      | 916                                 | 43                                            | 65                              |
| 2016              | 13.4                                                      | 889                                 | 226                                           | 68                              |

High temperatures during the growing season accelerate the onset of phenological phases and shorten the interphase periods. Cold weather, on the contrary, delays the onset of phases and lengthens the growing season. A decisive role in these processes is played by the relationship between the temperature regime and moisture supply of crops. For instance, in the dry year of 2010, when only 115 mm of precipitation fell during the growing season, the average daily temperature was 18.8°C and the growing season of Festulolium lasted 93 days. In 2012 the level of precipitation was 248 mm and the average daily temperature was 16.6°C, which caused the growing season of Festulolium to increase to 103 days.

In order to increase the seed productivity of Festulolium it is important to predict the terms of flowering and ripening in each soil-climatic zone. This can help to take timely measures aimed at reducing seed cast and choosing the right harvest terms.

The authors predicted the terms of flowering and ripening on the basis of regression analysis using the data from Table 7. The following regression equation was obtained:

\[ Y_1 = 100.06 - 1.30x_1 - 0.02x_2, \] (4)

Using this equation it is possible to predict the date of onset of the flowering phase. Seed ripening terms can be calculated using the following regression equation:

\[ Y_2 = 74.60 - 1.41x_1 + 0.03x_2 - 0.02x_3, \] (5)

where \( x_1 \) is the average air temperature in °C; \( x_2 \) is the amount of precipitation in mm; \( x_3 \) is the total of effective temperatures (> 5°C); \( Y_1 \) is the number of days to flowering; \( Y_2 \) is the number of days to ripening.

The estimates of coefficients of regression equations were obtained by the least squares method using the Statistica 10 statistical data analysis package. The quality of regression equation is reflected by the \( R^2 \) coefficient of determination. The proximity of this coefficient to 1 reflects good correspondence between the experimental material and the values calculated from the regression equation. The relationship with individual factors characterizes the pair correlation coefficient. When predicting the flowering terms, \( r_{Y_1x_1} = -0.954; \) \( r_{Y_1x_2} = -0.947; \) \( r_{Y_1x_3} = 0.412 \); i.e. the onset of flowering is significantly influenced by the average daily temperature and the total of effective (+5°C) temperatures.
4. Conclusions

To sum up, the Central Chernozem Region of Russia is distinguished by favorable climatic conditions for cultivating Festulolium for seed purposes. This region is characterized by a large amount of heat during the growing season, but the insufficient moisture supply (300-450 mm per year) is a limiting factor.

As a result of long-term (2005-2016) studies it has been established that weather conditions are of paramount importance in the formation of seed productivity of Festulolium. Alongside with the study of critical periods depending on weather conditions, a mathematical relationship was established between hydrothermal factors and seed productivity of Festulolium. The optimal conditions for the formation of Festulolium seeds yield arise when at least 147 mm of precipitation falls during the growing season (mostly within the period from aftergrowth to flowering), the hydrothermal coefficient is 0.8-1.7, the average daily temperature is within 17-19°С in the flowering phase and 18-21°С during the period of seed formation-ripening, and the proportion of days without precipitation in the flowering phase is at least 57%.

A detailed study of the prevailing weather conditions in different phases of the growing season allows improving the technology of growing Festulolium for seed purposes.

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