Precipitation and yield of spring wheat in the semiarid zone of Orenburg Cis-Urals

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Abstract. Spring wheat is produced in Orenburg Cis-Urals in conditions of moisture deficiency. Among 69 years studied (1951-2019), 16 turned out to be dry, 25 - arid, with a total precipitation of less than 380 mm. In terms of precipitation during the growing season 50 years were dry and arid, a total was less than 130 mm. According to the annual amount of precipitation, a cyclicity was established with alternation of two humid decades with one dry one. In support of the hypothesis, precipitation in the first half of the growing season of wheat is dominant, and the least in the second of all categories. Significant relationships were established between them and the yield, $r = 0.814$ and $r = 0.574$. Annual moisture resources have a weaker relationship with yield ($r = 0.566$) than precipitation during the growing season ($r = 0.730$). The surge in yield due to precipitation in the first half of the growing season of wheat is its response to the moistening of the upper soil layer during tillering and the formation of a secondary root system. Hence, the main requirement for the technology of growing spring wheat is to moisten the top 0-5 cm of the soil layer in the tillering phase to 17% of the mass of dry soil and above.

1. Introduction

Improving the efficiency of moisture resources in rainfed agriculture, which will increase production under conditions of widespread climate aridization, even if it is cyclical, is a promising way to increase the productivity of agrocenoses. Currently, one third of the world is facing water shortages [1]. It is predicted that the next century, the amount of atmospheric precipitation will decrease, which will lead to droughts and crop losses [2]. Confirmations are observed all over the world. For example, in 2003, a 6 °C increase in average annual temperature and 300 mm of annual rainfall in Europe resulted in the lowest cereal yields in recent years. Losses amounted to 13 billion euros [3]. In such a situation, increasing the efficiency of water use in arid regions becomes especially important.

In traditional farming, there is a weak relationship between rainfall and yield [4]. The efficiency of rainwater decreases due to surface runoff, unproductive evaporation and poor soil accumulation. Meanwhile, there are works proving that large reserves of moisture also do not guarantee high yields [5, 6]. The reason for the decline in yields with good reserves is the poor storage of moisture in the soil, due to unproductive evaporation and low efficiency in the use of summer precipitation, caused by the peculiarity of traditional technologies. To some extent, the No-till canning technology is devoid of these disadvantages, due to its ability to accumulate and retain moisture more. However, this is true...
only if there is a sufficient amount of organic mulch [7]. In arid regions, due to the low yield of crops, it is practically impossible to create the required thickness of mulch. The topsoil in conservation technologies dries out as quickly as in traditional ones. The difficulty of accumulating organic mulch, paradoxically, creates a problem in the use of moisture. Lack of mulch leads to soil compaction, creates an obstacle to moisture absorption and increases evaporation losses [8]. In this situation, there is a need for alternative methods. Within the range of ways that affect crop productivity, moisture (rainfall) is key.

In the central zone of Orenburg region, the yield of spring wheat is 1.0 t/ha, varying over the years from 0.2 t to 2.2 t/ha. The record harvest reaches 3.6-4.2 t/ha. Scientists explain such a rise in yield by the level of spring reserves in soil, the amount of precipitation during the growing season [9]. All this speaks about the importance of all categories of precipitation for the formation of the crop. Meanwhile, one of them should have a decisive influence on the result. We tend to prefer the amount of precipitation during the growing season and the timeliness of their fallout, in accordance with the most critical phase of plant development. Assessment of the contribution of certain categories of precipitation to ensuring yields, allows adjusting tactical decisions in technologies for growing spring wheat.

2. Materials and Methods

The study area is located in the zone with semi-arid (semi-arid) climate of temperate latitudes (BSk) of Orenburg Cis-Urals of Orenburg region (Orenburg region, Russia) with coordinates 51°78'72"N 55°28'80"E. The average monthly air temperature ranges from -24.3 to -27.4°C in January, to +19.9 to +22.4°C in July, and the average annual temperature is +5.3°C. The average annual precipitation is 350-450 mm. The soil is southern heavy loamy chernozem on red-brown calcareous loams. The 30 cm layer of soil contains: humus - 4.1%, easily hydrolyzable nitrogen (N) - 8.4 mg, labile phosphorus (P₂O₅) - 3.25 mg, exchangeable potassium (K₂O) - 27 mg and exchangeable calcium (CaO) - 39.0 mg per 100 g of soil. High carbonate content determines the alkaline reaction of the soil pH 7.6-8.0. Data on weather conditions during the study period were obtained at the Orenburg weather station (51°73’93”N 55°9’57”E), as well as the Internet portal (http://aisori.meteo.ru/). Data on the yield of spring wheat (1950-2019) were obtained from the database of scientific reports on the studies of the FSBEI HE OSAU. Statistical analysis of the data was carried out using Statistica 10.0 software packages (StatSoft Inc, USA). To determine the deviations of the observed values from the "norm" of precipitation for the year, the long-term average for the base period 1961-1990 was used (365 mm).

3. Results

Among 69 analyzed years, 16 (23%) were dry, 25 years (36%) were dry, when less than 280 mm and 281-380 mm of precipitation fell during the year, 22 years (32%) were wet and only 6 years (9%) were wet, with a total precipitation of 381-480 mm and more than 480 mm, respectively. This suggests that products in rainfed agriculture in the Orenburg Cis-Urals are produced in the most severe conditions of moisture deficiency. The situation with regard to the supply of plants with water in agrocenoses worsens even more due to the high dryness of the growing season of wheat. Here, 51 years (59%) fell into the class of dry and dry years, 13 (19%) were wet and 5 years (9%) were wet with a total precipitation of less than 80 mm, 81-130 mm, 131-180 mm and more than 180 mm, respectively. Average annual precipitation for an agricultural year from 1951 to 2019 (69 years) was 348 mm (figure 1, a), it is 17 mm less than the standard value (365 mm) provided on the website http://www.meteo-tv.ru for the generally accepted period (1961-1990). The amount of precipitation for the growing season of wheat was 112 mm (figure 1, b) and was 10 mm below the norm. An increase in climate aridity is evident.

Meanwhile, the data presented in the following histograms show that the amount of precipitation for the agricultural year in the period 1951-1985. It was 336 mm, and in the period 1986-2019 it was 360 mm, i. e. there was an increase in this indicator by 24 mm. During the growing season of spring wheat, on average, for 35 years (1951-1985), 108 mm fell, and in the next 34 years (1986-2019) only
116 mm, the difference is 8 mm, in favor of the last period. That is, the situation with water supply, on the contrary, has improved.

For a more detailed analysis of the presence of climatic changes in terms of the precipitation rate in the study area, it was decided to divide the 69-year time into seven ten-year periods (table 1).

Table 1. Dynamics of precipitation in the study area over ten-year periods.

| Periods   | Agricultural year | Deviation from the norm | Growing period of spring what | Deviation from the norm |
|-----------|-------------------|-------------------------|--------------------------------|-------------------------|
| 1951-1959 | 262               | -103                    | 79                             | -43                     |
| 1960-1969 | 375               | 10                      | 116                            | -6                      |
| 1980-1989 | 340               | -25                     | 101                            | -21                     |
| 1990-1999 | 362               | -3                      | 114                            | -8                      |
| 2000-2009 | 370               | 5                       | 142                            | 22                      |
| 2010-2019 | 338               | -27                     | 94                             | -28                     |
| Norm      | 365               | 0                       | 122                            | 0                       |

The data show that the number of periods with less than normal rainfall is five out of seven, both for the agricultural year and for the growing season. Comparison of the last decade with the previous one, as most researchers do, also indicates a significant increase in climate aridity. The amount of precipitation decreased over the year and over the growing season by 27 and 28 mm, respectively. However, if we compare the last (2010-2019) period with the first (1951-1959), we can see that the first was much drier. Cyclicality is noticeable, two wet (italicized in table 1) alternate with one dry year. And if we follow this logic, then the next two decades should be more humid than 2010-2019. Therefore, in the last 69 years, in terms of precipitation, changes in the climate in the study area did not occur on the side of aridity, and the variation of their amount over the years is cyclical.

Statistically significant correlations were established between the yield of spring wheat and precipitation of various categories. A close positive relationship ($r = 0.566$) is observed between the yield over 69 years and the amount of precipitation for the agricultural year (figure 2, a), a closer relationship ($r = 0.730$) was noted with precipitation over the growing season of spring wheat (figure...
2, b). The strongest influence (r = 0.814) on wheat yield is exerted by precipitation in the first half of the growing season (figure 2, d), much less (r = 0.574) - in the second half of the growing season (figure 2, c).

Figure 2. Relationship between spring wheat yield and rainfall: per an agricultural year (a); for the growing season of spring wheat - May- August, 1 decade (b); for the first half of the growing season of spring wheat - May- June, 1 decade (d), for the second half of the growing season of spring wheat – June, 2 decade-July (c).

4. Discussion
The highest yield of spring wheat in the central zone of Orenburg region for 1951-2019 was obtained in 1968 and amounted to 2.20 t/ha, a total precipitation for an agricultural year was 400 mm and 141 mm for a growing season. It can be taken for Orenburg CIS-URALS as a conventionally ideal year, with the optimal amount and distribution of the annual precipitation. The research site is located in the semi-arid (semi-arid) zone, where less than 410 mm of precipitation falls per year. Therefore, an increase in its amount relative to conventionally ideal values should lead to an increase in yield, and a decrease in its fall. However, the actual data show a different result. For example, with the total precipitation for the 1993-1994 agricultural year was 606 m and the growing season was 188 mm, the yield of spring wheat was 1.10 t/ha, and with 308 mm and 84 mm, respectively, in 1991-1992, the yield reached 1.47 t/ha. In terms of the rainfall rate for the agricultural year (367 mm and 385 mm) and their amount during the growing season (29 mm and 50 mm), 1974-1975 and 1994-1995 did not differ significantly. However, the yield in 1995 was 3.7 times higher than in 1975. With the same
precipitation rate (317 and 318 mm) for 2009-2010 and 2011-2012, the yield was 0.06 and 0.55 t/ha. These data indicate the presence of other, more effective water factors affecting the productivity of spring wheat, in addition to the amount of precipitation per year and the growing season.

Statistical analysis of data for 69 years showed the closest significant positive relationship (r = 0.814) of wheat yield and precipitation in the first half of its growing season. Let us try to figure out why. The diversity of the floristic composition of natural cenoses makes it possible to form a yield higher than in agrocenoses. At the same time, in dry summer (2016), plants with a deeply penetrating vertical root system have an advantage in biomass accumulation. In a relatively humid summer (2017) with frequent precipitation, but with low precipitation in the cold period, it means with a small amount of moisture in the soil - with a fibrous root system (table 2).

Table 2. Accumulation of dry matter by natural cenoses depending on the nature of precipitation distribution during the growing season.

| Year | A    | B    | C    | With a fibrous root system | With vertical root system | Total dry matter weight, g/m² |
|------|------|------|------|---------------------------|---------------------------|-------------------------------|
|      | g    | %    | g    | %                          | g                         |                               |
| 2016 | 366  | 84   | 88   | 106                        | 39                        | 273                           |
| 2017 | 267  | 116  | 118  | 114                        | 65                        | 176                           |

Consequently, the prevalence in the total dry matter weight of a particular group of plants in natural cenoses is in direct proportion to the timing of precipitation in summer. Since the degree and timing of moistening of various soil layers depends on this. In agrocenoses, this position is confirmed by the productivity of crops (table 3).

Table 3. Crop yield in agrocenoses depending on the nature of precipitation distribution during the growing season.

| Year | A    | B    | C    | Spring wheat | Sunflower | The sum of yield of two crops, t/ha |
|------|------|------|------|--------------|-----------|-------------------------------------|
|      | t/ha | %    | t/ha | % of total weight | t/ha | % of total weight |                               |
| 2016 | 366  | 84   | 88   | 1.02         | 37     | 1.77                  | 63                            | 2.79                          |
| 2017 | 267  | 116  | 118  | 1.25         | 49     | 1.30                  | 51                            | 2.55                          |

Note for table 2 and 3: A - the amount of precipitation for August, II decade - April, mm; B - the amount of precipitation for the growing season of spring wheat (May-II decade of August, mm); C - the amount of precipitation during the growing season of sunflower (May-September, mm).

For comparison, let us take spring wheat and sunflower with different types of root system, but providing practically the same average annual grain yield in the considered zone. In terms of water supply, sunflower provides high yield in a dry year, but with good precipitation in the cold season. In addition, wheat has a good yield in years with a lack of rainfall in winter, but humid and frequent rains in summer. This example shows that concerning spring wheat, summer precipitation is the most important.

It is also known that wheat provides a good grain yield only with the formation and high activity of the secondary root system [10]. In traditional technologies, the topsoil dries out after sowing and is moistened with precipitation before or during tillering of the crop. In the dry layer, the secondary root system is not formed, and the yield decreases by 1.5-2 times. All record harvests of spring wheat in Orenburg region were obtained in years when the 0-10 cm layer was in a wet state due to summer rains. The following fact speaks in favor of this statement. In the absence of summer precipitation and low wheat yield, unused moisture remains in layers deeper than 50 cm of well-moistened soil in spring. This means that for spring wheat, precipitation is of the greatest importance, contributing to the
moistening of the upper soil layer before or during its tillering. In areas with limited water resources, one of the main threats to production is the distribution of precipitation over time and space, and not just its shortage.

Thus, an important condition for high productivity of wheat in arid regions is the compliance of the spatial distribution of moisture in the soil with its biological needs, and not only the provision of moisture. These requirements, to some extent, are met by the conservation technologies offered today, due to their ability to accumulate and retain moisture more. In relation to cereals, their advantage is due to the redistribution of moisture in the soil, with the predominant moistening of the upper layers, due to the pulling of moisture from the lower ones. However, this is only true if there is enough organic mulch available. In arid regions, due to low crop yields, it is not possible to create the required thickness of mulch, as well as the creation of additional mulch by growing crop crops due to lack of moisture in the fall. Therefore, the topsoil in conservation technologies in the considered zone dries out as quickly as in traditional ones. Therefore, methods are needed to ensure that the topsoil is moistened. Not only due to precipitation, which we cannot influence, but also due to the retention and redistribution of water in the soil, with the predominant moistening of the upper layer during the tillering phase of wheat. In other phases, the spatial distribution of moisture in the soil is not so significant. A well-developed root system of wheat, which is facilitated by the formed secondary root system, will allow moisture to be obtained from deep soil layers.

Hence, the main requirement for the technology of growing spring wheat is to moisten the top 0-5 cm soil layer in the tillering phase to 17% of the mass of absolutely dry soil and above. One of the ways can be to manipulate the sowing dates, taking into account the points of maximum precipitation in the tillering phase, which are possibly cyclical. Another can be a way that allows you to maximize the accumulation of moisture in the soil and to minimize its losses for physical evaporation and to promote the preferential moistening of 10 cm of the soil layer, while maintaining the capillary connection with the lower layers.

Spring wheat in Orenburg Cis-Urals is produced in the most severe conditions of moisture deficit, especially during the growing season. Analysis of data for 69 years (1951-2019), contrary to popular belief, showed that the precipitation rate has not changed. The variation in the amount of precipitation over the years is explained by the cyclicity established for the studied period of time, a characteristic feature of which is the alternation of two humid decades with one dry one.

Of all the categories (precipitation time), precipitation in the first half of the growing season is very important for spring wheat, and the least important in the second half. It confirmed our hypothesis. Statistically significant correlation dependences \( r = 0.814 \) and \( r = 0.574 \) were established between them and wheat yield, respectively. Annual moisture resources have a weaker relationship with yield \( (r = 0.566) \) than precipitation during the growing season \( (r = 0.730) \). The yield surge due to precipitation in the first half of the wheat growing season is a response of spring wheat to moistening the topsoil before or during tillering and the formation of a secondary root system.

An important condition for high productivity of spring wheat in arid regions is the compliance of the spatial distribution of moisture in the soil with its biological needs, and not only the provision of moisture. The main requirement for the technology of growing spring wheat should be to provide moisture to the top 0-5 cm of the soil layer during the tillering phase of spring wheat. One of the ways could be to manipulate the sowing dates, taking into account the points of maximum precipitation in the tillering phase of wheat, which are possibly cyclical. Another is a method that allows you to maximize the accumulation of moisture, to minimize its losses for physical evaporation and to promote the preferential moistening of the 3-10 cm soil layer, while maintaining capillary connection with the lower layers. With proper soil moisture management, the yield limits can be shifted towards higher values, that is, more can be grown with less water.

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