An analysis of yield dynamics in Peredovik sunflower variety in the conditions of the North Caucasus Region

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Abstract

The results of observations for 1971–2002 were used to analyze the long-term trends of yield and the duration of the growing season in the sunflower variety Peredovik. The regression analysis has shown that the growing season duration decreases with the increase in the sum of temperatures above 15 °C. The yield of sunflower was negatively associated with the sums of temperatures and the sums of precipitation in May–August, and positively with the precipitation in April. According to the regression analysis in differences, the main factor influencing the yield variability was the hydrothermal coefficient for the period with temperatures above 20 °C, the second factor was spring precipitation. The possible presence of a non-linear trend in yield dynamics that is not related to weather and climate conditions has been revealed. With the sustained tendency of the last 30 years towards an increase in temperatures and a decrease in precipitation in April, the growing season will keep shortening and the yield decreasing.

Keywords: sunflower, yield, growing season duration

Introduction

Sunflower is the main oilseed crop in Russia. This country is the second homeland of the crop (Seiler and Gulya, 2016), since it was here in Central Russia at the Voronezh and Belgorod provinces boundary that the cultivation of sunflower as an oilseed crop and the production of oil on an industrial scale were initiated. The first varieties of folk selection were characterized by 30 % oil content in the seeds. Thanks to a highly efficient breeding scheme developed by Vasily S. Pustovoit, which involves individual selection with offspring assessment and controlled pollination of the best families, high-oil varieties of sunflower containing 45–50 % of oil in seeds were created (Pustovoit, 1975).

Peredovik sunflower variety was created in the Russian Federation at the All-Union Research Institute of Oilseed and Essential Oil Crops (now the V. S. Pustovoit All-Russian Research Institute of Oil Crops, VNIIMK) by selection from an intervarietal hybrid created by crossing VNIIMK 8931 variety with No. 6420. Peredovik was submitted to the State Variety Testing in 1957 and in terms of yield, oil content and oil yield in many testing locations it exceeded the then cultivated varieties Chernyanka 66, Armavirsky 3497, Armavirsky 9343 and VNIIMK 8883 (Sunflower varieties, 1962). The variety was released in 1960. This is a mid-ripening variety; the germination- ripening period is 98–115 days. The average seed yield is 1.6–2.6 t ha^{-1}, 3.0–3.2 t ha^{-1} in favorable years; oil content in seeds is 44–48 %, up to 52.8 % in some years. The variety was used as a standard in State Variety Testing of the State Variety Testing Committee (Results of the state variety testing of sunflower, 1972). From 1970 to 2002, until Peredovik was replaced as the major commercial variety with a more productive Master variety, the for-

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mer was used as a standard in the studies of the VIR sunflower collection at the Kuban Experiment Station (a branch of the N. I. Vavilov Research Institute of Plant Genetic Resources, VIR). Peredovik is known in all sunflower cultivating countries as one of the first high-oil varieties, however it proved to be high-yielding far from everywhere. Abroad, many lines were derived from it and then used for creating industrial heterotic sunflower hybrids (Friedt, 1992; Miller and Fick, 1997; Gavrilova and Anisimova, 2017).

The scientific basis of the program of intensification and adaptation of crop production to current and expected climatic fluctuations is the modeling and forecasting of the plant production process (Olesen et al., 2011; Carter and Mäkinen, 2011; Donatelli et al., 2015). The complex of numerical methods for predicting economically important traits of the major crops is constantly in need of adjustment, because the accuracy of the models is insufficient (Richardson et al., 2012). Climate changes that began in the 1970s are taking place against the background of trends related to changes in farming culture and breeding achievements (Lobell and Field, 2007; Sirotenko, 2012; Iler, Inouye, Schmid and Høye, 2017; Debaeke, Casadebaig, Flenet, and Langlade, 2017). Recently, methods of time series analysis are being increasingly introduced in agrometeorological, biological and agricultural research (Menzel and Sparks, 2006; Kaukoranta and Hakala, 2008; Sirotenko, 2012; Wenjiao, Fulu, and Zhao, 2013; Choudhury and Jones, 2014). To identify the climate dependence properly, there are several ways to detrend the analyzed series, for instance, explicit inclusion of time in the regression model (Eliseeva et al., 2006; Kaukoranta and Hakala, 2008), analysis of the relationship between deviations from trends (Eliseeva et al., 2006; Sirotenko, 2012), and estimation of variables in differences (Ayvazyan, Enyukov, and Meshalkin, 1985; Eliseeva et al., 2006; Sirotenko, 2012). Series detrending can lead to significant changes in regression models; the disappearance of up to 75 % of temperature-phenological relations after detrending is shown in (Iler, Inouye, Schmid, and Høye, 2017).

In Russia, temperature is considered to be the main factor limiting the growth and development of crops (Guide to agrometeorological forecasts, 1984; Mishchenko, 2009). For sunflower the economically optimal temperature during the germination is 9–12 °C, 15–18 °C during vegetative organs formation, 19–23 °C for the formation of generative organs and flowering, and 16–22 °C for fruiting (Belolyubtsev and Sennikov, 2012). Sunflower is a drought-tolerant crop (Debaeke, Casadebaig, Flenet, and Langlade, 2017), the dependence on humidification is nonlinear; in more humid areas, the relation becomes insignificant and even negative (Guide to agrometeorological forecasts, 1984). Sunflower requires minimum monthly temperature of 15 and maximum of no more than 39 °C, between April and September; at least 350 mm of rain per year (Debaeke, Casadebaig, Flenet, and Langlade, 2017).

To forecast sunflower yield, regression and dynamic models are used (Ayvazyan, Enyukov, and Meshalkin, 1985; Garcia-Lopez, Lorite, Garcia-Ruiz, and Dominguez, 2014; Debaeke, Casadebaig, Flenet, and Langlade, 2017). According to regression models, the sunflower yield in Russia in the 20th century was positively associated with the total amount of precipitation in the winter and growing seasons, and negatively — with the sum of active temperatures per season (Guide to agrometeorological forecasts, 1984). If the temperature increases and precipitation decreases during the growing season, it is predicted that the vegetation period of the main agricultural crops will shorten and their yield will decrease (Moriondo and Bindi, 2007; Garcia-Lopez, Lorite, Garcia-Ruiz, and Dominguez, 2014; Debaeke, Casadebaig, Flenet, and Langlade, 2017).

The technique of the VIR collection agrobiological screening envisages the use of reference varieties, which are planted annually. They help to compare varieties studied in different years, and conduct retrospective studies. Agrometeorological analysis of long-term time series of observations of economically important traits of these varieties has an advantage over the analysis of data on the industrially cultivated varieties, because there is no factor of variety replacement.

The aim of the study was to analyze and forecast the climate-dependent trend in the yield of sunflower variety Peredovik in the North Caucasus Region under the conditions of climate change.

Materials and methods

The initial data are presented by observations of the yield and the growing season duration of the Peredovik sunflower variety at the Kuban Experiment Station from 1971 through 2002. During this period, Peredovik was used as a standard variety when collection accessions were regenerated or studied, and was sown every 20 accessions. Over 600 sunflower accessions were regenerated annually. One plot accommodates 42 plants. Sunflower sowing was carried out between April 20–28, germination recorded between May 3–13, and the plants harvested in late September — October. The study is based on the annually averaged data on the germination-harvesting duration and yield from 30 plots of the standard cultivar. Data from 1987 are missing, since the crop was destroyed by hail.

The study used the daily observations data from the Kuban weather station of VIR. Literature data (Sirotenko, 2012) and our previous studies of factors affecting various crops in the European part of Russia under the changing climatic conditions (Novikova et al., 2012; Novikova, Kiru, and Rogozina, 2017; Novikova and Naumova, 2019) showed the promise of using generalized indicators of heat and moisture availability during the periods with temperatures above 5°, 10°, 15°, 20 °C, that is, the sum of temperatures, precipitation and Selyaninov's hydrothermal coefficient (HTC, the ratio of the total precipitation to the sum of temperatures divided by 10). Under the conditions of climate change and shifting sowing dates, the equations based on these indicators are better than those based on the monthly weather data.

The features of the dynamics of the main economically important and agroclimatic indicators were analyzed using the moving 11-year average. The linear trends were calculated as coefficients of linear dependence of the studied variable on the year. Weather-climatic indicators that determine the dynamics of economically important characters were identified by the method of regression analysis, including that of successive differences.

The analysis of differences was used to eliminate a possible extraneous trend in the case of the complex nature of the trends of the studied variables (Ayvazyan, Enyukov, and Meshalkin, 1985; Vukolov, 2004; Eliseeva et al., 2006; Sirotenko, 2012). The method consists in the transition from the analysis of the source variables to the analysis of their annual increments. Let y_t be approximated by a model value $\hat{y}_t$ with the ε_t error that satisfies the premises of the least squares method application.

$$y_t = \hat{y}_t + \varepsilon_t. \quad (1)$$

Let the dependence on the climatic factor K be linear with the coefficients a_K and b_K, and on the non-climatic factor also linear with the coefficients a, b:

$$y_t = (a_K + b_K K_t) + (a + bt). \quad (2)$$

Then, the analysis of the relationship between the variables' annual increments permits determination of b_K, the regression coefficient of the initial levels:

$$\Delta y_t = y_t - y_{t-1} = \Delta K_t + b + \Delta\varepsilon_t. \quad (3)$$

With the parabolic trend of the non-climatic factor, the climatic tendency is revealed by the transition to regression in second differences, i. e., analysis of the relations between the differences of the first differences (Eliseeva et al., 2006), the transition to the subsequent differences removes the trends of the following orders. The order of the differences is determined by the degree of the polynomial, which approximates the trend (Ayvazyan, Enyukov, and Meshalkin, 1985; Vukolov, 2004).

Regression analysis was performed using the Statistica 13.3 package (TIBCO Software Inc., USA) by the method of stepwise regression with forward selection of variables with F to enter equal to 1.

The study adopted a significance level of 5 %.

Results

Peredovik variety characteristics

Peredovik variety was noted not only for its good productivity, but it also possessed a set of adaptability traits, which is characteristic of many landraces of different crops. A set of adaptability traits helps to obtain stable crops in a certain cultivation zone under changing weather conditions. With a change in the growing zone, the complex of adaptability traits does not manifest itself. For instance, when cultivating Peredovik in France, in the USA, Bulgaria and other countries, lodging of plants, infection with downy mildew, and a decrease in yield were observed. The well-balanced genotype of Peredovik variety grown in the south of the Russian Federation also manifests itself in the prolonged absence of inbred depression caused by selfing. Only after five generations of self-pollination, a decrease in plant height from 200 cm to 150 cm is observed, while no segregation for other characters was found even in the fifth generation.

Yields of the variety varied significantly in different years from 2.0 t ha^{-1} to 4.19 t ha^{-1} (Table). The lowest yields were observed in 1971, 1976, 1989 and 1997, while the highest yields of 4.0–4.19 t ha^{-1} were recorded in 1978, 1990, 1992 and 1993. The growing season duration varied from 89 days in 1972 to 112 days in 1989. In the years with high seed yields, the growing season du-

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Yield and growing season duration of Peredovik variety at the Kuban Experiment Station, a branch of VIR (Krasnodar Territory, 1971–2002)

Trait	Mean	St.Err.	Min	Max	CV, %	Trend in 1990–2002 (units per 10 years)
Yield (t ha^{-1})	3.2	0.1	2.0	4.2	19.3	−1.3 (p = 0.006)
Growing season duration (days)	100.8	0.9	89.0	112.0	5.2	−3.5 (p = 0.218)
Temperature sum during the growing season in 1997–2002 (°C)	2261.6	22.2	2058.7	2471.7	4.7	87.0 (p = 0.310)

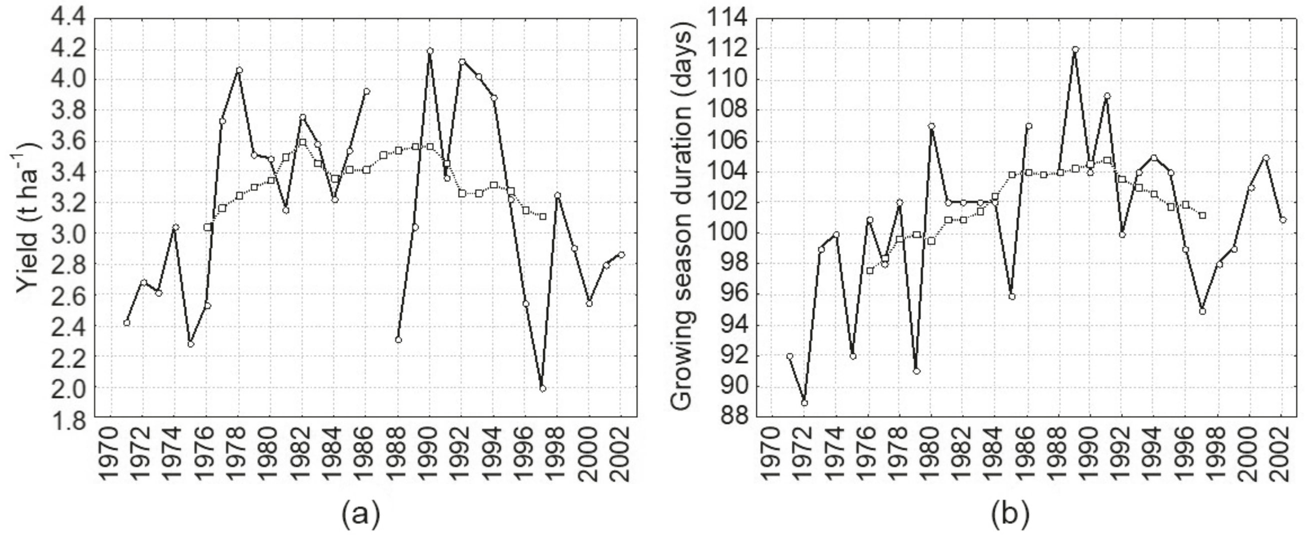

Fig. 1. Dynamics of the economically important traits of Peredovik sunflower variety in the North Caucasus Region, 1971–2002: a) yield; b) growing season duration. Designations: ▬▬ actual data; ‒ ‒ ‒ moving average.

ration was 100–104 days. However, no correlation was noted, as low yields were observed both in years with the shortest growing season and with a longer one.

The dynamics of yield and of the growing season duration for Peredovik sunflower variety in 1971–2002, and their values smoothed by the 11-year moving average, are shown in Fig. 1. Both indicators which have a non-linear dependence on time with a maximum around 1990, correlate with each other at r = 0.44. Since 1990, the yield has been showing a significant decrease at an average rate of v = –1.3 t ha^{-1} per 10 years, while the growing season duration and the sum of temperatures during the growing season did not change significantly.

Regression analysis (shown below) revealed the role of the sum of temperatures and precipitation in May — August for the formation of sunflower yield. The sum of temperatures for May — August has non-linear dynamics with a minimum in the early 1990s (Fig. 2a). From 1990 to 2002, heat supply increased significantly, as the temperatures kept increasing in July (v = 2.9 °C per 10 years) and in August (v = 1.8 °C per 10 years), and the sum of temperatures in May — August also increased (v = 163.6 °C per 10 years). There was a slight insignificant increase in precipitation in May — August (v = 43,3 mm per 10 years, p = 0.524). However, April precipitation decreased (v = –31.9 mm per 10 years, p = 0.154).

According to the data from (Sirotenko, Pavlova, and Abashina, 2007), the rate of temperature increase noted in 1975–2004 in the North Caucasus Region was 0.7 °C per 10 years in winter and 0.6 °C per 10 years in

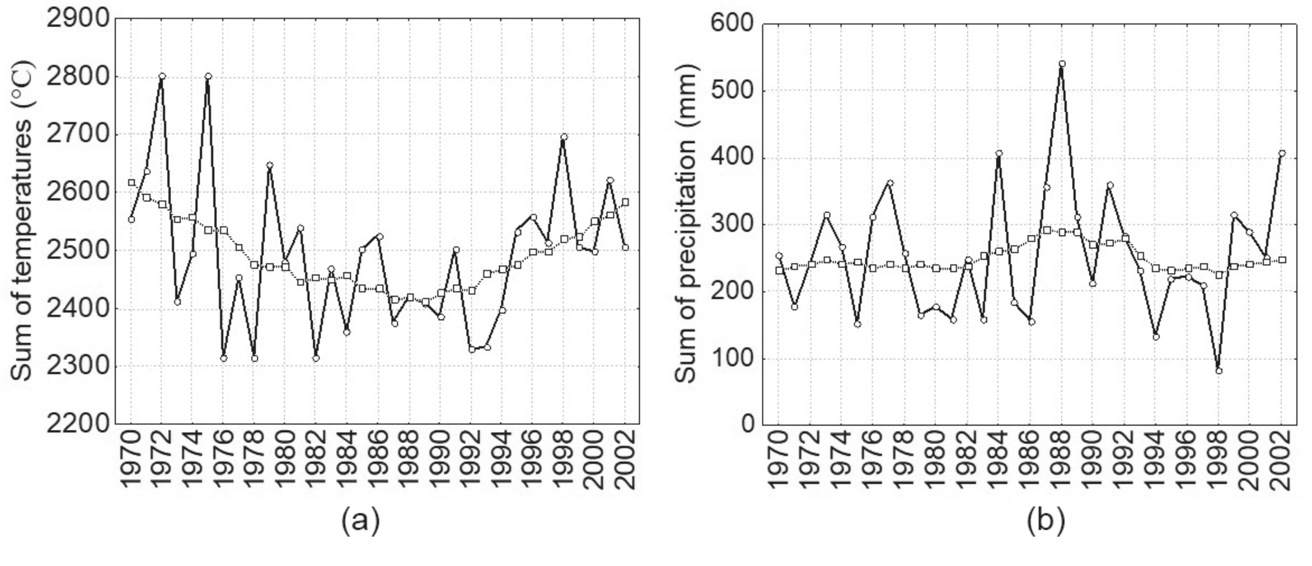

Fig. 2. Dynamics of agrometeorological conditions in May — August in the North Caucasus Region in 1971–2002: a) sum of temperatures; b) sum of precipitations. Designations: ▬▬ actual data; ‒ ‒ ‒ moving average.

June, while the rate of precipitation decrease was 2 mm per 10 years in winter and that of rainfall increase was 17.2 mm per 10 years in summer. The obtained data are consistent with these data.

Regression analysis

To the greatest extent, yield (Y) was related to the sum of temperatures in May — August ($\Sigma T_{May\,—\,August}$), the precipitation in May — August ($P_{May\,—\,August}$), and precipitation in April (P_{April}) with the model error of 0.4 t ha^{-1}:

$$Y = 10.786 - 0.003 \sum T_{May\,—\,August} - 0.003 \sum P_{May\,—\,August} + 0.006 P_{April}$$
$$R^2 = 0.48 \quad (4)$$
$$(0.000;\ 0.001;\ 0.010;\ 0.115)$$

R^2 here is the coefficient of determination, in brackets are the significance levels of regression coefficients.

The actual and model values are shown in Fig. 3a. Thus, an increase in temperatures during the active vegetation reduces the yield. Precipitation in the North Caucasus Region is excessive and its increase in May — August causes a decrease in yield, while a decrease in spring precipitation creates unfavorable conditions for the future crop.

The germination-ripening period duration (L) depends on the growing degree-days above 15 °C (ΣT_{15}) and duration of the period with temperatures of 10–15 °C in spring (L_{10-15}). These two factors provide 59 % of the total variability of the growing season duration with the standard error of the model of 3.4 days. (Fig. 3):

$$L = 114.520 - 0.007 \sum T_{15} + 0.186 L_{10-15}$$
$$R^2 = 0.61 \quad (5)$$
$$(0.000;\ 0.002;\ 0.000)$$

Thus, the growing season duration decreases with the increasing summer temperatures; the period with temperatures of 10–15 °C is favorable for the accumulation of vegetative mass, and its decrease also shortens the growing season.

However, the factors identified by regression may be false, entered into the models only because of the coincidence of the type of trends in agro-climatic and agro-biological characteristics.

Analysis in differences

Within such a significant time interval as the considered one, i.e., from 1971 to 2002 (32 years), a systematic influence of non-weather-related factors, e.g., technological, is possible. Due to the uncertainty and the possible complex nature of the trend, the analysis in differences was used. The analysis of yield has shown that the equations improve significantly with the use of third differences, as the determination coefficient reaches 50 %, and the predictors change:

$$\Delta^3 Y = 0.042 - 0.569 \Delta^3\, HTC_{20} + 0.002 P \Delta^3 P_{5-20}$$
$$R^2 = 0.50 \quad (6)$$
$$(0.863;\ 0.001;\ 0.045)$$

Δ^3 here designates the third difference.

A transition to the fourth differences improves the equations still more, though the coefficients of agroclimatic parameters do not change. An increase of HTC_{20} by 1 unit reduces the yield by 0.594 t ha^{-1}, while a 1-mm increase in rainfall during the period with the temperatures of 5–20°C in spring increases the yield by 0.002 t ha^{-1} (Fig. 4):

$$\Delta^4 Y = 0.053 - 0.594 \Delta^4\, HTC_{20} + 0.002 P \Delta^4 P_{5-20}$$
$$R^2 = 0.58 \quad (7)$$
$$(0.903;\ 0.000;\ 0.023)$$

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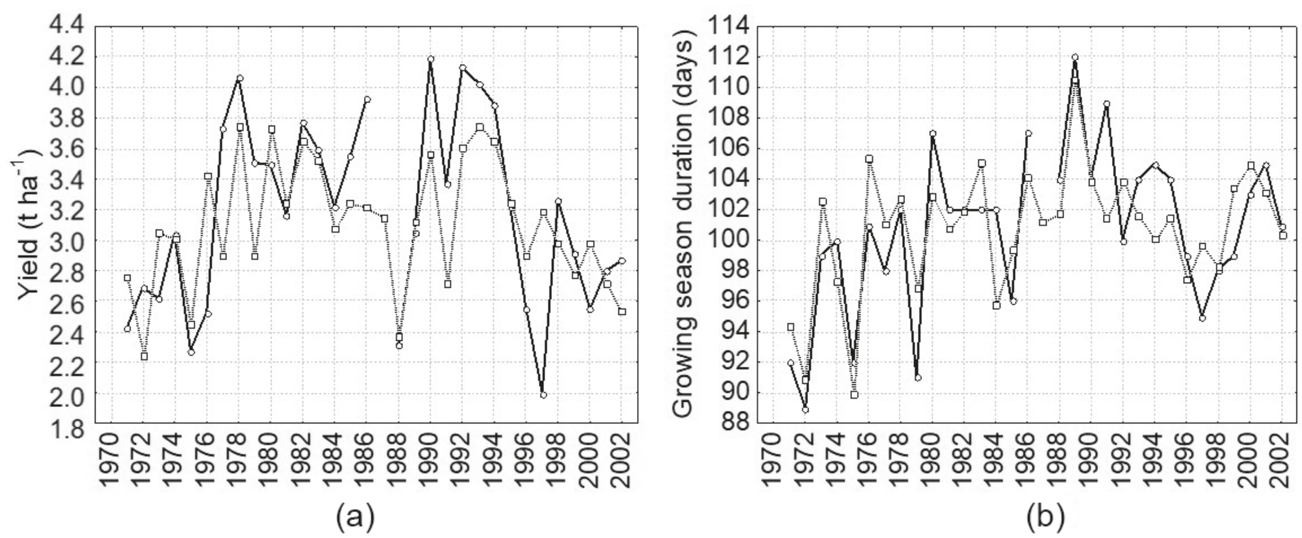

Fig. 3. Comparison of economically important traits of Peredovik sunflower variety: a) yield; b) growing season duration (North Caucasus Region, 1970–2002). Designations: ▬▬ actual data; ‒ ‒ ‒ calculated by regression models (4) and (5).

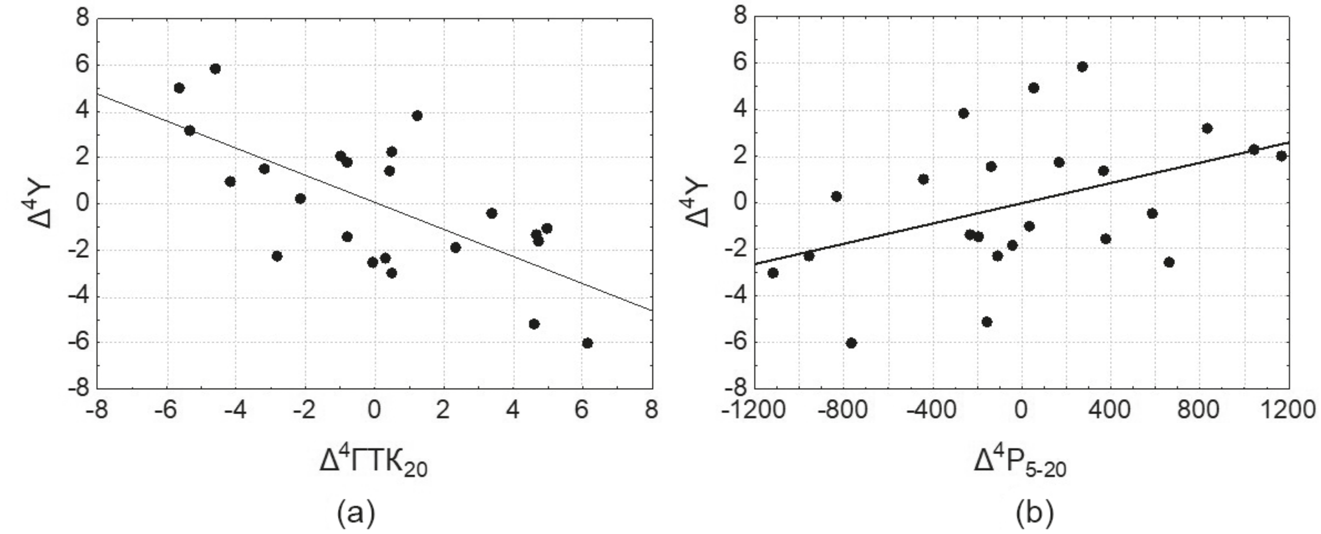

Fig. 4. Yield dependence on a) HTC_{20}; b) precipitation during the period with the temperatures of 5–20 °C in the fourth differences.

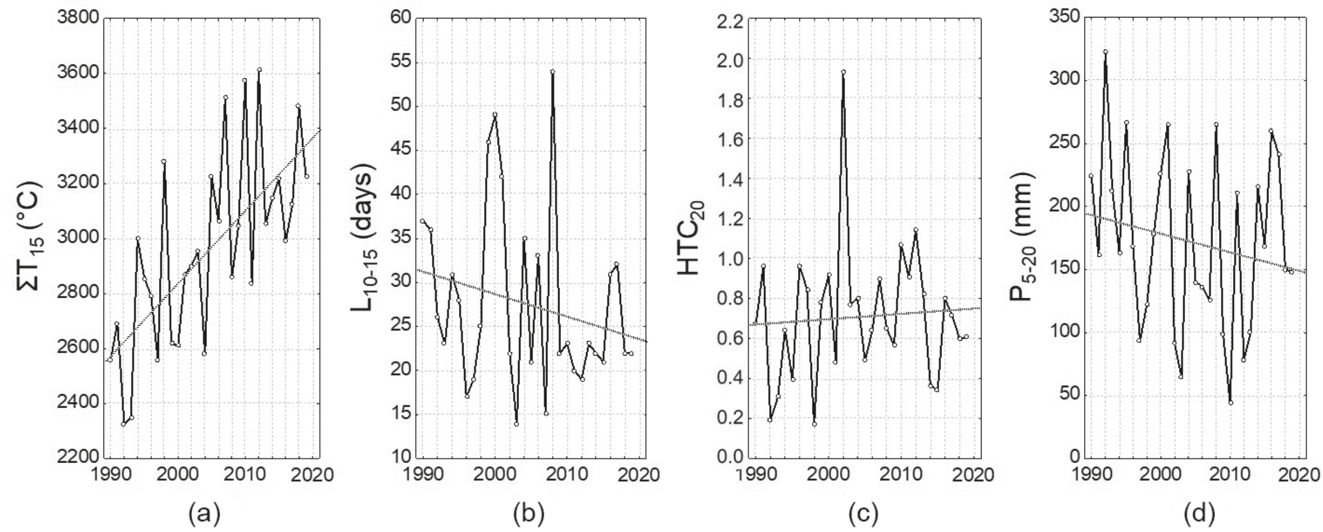

Fig. 5. Trends in agroclimatic predictors in the models of sunflower growing season duration (5) and yield (7): a) the sum of temperatures above 15 °C; b) duration of the spring period with the temperatures of 10–15 °C; c) hydrothermal coefficient (HTC) for a period with temperatures above 20 °C; d) precipitation for a period with the temperatures of 5–20 °C in spring.

In this way, the actual agro-climatic factors and regression coefficients are determined, and the transition to the following differences does not add information and is not necessary. The fundamental difference between the equations (6) and (7) from the equation (4) is that an increase in temperatures in constant precipitation will increase productivity. The false negative effect of temperature growth was caused by coinciding trends in yield and heat supply. An increase in the accuracy of the model at the transition to differences indicates the presence of extraneous non-climatic (or undetected climatic) influence on the yield dynamics. The resulting model in the differences is more accurate than in initial levels, it explains more than half of the yield variability and is suitable for calculating the climate-dependent forecast. However, the disadvantage of the method of differences is in the reduction in the length of the considered series when moving to each subsequent difference for one year, or for 2 years if there is a gap. Thus, a different set of input data was used when constructing the model. The structure of the equation for the germination-ripening period duration does not change with the transition to differences, so a higher quality equation could not be obtained. This indicates that on the rate of development there is no influence of non-climatic factors and about a high degree of dependence of phenology on climate.

Climate change-related trend

From 1990 through 2019, the variables used in model (4) had the following trends: a significant increase was noted for the sum of temperatures in May — August (v = 121.0 °C per 10 years, p = 0.000); precipitation in May — August increased insignificantly (v = 14.8 mm per 10 years, p = 0.415), while precipitation in April had a significant decrease (v = –10.6 mm/10 years, p = 0.038). If the observed trends continue, the calculated rates of further changes in the yield will be v = –0.43 t ha^{-1} per 10 years according to model (4).

The variables used in model (5) had the following trends (Fig. 5a, b): there was a significant increase in the sum of temperatures above 15 °C (v = 263.0 °C per 10 years, p = 0.000) and a slight decrease in duration of the period in spring with temperatures of 10–15 °C (v = –2.6 days per 10 years, p = 0.228). For the growing season duration the model rate will be v = –2.3 days per 10 years according to model (5).

Predictors of model (7) had no significant trends in 1990–2019 (Fig. 5c, d), there was a slight increase in HTC_{20} (v = 0.003 units per 10 years, p = 0.696) and a decrease in precipitation in the period with temperatures of 5–20 °C in spring (v = –15.3 mm per 10 years, p = 0.310). The climate-related forecast was calculated. For this, only the coefficients at agroclimatic variables, without an intercept, were taken into account. The climate-related change of the yield derived from the equation in differences (7) (v = –0.03 t ha^{-1} per 10 years) is less than actually observed since 1990 (v = –1.3 t ha^{-1} per 10 years) andless than that calculated by equation (4) (v = –0.43 t ha^{-1} per 10 years), which may be caused by the non-climatic reason of the observed significant decrease in the yield in 1990–2002.

Discussion and conclusions

The regression model has shown that that the main factor affecting the yield of sunflower in the North Caucasus Region at last decades of the 20th century was negatively associated with the sums of temperatures and the sums of summer precipitation, and positively with the precipitation in April, the determination coefficient for these traits being 48 %. The analysis in differences made it possible to increase the accuracy of the model up to 58 % and confirmed that the yield is negatively connected with precipitation in the middle of summer having negative connection with the hydrothermal coefficient for the period with temperatures above 20 °C. The yield is lower in those years when the moisture is excessive during the flowering-seed filling period. Precipitation in the spring period with temperatures below 20 °C is positively associated with the yield, i. e., moisture sufficiency during the vegetative stage of the development contributes to high yields.

The analysis in differences made it possible to increase the accuracy of the model of yield and avoid false correlations connected with unidirectional trends of agrobiological and agrometeorological indicators. Refinement of the yield affecting factors by the method of successive differences showed that there may be a trend in its dynamics that is not related to weather and climate conditions.

The regression analysis showed that the rate of sunflower development is regulated differently in temperature ranges up to 15 °C and above 15 °C. The special role of temperature growth above 15 °C for the acceleration of the development rate was demonstrated by us for cereals and potatoes (Novikova et al., 2012; Novikova, Kiru, and Rogozina, 2017). A universal type of temperature dependence for cultures of one climate zone is noted in the literature (Parent and Tardieu, 2012). The model of the cereals' growing season duration that we constructed earlier has the same predictors as model (5), i. e., the negative effect of the sums of temperatures above 15 °C and the positive effect of the spring period with temperatures of 10–15 °C. Therefore, the identified predictors are universal for a number of temperate crops. The temperatures below 15 °C in spring do not accelerate the development; such temperatures contribute to the accumulation of vegetative mass. The transition of temperatures over the 15 °C threshold stimulates the transition to generative development, and the further accumulation of the sum of temperatures accelerates the development.

As for the growing season duration, the structure of the equation does not change with the transition to differences, so a higher quality equation could not be obtained. According to the published sources (Richardson et al., 2012; Yue et al., 2015) and our earlier observations (Novikova et al., 2012), phenology is the most reliable indicator of climatic changes.

If the trend of the last 30 years toward an increase in summer temperatures and a decrease of spring precipitation remains, the growing season of old sunflower varieties will keep reducing and the yield decreasing. Therefore, warming creates opportunities for later and more productive varieties.

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