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# Assessing the impact of climate change on sunflower yields using mathematical modeling

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**Abstract.** The article examines the agroclimatic conditions for influencing sunflower yield formation under the influence of climate change according to the RCP4.5 and RCP8.5 scenarios. Based on a water-heat regime and sunflower productivity formation model, calculations and a comparative analysis of sunflower and seed yields were conducted for the climate periods 1986-2005 and 2031-2050. Under both scenarios, the expected climate and weather conditions are expected to be more favourable for sunflower cultivation in the Eastern Forest-Steppe of Ukraine. The highest risk of sunflower seed yield shortfalls in certain years is anticipated in the Southern Steppe of Ukraine, with the most significant losses expected under the RCP4.5 scenario.

**Keywords:** sunflower, growing season, climate change, agro-climatic conditions, yield shortfall risks.

## 1 Introduction

Global climate change is a significant challenge for humanity as a whole and for individual countries. It is primarily associated with changes in average annual temperatures (in most cases, their increase—referred to as "global warming"), the amount of precipitation (increasing in some regions and decreasing in others), as well as accompanying phenomena such as rising sea levels, glacier melting, and more. These factors lead to substantial socio-economic consequences and create long-term risks for sustainable development. Global climate change has a noticeable impact on the agro-industrial sector, which is quite natural considering the dependence of crop yields and the implementation of basic agricultural practices on weather conditions, which are the short-term manifestation of climate and its dynamics [1,2].

Both foreign and domestic scientists acknowledge that global climate change creates risks for agriculture [3,4,5,6,7]. It is quite clear that agriculture, and particularly crop production,

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is the most climate-dependent and vulnerable sector, meaning it is heavily influenced by climatic factors. On one hand, the yield of major crops is directly related to temperature regimes and moisture levels. On the other hand, crop production is "tied" to specific territories with particular land resources and traditions of their use, among other factors. Adapting to changing conditions is possible only through the development and use of new crop varieties, fundamental adjustments to agricultural practices, and the implementation of new technologies. To assess the effectiveness of such measures, timely monitoring of both ongoing climate changes and the impact of adaptation strategies on the crop production sector must be conducted.

Agriculture worldwide must adapt to the new conditions of global climate change in order to ensure food security for humanity, which is absolutely impossible without forecasting future factors. Therefore, the issue of determining the impact of expected climate changes on the agro-climatic conditions for cultivation, productivity, and total crop yield of major crops, particularly sunflower, becomes more relevant than ever.

In previously published works [8-10] we have presented the results of modeling the impact of climate change on sunflower yield in Ukraine under the RCP2.6 and RCP4.5 scenarios based on a mathematical model for assessing the agro-climatic resources of crop productivity formation.

## 2 Materials and Methods of Research

In this work, the modern scenarios from the RCP (Representative Concentration Pathways) family – RCP4.5 and RCP8.5 – were used to model and assess changes in agro-climatic resources under potential climate change. These scenarios represent medium and high greenhouse gas emission levels [11].

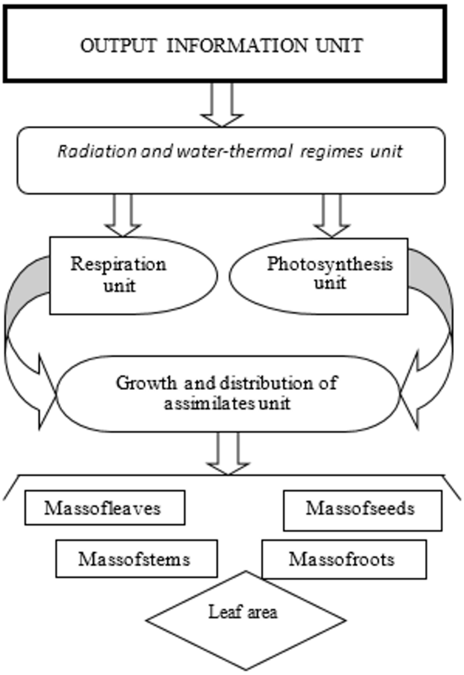

**Fig. 1.** Flowchart of the mathematical model of the water-heat regime and sunflower productivity.

The study of sunflower productivity formation was conducted using a mathematical model of the water-heat regime and sunflower productivity (Fig. 1). models plant growth (accumulation of dry biomass) through the distribution of photosynthesis products, taking into account the need for assimilates for the growth of both aboveground and underground plant parts; simulates plant aging under stress conditions and the transfer of assimilates from leaves, stems, and roots to reproductive organs; and models the impact of agro-meteorological conditions on yield formation during the main interphase periods of sunflower.

Numerical calculations were carried out based on the mathematical model for two climate periods: 1986-2015 [12], which serves as the baseline and from 2031 to 2050 under the RCP4.5 and RCP8.5 scenarios.

Calculations were carried out for the natural-climatic zones of Ukraine: Eastern Forest-Steppe, Northern Steppe, and Southern Steppe.

The impact of agro-climatic conditions on sunflower cultivation was studied during two interphase periods: seedling to flowering and flowering to harvest maturity. To assess the temperature regime and moisture conditions, indicators of average air temperature and total precipitation were used. The assessment of thermal and moisture availability was based on the sums of active and effective temperatures, as well as moisture requirements and consumption.

## 3 Research Results

The water-heat regime and productivity model for sunflower realistically reproduces agro-climatic changes during the sunflower growing periods from seedling to flowering and from flowering to harvest maturity. Specifically, in the period from seedling to flowering, a decrease in average air temperature is expected across the entire studied area (Table 1). The lowest temperature is anticipated in the Southern Steppe, with a decrease of -2.6 °C under the RCP4.5 scenario and -2.4 °C under the RCP8.5 scenario.

The amount of precipitation expected during the seedling to flowering period is projected to decrease in the Eastern Forest-Steppe and Southern Steppe, while it will increase in the Northern Steppe. According to the RCP4.5 climate change scenario, the changes are estimated at -23%, -14%, and +15% respectively, while under the RCP8.5 scenario, they are projected at -15%, -9%, and +15%.

The expected moisture-heat regime under the RCP4.5 and RCP8.5 scenarios will create favorable conditions for good moisture availability in the Eastern Forest-Steppe (0.84 and 0.83 relative units), while in the Northern and Southern Steppe, moisture availability during the seedling to flowering period will remain satisfactory.

In contrast to the first interphase period, the temperature regime during the flowering to harvest maturity period is expected to be higher than the baseline. The greatest deviations (+1.8 °C) under the RCP4.5 scenario are anticipated in the Eastern Forest-Steppe, while under the RCP8.5 scenario, the increase in the Northern Steppe is projected to be +1.2 °C.

The precipitation regime expected during the seedling to flowering period will be characterized by a significant decrease. Specifically, under the RCP4.5 scenario, precipitation in the Eastern Forest-Steppe is expected to decrease by 70%, by 60% in the Northern Steppe, and nearly by half (48%) in the Southern Steppe. Under the RCP8.5 scenario, a significant decrease is also expected in the Eastern Forest-Steppe (65%), but compared to the RCP4.5 scenario, the amount of precipitation will be greater. In the Steppe zone, precipitation in the Northern Steppe is expected to be 44% of the baseline, while in the Southern Steppe, it is projected to be 46%.

The anticipated hot conditions are likely to result in very low moisture availability for sunflower during this growing period. It should be noted that for the Southern Steppe, moisture availability under both scenarios will not decrease significantly (by -9% and -4% respectively), but in the Northern Steppe, moisture provision for sunflower is expected to decrease by 25% and 28%, while in the Eastern Forest-Steppe, it will be 60% and 62% of the baseline.

Overall, during the growing season from seedling to harvest maturity, moisture availability under the RCP4.5 scenario is expected to be slightly higher than the baseline. Under the RCP8.5 scenario, an increase will also be observed in the Eastern Forest-Steppe and Southern Steppe, while in the Northern Steppe, moisture availability is projected to decrease by 20%. The best moisture conditions under both scenarios will be found in the Eastern Forest-Steppe.

**Table 1.**Agro-climatic conditions for sunflower (Helianthus annuus L.) cultivation in Ukraine

| **Natural-climatic zone** | Climatic period, years | Interphase period | | | | | | | | | | Growing season | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Shoots – flowering | | | | | flowering – fully ripe | | | | | | |
| | | $T_{av.}$, °C | $\Sigma_{per}$, mm | $E_{ac}$, mm | $E_o$, mm | V, rel. un. | $T_{av.}$, °C | $\Sigma_{per}$, mm | $E_{ac}$, mm | $E_o$, mm | V, rel. un. | $\Sigma_{per}$, mm | V, rel. un. |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| **Base** | | | | | | | | | | | | | |
| **Eastern Forest-steppe** | 1986-2015 | 18,8 | 162 | 193 | 292 | 0,66 | 18,5 | 98 | 90 | 214 | 0,42 | 260 | 0,56 |
| | **Scenario RCP4.5** | | | | | | | | | | | | |
| | 2031-2050 | 16,9 | 125 | 217 | 258 | 0,84 | 20,3 | 30 | 79 | 316 | 0,25 | 155 | 0,61 |
| | **Scenario RCP8.5** | | | | | | | | | | | | |
| | 2031-2050 | 16,4 | 138 | 192 | 231 | 0,83 | 19,2 | 34 | 63 | 212 | 0,26 | 172 | 0,61 |
| | **Base** | | | | | | | | | | | | |
| **Northern Steppe** | 1986-2015 | 19,2 | 95 | 194 | 277 | 0,70 | 20,7 | 88 | 88 | 275 | 0,32 | 183 | 0,51 |
| | **Scenario RCP4.5** | | | | | | | | | | | | |
| | 2031-2050 | 17,8 | 109 | 177 | 290 | 0,61 | 21,9 | 35 | 71 | 296 | 0,24 | 144 | 0,53 |
| | **Scenario RCP8.5** | | | | | | | | | | | | |
| | 2031-2050 | 18,1 | 109 | 182 | 308 | 0,59 | 21,9 | 38 | 66 | 287 | 0,23 | 147 | 0,41 |
| **Base** | | | | | | | | | | | | | |
| **Southern Steppe** | 1986 - 2015 | 19,8 | 110 | 191 | 329 | 0,58 | 22,7 | 55 | 57 | 248 | 0,23 | 165 | 0,46 |
| | **Scenario RCP4.5** | | | | | | | | | | | | |
| | 2031-2050 | 17,2 | 95 | 153 | 273 | 0,56 | 23,5 | 28 | 73 | 348 | 0,21 | 123 | 0,51 |
| | **Scenario RCP8.5** | | | | | | | | | | | | |
| | 2031-2050 | 17,4 | 100 | 156 | 256 | 0,61 | 23,7 | 25 | 79 | 359 | 0,22 | 125 | 0,52 |

*Note:* $T_{cp.}$, *℃ - average air temperature;* $\Sigma_{per}$, *mm - the amount of precipitation;* $E_{ac}$, *mm - total evaporation;* $E_o$, *mm – evaporation rate; V, rel. un. – moisture supply.*

Agroclimatic conditions that will change under the influence of climate change will cause changes in the photosynthetic activity of sunflower crops, which will determine their yield level. In this study, such indicators are the size of the photosynthetic leaf surface, the formation of the total biomass of crops, and the yield of seeds.

The dynamics of leaf area and total biomass are presented in Figure 2

Leaf area during the period of maximum development (Fig. 2A, 2B, 2C) averaged over the baseline period ranged from 2.2 m²/m² in the Southern Steppe to 2.7 m²/m² in the Northern Steppe. In the 'climate' scenario under RCP4.5, leaf area is expected to increase to 4.0 m²/m² in the Eastern Forest-Steppe, to 2.4 m²/m² in the Southern Steppe, while in the Northern

Steppe, leaf area will remain at the baseline level. In the 'climate + $CO_2$' scenario, an increase in leaf area is anticipated compared to its average long-term value and the 'climate' scenario, specifically: to 4.3 m²/m² in the Eastern Forest-Steppe, to 2.9 m²/m² in the Northern Steppe, and to 2.6 m²/m² in the Southern Steppe.

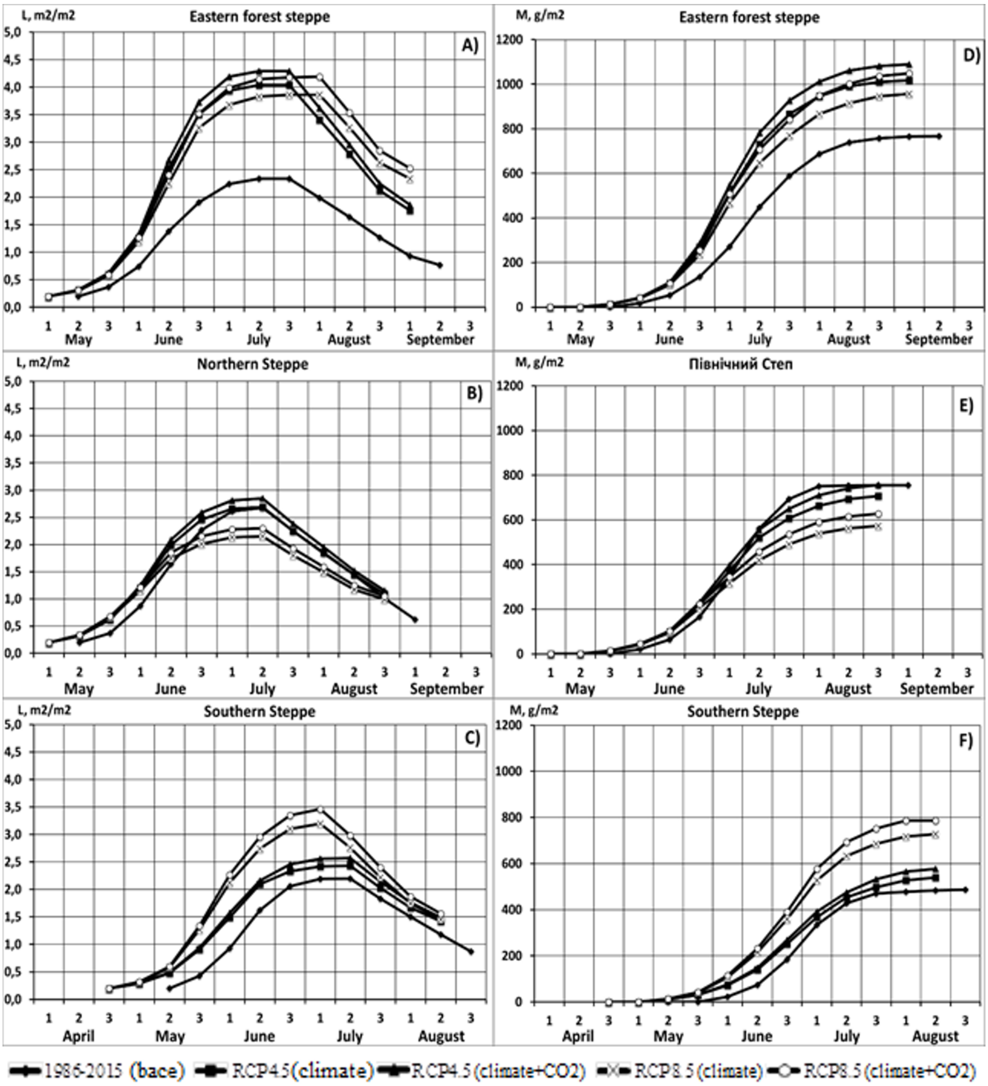

**Fig. 2.** The dynamics of leaf area and dry total biomass of sunflower.

In the implementation of the RCP8.5 scenario, in the 'climate' and 'climate + CO2' variants in the Eastern Forest-Steppe (Fig. 2A), there will be an increase in leaf area compared to the average long-term values, and compared to the values of the first scenario, the maximum values will be almost equal (3.9 m²/m² and 4.2 m²/m²). In the Northern Steppe (Fig. 2B), there will be a decrease in leaf area compared to the average long-term values and the values of the first scenario to 2.2 m²/m² and 2.3 m²/m², respectively. In the Southern Steppe (Fig. 2C), a more significant increase in leaf area is expected compared to the average long-term values of the baseline period and the values of the first scenario, reaching 3.2 m²/m² and 3.5 m²/m², respectively.

The average long-term values of dry biomass of sunflower in the baseline period (Fig. 2D, 2E, 2F) ranged from 768 g/m² in the Eastern Forest-Steppe, gradually decreasing to the south, with 468 g/m² in the Southern Steppe. Under the RCP4.5 and RCP8.5 scenarios, dry biomass is expected to increase in all variants in the Eastern Forest-Steppe and Southern Steppe regions, while it will decrease in the Northern Steppe region.

In the case of implementing the RCP4.5 scenario in the 'climate' variant, the increase will be 33% in the Eastern Forest-Steppe (Fig. 2D), 11% in the Southern Steppe (Fig. 2F), and a decrease of 6% in the Northern Steppe (Fig. 2E). Under the same scenario in the 'climate + CO2' variant, the increase in dry biomass in the Eastern Forest-Steppe and Southern Steppe will be higher compared to both the average long-term values and the values of the 'climate' variant, reaching 1090 g/m² and 578 g/m², which is 42% and 19% higher than the average long-term values of dry biomass, respectively, while in the Northern Steppe it will be almost equal to the average long-term value of the baseline period (757 g/m²).

In the implementation of the RCP8.5 scenario, calculations for the 'climate' variant also indicate an increase in plant dry biomass compared to the average long-term values in the Eastern Forest-Steppe - by 25% (Fig. 2D), and even more significantly (Fig. 2F) in the Southern Steppe (by 50%). In the Northern Steppe, a decrease in dry biomass of 24% is expected (Fig. 2E). In the 'climate + CO2' variant, a significant increase in dry biomass of 61% will be observed in the Southern Steppe. In the Eastern Forest-Steppe, there will be an increase in dry biomass of 36% compared to the average long-term values, while in the Northern Steppe, dry biomass is expected to decrease by 17%.

In certain years, weather conditions may favor sunflower seed yields of 40-50 quintals per hectare, while very unfavorable conditions could lead to a decrease in sunflower crop productivity, causing seed yields to drop to 5-10 quintals per hectare.

To assess the vulnerability of the area and the climatic risk of significant sunflower crop failures in the main cultivation regions, calculations were performed to estimate the expected risks of sunflower seed shortfalls in specific years (from 2031 to 2050) under the RCP4.5 and RCP8.5 scenarios (Fig. 3).

Thus, under the moderate anthropogenic impact scenario RCP4.5, low risks of 2-4% are expected in the Western and Eastern Forest-Steppe (Fig. 3A). In the central part of the Forest-Steppe, Northern Steppe, and the western part of the Donetsk region, moderate risks of crop shortfall are anticipated: specifically, 6.1% in Kyiv region, 8.5% in Cherkasy and Kirovohrad, 10.6% in Kharkiv and Donetsk, and 12.8% in Dnipropetrovsk. High risks of up to 17.2% will be observed in the southwestern part of the Steppe and the eastern part of the Donetsk region. In the central part of the Southern Steppe, significantly high risks of crop shortfall (26%) are expected

In the case of implementing the most aggressive scenario RCP8.5, significantly high risks of crop shortfall are not expected (Fig. 3B). However, in the Southern Steppe region, high risks of crop shortfall (15.5% – 18.0%) will occur everywhere. In the central and eastern parts of the Steppe and Forest-Steppe regions, moderate risks of crop shortfall are anticipated, specifically 7.5% in Cherkasy region, 10.3% in Poltava and Kirovohrad, 13.2% in Kharkiv, and 12.6% in Dnipropetrovsk.

It should be noted that under the climate change scenario RCP4.5, the risk of crop shortfall in Poltava region is expected to be lower by 7% (Fig. 3A).

Low risks of crop shortfall can be expected in the Western Forest-Steppe (0.2%) and in the northern part of the Eastern Forest-Steppe (1.8%). In Kyiv region, compared to the risks under the RCP4.5 climate change scenario, which are expected to be 6.1%, the risks under this scenario will be lower, at 4.2%.

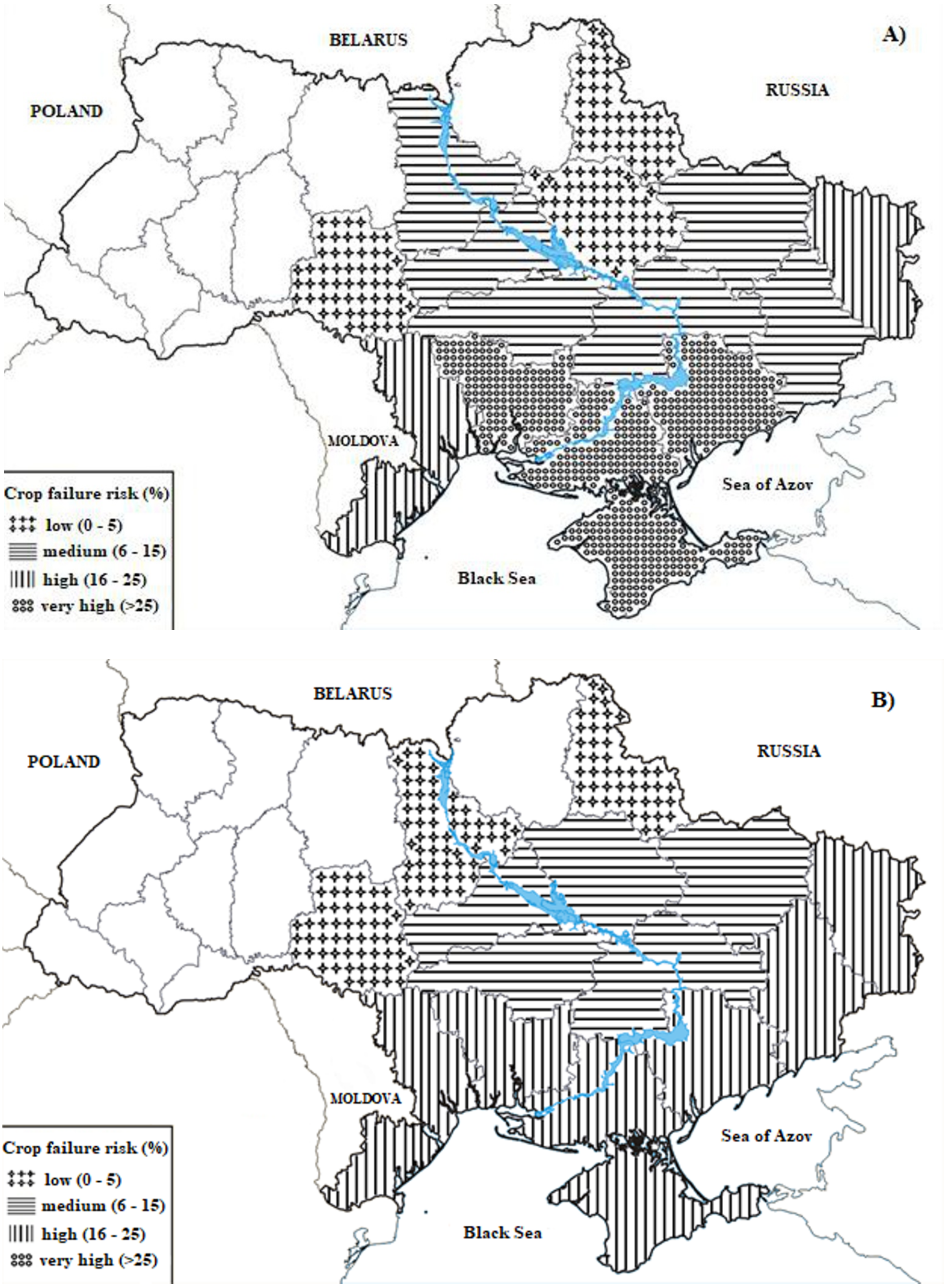

**Fig. 3.** Distribution of expected risks of sunflower seed shortfall (%) in Ukraine from 2031 to 2050: A) under the RCP4.5 scenario, B) under the RCP8.5 scenario.

## 4 Conclusion

The model of water-thermal regime and productivity of sunflower realistically reproduces agroclimatic changes during the periods of sunflower vegetation from germination to flowering and from flowering to harvest maturity. It is expected that during the period of formation of vegetative mass, the best climatic conditions will prevail, and during the period of formation of generative organs, severe drought will be observed. In both scenarios, the risks of crop failure will increase, with high risks expected in the Southern Steppe under the RCP8.5 scenario and very high risks under the RCP4.5 scenario.

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