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YIELD SHORTFALL OF CEREALS IN UKRAINE CAUSED BY THE CHANGE IN AIR TEMPERATURE AND PRECIPITATION AMOUNT

V. O. Balabukh

Ukrainian Hydrometeorological Institute, State Emergency Service of Ukraine,
National Academy Sciences of Ukraine,
37, Nauky prosp., Kyiv, Ukraine, 03028

E-mail: Balabukh@uhmi.org.ua

Orcid: 0000-0003-3223-7531

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Aim. To determine the trends in precipitation patterns, the precipitation productivity, and the cumulative impact of the change in air temperature and precipitation levels on cereal yield, including corn and spring barley, throughout the vegetation cycle stages. Furthermore, the examination of the alterations in the climate suitability, crop yield shortfall, and their specific characteristics within in the soil-climatic zones of Ukraine during 1981–2010 years **Methods.** In order to accomplish the outlined aims conventional and more specific research methods were used: 1) An analytical-synthetic approach – to examine the existing state-of-the art research; 2) A statistical approach – to assess the intensity and significance of changes in agroclimatic conditions pertaining to crop cultivation; 3) A comparative analysis – to determine the specificities mentioned under 2) in soil-climatic zones of Ukraine and in different stages of plant development; 4) A climatic approach – to characterize precipitation levels and to evaluate their impact on crop productivity; 5) modelling – to assess the effect of changes in precipitation amounts on the productivity of corn and spring barley, to assess the cumulative impact of the variations in surface temperature and precipitation on climate productivity and yield shortfall of these crops; 6) application of abstract and logical method – to formulate the generalizations and draw conclusions based on the findings. **Results.** During the years 1981–2010, Ukraine experienced changes in precipitation patterns and increased air temperature throughout the vegetation cycle of corn and spring barley in different soil-climatic zones. These changes had implications for climate suitability and crop productivity. In the Polissia region, although there were increases in precipitation during most of the crops` growth cycle, the changes were insignificant and had a minimal impact on crop productivity, except during certain periods. Similarly, the cumulative coefficient of temperature and precipitation productivity showed low probability for changes in climate suitability and yield shortfalls in the entire Polissia region, maintaining avorable cultivation conditions for corn and spring barley. In the Forest-Steppe region, precipitation changes varied. There was an increase in the amount of precipitation in the western Forest-Steppe. The speed of these changes was 10–20 % in 10 years in certain areas, leading to decreased corn and spring barley productivity by 3–6 % over the same duration. The central Forest-Steppe witnessed increases and decreases in precipitation levels during specific crop development stages, negatively impacting productivity. The eastern Forest-Steppe had increased precipitation deficits during the vegetation cycle, resulting in reduced productivity. Overall, the changes in precipitation and the increased air temperature had unfavorable effects on field crop cultivation in the Forest-Steppe, particularly in the central region. Corn yield shortfalls of 3–5 % and spring barley yield shortfalls of 2–3 % were observed over each 10 years. In general, however, for spring barley favorable agroclimatic conditions persisted throughout the Forest-Steppe, and corn cultivation remained favorable in the western and satisfactory in the central and eastern areas. In the Steppe region, changes in precipitation levels were minimal, with fluctuations of 5 % over each 10 years. However, significant variations in moisture levels occurred during specific crop development stages. An increase in precipitation levels during the stage milky ripeness-middle dough phase of corn resulted in 3 % yield decrease over each 10 years. Spring barley benefited from increased precipitation during the tillering stage and decreased precipitation during the stagemilky ripeness and middle dough stages, leading to higher (precipitation) productivity. Overall, the considerable increase in air temperature and changes in moisture conditions in many cases adversely affected corn and spring barley cultivation, especially in the southern Steppe. These changes led to a 7–

10 % decrease in corn climate suitability cultivation and 3–4 % decrease in spring barley over each 10 years. Corn cultivation conditions in the southern Steppe were deemed unsatisfactory, while those for spring barley remained satisfactory. Yield shortfalls due to the changes in air temperature and precipitation from 1981 to 2010 were 35–40 % for corn and 22–25 % for spring barley. **Conclusions.** The changes in precipitation and air temperature in Ukraine have significant implications for field crop productivity throughout the vegetation cycle. Decreases in precipitation levels during crop ripening stages and higher precipitation deficits during certain vegetation stages have resulted in reduced precipitation suitability and lower crop productivity. When combined with increased air temperature, these changes further contribute to decreased climate productivity and increased yield shortfalls for corn and spring barley. The most pronounced effects are observed in the Steppe region, particularly in the southern Steppe, where corn yield shortfalls due to air temperature and precipitation changes from 1981 to 2010 reached 35–40 % of the maximum potential yield under optimal climatic conditions, compared to 22–25 % for spring barley In contrast, the agroclimatic conditions for corn and spring barley cultivation in Polissia remained favorable throughout the observation period (1981–2010), regardless of changes in air temperature and precipitation. In the Forest-Steppe zone, conditions were favorable for barley cultivation and satisfactory for corn in the central and eastern areas. Abnormally high air temperatures coupled with precipitation deficits have resulted in higher yield shortfalls for cereals in significant areas of the country. The combination of increased air temperature and drier conditions underscores the diminishing potential of dryland farming in Ukraine, particularly in the Steppe region.

Key words: corn, spring barley, agroclimatic conditions, climate suitability, climate change, temperature increase, precipitation change, precipitation productivity, yield shortfall.

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INTRODUCTION

Climate change has a considerable effect on agricultural production and food safety in the world and requires efficient solutions for their adjustment (Asseng et al, 2015; Lobell et al, 2011; FAO, 2021). Modelling and empirical research demonstrated that the observed climate changes led to significant variability in many crops (Field et al, 2014; Challinor et al, 2014; Bassu et al, 2014; Lesk et al, 2016; Polevoy et al, 2007; Balabukh, 2017, Balabukh et al, 2021). It was determined that this effect depended considerably on geographic location and the crop involved. In northern regions of the world, where air temperature increased considerably in spring and summer, there was an increase in the duration of the vegetation period and its heat provision, the conditions for the cultivation of many crops became more favorable and probably would be improved in short- and middle-term (Darwin et al, 1995; Cuculeanu et al, 1999; Isik and Devadoss, 2006; Xuhui Wang et al, 2014 Shrestha et al, 2013). Due to climate changes in these northern cool climate regions, there is generally an increase in crop yield, new varieties are introduced, the crop cultivation areas are expanded and there is a possibility to obtain increased yield (Wang et al, 2014). However, in southern warm climate regions of the world, negative consequences of the climate change on crops are much more significant than the positive ones, and the tendency will accelerate with further temperature increase (Wang et al, 2014; Işık and Devadoss, 2006; Fishman, 2016). The increase in the recurrence and intensity of extreme weather phenomena, especially waves of heat and droughts, conditioned the shortage of moisture and nutrients, a decrease in the productivity and quality of cereals, reduced agricultural production and affected the food safety in the world (Parkes et al, 2018; Cammaranoa et al, 2019; Asseng et al, 2015; Lobell et al, 2011; FAO, 2021). In some countries, negative consequences of climate change get to such a scale that the decrease in the productivity of cereals cannot be compensated even with the application of modern technologies, the introduction of fertilizers and other factors (FAO, 2021).

The changes in air temperature affect the productivity and quality of grain much more than the variations in precipitation, especially if these changes are beyond the limits of the values, optimal for plant growth (Högy et al, 2013; Lobell, 2007). Increase in mean maximum air temperature during the vegetation period causes much more damage to crop productivity than increase in minimal temperature. This effect is more pronounced under precipitation deficiency, especially when precipitation amount during the vegetation period is under 400 mm (Wang et al, 2014; Işık et al, 2006; Blanc, 2012). Precipitation has a considerable effect on the growth of crops and their productivity in dry land, as for example is the case for a large part of Ukraine. The impact of moisture on the productivity of crops is usually evaluated by the cumulative annual amount of precipitation or the amount of precipitation available during the vegetation period (Dmitrenko, 1973; Schipper et al, 2010). However, climate change also often induces re-distribution of precipitation both during the year and during the vegetation period which can substantially affect crop productivity (Balabukh et al, 2022). Understanding of the way, in which different climate factors interact and affect crop productivity during their vegetation cycle enables elaboration of efficient agricultural adjustment strategies towards the effects of climate change (Porter et al, 2014; Schipper et al, 2019)

The aim of this study was to determine the tendencies in changes in precipitation (amount and periodicity), the precipitation suitability and the cumulative impact of changes in air temperature and precipitation amount on the yield of crops, the change in the climate suitability, yield shortfall of crops and their specificities in the soil-climatic zones of Ukraine over 1981–2020 years.

MATERIALS AND METHODS

The effect of agrometeorological conditions on corn and spring barley productivity was evaluated using the hydrometeorological methodology of the so-called Weather-Yield model, developed by V.P. Dmitrenko, including the cumulative climate suitability coefficient *S (T, R)*, which characterizes the impact of the air temperature (T) and the precipitation amount (*R*) during the main stages of field crop development. This coefficient is a leading agrometeorological factor in measuring effects of climate change on agricultural suitability, i.e. soil fertility and crop yield (reduction) (Dmitrenko, 2010; Dmitrenko et al, 2017). The value of the cumulative productivity coefficient allows optimization of the spatial location of field crops by the degree of climate suitability, and evaluation of the unprofitability of some factors of meteorological origin in the form of yield shortfall. The cumulative productivity (suitability) coefficient of climate is calculated by the following formula (Dmitrenko VP, 2010):

$$S(T, R) = \Sigma^{n}_{i=1}\eta(T_i)\eta(R_i) \cdot \alpha_i \tag{1}$$

where $\eta(T_i)$, $\eta(R_i)$ – productivity coefficients, which describe the effect of air temperature and precipitation on the yield during the *i*-th stage of the vegetation cycle; α_i – a weighing factor for contribution of the duration of each *i*-th stage of the vegetation cycle to the productivity level under optimal conditions of temperature and precipitation

The temperature productivity coefficient $\eta(T)$ characterizes the degree of correspondence between thermal conditions and the needs of plants and is calculated according to the formula (Dmytrenko VP, 2010):

$$\eta(T) = \frac{y(T)}{Y(T_{opt})} = \left(\left(1 + \frac{T - T_{opt}}{T_{opt} - T_{min}}\right)^{q_1}\left(1 - \frac{T - T_{opt}}{T_{opt} - T_{max}}\right)^{q_2}\right), \tag{2}$$

where $y(T)$ – productivity under current thermal conditions T; $Y(T_{opt})$ – productivity under optimal temperature T_{opt} during each period of the vegetation cycle; T_{min}, T_{max} – biological extremes of temperature in the corresponding period of the vegetation cycle; q_1, q_2 – model parameters which are determined by the formulas:

$$q_1 = \frac{T_{opt}}{T_{max}}, \tag{3}$$

$$q_2 = 1 - q_1 = 1 - \frac{T_{opt}}{T_{max}}. \tag{4}$$

The coefficient of crop productivity by the precipitation amount characterized the degree of correspondence of the moisturization conditions to the needs of plants in all the stages of the vegetation cycle, except for the ripening stage, and is described by the equation (Dmytrenko, 2010):

$$\eta(R) = \frac{y(R)}{Y(R_{opt})} = \left(\left(1 + \frac{R - R_{opt}}{R_{opt} - R_{min}}\right)^{v_1}\left(1 - \frac{R - R_{opt}}{R_{opt} - R_{max}}\right)^{v_2}\right), \tag{5}$$

where $y(R)$ – productivity under the current amount of precipitation R; $Y(R_{opt})$ – maximum productivity under the optimum amount of precipitation R_{opt} during a certain stage of the vegetation cycle; R_{min}, R_{max} – biological extremes of the precipitation amount in the corresponding stage of the vegetation cycle; v_1, v_2 – model parameters, determined by the formulas:

$$v_1 = \frac{R_{opt}}{R_{max}}, \tag{6}$$

$$v_2 = 1 - v_1 = 1 - \frac{R_{opt}}{R_{max}}. \tag{7}$$

The determination of the correspondence of the thermal regime and the precipitation amount to the needs of the field crop for all the stages of the vegetation cycle was conducted using the cumulative productivity coefficient $\eta(T, R)$ (Dmitrenko, 2010):

$$\eta(T, R) = \eta(T)\eta(R) \tag{8}$$

The obtained values of the cumulative productivity coefficient were transformed into percentages and the suitability scale (Dmitrenko, 2010) was used to estimate the correspondence of the regime of heat and moisture to the needs of the field crop: 86–100 % – favorable, 66–85 % – satisfactory, 36–65 % – unsatisfactory, 16–35 % – very unsatisfactory, 0.0–15 % extreme.

The value of the climate suitability index can be used to estimate the climatic yield shortfall δy_c by the formula (Dmitrenko, 2010):

$$\delta y_c = 100 - S(T, R) \qquad (9)$$

The study on the cumulative influence of changes in precipitation amount and air temperature on the crop productivity was conducted using daily data about the precipitation amount and the average daily air temperature from the network of hydrometeorological monitoring of Ukraine (187 points) for 1981–2010 [CGO. Sectoral State Archive of hydrometeorological observations of the State Emergency Service of Ukraine].

The optimum values of precipitation amount in specific vegetative stages of corn and spring barley in Ukraine are presented in **Table 1**.

The average values of air temperature, precipitation amount, the coefficients of temperature and precipitation productivity, and the cumulative productivity coefficient for 1981–2010 were determined for each phase of the vegetative cycle of corn and spring barley and the mentioned scale was used to estimate the correspondence of the heat and moisture regime to the needs of field crops in all the soil-climatic zones of Ukraine. The evaluation of the intensity, relevance, and significance of the changes in the average annual values of the agroclimatic indices was conducted for the period under investigation. The coefficient of the linear trend (*a*), characterizing the rate and direction of their change, was used as a measure of intensity in the change of indices. The significance of the coefficients of the linear trend (p) was evaluated by Student's t-criterion. According to the recommendation of the Intergovernmental Panel on Climate Change (IPCC, 2014; IPCC, 2021), the following relevant criteria were used: $p \leq 0.01$, probability – 99–100 %, the change is practically undoubted; $0.01 < p \leq 0,1$, probability – 90–99 %, the change is very probable; $0.1 < p \leq 0.34$, probability – 66–90 %, the change is probable; $0.34 < p \leq 0.67$, probability – 33–66 %, the change is both probable and improbable; $0.67 < p \leq 0.90$, probability – 10–33 %, the change is hardly probable; $0.90 < p \leq 0 .99$, probability – 1–10 %, the change is ever hardly probable; $p > 0.99$, probability – 0–1 %, the change is of extremely low probability. The evaluation of intensity, and significance of the change in the average annual values of the agroclimatic indices was conducted for each administrative region of Ukraine and for its soil climatic zones using these indices (*a* and *p*): Forest (Polissia), Forest-Steppe (western, central, eastern Forest-Steppe), and Steppe (northern and southern Steppe). The comparative analysis of agroclimatic indices changes demonstrated their specificities in the soil climatic zones of Ukraine and in different stages of plant development, and the abstract logical methods helped form generalizations and conclusions.

RESULTS

The influence of the change in the precipitation amount on corn productivity by the stages of crop development during 1981–2010. The analysis of precipitation levels during the vegetation cycle of corn cultivation during 1981–2010 revealed notable variation in moisture conditions across different agroclimatic zones in Ukraine. The presowing period exhibited sig-

Table 1. The optimum values of the precipitation amount (mm) and air temperature (^{o}C) in specific stages of corn and spring barley vegetation in Ukraine (according to Dmitrenko, 2010)

Field crop	Vegetative stages (months)	Optimum precipitation amount Ropt, mm	Optimum air temperature, Topt, ^{o}C
Spring barley	Presowing (December–February)	100	–1
	Sowing–tillering (March–April)	100	4
	Tillering–stem elongation (May)	120	13
	Stem elongation–milky ripeness (June)	90	18
	Milky ripeness–middle dough (July)	<10	19
Corn	Presowing period (December–March)	170	–1
	Sowing–third leaf (April–May)	100	12
	Third leaf–panicle emergence (June–July)	180	18
	Panicle emergence–milky ripeness (August)	70	18
	Milky ripeness–middle dough (September)	10	12

nificantly lower precipitation amounts (16–38 % below optimum values) in Polissia, western and central Forest-Steppe, and southern Steppe, insufficient moisture for corn sowing. The moisturization conditions during this stage were more or less satisfactory in the eastern Forest-Steppe and southern Steppe (**Table 2**).

During the third leaf to panicle emergence stage of corn, unfavorable moisturization conditions were observed in the eastern Forest-Steppe and the Steppe of Ukraine. In the final milky ripeness to middle dough stage, excessive moisturization and unsatisfactory cultivation conditions in all the agroclimatic zones were present (Table 2).

Table 2. Agroclimatic conditions of corn cultivation during 1981–2010

Stages of development	T, °C	$T–T_{opt}$, °C	R, mm	$R–R_{opt}$, mm	$R–R_{opt}$, %	$\eta(T, R)$, %
Polissia						
Presowing period	–1.9	–0.9	146	–64	–38	84
Sowing – third leaf	11.4	–0.6	101	1	1	93
Third leaf – panicle emergence	18.2	0.2	174	–6	–30	86
Panicle emergence – milky ripeness	18.2	0.2	61	–9	–13	77
Milky ripeness – middle dough	13.1	1.1	60	50	500	65
Western Forest-Steppe						
Presowing period	–1.6	–0.6	142	–28	–16	85
Sowing – third leaf	10.5	–1.5	204	104	104	91
Third leaf – panicle emergence	17.1	–0.9	183	3	2	90
Panicle emergence – milky ripeness	17.4	–0.6	75	5	7	80
Milky ripeness – middle dough	12.8	0.8	60	50	500	60
Central Forest-Steppe						
Presowing period	–1.9	–0.9	136	–34	–20	84
Sowing – third leaf	11.8	–0.2	99	–1	–1	91
Third leaf – panicle emergence	18.8	0.8	169	–11	–6	82
Panicle emergence – milky ripeness	18.9	0.9	64	–6	–9	70
Milky ripeness – middle dough	13.8	1.8	58	48	480	60
Eastern Forest–Steppe						
Presowing period	–2.5	–1.5	156	–14	–8	82
Sowing – third leaf	11.8	–0.2	90	–10	–10	89
Third leaf – panicle emergence	19.4	1.4	138	–42	–23	70
Panicle emergence – milky ripeness	19.3	1.3	48	–22	–31	57
Milky ripeness – middle dough	13.8	1.8	54	44	440	57
Northern Steppe						
Presowing period	–2.3	–1.3	155	–15	–9	85
Sowing – third leaf	12.4	0.4	86	–14	–14	88
Third leaf – panicle emergence	20.4	2.4	127	–53	–29	65
Panicle emergence – milky ripeness	20.6	2.6	43	–27	–39	49
Milky ripeness – middle dough	15.0	3.0	47	37	370	49
Southern Steppe						
Presowing period	–0.2	0.8	134	–36	–21	81
Sowing – third leaf	12.9	0.9	74	–26	–26	80
Third leaf – panicle emergence	21.4	3.4	107	–73	–40	44
Panicle emergence – milky ripeness	21.9	3.9	40	–30	–43	26
Milky ripeness – middle dough	16.6	4.6	43	33	330	28

Note. R_{opt} – optimum precipitation amoun for stages of development, mm; R – precipitation amount for stages of development in 1981–2010; T_{opt} – optimum air temperature for stages of development, °C; T – average air temperature for stages of development in 1981–2010; $\eta(T, R)$ – cumulative productivity coefficient.

Quantitative evaluation indicated mainly satisfactory conditions for corn cultivation during the presowing period in all agroclimatic zones, with favorable conditions during the sowing-third leaf stage (Table 2). However, during the third leaf–panicle emergence stage, only Polissia and the western Forest-Steppe exhibited favorable conditions, while the central Forest-Steppe experienced satisfactory conditions and the eastern Forest-Steppe and the Steppe of Ukraine faced unfavorable ones. During the milky ripeness – middle dough stage, all soil-climatic zones exhibited unfavorable conditions, with productivity levels ranging only 28 to 65 % of the maximal potential (Table 2).

The climate suitability index *S*(*T,R*) provided insights into the overall suitability of corn cultivation in the agroclimatic zones of Ukraine from 1981 to 2010. Corn cultivation was determined to be favorable in Polissia and the western Forest-Steppe (85–86 %), satisfactory in the central and eastern Forest-Steppe and northern Steppe (72–82 %) and unfavorable in the southern Steppe (56 %) based on the maximum productivity level.

The agroclimatic conditions for corn cultivation significantly changed towards the end of the 20th and the beginning of the 21st century. Notably, there was an overall increase in air temperature throughout the entire vegetation cycle of corn across all soil-climatic zones in Ukraine. This rise in temperature influenced temperature productivity and negatively impacted crop productivity formation (Balabukh et al, 2021). The combined effect of temperature and precipitation changes had varying impact on corn productivity during different stages of development and exhibited specific characteristics in each soil-climatic zones of Ukraine

Polissia. The analysis of precipitation changes in Polissia from 1981 to 2010 revealed an overall increase in precipitation levels throughout the entire vegetation cycle of corn, particularly in the presowing period. However, exceptions were observed in Zhytomyr and Chernihiv districts during the third leaf to panicle emergence stage, where there was an increase in precipitation deficit by 18–19 %, and a 5 % decrease during the blossoming stage over 10 years in the Chernihiv region (**Table 3**). The impact of precipitation on productivity remained relatively stable throughout the vegetation cycle, with only a probable increase observed during the presowing period in Volyn and Rivne regions (**Table 4**).

The cumulative coefficient of temperature and precipitation productivity in Polissia exhibited significant changes only during the presowing period, with a probable increase observed (**Table 5**). However, the change in the climate suitability and corn yield shortfall was considered to be hardly probable, i.e. statistically virtually insignificant (**Table 6**).

Forest-Steppe. Moisturization patterns also underwent changes during the vegetation cycle of corn, albeit unevenly. In the western Forest-Steppe, there was an increase in precipitation levels throughout most of the vegetation stages (Table 3). The most significant changes were observed in the Lviv region, with a probable and very probable increase in precipitation by 10–20 % over 10 years during each stage of crop development. However, these changes had unfavorable implications for corn cultivation, particularly during the milky ripeness to middle dough stage, resulting in 4–5 % decrease in crop productivity over 10 years (Table 4).

In the central Forest-Steppe, the precipitation amount increased only during the presowing period, and blossoming, and milky ripeness to middle dough stages. These changes ranged from 5–10 % over 10 years. However, during corn sowing, germination, and the third leaf to panicle emergence stage, precipitation decreased by an average of 4–10 % over 10 years in the region (Table 3). In the Kyiv and Cherkasy regions, these changes were even more pronounced, reaching 13 % over 10 years. The increased moisture deficit and excess were detrimental to corn cultivation throughout the vegetation cycle, except during the presowing period, leading to a decreased crop productivity, as evidenced by changes in the precipitation productivity coefficient (Table 4).

The eastern Forest-Steppe experienced a significant decrease in precipitation levels throughout almost the entire corn vegetation cycle, except during the milky ripeness to middle dough and the presowing stage. The highest increase in moisture deficit was observed in the Sumy region. These changes resulted in decreased precipitation productivity during almost the entire corn vegetation cycle, particularly during the blossoming and the milky ripeness to middle dough stage (Table 4).

The analysis of the cumulative coefficient of temperature and precipitation productivity revealed predominantly unfavorable changes in temperature and precipitation for corn cultivation in the Forest-Steppe, particularly during the vegetation cycle, except for the presowing period (Table 6). These unfavorable conditions were most pronounced in the central and eastern Forest-Steppe during the third leaf to panicle emer-

Table 3. Changes in precipitation rate during the stages of the vegetation cycle of corn cultivation and its significance (*p*)

Soil-climatic zone, administrative region	The stages of the vegetation cycle of corn cultivation														
	Presowing (XII–III)			Sowing – germination (IV–V)			Third leaf – panicle emergence (VI–VII)			Anthesis (VIII)			Milky ripeness – middle dough (VII)		
	1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change	
		a	*p*		*a*	*p*		*a*	*p*		*a*	*p*		*a*	*p*
Polissia															
Chernihiv	160	7.4	0.36	99	0.4	0.96	156	–17.6	0.08	60	–5.4	0.38	60	0.3	0.97
Volyn	146	14.4	0.03	104	8.8	0.07	172	11.1	0.34	63	18.0	0.02	60	1.6	0.82
Rivne	133	12.3	0.07	101	3.9	0.50	186	6.0	0.68	58	7.6	0.21	59	6.8	0.31
Zhytomyr	145	7.0	0.28	101	4.8	0.46	181	–19.2	0.15	64	3.0	0.67	59	–0.1	0.98
Western Forest-Steppe															
Lviv	160	18.5	0.02	128	11.9	0.10	185	15.5	0.20	77	9.4	0.19	70	9.2	0.25
Ternopil	141	5.1	0.46	113	–1.6	0.83	178	–1.8	0.88	72	2.1	0.78	60	9.8	0.21
Chernivtsi	124	9.1	0.27	122	–5.9	0.55	186	18.0	0.14	75	14.9	0.15	50	10.5	0.17
Central Forest-Steppe															
Kyiv	138	7.0	0.29	98	–0.6	0.92	160	–12.8	0.10	59	0.9	0.87	56	5.1	0.51
Vinnytsia	129	6.7	0.10	103	–8.1	0.25	180	–8.5	0.47	66	4.4	0.62	59	5.2	0.55
Cherkasy	139	5.8	0.49	88	–3.7	0.51	147	–13.4	0.16	55	–1.8	0.76	57	10.5	0.19
Khmelnytsky	138	4.3	0.50	107	–5.5	0.48	196	–3.8	0.76	75	9.6	0.33	59	7.3	0.33
Eastern Forest-Steppe															
Poltava	157	5.5	0.54	89	–2.6	0.64	135	0.6	0.95	48	–7.6	0.13	56	14.5	0.05
Kharkiv	159	7.5	0.35	88	–0.5	0.94	131	–0.1	0.99	43	–5.4	0.18	51	9.1	0.20
Sumy	150	4.3	0.60	93	–4.6	0.41	148	–11.0	0.25	54	–11.3	0.07	56	–0.1	0.99
Northern Steppe															
Luhansk	159	5.8	0.48	87	–3.5	0.62	123	–0.9	0.92	38	–5.1	0.22	49	9.2	0.21
Kirovohrad	131	10.8	0.21	83	–2.8	0.64	145	–3.8	0.69	52	–1.0	0.88	53	15.5	0.04
Dnipropetrovsk	150	13.1	0.12	85	1.5	0.79	120	–0.2	0.98	43	0.3	0.96	43	10.1	0.15
Donetsk	179	15.8	0.14	88	0.2	0.97	121	–6.3	0.56	38	–2.1	0.66	44	6.5	0.33
Southern Steppe															
Odesa	126	8.4	0.34	72	0.3	0.97	111	–8.0	0.26	43	–0.3	0.96	47	9.3	0.24
Zaporizhzhia	160	10.1	0.30	81	1.3	0.84	111	–10.3	0.35	37	1.1	0.89	39	7.2	0.33
Mykolayiv	123	8.8	0.30	75	–1.5	0.81	117	1.9	0.82	43	–2.0	0.72	47	8.7	0.28
Kherson	125	13.5	0.08	69	–2.9	0.62	90	3.0	0.72	36	1.1	0.86	38	8.8	0.11
AR of Crimea	177	10.9	0.26	68	–5.9	0.22	90	–5.4	0.48	46	0.1	0.99	42	4.6	0.47
Ukraine	**159**	**10.7**	**0.10**	**97**	**–1.4**	**0.73**	**147**	**–2.7**	**0.68**	**56**	**0.9**	**0.82**	**55**	**7.0**	**0.20**

Note. *a* – the coefficient of the linear trend , %/10 years ; *p* – the significance of the coefficients of the linear trend.

Table 4. The change rate in the productivity coefficient of precipitation during the stages of the vegetation cycle of corn cultivation and its significance (*p*)

Soil-climatic zone, administrative region	The stages of the vegetation cycle of corn cultivation														
	Presowing (XII–III)			Sowing – germination (IV–V)			Third leaf – panicle emergence (VI–VII)			Anthesis (VIII)			Milky ripeness – middle dough (VII)		
	1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change	
		a	*p*		*a*	*p*		*a*	*p*		*a*	*p*		*a*	*p*
Polissia															
Chernihiv	98.4	–0.2	0.62	98.2	–0.2	0.67	97.1	–0.4	0.57	96.4	–1.3	0.07	82.6	–0.2	0.94
Volyn	97.7	1.0	0.07	98.8	–0.3	0.53	96.9	0.1	0.94	95.4	–0.7	0.71	82.5	–1.2	0.72
Rivne	96.9	0.9	0.10	98.6	0.5	0.35	95.9	0.4	0.72	96.3	–0.3	0.75	83.1	–3.3	0.27
Zhytomyr	98.0	0.4	0.44	98.3	–0.2	0.66	96.7	0.5	0.48	95.9	0.3	0.75	83.4	–0.5	0.84
Western Forest-Steppe															
Lviv	98.3	0.3	0.38	96.7	–1.9	0.07	97.1	–0.3	0.82	96.9	–2.0	0.08	78.4	–4.4	0.23
Ternopil	97.6	0.7	0.24	97.6	–1.4	0.16	97.2	–0.6	0.47	96.6	–1.6	0.19	82.5	–4.6	0.19
Chernivtsi	95.4	0.9	0.32	95.4	–1.1	0.43	97.0	–0.3	0.74	94.0	–3.1	0.12	86.0	–4.4	0.16
Central Forest-Steppe															
Kyiv	97.5	–0.1	0.92	98.1	–0.5	0.33	98.2	–0.7	0.16	96.6	–1.1	0.29	84.2	–2.4	0.45
Vinnytsia	96.6	0.6	0.41	97.7	–0.7	0.25	97.3	0.5	0.48	94.2	–0.8	0.45	82.7	–2.4	0.52
Cherkasy	96.9	–0.9	0.24	98.0	–0.6	0.37	96.8	–0.5	0.46	95.7	–1.7	0.20	83.2	–4.4	0.19
Khmelnytsky	97.5	0.5	0.42	97.5	–0.5	0.55	96.9	0.1	0.83	94.6	–1.8	0.31	83.1	–3.5	0.28
Eastern Forest-Steppe															
Poltava	98.0	–0.1	0.85	98.1	–0.9	0.03	95.7	0.8	0.40	94.6	–2.3	0.11	83.7	–6.1	0.03
Kharkiv	98.3	–0.2	0.64	97.8	–0.4	0.50	95.4	0.2	0.83	94.8	–1.9	0.11	85.8	–3.9	0.16
Sumy	97.8	0.5	0.44	98.4	–0.8	0.09	96.7	–0.1	0.88	95.0	–3.6	0.00	84.6	0.1	0.97
Northern Steppe															
Luhansk	98.4	–0.1	0.75	97.2	–0.7	0.31	94.1	–0.4	0.74	92.6	–1.6	0.41	86.4	–3.4	0.23
Kirovohrad	96.1	0.0	0.96	97.2	–1.0	0.28	96.5	0.3	0.73	94.6	–1.2	0.41	84.6	–6.3	0.04
Dnipropetrovsk	97.7	0.2	0.75	97.7	–1.0	0.09	94.6	0.2	0.82	91.7	–1.0	0.66	88.8	–3.6	0.18
Donetsk	97.9	–1.0	0.09	97.6	–1.1	0.10	92.9	–0.6	0.70	91.7	–1.9	0.33	88.5	–2.3	0.37
Southern Steppe															
Odesa	95.2	1.0	0.45	95.8	–0.2	0.88	93.3	–1.8	0.17	93.6	–2.2	0.14	87.2	–3.0	0.37
Zaporizhzhia	97.7	0.2	0.70	96.7	–1.3	0.15	91.1	–1.5	0.39	86.5	–3.7	0.21	90.3	–2.4	0.43
Mykolayiv	95.1	0.4	0.72	96.0	–1.0	0.41	93.6	0.2	0.87	93.3	–1.8	0.20	86.7	–2.8	0.39
Kherson	95.6	0.7	0.45	95.4	–1.4	0.18	88.1	0.7	0.71	88.8	–2.9	0.20	91.1	–2.8	0.18
AR of Crimea	98.3	–0.2	0.62	95.8	–1.9	0.04	88.3	–1.0	0.62	90.6	–3.8	0.05	89.8	–1.2	0.65
Ukraine	**98.8**	**0.1**	**0.86**	**99.3**	**–0.6**	**0.02**	**97.9**	**–0.1**	**0.86**	**97.8**	**–1.1**	**0.05**	**85.2**	**–2.9**	**0.21**

Note. *a* – the coefficient of the linear trend, %/10 years ; *p* – the significance of the coefficients of the linear trend.

Table 5. The change rate in the cumulative coefficient of T and R productivity during the stages of the vegetation cycle of corn cultivation and its significance (*p*)

Soil-climatic zone, administrative region	The stages of the vegetation cycle of corn cultivation														
	Presowing (XII–III)			Sowing – germination (IV–V)			Third leaf – panicle emergence (VI–VII)			Anthesis (VIII)			Milky ripeness – middle dough (VII)		
	1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change	
		a	*p*		*a*	*p*		*a*	*p*		*a*	*p*		*a*	*p*
Polissia															
Chernihiv	12.7	0.6	0.36	24.3	–0.1	0.87	33.7	–1.8	0.11	12.5	–1.1	0.01	5.2	–0.2	0.39
Volyn	13.0	0.4	0.45	24.6	0.0	0.99	35.5	–0.3	0.60	12.8	–0.2	0.53	5.1	0.0	0.82
Rivne	12.9	0.5	0.37	24.4	0.2	0.61	35.0	–0.3	0.58	12.9	–0.2	0.47	5.1	–0.2	0.48
Zhytomyr	13.1	0.5	0.34	24.3	0.0	0.97	35.0	–0.7	0.28	12.7	–0.3	0.31	5.2	–0.1	0.62
Western Forest-Steppe															
Lviv	13.1	0.2	0.67	24.0	–0.4	0.28	35.8	0.1	0.90	13.1	–0.3	0.19	4.8	–0.2	0.43
Ternopil	13.0	0.5	0.31	24.3	–0.3	0.45	35.8	–0.2	0.65	12.9	–0.4	0.15	5.0	–0.3	0.31
Chernivtsi	12.7	0.3	0.56	22.6	–0.8	0.16	34.3	–2.2	0.00	11.8	–1.3	0.00	4.5	–0.1	0.60
Central Forest-Steppe															
Kyiv	13.0	0.5	0.34	23.4	–0.4	0.44	33.3	–2.7	0.02	12.1	–1.2	0.02	4.8	–0.3	0.13
Vinnytsia	12.9	0.5	0.32	23.7	–0.5	0.30	34.4	–1.8	0.03	12.0	–0.9	0.04	4.8	–0.2	0.43
Cherkasy	12.9	0.3	0.53	22.9	–0.5	0.36	31.7	–3.1	0.01	11.4	–1.5	0.01	4.5	–0.4	0.07
Khmelnytsky	13.0	0.5	0.34	24.1	–0.2	0.57	35.4	–0.6	0.30	12.5	–0.6	0.09	5.0	–0.2	0.33
Eastern Forest-Steppe															
Poltava	12.9	0.5	0.37	22.5	–0.4	0.53	29.6	–2.7	0.08	10.8	–1.7	0.01	4.4	–0.6	0.02
Kharkiv	12.6	0.5	0.41	22.8	–0.1	0.92	29.0	–2.9	0.08	10.8	–1.8	0.00	4.6	–0.5	0.03
Sumy	12.3	0.6	0.34	24.4	–0.3	0.46	33.2	–1.7	0.17	12.2	–1.4	0.00	5.3	–0.2	0.41
Northern Steppe															
Luhansk	12.7	0.4	0.48	22.4	0.1	0.87	26.3	–2.9	0.11	9.7	–1.7	0.02	4.2	–0.5	0.03
Kirovohrad	12.9	0.4	0.44	22.5	–0.6	0.38	29.7	–3.2	0.02	10.2	–1.7	0.01	4.1	–0.5	0.08
Dnipropetrovsk	13.2	0.4	0.34	21.4	–0.5	0.52	25.7	–3.5	0.06	8.7	–1.8	0.01	3.7	–0.5	0.10
Donetsk	13.2	0.2	0.56	22.5	–0.4	0.58	25.4	–3.8	0.06	8.7	–2.0	0.01	3.8	–0.6	0.04
Southern Steppe															
Odesa	11.7	–0.2	0.72	20.3	–1.1	0.18	22.8	–4.9	0.00	7.1	–2.1	0.00	2.5	–0.2	0.50
Zaporizhzhia	13.3	0.2	0.53	21.1	–0.7	0.38	21.6	–3.8	0.03	6.8	–1.9	0.00	3.0	–0.5	0.08
Mykolayiv	12.4	0.1	0.91	20.3	–1.1	0.21	22.8	–4.3	0.01	7.2	–2.0	0.00	2.8	–0.3	0.31
Kherson	12.1	–0.1	0.84	20.6	–1.2	0.10	18.6	–3.9	0.01	5.7	–1.8	0.00	2.4	–0.4	0.12
AR of Crimea	9.4	–0.9	0.15	22.9	–0.8	0.14	22.7	–4.5	0.00	6.5	–2.1	0.00	2.2	–0.4	0.10
Ukraine	**13.5**	**0.2**	**0.55**	**24.0**	**–0.3**	**0.40**	**32.2**	**–3.1**	**0.01**	**11.3**	**–1.6**	**0.00**	**4.3**	**–0.4**	**0.10**

Note. *a* – the coefficient of the linear trend , %/10 years ; *p* – the significance of the coefficients of the linear trend.

gence and blossoming and milky ripeness to middle dough stages (Table 5). Changes in air temperature and precipitation had a probable and very probable negative impact on climate suitability and yield shortfall, resulting in a 3–5 % decrease in yield over 10 years, especially in the central and eastern Forest-Steppe (**Table 7**).

In the Steppe zone, the changes in the precipitation level fluctuated between –5 and 5 % over each 10-year period throughout almost the entire corn vegetation cycle (Table 3). These changes in precipitation were found to be insignificant for the Steppe zone. However, exceptions were observed during the pre-sowing period and the milky ripeness to middle dough stage, where there was an average increase of 10–15 % in the precipitation 10 years in the region. Despite these changes, the overall effect of this fluctuation in moisture was unfavorable for corn cultivation throughout the entire vegetation period, as indicated by a decrease in the precipitation produc-

Table 6. The change rate in the climate suitability and corn yield shortfall at the during 1981–2010 in the soil-climatic zones of Ukraine and its significance (*p*)

Soil-climatic zone, administrative region	Climate suitability			Yield shortfall		
	1981–2010	change		1981–2010	change	
		a	*p*		*a*	*p*
Polissia						
Chernihiv	88.4	–2.5	0.120	11.6	2.5	0.120
Volyn	91.0	–0.2	0.798	9.0	0.2	0.798
Rivne	90.3	–0.05	0.957	9.7	0.05	0.957
Zhytomyr	90.3	–0.6	0.548	9.7	0.6	0.548
Western Forest-Steppe						
Lviv	90.7	–0.7	0.432	9.3	0.7	0.432
Ternopil	91.0	–0.6	0.438	9.0	0.6	0.438
Chernivtsi	85.9	–4.2	0.001	14.1	4.2	0.001
Central Forest-Steppe						
Kyiv	86.5	–4.1	0.011	13.5	4.1	0.011
Vinnytsia	87.7	–2.9	0.018	12.3	2.9	0.018
Cherkasy	83.4	–5.2	0.005	16.6	5.2	0.005
Khmelnytsky	89.9	–1.2	0.158	10.1	1.2	0.158
Eastern Forest–Steppe						
Poltava	80.3	–4.9	0.014	19.7	4.9	0.014
Kharkiv	79.8	–4.9	0.020	20.2	4.9	0.020
Sumy	87.4	–2.9	0.089	12.6	2.9	0.089
Northern Steppe						
Luhansk	75.3	–4.7	0.035	24.7	4.7	0.035
Kirovohrad	79.4	–5.6	0.008	20.6	5.6	0.008
Dnipropetrovsk	72.8	–5.8	0.008	27.2	5.8	0.008
Donetsk	73.6	–6.5	0.005	26.4	6.5	0.005
Southern Steppe						
Odesa	64.4	–8.5	0.000	35.6	8.5	0.000
Zaporizhzhia	65.8	–6.7	0.003	34.2	6.7	0.003
Mykolayiv	65.6	–7.6	0.002	34.4	7.6	0.002
Kherson	59.4	–7.5	0.001	40.6	7.5	0.001
AR of Crimea	63.8	–8.7	0.000	36.2	8.7	0.000
Ukraine	**85.2**	**–5.1**	**0.001**	**14.8**	**5.1**	**0.001**

Note. *a* – the coefficient of the linear trend , %/10 years *;* *p* – the significance of the coefficients of the linear trend.

tivity coefficient (Table 4). Only the increase in the precipitation during the presowing period contributed to an increase in crop productivity. Nevertheless, the moisturization conditions remained favorable for corn cultivation in the Steppe during 1981–2010 (Table 4).

The analysis of the cumulative productivity coefficient of temperature and precipitation revealed that the changes in temperature and precipitation were unfavorable for corn cultivation, in the southern Steppe (Table 5). These changes resulted in a 3–5 % decrease in productivity over 10 years, particularly

Table 7. Agroclimatic conditions of spring barley cultivation during 1981–2010

Stages of development	T, °C	$T–T_{opt}$, °C	R, mm	R-R_{opt}, mm	$\eta(T, R)$, %
Polissia					
Presowing period	–3.0	–2.0	109	9	90
Sowing – third leaf	4.9	0.9	76	–24	91
Third leaf – panicle emergence	14.4	1.4	59	–61	93
Panicle emergence – milky ripeness	17.3	–0.7	81	–9	92
Milky ripeness – middle dough	19.2	0.2	93	83	80
Western Forest-Steppe					
Presowing period	–2.7	–1.7	114	14	92
Sowing – third leaf	4.6	0.6	99	–1	91
Third leaf – panicle emergence	13.3	0.3	88	–32	95
Panicle emergence – milky ripeness	16.2	–1.8	105	15	93
Milky ripeness – middle dough	18.1	–0.9	114	104	77
Central Forest-Steppe					
Presowing period	–3.0	–2.0	103	3	91
Sowing – third leaf	5.0	1.0	75	–25	89
Third leaf – panicle emergence	14.9	1.9	56	–64	89
Panicle emergence – milky ripeness	17.8	–0.2	86	–4	94
Milky ripeness – middle dough	19.7	0.7	85	75	81
Eastern Forest–Steppe					
Presowing period	–4.2	–3.2	118	18	86
Sowing – third leaf	4.6	0.6	77	–23	89
Third leaf – panicle emergence	15.0	2.0	51	–69	86
Panicle emergence – milky ripeness	18.5	0.5	69	–21	88
Milky ripeness – middle dough	20.4	1.4	69	59	81
Northern Steppe					
Presowing period	–3.4	–2.4	119	19	89
Sowing – third leaf	5.3	1.3	73	–27	88
Third leaf – panicle emergence	15.2	2.2	48	–72	86
Panicle emergence – milky ripeness	19.0	1.0	69	–21	88
Milky ripeness – middle dough	21.1	2.1	59	49	80
Southern Steppe					
Presowing period	–1.2	–0.2	102	2	93
Sowing – third leaf	6.4	2.4	65	–35	79
Third leaf – panicle emergence	16.0	3.0	41	–79	79
Panicle emergence – milky ripeness	20.2	2.2	57	–33	81
Milky ripeness – middle dough	22.6	3.6	51	41	69

Note. R_{opt} – optimum precipitation amoun for stages of development, mm; R – precipitation amount for stages of development in 1981–2010; T_{opt}, – optimum air temperature for stages of development, °C; T – average air temperature for stages of development in 1981–2010; η(T, R)– cumulative productivity coefficient.

during the stage from the third leaf to panicle emergence.

The change in the thermal and moisturization regimes led to the decrease in climate suitability for corn cultivation by 7–10 % in 10 years in the southern Steppe and by 5–7 % in 10 years in the northern Steppe (Table 6). Overall, in the southern Steppe, the conditions for corn cultivation were deemed satisfactory, with a yield shortfall averaging 20–25 % and above in the region due to climate factors. However, the current climatic period has presented unsatisfactory conditions for corn cultivation in the southern Steppe, resulting in a yield shortfall of 35–40 %.

The influence of the change in the precipitation amount on spring barley productivity by the stages of crop development during 1981–2010. The analysis of the moisturization conditions for spring barley during 1981–2010 revealed significant variability throughout the vegetation cycle, although generally favorable conditions prevailed across a substantial area of Ukraine, with the exception of the southern Steppe region where conditions were deemed satisfactory. Notably, there was a decrease in precipitation levels during the stagesowing to third leaf and tillering stages across all the agroclimatic zones, compared to the optimum values. The most pronounced precipitation deficit was observed in the eastern Forest-Steppe and Steppe zones, particularly in the southern Steppe, where the sowing to third leaf stage experienced nearly a 35 % reduction in precipitation compared to the optimum amount. Similarly, the tillering stage encountered an approximate 80 % decrease in precipitation (Table 7). Unfavorable moisturization conditions persisted across all the agroclimatic zones during the stagemilky ripeness to middle dough stage. However, excessive moisture was observed during this phase of crop development, particularly in Polissia, the western Forest-Steppe, and central Forest-Steppe. These conditions had a detrimental impact on spring barley productivity, while remaining conducive to their cultivation during this stage. During 1981–2010, the climate suitability index $S(T, R)$ demonstrated favorable conditions for the cultivation of spring barley in all the agroclimatic zones of Ukraine, ranging from 86 to 92 % of the maximum productivity level, except for the southern Steppe region, where conditions were satisfactory at 80 %. Consequently, due to climate factors, the spring barley yield fell short (δy_c) by 8 to 14 and 20 % of the maximum possible level.

In the ***Polissia*** region, an overall rise in precipitation level throughout most of the growth cycle took place in the period 1981–2010. Nevertheless, exceptions were observed during the stem elongation to ear formation stage across the entire Polissia territory and during the milky ripeness to middle dough stage in Zhytomyr and Chernihiv Polissia. These regions experienced a 3–6 % increase in precipitation deficit over a span of 10 years, with a particularly notable 15 % increase in June (**Table 8**).

The alteration in moisture pattern proved to be advantageous for barley solely during the tillering stage, where an upsurge in precipitation resulted in improved crop productivity up to 4%. However, during other stages of development, both increases and decreases in precipitation levels proved detrimental to barley cultivation, especially during the crop ripening stage (**Table 9**).

It is *very probably* and *probably* that the changes in the thermal regime and the moisture regime were responsible for a decline in the cumulative productivity coefficient of temperature and precipitation across the entire Polissia region. This decline was evident during the sowing of barley, and the emergence of the third leaf, milky ripeness, and middle dough stages. In Chernihiv and Zhytomyr Polissia, a decrease was also observed during the stem elongation and ear formation stages (**Table 10**). However, an increase in air temperature during the presowing period, combined with a decrease in precipitation, proved beneficial for barley. Similarly, during the tillering stage, an increase in precipitation, accompanied by insignificant temperature changes, had a positive impact.

Overall, the alterations in both the thermal regime and the moisture regime during the climate period of 1981–2010 likely contributed to 1 % decrease in climate suitability for barley cultivation over 10 years in the Volyn region. Consequently, this decrease resulted in a decline in yield shortfalls. In the remaining area of Polissia, changes in climate suitability were predominantly negative, although their likelihood remains uncertain (**Table 11**).

Forest-Steppe. In contrast to the temperature fluctuations the variations in precipitation levels in the Forest-Steppe region during the vegetation cycle of spring barley cultivation were highly uneven. In the predominant part of the Forest-Steppe, these changes ranged from – 5 to 5 % over a span of 10 years (Table 8). However, these precipitation changes had minimum impact on the Forest-Steppe. In the western Forest-Steppe, there was a *probable* increase of 10–20 % in precipitation over 10 years during the sowing, third leaf, milky

Table 8. The change rate in the precipitation amount during the stages of the vegetation cycle of spring barley cultivation and its significance (p)

Soil-climatic zone, administrative region	The stages of the vegetation cycle of corn cultivation														
	Presowing (XII–II)			Sowing –third leaf (III–IV)			Tillering (V)			Stem elongation – ear formation (VI)			Milky ripeness – middle dough (VII)		
	1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change	
		a	*p*		*a*	*p*		*a*	*p*		*a*	*p*		*a*	*p*
Polissia															
Chernihiv	124	3.8	0.61	80	–1.83	0.78	55	5.8	0.23	76	–15.0	0.03	80	–2.6	0.72
Volyn	109	6.3	0.28	79	12.40	0.03	62	4.5	0.33	79	–3.0	0.64	93	14.1	0.09
Rivne	100	4.7	0.32	72	10.81	0.07	62	0.6	0.90	82	–6.9	0.36	105	12.9	0.29
Zhytomyr	107	1.4	0.78	80	3.52	0.62	59	6.8	0.18	86	–13.3	0.09	95	–5.9	0.56
Western Forest-Steppe															
Lviv	118	8.8	0.10	89	15.38	0.02	81	6.2	0.35	87	2.1	0.76	97	13.4	0.14
Ternopil	104	–2.2	0.63	80	9.53	0.15	70	–3.9	0.51	86	–5.4	0.48	93	3.6	0.70
Chernivtsi	91	3.6	0.58	80	6.88	0.37	75	–7.3	0.42	89	5.8	0.54	96	12.2	0.37
Central Forest-Steppe															
Kyiv	106	3.0	0.61	76	0.30	0.96	54	3.0	0.55	82	–11.8	0.08	77	–0.9	0.89
Vinnytsia	98	1.5	0.79	78	1.47	0.79	57	–4.4	0.38	91	–9.3	0.24	89	0.8	0.94
Cherkasy	105	0.7	0.93	73	–0.36	0.95	49	1.9	0.63	77	–10.4	0.11	70	–3.1	0.66
Khmelnytsky	105	–2.4	0.61	78	6.85	0.24	62	–5.6	0.41	93	–7.3	0.44	103	3.5	0.76
Eastern Forest-Steppe															
Poltava	119	–2.6	0.74	78	–1.48	0.82	49	6.9	0.13	70	–4.3	0.50	65	5.0	0.51
Kharkiv	121	–0.8	0.91	75	4.98	0.44	51	2.8	0.58	68	–1.3	0.84	62	1.2	0.85
Sumy	114	–0.2	0.98	77	–2.05	0.75	51	2.0	0.68	69	–13.4	0.04	80	2.4	0.78
Northern Steppe															
Luhansk	126	0.1	0.99	69	3.39	0.52	51	–1.2	0.84	63	–2.3	0.71	60	1.4	0.84
Kirovohrad	99	4.6	0.57	67	0.05	0.99	48	3.3	0.43	78	–8.0	0.16	67	4.2	0.61
Dnipropetrovsk	113	5.1	0.55	75	2.48	0.71	46	7.0	0.12	68	1.2	0.82	52	–1.4	0.82
Donetsk	138	7.7	0.45	83	6.73	0.29	47	1.6	0.77	65	–4.1	0.56	56	–2.2	0.77
Southern Steppe															
Odesa	96	4.7	0.58	62	–0.19	0.98	40	4.1	0.38	60	–6.9	0.10	52	–1.1	0.84
Zaporizhzhia	121	5.6	0.55	76	0.10	0.99	43	5.8	0.26	59	–3.5	0.62	52	–6.8	0.35
Mykolayiv	95	5.1	0.54	59	–1.91	0.71	44	4.1	0.44	61	3.5	0.49	56	–1.6	0.80
Kherson	95	8.3	0.29	62	0.55	0.93	37	1.8	0.70	47	3.2	0.40	43	–0.2	0.98
AR of Crimea	136	4.4	0.60	75	1.16	0.85	34	–0.6	0.87	51	–1.3	0.79	39	–4.0	0.47
Ukraine	**121**	**4.0**	**0.51**	**80.0**	**3.53**	**0.45**	**55.0**	**1.8**	**0.57**	**74.0**	**–4.5**	**0.24**	**73.0**	**1.8**	**0.74**

Note. *a* – the coefficient of the linear trend , %/10 years ; *p* – the significance of the coefficients of the linear trend.

Table 9. The change rate in the precipitation productivity coefficient of during the stages of the vegetation cycle of spring barley cultivation and its significance (p)

Soil-climatic zone, administrative region	The stages of the vegetation cycle of corn cultivation														
	Presowing (XII–II)			Sowing –third leaf (III–IV)			Tillering (V)			Stem elongation – ear formation (VI)			Milky ripeness – middle dough (VII)		
	1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change	
		a	*p*		*a*	*p*		*a*	*p*		*a*	*p*		*a*	*p*
Polissia															
Chernihiv	98.0	–0.9	0.11	95.7	–0.7	0.58	85.3	4.2	0.07	97.1	–2.2	0.01	87.2	0.6	0.69
Volyn	99.0	–0.3	0.46	95.4	–2.3	0.03	88.9	1.4	0.44	98.0	–0.1	0.92	84.2	–3.3	0.07
Rivne	99.3	–0.1	0.45	96.0	–0.6	0.68	88.6	1.6	0.36	97.7	0.1	0.94	81.4	–3.1	0.28
Zhytomyr	99.2	0.0	0.76	95.3	–1.3	0.34	86.9	2.5	0.20	97.5	–0.9	0.14	83.8	1.4	0.56
Western Forest-Steppe															
Lviv	98.9	–0.5	0.04	89.7	–5.8	0.00	93.2	0.4	0.74	98.3	–0.1	0.77	83.2	–3.1	0.13
Ternopil	99.4	0.2	0.35	93.1	–2.0	0.32	90.6	–0.7	0.72	97.9	–0.8	0.11	84.3	–0.9	0.66
Chernivtsi	98.5	–0.3	0.46	90.6	–1.3	0.60	88.4	–0.4	0.88	96.8	–1.0	0.18	83.2	–2.8	0.37
Central Forest-Steppe															
Kyiv	99.0	–0.5	0.09	96.5	–0.8	0.28	84.7	2.6	0.31	97.8	–1.8	0.02	87.9	0.2	0.90
Vinnytsia	99.0	–0.1	0.76	95.4	–0.6	0.61	86.0	–1.3	0.57	97.7	–1.3	0.01	85.0	–0.1	0.96
Cherkasy	98.4	–1.2	0.03	97.2	–0.3	0.61	83.1	1.9	0.43	97.9	–0.8	0.10	89.4	0.7	0.63
Khmelnytsky	99.3	0.0	0.97	94.7	–0.6	0.72	86.6	0.0	1.00	97.3	–0.4	0.55	81.9	–0.9	0.73
Eastern Forest-Steppe															
Poltava	98.1	–0.2	0.71	96.8	–1.2	0.16	82.6	3.7	0.10	97.2	–1.2	0.09	90.5	–1.1	0.48
Kharkiv	98.2	–0.4	0.49	97.0	–1.1	0.11	83.5	1.7	0.43	96.6	–0.3	0.76	91.1	–0.3	0.84
Sumy	98.6	0.1	0.84	96.6	–0.6	0.53	83.9	1.0	0.64	96.8	–1.6	0.05	87.2	–0.6	0.75
Northern Steppe															
Luhansk	97.8	–0.6	0.40	97.2	–0.3	0.73	82.3	–1.3	0.61	95.8	–0.7	0.60	91.5	–0.3	0.84
Kirovohrad	98.2	–1.3	0.05	97.0	–0.7	0.44	82.4	2.2	0.37	98.2	–0.5	0.28	89.9	–1.0	0.57
Dnipropetrovsk	98.1	–1.0	0.19	97.2	–0.8	0.18	81.4	2.7	0.20	97.4	0.7	0.33	93.1	0.3	0.78
Donetsk	96.3	–1.8	0.16	96.4	–1.5	0.04	79.6	0.0	1.00	96.0	–0.9	0.36	92.2	0.4	0.80
Southern Steppe															
Odesa	97.7	–0.8	0.22	97.2	0.8	0.27	77.0	1.5	0.59	97.0	–0.7	0.24	93.3	0.0	0.98
Zaporizhzhia	97.5	–0.9	0.29	96.7	–0.7	0.38	77.5	1.0	0.77	94.7	0.0	1.00	93.0	1.4	0.35
Mykolayiv	97.8	–1.1	0.06	97.2	0.0	0.98	78.2	1.9	0.55	96.8	0.4	0.63	92.3	0.3	0.82
Kherson	98.1	–1.2	0.05	97.6	–0.5	0.25	74.5	–0.2	0.95	94.2	1.7	0.19	94.6	0.0	0.98
AR of Crimea	97.0	–1.0	0.23	98.3	0.5	0.39	72.8	–1.7	0.57	94.5	–0.5	0.68	95.4	0.8	0.44
Ukraine	**98.6**	**–0.7**	**0.15**	**96.7**	**–1.1**	**0.13**	**87.0**	**0.7**	**0.60**	**98.9**	**–0.4**	**0.09**	**89.0**	**–0.4**	**0.73**

Note. a – the coefficient of the linear trend , %/10 years ; p – the significance of the coefficients of the linear trend.

Table 10. The change rate in the cumulative coefficient of T and R productivity during the stages of the vegetation cycle of spring barley cultivation and its significance (p)

Soil-climatic zone, administrative region	The stages of the vegetation cycle of corn cultivation														
	Presowing (XII–II)			Sowing –third leaf (III–IV)			Tillering (V)			Stem elongation – ear formation (VI)			Milky ripeness – middle dough (VII)		
	1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change		1981–2010	change	
		a	*p*		*a*	*p*		*a*	*p*		*a*	*p*		*a*	*p*
Polissia															
Chernihiv	7.7	0.2	0.49	27.2	–0.3	0.61	20.9	0.8	0.36	20.5	–0.6	0.07	9.9	–0.4	0.17
Volyn	8.3	0.1	0.56	26.8	–1.1	0.04	22.4	0.2	0.70	21.0	0.2	0.25	9.7	–0.5	0.01
Rivne	8.3	0.1	0.52	26.7	–0.4	0.54	22.0	0.2	0.76	20.9	0.2	0.40	9.4	–0.5	0.14
Zhytomyr	8.2	0.2	0.35	26.9	–0.7	0.23	21.5	0.4	0.54	20.9	–0.2	0.44	9.6	–0.1	0.83
Western Forest-Steppe															
Lviv	8.3	0.1	0.63	24.8	–2.1	0.00	23.7	–0.2	0.79	21.1	0.3	0.09	9.7	–0.4	0.14
Ternopil	8.3	0.2	0.35	26.1	–0.9	0.23	22.9	–0.5	0.47	21.0	0.1	0.57	9.8	–0.1	0.62
Chernivtsi	8.3	0.1	0.62	23.9	–1.1	0.17	21.5	–0.7	0.47	20.9	–0.3	0.10	9.5	–0.7	0.05
Central Forest-Steppe															
Kyiv	8.1	0.2	0.45	26.7	–0.7	0.24	20.0	0.4	0.68	20.6	–0.7	0.04	9.8	–0.6	0.03
Vinnytsia	8.2	0.2	0.43	26.3	–0.6	0.30	20.9	–0.7	0.43	20.9	–0.4	0.09	9.7	–0.4	0.12
Cherkasy	8.1	0.1	0.70	26.5	–0.5	0.43	19.3	0.2	0.88	20.5	–0.6	0.09	9.8	–0.6	0.04
Khmelnytsky	8.2	0.2	0.44	26.5	–0.5	0.44	21.6	–0.4	0.68	20.9	0.0	0.86	9.5	–0.2	0.40
Eastern Forest-Steppe															
Poltava	7.9	0.2	0.41	26.4	–0.7	0.28	18.9	18.9	0.46	19.9	–0.7	0.12	9.6	–0.9	0.01
Kharkiv	7.7	0.2	0.55	26.6	–0.4	0.53	19.3	19.3	0.85	19.6	–0.5	0.36	9.6	–0.9	0.02
Sumy	7.5	0.3	0.39	27.0	–0.1	0.86	20.5	20.5	0.84	20.3	–0.4	0.22	9.8	–0.6	0.07
Northern Steppe															
Luhansk	7.7	0.1	0.85	26.5	0.0	0.96	19.1	–0.3	0.78	19.1	–0.7	0.31	9.1	–0.9	0.02
Kirovohrad	8.1	0.1	0.73	26.2	–0.6	0.33	19.1	0.3	0.79	20.3	–0.7	0.08	9.5	–0.9	0.01
Dnipropetrovsk	8.2	0.1	0.75	25.6	–0.7	0.31	18.1	0.5	0.65	19.4	–0.6	0.35	9.1	–0.9	0.02
Donetsk	7.9	0.0	0.89	26.4	–0.8	0.19	18.4	–0.2	0.86	19.1	–0.9	0.17	8.9	–1.0	0.02
Southern Steppe															
Odesa	8.3	–0.1	0.47	23.6	–1.2	0.15	16.8	–0.2	0.85	19.0	–1.2	0.02	8.5	–1.2	0.00
Zaporizhzhia	8.4	0.0	0.95	25.2	–0.8	0.25	17.4	0.0	0.99	18.2	–1.0	0.20	8.3	–0.9	0.03
Mykolayiv	8.3	0.0	0.84	24.5	–1.1	0.15	17.1	0.1	0.95	18.9	–1.0	0.11	8.4	–1.1	0.00
Kherson	8.4	–0.1	0.40	24.5	–1.4	0.07	16.5	–0.5	0.65	17.7	–1.0	0.12	7.8	–1.1	0.01
AR of Crimea	7.4	–0.3	0.24	24.4	–1.1	0.13	18.0	–0.9	0.41	19.2	–1.2	0.02	8.6	–1.0	0.01
Ukraine	**8.4**	**0.1**	**0.68**	**26.4**	**–0.8**	**0.14**	**21.1**	**–0.2**	**0.82**	**21.0**	**–0.5**	**0.06**	**9.7**	**–0.7**	**0.01**

Note. *a* – the coefficient of the linear trend , %/10 years; *p* – the significance of the coefficients of the linear trend.

ripeness, and middle dough stages, and an increase up to 8–9 % during the presowing period.However, in the central and eastern Forest-Steppe, there was a *probable* decrease of 10–13 % precipitation over 10 years during the stem elongation and ear formation stages. These changes had detrimental effects on barley cultivation, as evidenced by the decrease in the precipitation productivity coefficient and a probable 3–6 % decrease in crop productivity during the corresponding phase of development (Table 9).

An analysis of the cumulative coefficient of temperature and precipitation productivity, revealed that the temperature and precipitation changes during the current climatic period were mostly unfavorable for spring barley cultivation in the Forest-Steppe throughout the vegetation cycle (Table 10). The most signifi-

Table 11. The change rate in the climate suitability and spring barley yield shortfall during 1981–2010 in the regions of Ukraine and its significance (*p*)

Soil-climatic zone, administrative region	Spring barley					
	Climate suitability			Yield shortfall		
	1981–2010	change		1981–2010	change	
		a	*p*		*a*	*p*
1	2	3	4	5	6	7
Polissia						
Chernihiv	86.2	–0.3	0.790	13.8	0.3	0.790
Volyn	88.2	–1.1	0.217	11.8	1.1	0.217
Rivne	87.4	–0.4	0.702	12.6	0.4	0.702
Zhytomyr	87.1	–0.2	0.835	12.9	0.2	0.835
Western Forest-Steppe						
Lviv	87.6	–2.3	0.010	12.4	2.3	0.010
Ternopil	88.1	–1.3	0.215	11.9	1.3	0.215
Chernivtsi	84.2	–2.8	0.035	15.8	2.8	0.035
Central Forest-Steppe						
Kyiv	85.3	–1.3	0.243	14.7	1.3	0.243
Vinnytsia	86.0	–1.9	0.096	14.0	1.9	0.096
Cherkasy	84.3	–1.4	0.260	15.7	1.4	0.260
Khmelnytsky	86.7	–0.9	0.398	13.3	0.9	0.398
Eastern Forest–Steppe						
Poltava	82.8	–1.3	0.307	17.2	1.3	0.307
Kharkiv	82.8	–1.4	0.302	17.2	1.4	0.302
Sumy	85.1	–0.7	0.572	14.9	0.7	0.572
Northern Steppe						
Luhansk	81.4	–1.9	0.140	18.6	1.9	0.140
Kirovohrad	83.2	–1.8	0.185	16.8	1.8	0.185
Dnipropetrovsk	80.3	–1.7	0.204	19.7	1.7	0.204
Donetsk	80.7	–2.9	0.027	19.3	2.9	0.027
Southern Steppe						
Odesa	76.3	–3.9	0.020	23.7	3.9	0.020
Zaporizhzhia	77.5	–2.6	0.069	22.5	2.6	0.069
Mykolayiv	77.1	–3.1	0.067	22.9	3.1	0.067
Kherson	75.0	–4.2	0.009	25.0	4.2	0.009
AR of Crimea	77.7	–4.4	0.002	22.3	4.4	0.002
Ukraine	**86.6**	**–2.1**	**0.025**	**13.4**	**2.1**	**0.025**

Note. *a* – the coefficient of the linear trend, %/10 years; *p* – the significance of the coefficients of the linear trend.

cant changes were observed during the stage milky ripeness and middle dough stages, as well as during the stem elongation and ear formation stage. The increase in the air temperature and precipitation levels in the western Forest-Steppe during the milky ripeness and middle dough stages, along with a notable temperature increase and insignificant precipitation change in the central and eastern Forest-Steppe, were likely unfavorable for barley cultivation. Furthermore, the increase in temperature and decrease in precipitation levels in the central and eastern Forest-Steppe were also unfavorable. During other stages of barley development, the changes in the cumulative productivity coefficient were generally insignificant across the entire Forest-Steppe region, albeit with varying tendencies (Table 10).

Alterations in air temperature and precipitation levels contributed to a decrease in climate suitability for barley cultivation and resulted in higher yield shortfalls in the Forest-Steppe, particularly in the western and central regions, where they was a probable change of 2–3 % over 10 years (Table 11).

Steppe. The analysis conducted on the climate period of 1981–2010 revealed notable variation in precipitation levels within the northern and southern Steppe region. In the northern Steppe, an overall increase in precipitation was observed throughout almost the entire vegetation cycle of barley cultivation, with the exception of the stem elongation to ear formation stage (Table 8). However, these changes were found to fluctuate within 5 % over a span of 10 years and were considered insignificant and highly improbable.However, the southern Steppe experienced a remarkable decrease in precipitation levels throughout most of barley cultivation period, with the only exceptions being the presowing period and tillering stage. Nevertheless, similar to the northern Steppe, these changes were also deemed insignificant and highly improbable, and fluctuating within 5 % over 10 years (Table 8).

The increase in precipitation during the tillering stage and its decrease during the milky ripeness and middle dough stages likely had a potentially favorable impact on spring barley, as evidenced by a higher precipitation productivity coefficient (Table 9).

Furthermore, an analysis of the cumulative productivity coefficient, considering the combined effects of temperature and precipitation, indicated that the temperature and precipitation changes observed between 1981 and 2010 were generally unfavorable for spring barley cultivation, particularly in the southern Steppe (Table 10). These changes resulted in a probable 1–2 % decrease in productivity over 10 years, especially during the milky ripeness and middle dough, stem elongation to ear formation, and tillering stages. The alterations in both the thermal regime and moisture regime contributed to a decrease in climate suitability for spring barley cultivation, very probably by 3–4 % over 10 years in the southern Steppe and probably by 2–3 % in the northern Steppe. Consequently, there was a corresponding increase in yield shortfalls for this crop of 2%…to 4 % (Table 11).

DISCUSSION

Climate change poses one of the greatest threats to global food security in the 21st century (Wheeler and von Braun, 2013). In numerous cereal producing regions since the 1980s, changes in air temperature and precipitation pattern have led to a decrease in crop productivity compared to historical norms unaffected by climate change (Lobell et al, 2011; Zhao et al, 2017). For example, between 1981 and 2010, climate changes resulted in a 19–33 % reduction in the productivity of corn, soybeans, rice, and wheat (Iizumi, 2016). The most substantial decline in corn and soybean productivity were observed in Argentina and northern-eastern China, while reductions in rice productivity were more prominent in Indonesia and southern China. Wheat productivity experienced significant decreases in Australia, France, and Ukraine (Iizumi, 2016). In the pampas of southern America, the potential productivity increase during the same period could have been 15–20 % higher if the climate had remained stable (Verón, 2015).

Studies have shown that the average yield shortfall caused by climate changes between 1981 and 2008 was 3.8 % for corn and 5.5 % for wheat (Lobell et al, 2011). The cumulative annual shortfall of these two crops, along with barley, amounted to 40 million tons per year, which accounted for approximately 2–3 % of global production (Lobell and Field, 2007). In Kazakhstan, climate change led to a decrease in wheat and barley productivity by 1.9 % and 4.8 %, respectively, compared to a scenario without climate change (Schierhor, 2020). In western and central Europe, the increase in the precipitation deficits and heightened risk of severe droughts have contributed to a decline in the potential with rainfed agriculture (Trnka et al, 2010). In high latitudes, such as Finland, there have been positive effects on barley productivity resulting from increases in temperature and CO_2 levels under optimistic climate scenarios (Rötter et al, 2012). Forecasts concerning the potential impact of climate change on cereal productivity suggest that most regions where spring barley is cultivated will experience warmer and drier conditions, leading to a global decrease in productivity and production ranging from 3 to 17 %, depending on the specific environment (Xie et al, 2018, Cheng et al, 2019). Similar decreases in barley productivity due to climate change are anticipated in other regions as well. For instance, in the Mediterranean region, projected declines range from 25 to 8 %, while Kazakhstan is expected to see a reduction of 4.8 %. The Czech Republic may experience declines ranging from −19 to +5 %, and Iran could face a potential decrease of up to 50 % (Cammarano et al, 2019, Mirgol et al, 2020, Schierhorn et al, 2020).

It has been determined that changes in air temperature, especially when exceeding the optimal range for productivity, have a greater influence on crop yield variability compared to temperatures below the optimal range and soil moisture deficits (Iizumi, 2016). On average, crop productivity is more responsive to trends in air temperature change and diurnal patterns than changes in precipitation (Verón et al, 2015).

The findings obtained in Ukraine regarding changes in corn and spring barley productivity between 1981 and 2010, attributed to climate change, are consistent with data, obtained from other regions such as western and central Europe, northern-eastern China, Argentina, Mediterranean region, Kazakhstan and other (Trnka et al, 2010; Iizumi, 2016; Schierhor, 2020). Determined that, similar to other countries, the impact of climate change on crop productivity in Ukraine varies depending on the specific crop and the region where it is cultivated. In Ukraine, there has been an increase in air temperature and a decrease in precipitation along with their altered distribution during the vegetation cycle of cereal cultivation (Balabukh, 2019; Balabukh et al, 2021). These changes and their impact on crop productivity intensify from the northern regions of the country (Polissia) to the southern ones (southern Steppe), where the most significant increases in air temperature and precipitation are observed. Consequently, the average yield shortfall amounts to 35–40 % for corn of and 10–15 % for spring barley.

An analysis of the relationship between air temperature, precipitation and their suitability for corn and spring barley cultivation in Ukraine confirms previous findings that changes in cereal productivity depend more on air temperature and evaporation than on variations in precipitation, particularly in the northern regions (Liu et al, 2020; Verón et al, 2015).

The changes observed in the agroclimatic conditions of corn and spring barley cultivation indicate a decline in the potential of dryland farming in Ukraine, including the Forest-Steppe soil-climatic zone. These observations align with similar trends identified in other regions such as southern America, western and central Europe, northern-eastern China, Argentina, Mediterranean region, Kazakhstan (Schierhor, 2020; Verón et al, 2015; Iizumi, 2016; Cammarano et al, 2019, Mirgol et al, 2020; Schierhorn et al, 2020; Trnka et al, 2010; Rötter et al, 2012).

It is important to note that the study on the impact of changes in precipitation and the cumulative effects of precipitation and air temperature on corn and spring barley productivity and the climate suitability in Ukraine only covers the period from 1981 to 2010. It does not account for the most recent decade, which has been recognized as the warmest globally and in Ukraine specifically (State of the Global Climate 2020, 2021; Balabukh et al, 2021; National Report EN 2020, 2021). The observed decrease in cereal productivity and increase in yield shortfalls due to rising air temperatures and precipitation deficits were further confirmed in 2020, which experienced record-breaking temperature since the late 19th century. Prolonged drought conditions persisted for eight months in 2019 and continued throughout 2020 (except for February, May, and June) (Balabukh et al, 2021; National Report EN 2020, 2021), resulting in crop losses across an area of 770,878 ha, with the total damage exceeding 23.4 billion hryvnia (National Report EN 2020, 2021). The Steppe region, which had both favorable and unfavorable thermal and moisture conditions for cereal cultivation between 1981 and 2010, exhibited the highest susceptibility to changes in the agroclimatic conditions, leading to reduced productivity, decreased climate suitability, and increased yield shortfalls influenced by climate factors. For instance, in Mykolayiv region, cereal crops were lost across an area of 24,602 ha, including 2,000 ha of corn, while a decrease in corn yield was observed across 43,200 ha. In Kirovohrad region, cereal losses amounted to 23,378 ha (21,300 ha of corn), with low corn yield observed across 146,700 ha (Balabukh et al, 2021; National Report EN 2020, 2021).

In conclusion, both decrease and increase in crop productivity variability resulting from climate change depend on the specific crop and the region where it is cultivated. These findings underscore the importance of long-term global monitoring of productivity, along with comprehensive data collection, to enhance our understanding of the current variability in productivity and its crucial influencing factors (Iizumi T, 2016).

CONCLUSIONS

The changes in the moisturization conditions during the vegetative cycle of corn and spring barley at the during 1981–2010 have been uneven across soil-climatic zones in Ukraine. In Polissia, these changes were mostly insignificant and unlikely, while in the Forest-Steppe and Steppe regions experienced an increase in precipitation deficits, with levels 35–80 % lower than optimal in certain stages of the crop`s growth cycle. When considering changes in precipitation amount, moisture conditions for spring barley remained favorable in most regions of Ukraine, except for the southern Steppe, where conditions were satisfactory. For corn moisture conditions were favorable in Polissia, improved in the western Forest-Steppe and some central and other regions, satisfactory in the eastern Forest-Steppe and northern Steppe, and unsatisfactory in the southern Steppe, where conditions deteriorated significantly. The impact of changes in precipitation amounts on corn and spring barley productivity was found to be smaller than the impact of changes in air temperature.

Since the 1980s, cumulative changes in temperature and precipitation in Ukraine have led to decreased field crop productivity in significant parts of the country compared to calculations assuming absence of climate change. The observed changes in air temperature and precipitation, and their influence on climate suitability and cereal productivity, indicate a decline in the potential for dryland agriculture in both the Steppe and Forest-Steppe regions. The impact of climate change on corn productivity has been more pronounced than on spring barley, increasing from north to south correlation with the rise in precipitation deficits and air temperature.

The changes in air temperature and precipitation levels have likely contributed to a decrease in climate suitability and an increase in yield shortfalls in corn cultivation, with an average increase of 3–5 % over each 10 years in the central and eastern Forest-Steppe, 5–7 % over each 10 years in the northern Steppe, and 7–10 % over each 10 yearsin the southern Steppe. Overall, corn yield shortfalls due to climate factors in the Forest-Steppe averaged 10–20 %, over 30 years. In the northern Steppe, yield shortfalls reached 20–25 % and higher, while in the southern Steppe, where unfavorable agroclimatic conditions for corn cultivation were observed, yield shortfalls were 35–40 % over 30 years.

In a considerable part of Polissia, except for the Volyn region, the increase in air temperature and changes in precipitation during the barley vegetation period did not significantly affect climate suitability or yield shortfalls. In the Forest-Steppe, however, these changes were mostly unfavorable for barley cultivation, particularly in the western and central regions, resulting in a decrease in climate suitability and an increase in yield shortfalls of 2–3 % over 10 years and an average of 5–10 % over 30 years in the region. The Steppe region experienced the most significant changes in air temperature and precipitation, leading to grain yield shortfalls of 5–10 % on average in the northern Steppe and 10–15 % in the southern region.

Further research should focus on evaluating the changes in thermal regime and moisturization regimes during the vegetation cycle of field crop cultivation in short and medium-term perspectives, considering different impact and socio-economic scenarios. This research should also explore their effects on climate suitability and cereal productivity in Ukraine. Additionally, a more detailed analysis of the spatial and temporal variability of potential climate changes is necessary when developing recommendations for adjusting agrotechnology in response to climate changes, aiming to minimize yield shortfalls caused by changing agroclimatic conditions. Relevant adjustment strategies should include transitioning to more drought-resistant crops in regions, where climate change has a negatively impacted productivity and expanding cereal production in regions benefiting from climate change.

Adherence to ethical principles. All the experimental results, presented in this article, were obtained without the use of any animals.

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Недобір урожаю зернових культур в Україні, зумовлений зміною температури повітря та кількістю опадів

В. О. Балабух

Український гідрометеорологічний інститут
Державної служби України з надзвичайних ситуацій,
Національної академії наук України,
Проспект Науки, 37, м. Київ, Україна, 03028

E-mail: Balabukh@uhmi.org.ua

orcid: 0000-0003-3223-7531

Мета. Виявити тенденції зміни кількості опадів, плодотворності опадів та сумісного впливу зміни температури повітря і кількості опадів на врожайність зернових культур, зокрема, кукурудзи та ячменю ярого, у періоди вегетаційного циклу, зміну плодотворності клімату, недобору урожаю культур та їхні особливості у ґрунтово-кліматичних зонах України на межі XX–XXI ст. (1981–2020 рр.). **Методи**. Для вирішення поставлених завдань застосовували як загальнонаукові, так і спеціалізовані методи досліджень: аналітико-синтетичний – для аналізу сучасного стану досліджень, статистичний – для оцінки інтенсивності та значущості зміни агрокліматичних умов вирощування польових сільськогосподарських культур, порівняльний аналіз – для виявлення їхніх особливостей у ґрунтово-кліматичних зонах України та на різних фазах розвитку рослин, кліматичні – для характеристики кількості опадів й оцінки їхнього впливу на урожайність культур, моделювання – для оцінки впливу зміни кількості опадів на продуктивність кукурудзи та ячменю ярого, оцінки сумісного впливу зміни приземної температури та кількості опадів на продуктивність клімату і недобір урожаю цих культур; абстрактно-логічний – для формування узагальнень і висновків. **Результати.** Встановлено, що на межі XX–XXI ст. упродовж усього вегетаційного циклу кукурудзи та ячменю ярого у ґрунтово-кліматичних зонах України відмічалась зміна кількості опадів, яка супроводжувалась підвищенням температури повітря і приводила до зміни плодотворності клімату. Впродовж останнього десятиліття (2011–2020 рр.) в Україні відмічались найвищі температури повітря за період інструментальних спостережень. У багатьох регіонах країни вони супроводжувались дефіцитом опадів протягом тривалого періоду, що негативно впливало на урожайність зернових. Виявлено що на Поліссі кількість опадів збільшувалась майже протягом усього вегетаційного циклу кукурудзи та ячменю ярого. Проте ці зміни, за винятком окремих періодів, були незначущими і несуттєво впливали на урожайність культур. Такі ж тенденції були характерні і для сумісного коефіцієнту продуктивності температури та опадів. Як наслідок, зміна плодотворності клімату і недобору урожаю кукурудзи та ячменю ярого майже на усій території Полісся була малоймовірною, а умови для їхнього вирощування залишались сприятливими. Встановлено, що у Лісостепу зміна кількості опадів була неоднорідною впродовж усього періоду вегетації кукурудзи та ячменю ярого. У західному Лісостепу відмічалось зростання кількості опадів, які в окремих областях становили 10–20 % за 10 років. Такі зміни були несприятливими для кукурудзи і ячменю ярого та зумовлювали зменшення продуктивності польових культур на 3–6 % за 10 років У центральному Лісостепу відмічалось як збільшення, так і зменшення кількості опадів в окремі фази розвитку культур. Ці зміни були несприятливими для їхнього вирощування і приводили до зменшення урожайності. Для східного Лісостепу характерне зростання дефіциту опадів, яке зумовлювало зменшення продуктивності опадів упродовж майже усього вегетаційного циклу рослин. Зміна кількості опадів разом із підвищенням температури були загалом несприятливими для вирощування польових культур у Лісостепу, особливо у центральному, і призводила до збільшення недобору врожаю кукурудзи на 3–5 % за 10 років та ячменю ярого на 2–3 % за 10 років. Загалом агрокліматичні умови для вирощування ячменю ярого залишались сприятливими у всій лісостеповій зоні, а для вирощування кукурудзи сприятливими у західному Лісостепу і задовільними у центральному та східному. У степовій зоні зміна кількості опадів протягом майже усього вегетаційного циклу кукурудзи та ячменю ярого коливались у межах 5 % за 10 років і були несуттєвими та малоймовірними, хоча в окремі фази розвитку культур відмічались значні зміни зволоження. Так, значне збільшення кількості опадів (на 10–15 % за 10 років) у період молочної-воскової стиглості кукурудзи зумовлювало зменшення урожайності до 3 % за 10 років. Для ячменю ярого ймовірно сприятливим було збільшення кількості опадів у період кущіння та їхнє зменшення в період молочної і воскової стиглості, про що свідчить зростання коефіцієнту продуктивності опадів. Загалом, інтенсивне підвищення температури повітря разом зі зміною зволоження було несприятливим для вирощування кукурудзи і ячменю ярого, особливо у південному степу, де призводило до зменшення плодотворності клімату для вирощування кукурудзи на 7–10 % за 10 років та ячменю ярого на 3–4 % за 10 років. Як наслідок, умови для вирощування кукурудзи у цьому регіоні були незадовільними, а ячменю – задовільними. Недобір урожаю кукурудзи за рахунок зміни температури повітря і опадів протягом 1981–2010 рр. сягав 35–40 % від максимально можливого за оптимальних кліматичних умов, а ячменю ярого – 22–25 %. Впродовж 2011–2020 рр. втрати урожаю були ймовірно більшими. Такі зміни температури повітря, режиму зволоження та продуктивності клімату свідчить про зменшення потенціалу богарного землеробства в Україні, особливо в степовій зоні. **Висновки**. Зміна кількості опадів в Україні, яка супроводжується суттєвим підвищенням температури повітря, впливає на формування урожайності польових культур упродовж їхнього вегетаційного циклу. Збільшення кількості опадів у період дозрівання культур, як і зростання дефіциту опадів в окремі вегетаційні фази призводить до зменшення продуктивності опадів, зниження урожайності польових культур. Разом із підвищенням температури повітря такі зміни сприяють зниженню продуктивності клімату та збільшенню недобору урожаю кукурудзи і ячменю ярого. Найбільші зміни характерні для степової зони, особливо Степу південного. У цьому регіоні недобір урожаю кукурудзи за рахунок зміни температури повітря і опадів упродовж 1981–2010 рр. сягав 35–40 % від максимально можливого за оптимальних кліматичних умов, а ячменю ярого – 22–25 %. Тобто, урожайність кукурудзи та ячменю ярого могла бути на такий відсоток вищою, якби клімат в Україні залишався без змін. Незважаючи на зміни температури повітря і кількості опадів протягом вегетаційного циклу кукурудзи й ячменю ярого, на Поліссі агрокліматичні умови для їхнього вирощування у 1981–2010 рр. залишались сприятливими. У лісостеповій зоні вони були сприятливими для ячменю і задовільними для кукурудзи у центральному та східному Лісостепу. У степовій зоні, вплив зміни клімату був найбільш відчутним, особливо у південному Степу. Агрокліматичні умови для вирощування ячменю у цьому регіоні були задовільними, а кукурудзи – не задовільними. Останнє десятиліття (2011–2020 рр.) в Україні, як і в Європі та північній півкулі виявилось найтеплішим з 1961 року і ймовірно з початку інструментальних спостережень за погодою. Аномально високі температури повітря, що супроводжувались дефіцитом опадів, сприяли зростанню недобору урожаю зернових на значній території країни. Підвищення температури повітря та зростання посушливості свідчить про зменшення потенціалу богарного землеробства в Україні, особливо у степовій зоні.

Ключові слова: кукурудза, ячмінь ярий, агрокліматичні умови, плодотворність клімату, зміна клімату, підвищення температури, зміна опадів, продуктивність опадів, недобір урожаю.

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