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INFLUENCE OF CHANGES IN AIR TEMPERATURE ON CROP PRODUCTIVITY FORMATION IN UKRAINE AT THE TURN OF XX–XXI CENTURIES (1981–2010)

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Aim. To determine the tendencies in the changes in air temperature and their influence on the productivity of crops during the vegetative cycle periods, especially in soil-climatic zones of Ukraine for the 1981–2010 climate normals period. **Methods.** The analytical and synthetic, statistical, climatic methods, simulation (model of V.P. Dmitrenko "Weather-yield" (Dmitrenko VP et al, 2017, 2010), used to forecast the productivity of grains in the Ukrainian Hydrometeorological Center since 1970), abstract-logical method. **Results.** The rising air temperatures were determined throughout the whole vegetative period of growing corn and spring barley over the period of 1981–2010. It was found that this rise in different phases of crop development was of different magnitude and relevance in all regions and soil-climatic zones of Ukraine. The reliable changes in the surface air temperature were noted in the phases of the third leaf, panicle emergence, and blossoming of corn in Polissia, Forest-Steppe, and especially Steppe (0.7–0.8 °C/10 years, 0.8–0.9 °C/10 years and 0.9–1.1 °C/10 years, respectively). During the pre-sowing period, the periods of corn sowing and seedlings, the velocity of changes was twice lower in the whole territory of the country, and during the periods of milky ripeness and middle dough – in the eastern Forest-Steppe and dry Steppe, amounting to 0.4–0.5 °C/10 years. A considerable rise in the temperature during the period of the third leaf, panicle emergence, and blossoming promoted the decrease in the influence of temperature during these phases of crop development, especially in the Steppe (up to 10–15 % in 10 years). Only the rise in the temperature during the pre-sowing period promoted the 3–6 % increase in the whole territory of the country, and during the periods of milky ripeness and middle dough of corn – up to 8 % in 10 years in the Forest-Steppe and Steppe. Generally, the thermal conditions for corn cultivation deteriorated considerably but remained favorable in Polissia, satisfactory – in the Forest-Steppe and northern Steppe, and unsatisfactory – in the south, in the dry Steppe. The most intense changes in the air temperature during the vegetation period of spring barley were noted in the phase of milky ripeness and middle dough in all soil-climatic zones, amounting to 0.8–1.1 °C/10 years. During the sowing period, the phases of the third leaf, stem elongation, and ear formation, they were 0.6–0.7 °C/10 years, and during the pre-sowing period – 0.3–0.4 °C/10 years. During the spring barley tillering phase, the change in the air temperature was insignificant in the whole territory of the country. A considerable increase in the air temperature was unfavorable for crop cultivation in all the soil-climatic zones of Ukraine during the vegetative cycle of spring barley, especially during the phases of milky ripeness and middle dough, and promoted the decrease in its productivity in Polissia, Forest-Steppe, and Steppe by 5, 7.5 and 10 % in 10 years, respectively. In general, the increase in the air temperature conditioned the deterioration in thermal conditions of cultivating spring barley but they remained favorable in Polissia and Forest-Steppe, and favorable or satisfactory in the Steppe during the pre-sowing period and the vegetative cycle.

Key words: corn, spring barley, agroclimatic conditions, climate change, surface temperature, temperature rise, productivity of temperature, yield, satellite information, normalized difference vegetation index (NDVI), photosynthetically active biomass, RCP4.5, RCP8.5.

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CONCLUSIONS

During 1981–2010, there was a notable increase in the air temperature during the whole vegetative cycle of corn and spring barley but in different phases of crop development, these changes had different magnitude and relevance in the soil-climatic zones of Ukraine. The highest velocity of the increase in the air temperature was registered during the periods of milky ripeness and middle dough of spring barley in the whole territory of the country and during the period of corn blossoming, especially in the Steppe, exceeding 1.0 °C/10 years. A considerable increase in the air temperature promoted the decrease in the productivity of grains in these development phases down by 10–15 % in 10 years, which is most evident in dry Steppe. The increase in the air temperature conditioned the deviation from optimal conditions of cultivating crops, the decrease in temperature productivity, and regardless of the fact that the velocity of the air temperature changes during this period did not differ much, it had different consequences for soil-climatic zones. The conditions of corn and spring barley cultivation in Polissia remained favorable, in Forest-Steppe – favorable and satisfactory, in Steppe – satisfactory, and in dry Steppe – unsatisfactory for corn in 1981–2010. Thus, the same changes in temperature under different initial conditions may lead to different results. So, when developing the adaptation measures aimed at mitigating negative consequences of climate changes, one should consider not only the direction and intensity of changes in agroclimatic conditions, but also the degree, by which the initial conditions differ from the optimal conditions for grain cultivation, and these measures should be taken, first and foremost, in the regions, where the agroclimatic conditions are unsatisfactory and deteriorating, and during the period, when these changes are of the most relevance.

The sustainable development of agricultural production of grains is considerably dependent on agroclimatic resources, which are the main factor for the life of plants, influencing their growth, development, productivity formation, and being determined by the ratio of heat, moisture, and light. Special significance in the formation of grain productivity and its variability is attributed to air temperature. If the values of the latter are optimal during the whole vegetative cycle, plants develop in the best possible way, ensure the highest productivity, and use nutrients and energy resources sparingly (Dmitrenko VP, 2010; Angus JF, 1980). If the actual climate conditions differ from the optimal temperature values, the productivity of grains decreases. Low temperatures, approximating the biological minimum, cause the prolonged formation of organic substances; thus, under these conditions, they are formed in insignificant amounts. High temperatures, bordering the biological maximum, promote a higher velocity of plant development, and full-fledged organic substances do not have enough time to get formed in sufficient amounts. Only when air temperature corresponds to the optimum, the highest amount of organic substances is formed (Dmitrenko VP et al, 2017, 2010; Angus JF, 1980).

Climate changes, observed on our planet during recent decades, have considerably influenced the development and formation of crop productivity (Field CB et al, 2014; IPCC, 2018; IPCC, 2021). At present, there are no doubts that climate changes have also conditioned considerable variability in the yield of many crops (Challinor AJ et al, 2014; Bassu S et al, 2014; Lesk C et al, 2016), the reduction in the production of agricultural produce and impacted food safety in the world (Asseng S et al, 2015; Lobell D et al, 2011; FAO, 2021). According to the data of FAO [FAO, 2021], in 1980–2008, the global production of corn and wheat decreased by 3.8 and 5.5 %, respectively. In some countries, the influence of climate changes on the mean yield of grains was so strong that it could not be compensated even with the application of modern technologies, the introduction of fertilizers, and other factors (FAO, 2021).

The increase in the air temperature up to a certain level may promote the increase in the productivity of some crops, but if it exceeds the level, optimal for a specific crop, or there is a shortage of moisture and nutrients, then the productivity may decrease (Deb P et al, 2015).

In the late 20th century, when a considerable rise in global air temperature was noted, the loss of crop yield was higher than in the early 20th century, especially in tropic regions (IPCC, 2018).

The rise in the incidence of extreme events, especially floods and droughts, also damages crops and reduces their productivity. The decrease in global grain production was promoted by droughts and extreme heat, the recurrence and intensity of which is considerably increasing (Deb P et al, 2015; Parkes B et al, 2018; Cammaranoa D et al, 2019). During the recent decade, remarkable for the highest temperature values since 1850, droughts and extreme heat caused the reduction of areas and productivity of grains (Field CB et al, 2014; FAO, 2021).

However, the studies demonstrate (Asseng S et al, 2015) that even moderate warming may decrease the productivity of crops in a large territory. In middle latitudes, grains are less sensitive to climate changes than in the tropics but in the future, their production will become riskier, as the competition for water resources will be more fierce, and the frequency of extreme temperatures will increase.

Climate changes influence both the mean productivity of grains and year-to-year variations (Field CB et al, 2014; Bassu S et al, 2014). The fluctuations in gross yields of grains, caused by climate changes, are common for Ukraine as well (Polevoy A et al, 2007; Balabukh VO, 2017), where in recent decades the velocity of the increase in the air temperature, average for a year, exceeded the increase in the global air temperature thrice (Balabukh VO et al, 2017). These factors caused the change in agroclimatic conditions in the territory of the country (Balabukh VO and Malitskaya LV, 2017; Stepanenko SM, 2011), the productivity of grains and the fluctuations in soil-climatic zones (Polevoy AN et al, 2014; Polevoy A et al, 2021; Balabukh VO, 2019).

From the short- and long-term perspective, the influence of climate change on agriculture will intensify. According to the data (Asseng S, 2015), the global wheat production is expected to drop by 6 % per each 1 °C of further temperature increase and will become more variable in space and time. The increase in the global surface air temperature by 1.5 °C is likely to cause a decrease in the productivity of the main grains in Africa to the south of Sahara, south-eastern Asia, and Central and South America (Deb P et al, 2015; Parkes B et al, 2018). In the territory of western Africa, the expected decrease in corn productivity is by 5.95 % at the temperature increase of 2 °C, and if the temperature rises by 4 °C – by 37 %. It has been noted that a considerable shortage of yield, previously occurring only once in 19.7 years, will be observed every 2.5 years (Parkes B et al, 2018). The change in the productivity of grains is possible in other regions. For instance, in the Mediterranean region the decrease in barley yield is likely to amount to 25 % under the scenario RCP4.5, if the climate becomes drier (Field CB et al, 2014;Cammaranoa D et al, 2019).

In Ukraine, the increase in the air temperature, the change in heat and moisture provision for the vegetative period will also influence the productivity of grains both in short and long-term under different climate scenarios. For instance, according to the data (Balabukh VO, 2019), by the middle of the century (2021–2050), under the climate scenario of A1B according to the scheme of a rise in global air temperature by 2.8 °C by 2100 as compared with the late 20th century, the cultivation conditions for winter wheat in Polissia will remain satisfactory, but a probable loss of grain yield in Volyn will be 14–15 %. The conditions will deteriorate in the Forest-Steppe, probably remaining satisfactory, just like for 1981–2010. In Steppe, the increase in temperature and the decrease in precipitation, especially during the pre-sowing period, will further enhance the reduction in climate productivity, especially in the southern Steppe, and may cause the loss of winter wheat yield by 25–30% on average in the regions. In 2040–2070, according to the data (Schierhorn F et al, 2018)), the production of winter wheat in the whole territory of Ukraine may decrease by 0.72 Mt under RCP 4.5 scenario (–6.5 %) and by 1.26 Mt (–11.4 %) under RCP 8.5 scenario as compared with 1976–2005. The most considerable changes are expected in the Steppe – 0.48 Mt less under RCP 4.5 (–11 %) and 0.81 Mt less under RCP 8.5 (–18 %). In the Forest-Steppe, these changes are likely to be less evident: 0.1 Mt less (–2.2 %) under RCP 4.5 and 0.26 Mt less (–6 %) under RCP 8.5 (Schierhorn F. et al, 2018). RCP 4.5 and RCP 8.5 are scenarios of the radiation impacts or Representative Concentration Pathways, presented in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Field CB et al, 2014). RCP 4.5 scenario is the scenario of stabilization, which envisages the scenarios of mitigating the impact of greenhouse gases and adaptation to climate change. According to the latter scenario, by the end of 2100 the concentrations of greenhouse gases will have reached 630 ppm, the radiation impact will have stabilized at the rate of 4.5 Wt/sq.m., and the increase in global surface air temperature will not have exceeded 2 °C since the late 20th century. RCP 8.5 scenario is the scenario of the radiation impact, which does not envisage any adaptation. Under this scenario, the highest concentration of greenhouse gases is expected – by 2100, they will have reached 1,313 ppm, the radiation impact – 8.5 Wt/sq.m. with a further increase for some time, and the global air temperature will have increased by 3.7 °C as compared with the late 20th century. This scenario is the closest to current tendencies in changes in greenhouse gas concentrations and is also comparable to the scenario of A2 emission. According to scenario A2, by 2100, the increase in the concentration of greenhouse gases will have reached 1250 ppm, and global surface air temperature will have increased by 3.4 °C as compared with the late 20th century (Field CB et al, 2014).

The agro-climatic conditions of corn cultivation in Ukraine have been changing in recent decades and are expected to go on both in the short- and long-term perspective (Polevoy A et al, 2021; Balabukh VO, 2019). The best conditions for the formation of corn productivity in the middle of the 21st century, as per the data (Schipper L et al, 2010), will be observed in Polissia (scenarios A2 and A1B), and the worst ones – in the territory of southern Steppe. However, although in Polissia the conditions of corn cultivation will remain favorable under A1B scenario, they are very likely to deteriorate as compared with 1981–2010 and may cause yield shortfall of 12–14 %. Under A2 scenario, there is an expected decrease in corn productivity in the western Forest-Steppe by 4–8 %, and under A1B scenario – up to 20 %, as compared with 1986–2005 (Polevoy A et al, 2021).

A considerable change in agro-climatic conditions of spring barley cultivation is foreseen in Ukraine (Stepanenko SM et al, 2019). These changes may condition higher risks of its yield shortfall in 2021–2050 as compared to 1986–2010 (Polevoy AN et al, 2017). The lowest yield shortfall of spring barley is expected in Polissia and Forest-Steppe – 5.6–9.5 % with no significant differences under scenarios RCP 4.5 and RCP 8.5. In the southern Steppe, the yield shortfall may fluctuate from 13.6 to 17.5 %. The highest risks of yield shortfall of spring barley may be observed in the central regions of the southern Steppe, amounting to 26 %.

The increase in the air temperature during specific phases of crop development, accompanied by the change in the moisturization regime and causing considerable fluctuations in their productivity, demands the adaptation of agriculture to probable climate changes (Tarariko OH et al, 2016; Challinor AJ et al, 2014; Porter JR et al, 2014). O.H. Tarariko et al. (Tarariko OH et al, 2016) note that efficient use of additional heat resources, caused by climate changes, is possible only on the condition of elaborating and implementing a system of adaptation measures. According to the data (Challinor AJ et al, 2014; Porter JR et al, 2014), the adaptation measures may ensure an increase in the mean productivity of crops by almost 7 % regardless of the warming rates. Their successful implementation requires information about the impact of climate changes on the formation of crop productivity during the whole vegetative cycle. To make decisions on adapting to the consequences of climate changes, one should understand how different climate factors interact and influence crop productivity. For instance, the difference in the surface air temperature requires a different adaptation strategy than the change in the precipitation amount (Porter JR et al, 2014; Schipper L et al, 2019). To implement these strategies, one should single out the influence of different climate factors on crop productivity and have their quantitative evaluation.

The aim of the study was to determine the tendencies in changes in the air temperature and their influence on the productivity of crops during the vegetative cycle periods for the specificities of different soil-climatic zones of Ukraine for the 1981–2010 climate normal periods.

MATERIALS AND METHODS

The study on the influence of changes in thermal conditions on crop productivity was conducted using the daily data about the average daily air temperature from the network of hydrometeorological monitoring of Ukraine (187 points) for 1981–2010. The influence of agrometeorological factors and their changes on the development, productivity, and yield of corn and spring

Table 1. The optimal values of surface air temperature (°C) in specific vegetative phases of corn and spring barley in Ukraine (Dmitrenko VP, 2010)

Field crop	Vegetative phases (months)	Optimal temperature, °C
Spring barley	Pre-sowing period (XII–II)	–1
	Sowing–tillering (III–IV)	4
	Tillering–stem elongation (V)	13
	Stem elongation–milky ripeness (VI)	18
	Milky ripeness–middle dough (VII)	19
Corn	Pre-sowing period (XII–III)	–1
	Sowing–third leaf (IV–V)	12
	Third leaf–panicle emergence (VI–VII)	18
	Panicle emergence–milky ripeness (VIII)	18
	Milky ripeness–middle dough (IX)	12

barley was studied using the model of V.P. Dmitrenko "Weather-Yield" (Dmitrenko VP, 2010), according to which the influence of the air temperature on the formation of crop productivity is expressed in the form of temperature productivity coefficients *η(T)*. These take into account the optimal meteorological values (T_o), under which the highest productivity is formed in each vegetative period of field crops, and current conditions (T). The optimal values of the air temperature in specific vegetative phases of corn and spring barley in Ukraine are presented in Table 1.

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

$$\eta(T) = \frac{y(T)}{Y(T)} * 100 = \left(1 + \frac{T - T_0}{T_0 - T_{\min}}\right)^q \left(1 - \frac{T - T_0}{T_{\max} - T_0}\right)^v * 100,$$

where $y(T)$ – the yield under current thermal conditions T; $Y(T)$ – maximal yield under optimal temperature T_o in each period of the vegetative cycle; T_{min}, T_{max} – biological extremes during the corresponding period of the vegetative cycle; *q, v* – model parameters, which are determined by formulas:

$$q = \frac{T_0}{T_{\max}},$$

$$v = 1 - q = 1 - \frac{T_0}{T_{\max}}.$$

The values of the productivity coefficient vary from 0 to 100 %. Under optimal ambient temperature (Table 1) *η(T)* is 100 %. If the values of *η(T)* are within 86–100 %, the thermal conditions are favorable for crop cultivation, 65–86% – satisfactory, 36–65 % – unsatisfactory, 16–35 % – very unsatisfactory, under 15% – extreme.

The values of the air temperature and the coefficient of temperature productivity, the average 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 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 in 1981–2010 (Jaiswal RK et al, 2015). According to the recommendation of the Intergovernmental Panel on Climate Change (Field CB et al, 2014), the following relevant criteria were used: $p \leq 0.01$, the probability of 99–100 %, the change can practically not be doubted; $0.01 < p \leq 0.1$, the probability of 90–99 %, the change is very probable; $0.1 < p \leq 0.34$, the probability of 66–90 %, the change is probable; $0.34 < p \leq 0.67$, the probability of 33–66 %, the change is approximately both probable and improbable; $0.67 < p \leq 0.90$, the probability of 10–3 3%, the change is of low probability; $0.90 < p \leq 0.99$, the probability of 1–10 %, the change is of very low probability; $p > 0.99$, the probability of 0–1 %, the change is of absolutely low probability.

The evaluation of intensity, relevance, 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: Forest (Polissia), Forest-Steppe, northern and southern Steppe (Ecological Atlas of Ukraine, 2009). The comparative analysis demonstrated their specificities in the soil climatic zones of Ukraine and in different phases of plant development, and the abstract logical methods helped the formation of generalizations and conclusions.

RESULTS

The influence of the temperature change on corn productivity by the phases of crop development for the 1981–2010 climate normals period. The thermal conditions of cultivating corn for 1981–2010 in the agroclimatic zones of Ukraine were favorable; the deviations from the optimal temperature were (0.2–1.3 °C), except for the Steppe, where they were satisfactory during some periods (2.4–2.6 °C – southern Steppe) and unfavorable (3.4–4.6 °C – southern Steppe). Rising temperatures were registered during the investigated period in the whole territory of Ukraine (Tables 2, 3). However, these changes occurred with different velocity in soil-climatic zones, and their relevance during some phases of the development of field crops was considerably different (Tables 2, 3).

It was found that in Polissia, there was a noted increase in the air temperature during the whole vegetation cycle of corn cultivation, but these changes were of different magnitude and relevance in different phases of the cycle (Table 2). It is virtually certain ($p \leq 0.01$) that air temperature during the period of the third leaf–panicle emergence (months VI–VII increased by 0.8 °C/10 years, very likely increased by 0.6–0.7 °C/10 years during the blossoming period and *likely* increased by 0.3 °C/10 years during the period of sowing–germination and by 0.5 °C/10 years during the pre-sowing period. During the periods of milky ripeness and middle dough, the increase in the temperature was 0.1–

Table 2. The rate of the change in the average air temperature during the periods of the vegetation cycle of corn cultivation (*average temperature for the period; **rate of temperature change for the period)

Soil-climatic zone, administrative region	The phases of the vegetation cycle of corn cultivation														
	Pre-sowing (XII–III)			Sowing-germination (IV–V)			Third leaf-panicle emergence (VI–VII)			Blossoming (VIII)			Milky ripeness-middle dough (IX)		
	1981–2010 *	Change **		1981–2010 *	Change **		1981–2010 *	Change **		1981–2010 *	Change **		1981–2010 *	Change **	
		°C/10 yrs	p		°C/10 yrs	p		°C/10 yrs	p		°C/10 yrs	p		°C/10 yrs	p
Polissia															
Chernihiv	–3.0	0.5	0.33	11.4	0.3	0.17	18.8	0.8	0.01	18.6	0.9	0.00	13	0.3	0.31
Volyn	–1.3	0.3	0.50	11.3	0.3	0.15	18.0	0.8	0.00	18.1	0.6	0.02	13	0.1	0.84
Rivne	–1.5	0.3	0.57	11.5	0.3	0.17	18.0	0.8	0.00	18.1	0.6	0.02	13	0.0	0.96
Zhytomyr	–1.9	0.5	0.35	11.4	0.3	0.18	18.2	0.8	0.00	18.1	0.7	0.01	13	0.2	0.56
Forest-Steppe															
Kyiv	–2.1	0.5	0.34	12.0	0.4	0.13	19.2	0.8	0.00	19.2	0.9	0.00	14	0.2	0.49
Lviv	–0.9	0.4	0.43	11.3	0.4	0.08	17.7	0.7	0.00	18.0	0.6	0.01	13	–0.2	0.50
Khmelnytsky	–1.8	0.4	0.42	11.5	0.4	0.08	18.2	0.8	0.00	18.4	0.7	0.01	13	0.0	0.93
Poltava	–2.5	0.5	0.32	12.4	0.4	0.19	19.9	0.8	0.02	20.0	0.9	0.01	14	0.3	0.43
Kharkiv	–3.0	0.5	0.35	12.2	0.3	0.29	20.0	0.7	0.04	20.0	1.0	0.00	14	0.4	0.22
Sumy	–3.3	0.5	0.32	11.2	0.6	0.02	18.9	0.8	0.02	18.7	0.9	0.00	13	0.4	0.28
Ternopil	–1.5	0.4	0.43	11.3	0.4	0.07	17.8	0.8	0.00	18.1	0.7	0.00	13	–0.1	0.84
Cherkasy	–1.9	0.5	0.32	12.3	0.4	0.08	19.5	0.8	0.00	19.7	0.9	0.00	14	0.2	0.52
Vinnytsia	–1.7	0.4	0.43	11.8	0.4	0.07	18.7	0.9	0.00	18.9	0.9	0.00	14	0.1	0.83
Chernivtsi	–0.9	0.4	0.36	12.1	0.7	0.01	19.0	1.0	0.00	19.2	1.1	0.00	14	0.0	0.90
Steppe															
Luhansk	–2.9	0.4	0.43	12.4	0.1	0.60	20.6	0.6	0.07	20.6	0.9	0.01	15	0.4	0.25
Kirovohrad	–1.9	0.5	0.30	12.4	0.4	0.12	20.0	0.8	0.01	20.4	0.9	0.00	15	0.1	0.68
Dnipropetrovsk	–1.3	0.5	0.33	11.3	0.3	0.25	18.0	0.7	0.03	18.1	1.0	0.00	13	0.3	0.36
Donetsk	–2.4	0.5	0.27	12.4	0.2	0.32	20.8	0.7	0.03	21.2	1.1	0.00	15	0.5	0.14
Odesa	0.4	0.5	0.26	13.1	0.4	0.06	21.3	0.8	0.00	22.0	1.0	0.00	17	0.1	0.85
Zaporizhzhia	–0.9	0.4	0.33	12.9	0.3	0.22	21.5	0.7	0.02	22.0	1.0	0.00	16	0.5	0.16
Mykolayiv	–0.4	0.5	0.31	13.1	0.4	0.10	21.3	0.8	0.00	22.0	1.0	0.00	16	0.2	0.62
Kherson	0.2	0.5	0.24	13.0	0.4	0.05	21.9	0.8	0.00	22.6	1.0	0.00	17	0.4	0.22
AR of Crimea	2.2	0.4	0.15	12.2	0.3	0.14	21.1	0.8	0.00	22.3	1.1	0.00	17	0.5	0.12
Ukraine	–1.2	0.5	0.29	12.0	0.4	0.10	19.6	0.8	0.00	19.9	0.9	0.00	15	0.2	0.45

Table 3. The rate of the change in the coefficient of temperature productivity during the periods of the vegetation cycle of corn cultivation

Soil-climatic zone, administrative region	The phases of the vegetation cycle of corn cultivation														
	Pre-sowing (XII–III)			Sowing-germination (IV–V)			Third leaf-panicle emergence (VI–VII)			Blossoming (VIII)			Milky ripeness-middle dough (IX)		
	1981–2010	Change		1981–2010	Change		1981–2010	Change		1981–2010	Change		1981–2010	Change	
		%10 yrs	p		%10 yrs	p		%10 yrs	p		%10 yrs	p		%10 yrs	p
Polissia															
Chernihiv	85.8	4.0	0.34	95.1	0.0	1.00	91.3	–4.6	0.11	92.7	–6.9	0.02	90.2	1.1	0.71
Volyn	88.8	1.5	0.62	95.8	0.3	0.80	96.3	–0.9	0.46	96.0	–0.8	0.62	89.5	–2.1	0.51
Rivne	88.4	2.4	0.48	95.0	0.3	0.81	96.1	–1.3	0.34	95.5	–1.1	0.53	89.2	–2.8	0.40
Zhytomyr	89.1	3.2	0.37	95.0	0.3	0.80	95.2	–2.4	0.17	94.9	–2.6	0.22	90.2	–0.2	0.96
Forest-Steppe															
Kyiv	88.7	3.5	0.33	91.6	–1.0	0.59	89.2	–6.7	0.02	89.1	–8.0	0.02	83.1	2.7	0.48
Lviv	88.6	1.0	0.74	95.6	0.3	0.77	97.1	0.4	0.62	96.3	–0.4	0.79	88.2	1.7	0.58
Khmelnytsky	89.2	2.8	0.39	94.8	–0.3	0.82	96.0	–1.9	0.18	94.3	–2.4	0.27	86.5	0.1	0.97
Poltava	88.1	3.4	0.36	88.0	–0.9	0.72	81.5	–8.2	0.04	81.1	–11.2	0.01	76.6	4.4	0.25
Kharkiv	85.7	3.5	0.39	89.4	0.1	0.96	80.0	–8.3	0.06	80.6	–12.0	0.01	77.3	7.0	0.07
Sumy	84.0	4.0	0.37	95.3	–0.3	0.80	90.1	–4.7	0.14	91.4	–7.9	0.01	89.6	1.9	0.55
Ternopil	89.0	2.6	0.39	95.6	0.3	0.73	96.9	0.1	0.93	95.6	–1.1	0.52	88.1	-1.4	0.72
Cherkasy	89.1	3.0	0.39	89.7	–1.4	0.45	86.1	–7.9	0.02	84.7	–10.0	0.01	77.9	3.6	0.36
Vinnytsia	89.0	3.0	0.38	93.2	–1.1	0.45	93.0	–5.4	0.01	91.0	–6.1	0.05	83.6	1.3	0.76
Chernivtsi	88.2	1.5	0.64	91.1	–2.3	0.25	93.0	–5.6	0.00	89.9	–6.9	0.02	77.3	2.0	0.64
Steppe															
Luhansk	86.1	2.8	0.48	88.5	1.1	0.67	72.9	–8.3	0.08	73.6	–12.2	0.01	70.7	6.2	0.14
Kirovohrad	89.4	2.8	0.42	88.7	–1.5	0.50	80.9	–9.2	0.01	76.5	–11.3	0.01	69.9	2.6	0.49
Dnipropetrovsk	90.1	2.7	0.37	84.1	–1.2	0.68	71.3	–9.9	0.04	67.0	–13.0	0.01	61.1	5.1	0.21
Donetsk	90.3	2.6	0.35	88.5	–0.5	0.83	71.0	–10.5	0.03	66.4	–14.8	0.00	61.9	7.9	0.08
Odesa	81.6	–2.0	0.56	81.1	–4.1	0.12	63.7	–12.8	0.00	53.3	–15.1	0.00	43.1	1.0	0.74
Zaporizhzhia	91.0	1.3	0.56	83.8	–1.6	0.54	61.7	–10.5	0.02	54.2	–14.0	0.00	47.8	4.8	0.21
Mykolayiv	86.7	0.1	0.98	81.0	–3.6	0.21	63.7	–12.1	0.01	54.6	–13.7	0.00	48.4	2.1	0.55
Kherson	84.4	–1.2	0.67	82.9	–3.9	0.11	55.0	–12.0	0.00	44.8	–13.3	0.00	38.0	2.5	0.38
AR of Crimea	64.0	–5.9	0.16	92.0	–1.2	0.45	67.3	–12.4	0.00	50.5	–14.8	0.00	35.8	2.0	0.48
Ukraine	91.1	1.6	0.55	92.8	–0.8	0.60	86.5	–8.1	0.01	82.4	–10.9	0.00	73.0	3.9	0.34

0.2 °C/10 years, but these changes were insignificant for Polissia) (Table 2).

There was also a change in the temperature-related productivity in 1981–2010: during the pre-sowing period and the sowing-germination period and a decrease in the temperature-related productivity in other phases of the corn vegetation cycle, especially during the blossoming period in Zhytomyr and Chernihiv Polissia from 2.6 to 6.9 % (Table 3).

The same regularities in the change of air temperature are remarkable for the Forest-Steppe during the current climatic period, similar to Polissia: the increase in the air temperature during the whole vegetation cycle, the most intensive increase during the period of the third leaf–panicle emergence, and, especially, blossoming – 0.7–0.9 °C/10 years, a very likely and likely increase during the period of sowing and germination and insignificant changes during the pre-sowing period and in the phase of milky ripeness and middle dough (Table 3).

The intense increase in the air temperature (0.8–1.1 °C/10 years) during the periods of the third leaf, panicle emergence, and blossoming was very likely and likely ($p < 0.14$) unfavorable for corn, especially in the eastern and central Forest-Steppe, which was con firmed by the decrease in temperature productivity in the region, amounting to 7–12 % in 10 years During the period of sowing–germination, the temperature-related productivity decreased as well, but these changes were insignificant. Instead, during the pre-sowing period in the Forest-Steppe and during the period of milky ripeness and middle dough in some regions of the eastern and central Forest-Steppe, the temperature-related productivity likely increased by 3–4 % in 10 years. A remarkable increase in temperature productivity was registered in western Forest-Steppe during the whole vegetation cycle of corn, except for blossoming, though this growth was insignificant (Table 3).

In the Steppe of Ukraine, the most intensive increase in air temperature was remarkable for the periods of blossoming (0.9–1.1 °C/10 years) and the third leaf-panicle emergence (0.7–0.8 °C/10 years). These changes were virtually certain, reaching the maximal values in the dry Steppe (Table 2). This intense increase in the temperature was unfavorable for corn and led to the decrease in temperature productivity by 10–15 %/10 years. As a result, the conditions for corn cultivation during the mentioned periods deteriorated considerably and were satisfactory in northern Steppe and unsatisfactory in the south, in the dry Steppe (Table 2). During other phases of corn development, the rate of the air temperature increase was twice slower, and its relevance was under 70 %. The increase in the temperature during the sowing-germination period was also unfavorable for corn. However, its increase during the pre-sowing period and especially during the period of milky ripeness and middle dough conditioned the increase by 3–6 % in the crop productivity in 10 years. Still, the conditions for corn cultivation during the period of milky ripeness and middle dough remained unsatisfactory, especially in the dry Steppe (Table 3).

The influence of the temperature change on spring barley productivity by the phases of crop development for the 1981–2010 climate normals period. In Polissia, during almost the whole vegetation cycle of spring barley cultivation in 1981–2010, there was an increase in the air temperature but in different phases of the cycle, these changes were of different magnitude and significance (Table 4). The exception was found only in the tillering period (May), when the air temperature decreased a little, but these changes were of *very low probability*. The strongest increase in the air temperature was registered during the periods of milky ripeness and milky dough of spring barley (July), amounting to 1.0–1.1 °C/10 years. These changes were practically undoubted, and their probability was 99 % and higher. Very likely and likely the air temperature increased by 0.5–0.7 °C/10 years during the period of sowing barley, in the phase of the third leaf, stem elongation, and ear formation. During the pre-sowing period, the increase in the temperature was 0.3–0.4 °C/10 years, but these changes were insignificant for Polissia, and their probability fluctuated from 40 to 60 % (Table 4).

The increase in the air temperature was unfavorable for spring barley cultivation almost during the whole vegetation cycle, especially in Polissia of Zhytomyr and Chernihiv, which was demonstrated by the decrease in the temperature productivity coefficient by 5 % in 10 years. The exception was found in the period of barley stem elongation and ear formation, during which the increase in the air temperature promoted the increase in the crop productivity by 1.0%/10 years, especially in Volyn (Table 5).

During the whole vegetation cycle of spring barley, the increase in the air temperature was registered for 1981–2010 in the Forest-Steppe (Table 4). Similar to Polissia, the most intense changes were registered during the periods of milky ripeness and middle dough, which amounted to 0.9–1.2 °C/10 years, reaching the maximum in the central Forest-Steppe. This increase is

Table 4. The rate of the change in the average air temperature during the periods of the vegetation cycle of spring barley cultivation

Soil-climatic zone, administrative region	The phases of the vegetation cycle of corn cultivation														
	Pre-sowing (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	
		°C/10 yrs	p		°C/10 yrs	p		°C/10 yrs	p		°C/10 yrs	p		°C/10 yrs	p
Polissia															
Chernihiv	–4.1	0.4	0.40	4.4	0.7	0.09	14.6	0.0	0.98	17.8	0.5	0.22	19.7	1.1	0.00
Volyn	–2.3	0.3	0.54	5.1	0.5	0.11	14.2	0.0	0.95	17.0	0.6	0.03	19.0	1.0	0.00
Rivne	–2.5	0.3	0.59	5.1	0.5	0.19	14.4	0.0	0.98	17.1	0.6	0.03	19.0	1.0	0.00
Zhytomyr	–3.0	0.4	0.41	4.8	0.6	0.07	14.5	0.0	0.93	17.3	0.5	0.07	19.1	1.1	0.00
Forest-Steppe															
Kyiv	–3.2	0.4	0.42	5.1	0.7	0.07	15.2	0.0	0.93	18.2	0.5	0.12	20.1	1.1	0.00
Lviv	–1.9	0.4	0.43	5.4	0.5	0.17	14.1	0.2	0.52	16.8	0.6	0.01	18.7	0.9	0.00
Khmelnytsky	–3.0	0.3	0.50	5.0	0.6	0.10	14.5	0.2	0.64	17.2	0.6	0.03	19.1	1.1	0.00
Poltava	–3.7	0.4	0.41	5.2	0.7	0.10	15.5	0.0	0.97	18.9	0.5	0.19	20.9	1.0	0.00
Kharkiv	–4.3	0.3	0.53	4.9	0.7	0.13	15.4	0.1	0.90	19.0	0.4	0.31	21.0	1.0	0.01
Sumy	–4.7	0.4	0.44	4.2	1.1	0.03	14.6	0.0	0.94	18.0	0.4	0.27	19.8	1.1	0.00
Ternopil	–2.6	0.3	0.50	5.0	0.6	0.09	14.2	0.2	0.55	16.9	0.6	0.02	18.8	1.0	0.00
Cherkasy	–3.1	0.4	0.41	5.3	0.7	0.09	15.6	0.1	0.65	18.6	0.6	0.08	20.5	1.1	0.00
Vinnytsia	–2.9	0.3	0.51	5.2	0.6	0.10	14.9	0.2	0.60	17.8	0.6	0.03	19.7	1.2	0.00
Chernivtsi	–2.0	0.4	0.42	5.9	0.7	0.06	14.9	0.6	0.06	18.0	0.9	0.00	19.9	1.1	0.00
Steppe															
Luhansk	–4.2	0.1	0.77	5.0	0.7	0.17	15.5	0.1	0.88	19.6	0.4	0.32	21.7	0.8	0.03
Kirovohrad	–3.0	0.4	0.40	5.4	0.7	0.09	15.5	0.1	0.73	18.9	0.6	0.08	21.1	1.0	0.00
Dnipropetrovsk	–2.3	0.3	0.54	5.1	0.8	0.10	14.2	0.1	0.83	17.0	0.5	0.20	19.0	0.9	0.01
Donetsk	–3.6	0.3	0.54	5.3	0.7	0.09	15.5	0.2	0.69	19.6	0.5	0.17	21.9	1.0	0.02
Odesa	–0.6	0.4	0.40	6.9	0.7	0.06	16.2	0.3	0.31	20.2	0.6	0.02	22.5	1.1	0.00
Zaporizhzhia	–2.0	0.2	0.61	6.1	0.7	0.10	16.0	0.2	0.51	20.3	0.5	0.10	22.7	0.8	0.02
Mykolayiv	–1.5	0.3	0.46	6.5	0.7	0.06	16.2	0.2	0.55	20.1	0.6	0.06	22.5	1.0	0.00
Kherson	–0.8	0.3	0.46	6.5	0.8	0.04	16.1	0.3	0.30	20.6	0.7	0.03	23.2	0.9	0.01
AR of Crimea	1.6	0.3	0.36	6.7	0.6	0.10	15.0	0.4	0.15	19.6	0.7	0.01	22.6	0.9	0.01
Ukraine	–2.3	0.4	0.39	5.5	0.7	0.08	15.0	0.0	0.85	18.5	0.6	0.04	20.7	1.0	0.00

Table 5. The rate of the change in the temperature productivity coefficient during the periods of the vegetation cycle of spring barley cultivation

Soil-climatic zone, administrative region	The phases of the vegetation cycle of corn cultivation														
	Pre-sowing (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	
		%/10 yrs	p		%/10 yrs	p		%/10 yrs	p		%/10 yrs	p		%/10 yrs	p
Polissia															
Chernihiv	87.5	–2.9	0.37	94.6	–0.2	0.86	90.8	–1.5	0.35	95.9	–0.6	0.64	94.2	–4.5	0.05
Volyn	93.0	–1.6	0.48	93.5	–1.6	0.29	93.5	–0.7	0.45	97.3	1.0	0.14	96.4	–1.4	0.13
Rivne	92.6	–1.7	0.49	92.7	–0.8	0.66	92.3	–1.0	0.44	97.3	0.8	0.27	96.5	–1.2	0.19
Zhytomyr	91.7	–2.5	0.35	94.1	–1.0	0.45	91.7	–1.1	0.46	97.2	0.2	0.78	95.9	–1.9	0.15
Forest-Steppe															
Kyiv	91.3	–2.6	0.35	92.3	–1.5	0.41	87.1	–1.3	0.55	95.9	–1.5	0.29	93.1	–5.4	0.02
Lviv	93.8	–1.3	0.46	92.2	–1.7	0.30	94.1	–1.1	0.53	97.3	1.4	0.03	97.2	0.0	0.94
Khmelnytsky	92.1	–1.9	0.44	93.2	–1.1	0.47	91.8	–1.5	0.37	97.7	0.6	0.31	96.5	–1.4	0.08
Poltava	89.6	–2.5	0.38	90.8	–1.4	0.50	84.2	–1.3	0.65	93.1	–2.2	0.27	88.9	–7.0	0.02
Kharkiv	86.9	–2.1	0.49	91.5	–0.4	0.82	85.0	–1.0	0.71	91.9	–2.2	0.35	88.1	–7.5	0.02
Sumy	84.6	–2.7	0.43	93.2	0.1	0.94	90.2	–1.4	0.43	95.1	–0.5	0.68	94.1	–4.5	0.06
Ternopil	92.7	–1.9	0.39	93.3	–1.1	0.45	93.5	–1.0	0.42	97.4	1.3	0.04	97.1	–0.1	0.86
Cherkasy	91.9	–2.2	0.40	91.0	–1.4	0.47	85.3	–1.8	0.45	95.2	–2.1	0.18	91.7	–5.8	0.01
Vinnytsia	92.3	–2.0	0.42	91.9	–1.3	0.47	89.5	–2.3	0.28	97.5	–0.5	0.54	94.9	–3.8	0.01
Chernivtsi	93.9	–1.1	0.52	88.3	–3.0	0.22	89.5	–2.9	0.27	98.2	–0.6	0.27	95.2	–3.3	0.00
Steppe															
Luhansk	87.2	–1.1	0.70	90.9	0.1	0.95	85.0	–1.0	0.71	90.2	–2.8	0.28	83.0	–7.8	0.03
Kirovohrad	92.3	–2.0	0.42	89.9	–1.6	0.43	84.9	–2.1	0.44	94.1	–2.7	0.12	87.9	–7.0	0.01
Dnipropetrovsk	92.6	–1.7	0.43	87.8	–1.9	0.43	81.3	–1.6	0.63	90.1	–3.4	0.20	81.6	–8.4	0.02
Donetsk	90.8	–1.5	0.50	91.2	–1.3	0.49	84.6	–1.8	0.50	90.1	–3.8	0.15	80.6	–9.2	0.02
Odesa	94.3	0.3	0.83	81.2	–4.8	0.09	79.9	–2.6	0.30	89.1	–4.9	0.02	76.4	–10.5	0.00
Zaporizhzhia	95.4	–1.0	0.46	86.8	–2.3	0.31	81.3	–2.2	0.44	87.1	–4.7	0.09	74.6	–8.8	0.02
Mykolayiv	94.8	–0.8	0.63	84.0	–3.8	0.14	79.5	–2.4	0.41	88.5	–4.7	0.07	75.7	-–10.1	0.00
Kherson	95.0	–0.2	0.88	83.7	–4.3	0.09	80.6	–3.0	0.24	85.3	–6.1	0.02	68.8	–9.9	0.01
AR of Crimea	84.8	2.2	0.34	82.9	–4.2	0.09	90.3	–1.8	0.18	92.3	–5.3	0.01	75.6	–9.4	0.01
Ukraine	94.8	–1.4	0.43	91.0	–2.0	0.28	89.5	–1.6	0.37	96.4	–1.7	0.12	91.2	–6.0	0.01

virtually certain ($p \leq 0.01$) in the territory of the whole Forest-Steppe. Very likely and likely, the air temperature increased during the period of sowing barley, in the phase of the third leaf, stem elongation, and ear formation. The rate of these temperature changes in the prevailing part of the Forest-Steppe was the same as in Polissia, amounting to 0.5–0.7 °C/10 years. During the pre-sowing period, the intensity of the increase in the air temperature was twice lower (0.3–0.4 °C/10 years). The changes in the air temperature during the period of spring barley tillering was insignificant and of low probability (0.1–0.2 °C/10 years) almost in the whole territory, except for Ivano-Frankivsk and Chernivtsi regions, where it was likely and very likely increased by 0.3 and 0.6 °C/10 years, respectively (Table 4).

These changes in the air temperature were unfavorable for spring barley cultivation in the Forest-Steppe during the whole vegetation cycle, and especially during the periods of milky ripeness and middle dough in the central and eastern Forest-Steppe, where very likely and likely they promoted the decrease in barley productivity by 7.5 %/10 years. This is evidenced by the coefficient of productivity of temperature, presented in Table 5. The decrease in barley productivity by 1–3 % in 10 years due to the temperature increase was also remarkable for other phases of crop development in the Forest-Steppe, but these changes were mostly insignificant. The exception was found in the period of stem elongation and ear formation in the western Forest-Steppe, where the increase in temperature was very likely favorable for the purpose of enhancing spring barley productivity.

In the Steppe zone of Ukraine, during the current climatic period, there were the following regularities in the changes of the thermal regime during the period of spring barley cultivation, similar to the Forest-Steppe and Polissia: the increase in the air temperature during the whole vegetation cycle of the crop, the most intense changes during the periods of milky ripeness and middle dough (0.8–1.1 °C/10 years), sowing–third leaf (0.7–0.8 °C/10 years), stem elongation–ear formation (0.4–0.6 °C/10 years) and insignificant changes during the pre-sowing period and during tillering (0.1–0.3 °C/10 years). In the south, in the dry Steppe, the increase in the air temperature was more intense than in the southern Steppe (Table 4).

As seen from the change in the temperature productivity coefficient, the increase in the air temperature was unfavorable for the cultivation of spring barley in the Steppe of Ukraine during the whole vegetation cycle of the crop, and caused a decrease in barley productivity, especially in the dry Steppe (Table 5). The biggest changes took place during the period of milky ripeness and middle dough and very probably reached 10 % in 10 years. There was a likely and very likely decrease in spring barley productivity due to the increase in the air temperature and during the periods of stem elongation–ear formation and sowing–third leaf, amounting to 5 % in 10 years on average in the regions. There was a likely decrease in the productivity of spring barley during the tillering period in Odesa and Kherson regions. During other phases of crop development, its productivity decreased as well, but these changes were insignificant.

However, during the research period of 1981–2010, the thermal conditions for spring barley cultivation in the dry Steppe were satisfactory during almost the whole vegetation cycle, except for the pre-sowing period, and deteriorated due to a considerable increase in the air temperature. In the north of the Steppe zone, the satisfactory conditions for spring barley cultivation were remarkable only for the periods of tillering, milky ripeness, and middle dough, but the intense increase in the air temperature promoted their deterioration during the whole vegetation cycle.

DISCUSSION

The intense increase in the air temperature conditioned a considerable change in the agroclimatic conditions of cultivating crops and their productivity (Balabuh VO et al, 2017). The studies of the influence of the change in the air temperature and its productivity on the yield of corn and spring barley in Ukraine singled out the influence of the air temperature from other climatic factors, evaluated its contribution to the formation of the yield of crops during the periods of the vegetation cycle, and revealed their specificities in soil-climatic zones of Ukraine. The results of evaluating the influence of changes in the air temperature on the yield of grains are in agreement with the data, obtained from other regions (Polevoy A et al, 2007; Polevoy A et al, 2015). According to the data of (Lobell DB, Field CB, 2007), there is a clear negative response of the global yield of wheat, corn, and barley on the increase in temperature. The warming since 1981 led to annual cumulative losses of these three crops of about 40 million tons or 5 billion dollars per year. In the main arable areas of the European Union, the yield of grain corn increased in the northern part of the EU, remained the same in the central part, and decreased in the south (Wolf J, Van Diepen CA, 1995). The studies, conducted in the US state of Wisconsin, demonstrated that the increase in the air temperature by 1 °C in 10 years during summer months may decrease corn yield by up to 13 % (Kucharik CJ, Serbin SP, 2008). These results correspond to the data, obtained in the work, which demonstrated that in the Forest-Steppe there was a decrease in the temperature productivity by 7–12 %/10 years at the increase in the temperature by 0.7–0.9 °C/10 years in summer months, when corn is predominantly in the phase of the third leaf, panicle emergence, and blossoming. In the Steppe zone of Ukraine, where the increase in the temperature was 0.9–1.1 °C/10 years, the decrease in the temperature productivity during this period was 10–15 %/10 years. The decrease in the temperature productivity is conditioned by the fact that the thermal conditions may go beyond the thresholds of the biological optimum of the crops. For instance, according to the data of (Schlenker W, Roberts MJ, 2008) the increase in the air temperature up to 29 °C promotes the increase in corn yield, but its further increase is very harmful for it. The study on the influence of the change in temperature and precipitation on spring barley yield in the territory of the Northern plans of the USA and Canada (Klink K, 2014) demonstrated that high temperatures during the pre-sowing period promoted the increase in barley productivity while during the vegetation period they decreased its yield. The results, obtained for Ukraine, demonstrated that during the pre-sowing period, the influence of the increase in the temperature on the formation of barley yield was insignificant, and during the vegetation period, especially in the phase of milky ripeness and middle dough (July) conditioned the decrease in the yield by up to 10 % in the Steppe. In addition, according to the data of (Högy P et al, 2013) high temperature decreased spring barley productivity and influenced the quality of its grain more than the change in the amount of precipitation and decreased its nutritional value. For instance, a decrease in TGW, lipids, A1, and NSC was noted in barley (except for maltose). The amount of several proteinogenic aminoacids was increased due to the high temperature. Further increase in the temperature will change the nutritional value and processing of grain (Högy P et al, 2013).

The study on the influence of the temperature change on the formation of corn and spring barley productivity in Ukraine was conducted using the data of the observations of the air temperature from 1981 till 2010 and did not cover the last decade. However, according to the information of the World Meteorological Organization (State of the Global Climate 2020, 2021), the period from 2011 till 2020 was found to be the warmest in our planet in the whole history of meteorological observations. The highest temperatures were observed in 2015–2020 and 2020 became the warmest in the history of observations after 2016. In Ukraine, the period from 2011 till 2020 was found to be the warmest since 1961 very probably, during the whole period of instrumental observations of the weather, and 2020 was the warmest in the last fifty years and probably, in the century (Balabukh V et al, 2021; National Report EN 2020, 2021). Its anomalies in the average annual air temperature as compared with the average perennial temperature values for 1991–2020 exceeded 1.5 °C, and as compared with 1961–1990, they amounted to 2.8 °C. Six out of twelve months were found to be the warmest during the whole period of instrumental observations of the weather in the whole territory of Ukraine, and May – one of the coldest and wettest months. Autumn of 2020 was the warmest in the last 140 years, and for the first time, no meteorological winter was observed in a considerable part of the country.

These weather conditions were extremely unfavorable for the cultivation of crops and conditioned great yield loss. According to current data of the State Emergency Service of Ukraine and the Ministry of Eco-nomy of Ukraine, the total area of perished crops was 770,878 ha in 2020, including winter crops – 568,237 ha. The total amount of the material loss due to perished crops exceeded 23.4 billion hryvnia, including winter crops for over 17.1 billion hryvnia (National Report EN 2020, 2021). Odesa, Cherkasy, Mykolayiv, and Kirovohrad regions were found to be the most susceptible areas. For instance, the area of the perished crops in Odesa region was 518,045 ha, including the area under winter crops – 484,541 ha and corn – 33,504 ha, a considerable decrease in corn yield was noted on 50,082 ha. In Cherkasy region, the crops perished in the area of 135,859 ha (2,019 ha of winter crops and 133,840 ha of corn), and low corn yield was observed in 234,000 ha more. In Mykolayiv region, the grains perished in the area of 24,602 ha (22,602 ha of winter crops, 2,000 ha of corn) and a decrease in corn yield was noted in 43,200 ha. In Kirovohrad region, the grains perished in the area of 23,378 ha (2,078 ha of winter crops and 21,300 ha of corn) and low yield of corn was observed in the area of 146,700 ha.

The recent decade and, especially last five years, in Ukraine was not only the warmest in almost 140 years, but also rather dry. A considerable shortage of moisture was registered in 2020 as well (National Report EN 2020, 2021). The drought, which started in 2019 and lasted for eight months in a considerable territory of Ukraine, continued in 2020. The shortage of precipitation was observed almost throughout the year except for February, May, and June. Even during these months, there was a moisture shortage in some regions. A long dry period was accompanied by abnormally high air temperature, which promoted considerable evaporation of current moisture, the increasing lack of soil moisture, and the development of both atmospheric and soil drought. (Polupan M, Velychko V, 2019).

The current high tempo of global warming, observed mainly in the last decade and forecast in the near and extended perspective, impacted the state of the vegetation considerably. According to NDVI index, in 1982–2021 (Tarariko OG et al, 2021; Huo R et al, 2021; Hirschi M et al, 2011; Sharma M et al, 2021), which characterizes the amount of photosynthetically active biomass, and depends on the temperature and moisture supply of the fields, generally the increase in the temperature had a positive impact on the state of vegetation, including the state of corn and barley in the zones of Polissia, Forest-Steppe, and Steppe. In the Steppe, where there still are high risks of droughts, the positive influence of the warming, which started in the 1980s, was manifested much less as compared with Polissia and Forest-Steppe. While in the first decade (1982–1991) the NDVI index was at the level of 0.3 on average for the vegetation period, in the following decade, it increased up to 0.33. The tendency to its increase slowed from 9.41 % during the second decade (1992–2001).

It should be noted that other climatic factors also influence the yield of grains. According to the data (Polevoy AN et al, 2014; Polevoy AN et al, 2017) the increase in the air temperature, caused by the rise in the concentration of greenhouse gases, including CO_2, favorable for the photosynthesis processes in grains, the increase in the photosynthetic potential of the fields and the increase in their potential yield. Thus, while evaluating the influence of the climate change on the yield of crops, it would be reasonable to conduct comprehensive studies, including the experimental work on the adjustment to zonal agrotechnologies of cultivating corn and spring barley under climate warming. In this respect, it is also essential to use the results of permanent field experiments, conducted by the scientific institutions of the National Academy of Agrarian Sciences of Ukraine (Zaryshnyak AS et al, 2016).

The temperature values, remarkable for medium ripe varieties (Table 1), were used as optimal temperature values in specific phases of their development to investigate the influence of the air temperature change on the yield of corn and spring barley (Table 1). However, farmers use different varieties in their activity, and their productivity may differ under the same climatic conditions. Thus, it would be reasonable to conduct such studies for different varieties of grains and to find the ones least susceptible under new climatic conditions with the consideration of phytopathogenic risks.

CONCLUSIONS

Since the middle of the 20th century there has been a gradual increase in the surface air temperature on the planet, which demonstrates the change in the climate system (IPCC, 2021). According to the data of IPCC (FAO, 2021), the 30-year-long period from 1983 till 2012 might have been the warmest period in the last 1,400 years in the northern hemisphere. The increase in the temperature was also remarkable for Ukraine: 1981–2010 – the rate of the increase in the average annual air temperature was 0.57 °C/10 years which was almost thrice higher than the tempo of the increase in the average annual global temperature – 0.166 °C/10 years (FAO, 2021; Tarariko OH et al, 2016). It was determined that during this period, there was a notable increase in the air temperature during the whole vegetative cycle of corn and spring barley in all the soil-climatic zones of Ukraine. The most significant changes were remarkable during the periods of the third leaf, panicle emergence, and blossoming of corn and in the phase of milky ripeness and middle dough of spring barley and increased from Polissia (0.7–0.8 °C/10 years) to the Steppe (0.9–1.1 °C/10 years). The increase in the surface air temperature conditioned the change in temperature productivity and promoted the decrease in the yield formation almost in all the phases of crop development in all the soil climatic zones of Ukraine. However, from 1981–2010, the conditions for cultivating corn and spring barley in Polissia remained favorable, and in the Forest-Steppe – favorable and satisfactory. In the Steppe, the thermal conditions were satisfactory for spring barley cultivation and unsatisfactory for corn, especially in the dry Steppe. Therefore, under the intense increase in the air temperature the cultivation of grains in the Steppe, especially in the dry Steppe, is the most susceptible, and in Polissia and western Forest-Steppe – the least susceptible. Further studies require the evaluation of the influence of the change in moisturization on the yield of grains, the cumulative influence of the temperature and precipitation, the agro-climatic potential of soils, more detailed consideration of spatial and temporal variabil-

ity of possible climatic changes, the enhanced risks of droughts. There is an urgent need to develop recommendations regarding the adjustment of agrotechnology for cultivating field crops under climate changes, improving agricultural management, and selecting drought-resistant varieties.
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Вплив зміни температури повітря на формування врожайності сільськогосподарських культур в Україні на межі XX–XXI століть (1981–2010 рр.)

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Мета. Виявити тенденції зміни температури повітря та їхній вплив на врожайність сільськогосподарських культур у періоди вегетаційного циклу, особливо у ґрунтово-кліматичних зонах України впродовж 1981–2010 рр. **Методи**. Аналітико-синтетичний, статистичні, кліматичні, моделювання (модель Дмитренко В.П. «Погода-урожай») (Dmitrenko et al, 2017; 2010), яка застосовується для прогнозування урожайності зернових культур в Українському гідрометеорологічному центрі з 1970 р. абстрактно-логічний. **Результати**. Встановлено підвищення температури повітря впродовж усього вегетаційного періоду вирощування кукурудзи та ячменю ярого в 1981–2010 рр. Виявлено, що це підвищення на різних фазах розвитку культур мало неоднакову величину та значущість у всіх областях та ґрунтово-кліматичних зонах України. Достовірні зміни приземної температури відмічені у періоди третього листка, викидання волоті та цвітіння кукурудзи на Поліссі, у Лісостепу і, особливо, Степу (0,7–0,8 °C/10 років, 0,8–0,9 °C/10 років та 0,9–1,1 °C/10 років, відповідно). У передпосівний період, період сівби і сходів кукурудзи швидкість змін була вдвічі меншою на всій території країни, а у період молочної та воскової стиглості – у східному Лісостепу та сухому Степу і становила 0,4–0,5 °C/10 років. Істотне підвищення температури у період третього листка, викидання волоті та цвітіння сприяло зменшенню впливу температури на врожайність за цих фаз розвитку культури, особливо у Степу (до 10–15 % за 10 років). Лише ріст температури у передпосівний період сприяв підвищенню урожайності на 3–6 % за 10 років на всій території країни, а в періоди молочної та воскової стиглості кукурудзи до 8 % за 10 років у Лісостепу та Степу. Загалом термічні умови для вирощування кукурудзи істотно погіршувались, проте на Поліссі залишались сприятливими, у Лісостепу та в північному Степу – задовільними, а на півдні, у сухому Степу – незадовільними. Найінтенсивніші зміни температури повітря у період вегетації ячменю ярого відмічено у фазі молочної та воскової стиглості в усіх ґрунтово-кліматичних зонах і становили 0,8–1,1 °C/10 р. У періоди сівби, третього листка, стеблування та колосіння вони були – 0,6–0,7 °C/10 р., а в передпосівний період – 0,3–0,4 °C/10 р. У період кущіння ячменю ярого зміна температури повітря була незначущою на території всієї країни. Істотне підвищення температури повітря було несприятливим для вирощування культури в усіх ґрунтово-кліматичних зонах України впродовж вегетаційного циклу ячменю ярого, особливо у період молочної та воскової стиглості і сприяло зменшенню його продуктивності у цей період на Поліссі, у Лісостепу та у степовій зоні на 5, 7,5 та 10 % за 10 років, відповідно. Загалом підвищення температури повітря зумовлювало погіршення термічних умов вирощування ячменю ярого, проте на Поліссі і в Лісостепу вони залишались сприятливими, а в Степу – сприятливими і задовільними впродовж передпосівного періоду та в періоди вегетаційного циклу. **Висновки.** У 1981–2010 рр., впродовж усього вегетаційного циклу кукурудзи та ячменю ярого відмічали підвищення температури повітря, проте ці зміни на різних фазах розвитку культур мали неоднакову величину та значущість у ґрунтово-кліматичних зонах України. Найвищими темпами температура повітря зростала у період молочної та воскової стиглості ячменю ярого по всій території країни та у період цвітіння кукурудзи, особливо у степовій зоні, і перевищила 1,0 °C/10 років. Істотне підвищення температури повітря сприяло зменшенню урожайності зернових культур на цих фазах розвитку до 10–15 % за 10 років, найбільше у Степу сухому. Підвищення температури повітря зумовлювало відхилення від оптимальних умов вирощування сільськогосподарських культур, зменшення продуктивності температури і, незважаючи на те, що темпи зміни температури повітря у цей період в усіх зонах суттєво не відрізнялись, мало різні наслідки в ґрунтово-кліматичних зонах.

На Поліссі умови вирощування кукурудзи та ячменю ярого на межі XX–XXI ст. залишались сприятливими, у Лісостепу – сприятливими та задовільними, у степовій зоні – задовільними, а у Степу сухому незадовільними для кукурудзи. Отже, за різних початкових умов одні і ті ж зміни температури можуть призвести до різних наслідків. Тому при розробленні адаптаційних заходів щодо зменшення негативних наслідків кліматичних змін необхідно враховувати не лише напрям та інтенсивність зміни агрокліматичних умов, а й те, наскільки початкові умови відрізняються від оптимальних для вирощування зернових культур і застосовувати їх, насамперед, у тих регіонах де агрокліматичні умови незадовільні і погіршуються та в період коли ці зміни найістотніші.

Ключові слова: кукурудза, ячмінь ярий, агрокліматичні умови, зміна клімату, приземна температура, ріст температури, продуктивність температури, урожай, супутникова інформація, NDVI – кількість фотосинтетично активної біомаси, RCP4.5, RCP8.5.

REFERENCES

Angus JF, Cunningham RB, Moncur MW, Mackenzie DH. (1980). Phasic development in field crops I. Thermal response in the seedling phase. Field Crops Res. (3):365–378. https://doi.org/10.1016/0378-4290(80)90042-8

Asseng S, Ewert F, Martre P et al. (2015) Rising temperatures reduce global wheat production. Nature Climate Change. **5**:143–147. https://doi.org/10.1038/nclimate2470

Balabukh V, Oreshchenko A, Yagodynets S. (2021) Emergency fire weather in September – October 2020 in the Luhansk region: causes and consequences. Proceedings_ Hydrometeorological_congress. pp. 147–148. ISBN 978-966-186-163-2. http://umhs.org.ua/wp-content/uploads/2021/11/Proceedings_Hydrometeorological_congress2021.pdf

Balabukh VO, Malitskaya LV. (2017) Assessment of current changes in the thermal regime of Ukraine Geoinformatics. (4):34–49. https://journals.ua/reader/22994.html?list=2

Balabukh VO, Odnoletok LP, Kryvoshein OO. (2017) Climate change impacts on the winter wheat productivity in Ukraine during vegetation cycle. Hidrolohiia, hidrokhimiia i hidroekolohiia. **3**(46):72–85. http://nbuv.gov.ua/UJRN/glghge_2017_3_10

Balabukh VO. (2019) The impact of climate change on the formation of corn yields in agro-climatic zones of Ukraine. Hidrolohiia, hidrokhimiia i hidroekolohiia. **3**(54):103–104. http://nbuv.gov.ua/UJRN/glghge_2019_3_48

Balabukh VO. (2020) Probable changes in agroclimatic conditions and bioproductivity of winter wheat in Ukraine by 2050. Agroelita (9). https://agroelita.info/2020/09/page/2/

Bassu S, Brisson N, Durand J L et al. (2014) How Do Various Maize Crop Models Vary in Their Responses to Climate Change Factors? Global Change Biology. **20**:2301–2320. https://doi.org/10.1111/gcb.12520

Cammaranoa D, Ceccarellib S, Grandoc S et al. (2019) The impact of climate change on barley yield in the Mediterranean basin. Eur. J. Agronomy. **106**:1–11. https://doi.org/ :10.1016/j.eja.2019.03.002

Challinor AJ et al. (2014) A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change. **4**:287–291. https://doi.org/10.1038/nclimate2153

Deb P, Shrestha S, Babel MS. (2015) Forecasting climate change impacts and evaluation of adaptation options for maize cropping in the hilly terrain of Himalayas: Sikkim, India Theor. Appl. Climatol. **121**:649–667. https://doi.org/10.1007/s00704-014-1262-4

Dmitrenko VP, Odnolyetok LP, Kryvoshein OO, Krukivska AV. (2017) Development of the methodology of estimating agricultural crop yield potential with the consideration of climate and agrophytotechnology impact Ukr Hydromete J (20):52–60 http://nbuv.gov.ua/UJRN/Uggj_2015_16_17. doi: 10.1007/s40710-015-0105-3

Ecological Atlas of Ukraine (2009). Ukrainian Ecological Academy of Sciences, 104 p.

FAO-2021: The impact of disasters and crises on agriculture and food security. Rome. https://doi.org/10.4060/cb3673en

Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL. (2014) IPCC Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32. https://www.ipcc.ch/report/ar5/syr/

Hirschi M, Seneviratne SI, Alexandrov V, Boberg F, Boroneant C, Christensen OB, Formayer H, Orlowsky B, Stepanek P. (2011). Observational evidence for soil-moisture impact on hot extremes in south-eastern Europe. Nature Geoscience. **4**:17–21. doi: 10.1038/ngeo 1032

Högy P, Poll C, Marhan S, Kandeler E, Fangmeier A. (2013). Impacts of temperature increase and change in precipitation pattern on crop yield and yield quality of barley. Food Chem. **136**(3–4):1470–1477. https://doi.org/10.1016/j.foodchem.2012.09.056

Huo R, Li L, Chen H, Xu C, Chen J, Guo S. (2021) Extreme Precipitation Changes in Europe from the Last Millennium to the End of the Twenty-First Century. J. Climate. **34**(2):567–588. https://doi.org/10.1175/JCLI-D-19-0879.1

IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate

Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp, https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. IPCC, Switzerland, ISBN 978-92-9169-158-6. Electronic copies of this Summary are available from the IPCC website www.ipcc.ch. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

Jaiswal RK, Lohani AK, Tiwari HL. (2015). Statistical analysis for change detection and trend assessment in climatological parameters. Environmental Processes **2**(4):729–749

Klink K, Wiersma JJ, Crawford CJ, Stuthman DD. (2014), Impacts of temperature and precipitation variability in the Northern Plains of the United States and Canada on the productivity of spring barley and oat. Int. J. Climatol **34**:2805–2818. https://doi.org/10.1002/joc.3877

Kucharik CJ, Serbin SP. (2008) Impacts of recent climate change on Wisconsin corn and soybean yield trends. Environ. Res. Lett. doi: 10.1088/1748-9326/3/3/034003

Lesk C, Rowhani P, Ramankutty N. (2016) Influence of extreme weather disasters on global crop production. Nature. **529**(7584):84–87. https://doi.org/10.1038/nature16467

Lobell D, Schlenker W, Costa-Roberts J. (2011) Climate trends and global crop production since 1980. Science. **333**(6042):616–620. doi: 10.1126/science.1204531

Lobell DB, Field CB. (2007) Global scale climate-crop yield relationships and the impacts of recent warming. Environ. Res. Lett. doi: 10.1088/1748-9326/2/1/014002

National Report on the State of the Environment in Ukraine in 2020. (2021) Ministry of Environment Protection and Natural Resources of Ukraine https://mepr.gov.ua/files/docs/Zvit/2022/%D0%9D%D0%B0%D1%86%D1%96%D0%BE%D0%BD%D0%B0%D0%BB%D1%8C%D0%BD%D0%B0%20%D0%94%D0%BE%D0%BF%D0%BE%D0%B2%D1%96%D0%B4%D1%8C%202020%20(2).pdf

Parkes B, Sultan B, Ciais P. (2018) The Impact of Future Climate Change and Potential Adaptation Methods on Maize Yields in West Africa Climatic Change. **151**:205–217. https://doi.org/10.1007/s10584-018-2290-3

Polevoy A, Kostiukievych T, Tolmachova A, Zhygailo O. (2021) The impact of climate changes on forming corn productivity in the western forest-steppe of Ukraine. Ukr. Black Sea REG Agrar. Sci. doi: 10.31521/2313-092X/2021-1(109)-4

Polevoy AN, Barsukova EA. (2015) Influence of climate changes on the rates of spring barley development in Ukraine. Ukr. Hydrometeorol. J. (16):113–119 http://nbuv.gov.ua/UJRN/Uggj_2015_16_17

Polevoy AN, Bozhko LE, Barsukova EA. (2017) Impact of climate changes on agro-climatic indices of the vegetative period of main agricultural crops. Ukrainian Hydrometeorological J (20):61–70. doi: 10.31481/uhmj.20.07.2017

Polevoy A, Kulbida N, Adamenko T, Trofimova I. (2007) Modelling of influence of climate changes on agroclimatic conditions of cultivation and photosynthetic productivity of winter wheat in Ukraine Ukr Hydrometeorol J (2):76–91

Polupan M, Velychko V. (2019) Ukrainian Agronomic Soil Science: Textbook. In 2 parts; Part 1: Historical stages of development. Soil formation factors. Regularities of soil formation on an ecological-genetic parametric systemic basis, their agronomic properties, and fertility. Kyiv: Agrarna nauka, 426 p. ISBN 978-966-540-475-0. doi: 10.31073/978-966-540-475-0; https://doi.org/10.31073/978-966-540-476-7

Porter JR, Xie L, Challinor AJ, Cochrane K, Howden SM, Iqbal MM, Lobell DB, Travasso MI. (2014) Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485–533. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap7_FINAL.pdf

Prokorenko K, Udova L. (2017) Ukrainian agriculture: challenges and ways of development under the climate change. Economy and Forecasting. (1):92–107 https://doi.org/10.15407/eip2017.01.092

Schierhorn F, Müller D, Hoffmann M. (2018) Der Klimawandel gefährdet den boomenden Getreidesektor in der Ukraine. Aus Ukraine-Analysen Nr. 210 v 13.12., S. 2–6. doi: 10.31205/UA.210.01

Schipper L, Liu W, Krawanchid D, Chanthy S. (2010) Review of climate change adaptation methods and tools. MRC Technical Paper No. 34, Mekong River Commission, Vientiane ISSN: 1683–1489 https://www.mrcmekong.org/assets/Publications/technical/Tech-No34-Review-of-climate-change.pdf

Schlenker W, Roberts MJ. (2008) Estimating the Impact of Climate Change on Crop Yields: The Importance of Nonlinear Temperature Effects. NBER Working Paper No. 13799. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w13799

Sharma M, Bangotra P, Gautam AS et al. (2021) Sensitivity of normalized difference vegetation index (NDVI) to land surface temperature, soil moisture and precipitation over district Gautam Buddh Nagar, UP, India Stoch Environ. Res. Risk Assess. https://doi.org/10.1007/s00477-021-02066-1

Stepanenko SM, Polevoy AM. (2011). Assessment of the influence of climate changes on economy branches of Ukraine. Odessa: «Ecology» ISBN 978–966–8740–83–1 http://eprints.library.odeku.edu.ua/id/eprint/2252/

Tarariko OH, Ilienko TV, Kuchma TL. (2016) Impact of climate change on productivity and gross harvest of grain crops: analysis and forecast. Ukr. Geograph. J. (1):14–22. doi: 10.15407/ugz2016.01.014

Tarariko OG, Ilienko TV, Kuchma TL, Bilokin OA. (2021) Assessment of the effects of climate change on agricultural productivity using satellite data: recommendations. Kyiv: Agrarna nauka. 40 p. https://doi.org/10.31073/978-966-540-536-8

WMO: State of the Global Climate 2020. (2021) WMO (1264):58 https://library.wmo.int/?lvl=notice_display&id=21880#.YhTM1-jP02w

Wolf J, Van Diepen CA. (1995) Effects of climate change on grain maize yield potential in the European Community. Climatic change (29):299–331. https://library.wur.nl/WebQuery/wurpubs/fulltext/215410

Zaryshnyak AS, Baliuk SA, Lisovoy MV. (2016) Stationary field test-trials of Ukraine. Kharkiv: Smuhasta Typohrafiya, p. 265. ISBN 617-7387-31-1(IC15467)