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THE IMPACT OF CLIMATE CHANGE ON CROP FARMING IN THE DRAINED LANDS OF THE EUROPEAN NON-CHERNOZEM REGION OF RUSSIA: VULNERABILITY AND ADAPTATION ASSESSMENT

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Abstract

The impact of climate change on agricultural sustainability has become a particularly acute and global problem. The human activity increasingly significant contributes to such changes. Therefore, investigations have been intensified worldwide to assess the regional agro-climatic consequences of global climate change in order to find ways to adapt to them. This work aimed to assess the vulnerability and adaptation of field crops to a changing weather in the zone of drained lands of the European Non-Chernozem Region, which is characterized by a humid climate and limited thermal resources. Although the thermal conditions for growing crops here are becoming more favorable due to the increase in heat supply, more frequent incessant and heavy rains lead to a sharp overwetting of crops, causing significant crop shortages and quality losses. The novelty of our study lies in the evaluation of a shift in the boundaries of vulnerable territories. The conclusions we came to resulted from the subdivision of the zone into subzones by natural environment attributes, given changes in existing agrolandscapes and farming systems in latitudinal zonality, including thermally deficient areas. In the European Non-Chernozem Region of Russia, with a warming climate, the altitudes of drained lands were shown to affect the magnitude and frequency of heavy precipitation and should be taken into account when regionalizing adaptation measures and strategies, which is done for the this zone for the first time. The paper submits the analysis of thermal changes and atmospheric moisture changes during grain formation in winter cereals and fodder cereals and during intensive accumulation of biomass of silage and hay crops for two periods that differ in the degree of anthropogenic influence on the climate, 1945-1980 and 1981-2017. Using a set of analytical methods (selection of agro-climatic indicators, frequency analysis) and mathematical methods (trend analysis and smoothing of time series, functional analysis, etc.), we revealed that the coverage of areas subject to an increasing risk of overwetting of crops is expanding to the north. An increase in high temperatures leads to an intensification of evaporation and, as a result, to an increased convection. Based on simulation modeling of agro-climatic conditions until 2030, it is also shown that in the future, the northern and marshy areas are the most vulnerable to sudden overwetting. That is, along with the atmospheric circulation (i.e., a higher cyclonic activity), the thermal factor combined with the moisture content of the underlying surface in the soil contribute more and more significantly to the aggravation of overwetting. Soil texture also plays an important role in the manifestation of the effects of atmospheric overwetting on crops. Adaptation of field crop growing to climate change includes a set of measures aimed at effective management of interrelated changes in the thermal regime in the active layer of the atmosphere and the water balance components of the underlying surface and upper layers of the soil. The adaptation measures should regard the agro-climatic, soil and landscape features of the natural and agricultural subzones of the European Non-Chernozem Region drained lands and consists both in optimizing reclamation techniques and in improving crop cultivation technologies and land use planning. It is also extremely important that elevated concentrations of technogenic pollutants in the atmosphere have a negative impact on the quantity and quality of precipitation. Therefore, targeted monitoring of compliance with environmental standards is mandatory.

Keywords: European Non-Chernozem Region, climate change, drained lands, vulnerability, adaptation

The problem of sustainable agriculture has acquired a global scale due to increasing climate change and an increase in the frequency of extreme weather events, including those arising from anthropogenic activities [1, 2]. In humid regions, such phenomena include ultra-intense precipitation and heat waves [3-5]. The latter are associated with an increase in temperature to extremely high values. At low latitudes, tropical cyclones of exceptional power arise [6, 7] with the contribution of the anthropogenic factor to their formation [8]. In the middle latitudes of both hemispheres, cyclonic activity intensifies, which also extends to high latitudes [9, 10].

One of these regions in the middle and high latitudes includes the zone of drained lands of the European Non-Black Earth Region. In agricultural terms, this territory differs from other regions of Russia in its moderately warm and humid climate. The factors influencing sustainable farming here, on the one hand, are limited heat resources, and on the other, excess atmospheric moisture. Based on natural landscape characteristics, the region is divided into three agricultural subzones: mid-taiga (60-63°N, 29-51°E), southern taiga (54-60°N, 28-47°E) and coniferous-deciduous (52-54°N, 31-33°E). Landscape features consist of a predominance of lowlands and lowlands and an increasing proportion of wetlands in the direction from the southwestern regions to the northeastern ones [11).

The soils of the region is podzolic with a wide distribution of loamy and heavy loamy soils with difficult permeability of moisture from the surface layers to the underlying ones. In addition, heavily waterlogged peaty soils are often found in all subzones, and in river floodplains the soil cover is represented by alluvial soils [12].

Soil and climatic conditions determine the set of field crops, their placement and directions of crop production. Along with the cultivation of cool-climate food crops, the region has developed grass sowing and the production of forage crops, which serve as fodder for dairy farming. The selection focus in regional field farming is high-yielding and flexible varieties that are quite unpretentious to soil conditions, but at the same time tolerant to the effects of biotic and abiotic stresses. However, when optimizing habitats from the point of view of economically justified placement of crops and varieties, the manifestation of global and regional climate changes should be accounted [13, 14].

This paper analyzes the interrelated changes in thermal conditions and the nature of atmospheric moisture in the zone of drained lands of the European Non-Black Earth Region of Russia under conditions of increasing anthropogenic influence on the climate. Unlike air temperature fluctuations, which are determined to a certain extent, the amount of precipitation is characterized by high stochasticity in spatiotemporal resolution. In a changing climate, there is a tendency to increase the heat supply of crops, but the appearance of extremely heavy precipitation leads to a sharp waterlogging of crops, causing significant crop shortages and loss of quality. The study focused on the changing conditions of July, the period of formation of the final harvest of winter grains and forage cereals, as well as the intensive accumulation of biomass of silage and hay crops, when air temperatures are high and rainfall can be very intense.

The novelty of the presented results lies in the establishment of a shift in the boundaries of such territories by differentiating the zone of drained lands of the European Non-Black Earth Region into subzones based on natural landscape characteristics with a change in the existing agricultural landscapes and farming systems in latitudinal zones, including thermally deficient areas. For the first time, it has been shown that the altitudinal layering of landscapes in the zone of drained lands in a warming climate affects the magnitude and frequency of heavy precipitation and should be taken into account when developing adaptation measures and strategies. Adaptation of regional field farming to climate change was assessed from the standpoint of effective management of climate-related agricultural risks, effective management of the productivity of agricultural lands and crops, as well as possible control of the quantity and quality of moisture coming from the atmosphere through compliance with environmental standards. Thus, the aspect of increasing anthropogenic impact on the humidity characteristics of the regional climate is added, which was not previously focused on.

The purpose of the work is i) to analyze the recurrence of adverse weather events associated with an excess of atmospheric moisture in combination with a thermal background that becomes more favorable for the cultivation of crops, and ii) to identify agricultural areas in the zone of drained agricultural lands of the European Non-Black Earth Region of Russia that are vulnerable to climate change.

Materials and methods. Data provided by temporary series of average monthly air temperatures and monthly precipitation were obtained from 1945 to 2017 based on observations at agrometeorological stations in the middle taiga subzone (Vyborg, Sortavala, Petrozavodsk, Vytegra, Shenkursk, Kotlas, Syktyvkar), in the southern taiga subzone (Pskov, Velikiye Luki, Tikhvin, Staraya Russa, Smolensk, Bologoe, Kostroma, Vologda, Totma, Nikolsk), and in the subzone of coniferous-deciduous forests (Bryansk). The location of the stations in space quite fully reflected the intrazonal features of the soil cover and landscapes. Data homogeneity in the observation series was achieved through a system for introducing corrections for improving instruments and refining measurement techniques, developed at the All-Russian Research Institute of Hydrometeorological Information — World Data Center (VNIIGMI-WCD, Obninsk, Kaluga Province). However, for the comparability with shorter series of other indicators (atmospheric circulation indices and simulated characteristics of the current climate), the study also used shortened initial data.

We combined analytical (selection of agroclimatic indicators, comparative frequency analysis) and mathematical methods of data analysis and processing. The latter included trend analysis and smoothing of time series, functional analysis (with access to the construction of regression dependencies), a method of bilinear interpolation of model estimates from nodes of regular climate model grids into station coordinates, and the use of a quadratic spline to smooth out isolines when delineating the boundaries of vulnerable areas.

As agroclimatic indicators, we used threshold values of the G.T. Selyaninov's hydrothermal coefficient, a complex indicator of moisture availability which also accounts the influence of thermal conditions [15]. The indicator has a general form:

$$\mathrm{HTC}_{i,j} = \frac{\Sigma P_{i,j}}{0.1 \cdot \Sigma t_{i,j}},$$

where $\sum P$ is the sum of precipitation, mm, $\sum t$ is the sum of air temperatures, °C for the growing season (time period) with an average daily air temperature above 10 °C, i is the selected year, j is the duration of the selected growing season (time period) .

Threshold HTC values of 1.8, 2.5 and 3.5 met the criteria for the occurrence of varying degrees of waterlogging of crops [16]. For a comparative analysis of the frequency of occurrence of waterlogging effects, HTC values were selected that were in the ranges between the threshold values: $1.8 \leq \mathrm{HTC} < 2.5$, $2.5 \leqq \mathrm{HTC} \leqq 3.5$ and $3.5 < \mathrm{HTC} \leqq 4.5$ and higher. This differentiates the HTC values, classifying them into the categories of pronounced, sharp and very sharp waterlogging of crops.

Results. Based on the analysis of long-term data, it was established that with the observed climate change, the increase in positive air temperatures was most pronounced in July compared to other warm months. Although July temperatures varied from year to year, there was a general upward trend from 1950 to 2017, with a maximum in 2010. One of the reasons behind this trend is the more frequent penetration of heat waves and their simultaneous intensification. According to studies conducted in Poland between 1951 and 2015, heat waves have intensified since the mid-1990s, spreading to northeastern Europe, with 49% of heat waves occurring in July during the May-September period [17].

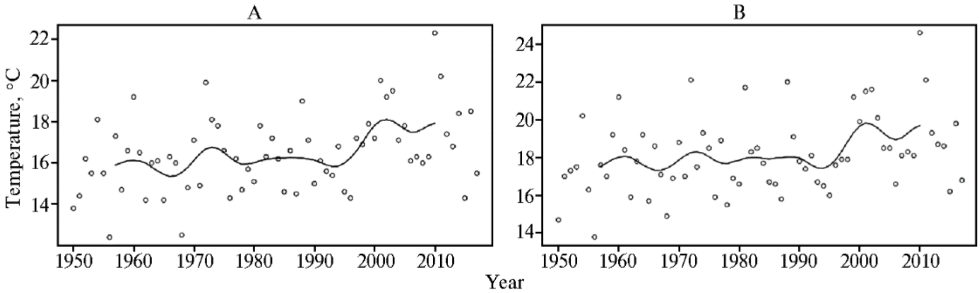

Fig. 1. Time course of average monthly air temperature in July (dots) **and 7-year moving averages** (lines) **in Petrozavodsk** (61.8°N, 34.3°E, altitude 110 m, average taiga subzone) (A) **and Kostroma** (57.7°N; 40.8°E, altitude 125 m above sea level, southern taiga subzone) (B).

A comparison of the course of moving averages (Fig. 1) showed that the average air temperature in July in Petrozavodsk since the late 1990s has been approaching the average air temperature in Kostroma in early decades, reaching the background level of 17.7 °C, which in terms of the amount temperatures ($\sum t_{VII}$) was 549 °C. The increase in heat supply noted at other northern stations also brought heat supply conditions in July closer to those in earlier decades in the territory of more southern stations. Thus, the sum of July temperatures in Vytegra (middle taiga subzone, altitude 55 m above sea level) since the late 1990s has reached the background value $\sum t_{VII}$ = 557 °C. This value was even slightly higher than the background value in Staraya Russa (southern taiga subzone, altitude 24 m above sea level) in early decades $\sum t_{VII}$ = 541 °C. At the eastern mid-taiga stations (Shenkursk and Kotlas), located in depressions of the relief, and in Vologda (southern taiga subzone, altitude 125 m above sea level), the sums of July temperatures since the late 1990s reached background values, $\sum t_{VII}$ = 570 °C, $\sum t_{VII}$ = 564 °C and $\sum t_{VII}$ = 567 °C, respectively. They are comparable to the value of heat supply in early decades in Bryansk (coniferous-broad-leaved subzone, altitude 214 m), for which $\sum t_{VII}$ was about 560 °C.

This spatio-temporal analogy can be considered as a factor contributing to the expansion of plantings of more productive varieties and valuable crops to the north of the traditional areas of their cultivation, given that the total contribution of other warm months to the increase in heat supply is approximately equal to the contribution of July conditions.

The amount of precipitation that falls in July is largely determined by air masses of oceanic origin [18]. Using data from 1950 to 2017 [19], the time course of the July East Atlantic Oscillation (EA) index was plotted and 7-year moving averages were obtained (Fig. 2). The index of this mode of climate variability, like the North Atlantic Oscillation (NAO) index, is calculated from the decomposition of the atmospheric pressure field into orthogonal components [20]. However, unlike the NAO index which characterizes the westerly transport as a whole; the EA index reflects changes in the intensity and number of cyclones [21, 22].

Since the late 1990s, there has been a sharp predominance of positive values of the EA index (Fig. 2), which corresponds to increased cyclonic activity in a warming climate [21], which is associated with increased surface water temperatures in the North Atlantic. This increase is manifested in the increasing advection of air masses saturated with moisture, which cause heavy rains while simultaneously lowering the air temperature due to cloudy weather.

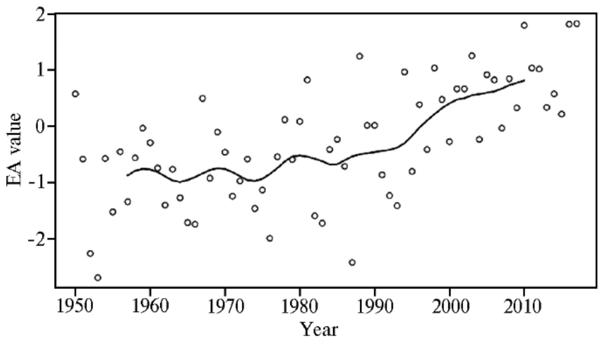

Fig. 2. Time course of July values of the East Atlantic Oscillation (EA) **index and 7-year moving averages** (according to reanalysis data from NCAR — National Center for Atmospheric Research, USA).

The development of convection processes, caused by intense evaporation at rising July temperatures, led to increased thunderstorm activity with heavy rainfall, especially in areas further inland, where daytime maximum July air temperatures were slightly higher.

In a changing climate, record amounts of precipitation were observed both at sums of air temperatures below and above the long-term average (Table 1).

1. Absolute maximum precipitation in July with sums of air temperatures below and above average long-term values, observed in early and late decades in the zone of drained lands of the European Non-Black Earth Region of Russia

Station	Coordinates, height above sea level	$\sum P_{average}$, mm	$\sum t_{average}$, °C	Year	$\sum P_i$, mm	$\sum t_i$, °C	Year	$\sum P_i$, mm	$\sum t_i$, °C
Stations with average long-term annual precipitation of more than 600 mm									
Staraya Russa	58.0°N, 31.2°E, 24 m	80[a]	553	1953	176	546	1990	234[a]	518[a]
Smolensk	54.5°N., 32.9°E, 236 m	92	539	1962	197[a]	515	1998	234[a]	518[a]
Bryansk	53.2°N, 34.2°E, 214 m	90	572	1980	197[a]	477	1999	215	670
Vytegra	61.0°N, 36.4°E, 55 m	80[a]	524	1961	171	521	2017	226	488
Stations with average long-term annual precipitation less than 600 мм									
Vyborg	60.7°N, 28.8°E, 10 m	74	551	1966	150	558	2012	169	564
Kotlas	61.2°N, 46.7°E, 55 m	76	532	1951	187	465	2000	254	623
Kostroma	57.7°N, 40.8°E, 125 m	77	560	1968	184	462	2008	204	567
Shenkursk	62.1°N, 42.9°E, 40 m	70	539	1978	154	459	1998	164	583

N o t e. $\sum P_{average}$. and $\sum t_{average}$. — long-term average sums of precipitation and air temperatures in July for 1945-2017, $\sum P_i$ and $\sum t_i$ — sums of precipitation and air temperatures in July in the indicated years; [a] — close values, differing in tenths. Absolute maximums of July precipitation also occurred in Bologoye, Tikhvin, Sortavala, Petrozavodsk, Pskov and Totma.

The absolute maximum precipitation in July in recent decades (1981-2017) exceeded the values of previous decades (1945-1980) (see Table 1). However, in the more moist part of the zone of drained lands, the absolute maximum of July precipitation usually corresponded to a reduced thermal background, while in the less moist part, on the contrary, to an increased thermal background. For stations located in lowlands and lowlands, there was a greater increase in the amount of extreme precipitation compared to stations located at higher elevations.

Based on data obtained at agrometeorological stations in different agricultural subzones, we compared the frequency of years when the amount of precipitation in July exceeded its long-term average amount (taken as 100%) by 1.5 times or more for two periods, 1945-1980 and 1981-2017. These periods were selected based on the characteristics of the anomalies of globally averaged air temperature from 1880 to 2020 [22]. Until the end of the 1970s, the anomalies were negative, with the exception of positive peaks in 1939-1944 (up to +0.2 °C). Since 1981, these peaks have been exceeded and the anomalies have had a sharp increase with a maximum in 2017 of +1.0 °C. This growth was closely linked to the impact of industrialization [23].

For these periods, which differ in the degree of anthropogenic influence on the climate, the proportion of years with heavy precipitation was calculated using the gradation of their anomalies and differentiation of the zone of drained lands (Table 2).

2. Proportion of years with an anomalous amount of July precipitation during periods differing in the degree of anthropogenic influence on the climate in different agricultural subzones

Natural landscape, agricultural subzone	Anomaly in precipitation from the long-term average value			
	150-200%	201-250%	251-300%	301-350%
	Years 1945-1980			
Middle taiga	39%	17%	3%	
South taiga	53%	25%	3%	6%
Coniferous-broadleaf	22%	3%		
	Years 1981-2017			
Middle taiga	35%	19%	6%	3%
South taiga	54%	22%	11%	3%
Coniferous-broadleaf	14%	8%		

In all natural landscape agricultural subzones, a shift towards an increase in the frequency of years with increasing rainfall was observed. At the same time, for the middle taiga subzone, the appearance of an additional range with the frequency of years with super-heavy precipitation was observed. In general, in the tiered differentiation of landscapes in the zone of drained lands, the largest increase in the percentage of years was noted for stations located in lowlands (height above sea level less than 70 m) and some lowland stations (height above sea level less than 143 m).

The European Environment Agency [24] also records changes in the dynamics of intense precipitation events. It was reported [25] that during the period 1981-2013, compared with the previous period (1951-1980), the number of days with very intense precipitation in Europe increased by 45% due to a sharp increase in the number of such precipitation events in the northern and northeastern parts of Europe. It has also been shown [26, 27] that, under expected climatic conditions, the most pronounced increase in the number of days with very intense precipitation, which is simultaneously contributed by an increasing temperature background, will be characteristic of northeastern Europe in the summer season.

To assess the changing contribution of humidity and thermal factors to the values of the hydrothermal coefficient G.T. Selyaninov, functional analysis was applied. Its essence is that the HTC is presented as a fractional function of two variables, the amount of precipitation and the air temperatures. In a three-dimensional image, this is a surface whose slope is determined by the magnitude of the partial derivatives with respect to the arguments. Horizontal lines are drawn on the surface. Using them, it is possible to count the number of cases where July HTC values fall into the ranges corresponding to the categories of waterlogging. The assessment of the contribution of each of these factors to the value of the HTC, as well as the change in this ratio over periods that differ in the degree of anthropogenic influence on the climate, is carried out by projecting the surface onto the corresponding plane [16].

Using the described method, we identified an increasing time-increasing contribution of the amounts of heavy July precipitation to high values of the HTC in July (HTC_{VII}), which was expressed in a decrease in the residual dispersion, that is, a decrease in the scatter of plotted points that lie closely along a straight line. The changing contribution of sums of air temperatures to high values of the HTC was manifested in a general shift of the cloud of points towards increasing sums of temperatures.

Thus, closer regression connections have been established between increasing amounts of July precipitation with the manifestation of their extremeness and high values of HTC_{VII}. For example, the coefficient of determination increased from 0.78 to 0.95 for Vytegra, from 0.90 to 0.97 for Smolensk and from 0.89 to 0.92 for Kostroma with a decrease in the standard deviation, respectively, from 0.24 to 0.16, from 0.21 to 0.16 and from 0.28 to 0.15. A similar pattern was revealed for other stations, which increases the reliability of extrapolation of moisture supply conditions.

The effects of waterlogging were also reflected in crop losses. It is convenient to present the latter in the form of relative deviations from the technological trend, described by a parabolic function, based on the characteristics of the dynamics of economic productivity.

Thus, in the excessively wet year of 1998 in the Smolensk region, the loss of winter rye yield relative to the trend level reached 54%. For the Smolensk station (medium loamy gleyed soil), moisture conditions were characterized by the following indicators: total precipitation for the summer months ($\sum P_{\text{VI-VIII}}$) is 459 mm (with $\sum P_{\text{VII}}$ = 234 mm), $\text{HTC}_{\text{V-VI}}$ = 2.19, HTC_{VII} = 4.64, $\text{HTC}_{\text{VII-VIII}}$ = 4.29. The July EA index value was 0.77. In the same year, in the Pskov region, the loss of winter rye yield was 37%. For the Pskov station (sandy loam soil) $\sum P_{\text{VI-VIII}}$ was 457 mm ($\sum P_{\text{VII}}$ = 174 mm), $\text{HTC}_{\text{V-VI}}$ = 3.32, HTC_{VII} = 3.42, $\text{HTC}_{\text{VII-VIII}}$ = 2.79. In the excessively wet 2017 in the Vologda region, the loss of winter rye yield relative to the trend level reached 40%. For the Vytegra station (medium loamy gley soil), the moisture conditions were as follows: $\sum P_{\text{VI-VIII}}$ = 406 mm ($\sum P_{\text{VII}}$ = 226 mm); $\text{HTC}_{\text{V-VI}}$ = 2.40; HTC_{VII} = 4.61; $\text{HTC}_{\text{VII-VIII}}$ = 3.15. The value of the July EA index this year is 1.96.

When comparing indicators throughout the growing season, it was found that excessively wet conditions in July made the most significant contribution to the loss of the final harvest in the zone of drained lands of the European Non-Black Earth Region. The above estimates of crop losses are comparable with estimates obtained earlier at the All-Russian Research Institute of Agricultural Meteorology for the Non-Black Earth Zone as a whole. According to these estimates, prolonged rains and downpours can lead to a reduction in yield vs. its average value for sown grasses by 25-35%, for winter cereals by 40-60%, and for corn hybrids in some years by 80% [28]. It should be noted that on soils with difficult water permeability, super-abundant moisture accumulates in the upper layers, sharply exacerbating root-stem lodging, which simultaneously leads to loss of food quality of the final harvest.

As for the periods without rain, they were short-lived and affected the upper layers of the soil. In the exceptionally warm and dry year of 2010, the loss of the winter rye harvest in the Smolensk and Pskov regions amounted to about 30% of its trend value, which is less than in the excessively wet 1998.

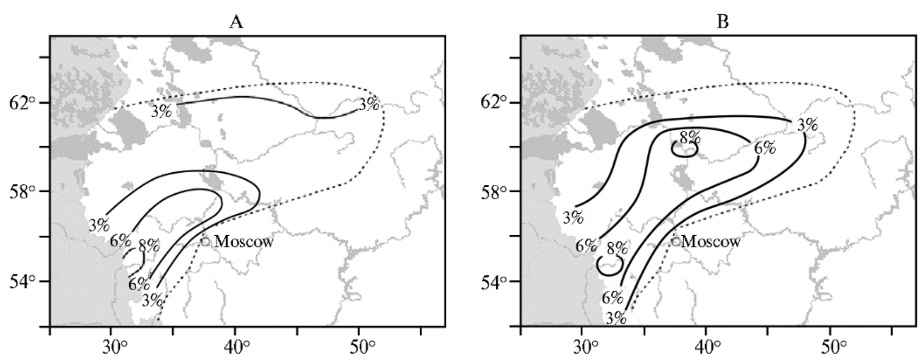

FIg. 3. Frequency of years (%) with very sharp waterlogging of crops in July in the zone of drained lands of the European Non-Black Earth Region of Russia: A — 1945-1980, B — 1981-2017. The dotted line is the border of the zone of drained lands.

The maps (Fig. 3) with isolines display the spatial change in the frequency of years with very sharp waterlogging of crops in July ($3.5 < HTC_{VII} \leq 4.5$ and above) in the zone of drained lands of the European Non-Black Earth Region. On the maps, this zone (outlined by a dotted line) corresponds to the classification of G.T. Selyaninov zone of excess moisture, for which the HTC values exceed 1.3 [29]. From the north, it is limited by the zone with the occurrence of July frosts, and from the southeast, it is surrounded by territories with conditions of sufficient moisture where the effects of waterlogging were weaker and much less frequent.

Due to local geomorphological features of the surface (undulation of the relief) and the increasing frequency of heavy precipitation, for greater completeness of cartographic estimates, data from additional stations with homogeneous and continuous series of observations from 1981 to 2017 were used: Pushkinskie Gory, Toropets, Staritsa, Babaevo and Kologriv (south -taiga subzone), as well as Trubchevsk (coniferous-broad-leaved subzone).

Comparing the course of isolines for two periods, one can trace how the coverage of agricultural areas, exposed to an increasing risk of very sharp waterlogging of crops, expanded. In 1945-1980, the frequency of years with conditions of very sharp waterlogging, exceeding 6%, occurred only for the southern part of the zone of drained lands. In 1981-2017, regions belonging to the northern part of the southern taiga subzone and the middle non-taiga subzone were added to the territories with such frequency of years.

In general, in the spatial configuration of territories vulnerable to waterlogging, a shift in boundaries in the northeast direction was observed. That is, in recent decades, areas where areas with waterlogged soils and wetlands accounted for a significant proportion of the total land area have been subject to an increasing risk of very sharp waterlogging.

Thus, along with the peculiarities of atmospheric circulation (increased cyclonic activity), the thermal factor in combination with the properties of the underlying surface (the degree of its moisture content) makes an increasingly significant contribution to the aggravation of waterlogging. An important role in the manifestation of the effects of atmospheric waterlogging in relation to the state of crops is also played by soil texture, on which the degree of permeability of atmospheric moisture into soil layers depends.

The assessment of the vulnerability of field farming to the effects of waterlogging for 2021-2030 [30] was based on the results of simulation of time series of air temperature, precipitation and HTC values for July using transitive atmospheric and oceanic general circulation models (AOGCMs). Models developed in Central Europe [31, 32] and Canada [33] were used. The scenario of controlled release of greenhouse gases into the atmosphere was considered as an emission scenario.

Since the models differed in the size of the regular grid cell and in the detail of the description of the physical mechanisms of feedback within the model blocks, this led to a discrepancy in the values of the modeled variables. However, through all selected models, the mid-taiga subzone was identified as more vulnerable to excess atmospheric moisture. At the same time, for this subzone, better comparability was achieved between the real and model-estimated percentage of years with the effects of sudden waterlogging, with a predicted increase in the frequency of such effects for 2021-2030. Thus, in agroclimatic conditions simulated using the MPI-ESM1-2-HR model (Max Planck Institute Earth System Model), the frequency of years with conditions of severe waterlogging ($2.5 \leqq HTC_{VII} \leqq 3.5$) in Vytegra was 35%. The frequency of such years in Petrozavodsk according to the EC Earth 3 (European community Earth-System Model) model was estimated at 20%. The Can ESM5 model (The Canadian Center for Climate Modeling and Analysis) estimated 18% years for Kotlas. This model also revealed the frequency of years with conditions of very sharp waterlogging ($HTC_{VII} > 3.5$), which in Kotlas for 2021-2030 amounted to 2%.

Since models are constantly being improved, we also mention the regional model HARMONIE-Climate (the Rossby Center) for Fennoscandinavia, which takes into account convection at the meso-orographic level [34]. Estimates for the near and distant future indicate that the greatest increase in precipitation intensity is expected during the summer season in the northern part of the subregion.

In this regard, adaptation of field farming to climate change acts as a set of measures aimed at effectively managing changes in the thermal regime of the active layer of the atmosphere and the components of the water balance of the underlying surface, including surface layers of soil.

As is known, managing the risks of atmospheric waterlogging of crops is achieved by regulating surface and subsoil runoff through the removal of excess water while simultaneously providing the cultivated soil layers with sufficient moisture to replenish its losses due to evaporation. Therefore, in a changing climate with increasing amounts of heavy rainfall, the management of such risks consists of optimizing reclamation technological and agrotechnical methods, taking into account the characteristics of soils and topography.

In the middle taiga subzone of the European Non-Black Earth Region with frequent soils of heavy mechanical composition, trench drainage should be used, which provides a runoff volume that is on average two times greater than the runoff volume of trenchless drainage [35, 36]. In the lowlands of the southern taiga subzone, which are characterized by a slight slope towards river beds, it is recommended to drain excess rain and storm water over the surface by optimally selecting the width and frequency of furrows [37]. In the coniferous-deciduous subzone, due to the presence of highly dissected topography, measures are needed to prevent increasing water erosion [38]. In floodplains of unregulated watercourses, optimization of the area of diked lands is required to eliminate the risk of flooding of agricultural land and washing out of the alluvial layer as a result of a sharp rise in water levels caused by heavy rains during the summer low-water period [39]. It is also necessary to improve the designs of closed drainage used in all subzones and for all soils based on selecting the optimal distance between drains and increasing their throughput [40].

It should be noted that under conditions of increasing surface and subsurface runoff, the removal of nutrients from agricultural fields increases. To reduce the risk of their entry into water bodies, it is necessary to increase the efficiency of the treatment modules of drainage systems and, if necessary, carry out partial reconstruction of the latter [35].

Managing the productivity of agricultural land and planting crops in changing climatic conditions comes down to proactive adaptation measures aimed at both mitigating the negative effects of atmospheric waterlogging [41] and taking advantage of the increased temperature background [42-44].

Leveling the surface of fields and using lightweight propellers in lowland meadows ensures uniform absorption of moisture into the soil, while simultaneously improving aeration and heat exchange between soil layers [45]. Due to the increasing supply of atmospheric moisture, which is a very weak acidic solution, fertilizer doses and rates of lime application for crops on acidic soils are optimized [46]. Achievements of genetic engineering, selection and seed production are being introduced into agricultural production, including the sowing of high-quality elite seeds to increase the proportion of varieties in crops that are highly resistant to lodging and highly resistant to pathogens that become active in excessively wet conditions [47, 48].

Climate changing promotes more heat-demanding and moisture-loving crops and varieties further north of their traditional areas (for example, buckwheat crops in the middle part of the southern taiga subzone) and allows the inclusion of more productive plants in forage and grass crop rotations due to an increase in heat supply.

Draining low-lying swamps, the soils of which are rich in organic matter, for the creation of cultivated hayfields and pastures with an expansion of the species composition of high-yielding sown grasses can lead to an increase in productivity, potential for the use of agricultural land and reduces the negative effects of atmospheric waterlogging due to weakened convection.

The intensification of economic activity has an increasing impact not only on the components of the radiation balance of the atmosphere-surface of the Earth system, but also leads to an increasing release of pollutants into the atmosphere in the form of chemical compounds and suspended particles of technogenic origin [49, 50]. They are aerosols, either concentrated solutions or solid particles suspended in the atmosphere. Aerosols have a surface that is necessary for water vapor to condense. Some of them serve as so-called nuclei of water vapor condensation with the subsequent formation of clouds and precipitation. Compliance with environmental standards creates the possibility of targeted control of the quantity and quality of moisture coming from the atmosphere at the regional and intraregional levels.

Better land management and improved internal combustion engines can reduce precipitation. In this case, the entry into the atmosphere of suspended particles of technogenic origin (particles of dust, clay and soot), on which water vapor condenses to form cloud droplets, which through coagulation are converted into droplets of water and fall as rain from water clouds.

Improved recycling technologies provide a reduction in the amount of aerosols in the atmosphere consisting of sulfur and nitrogen oxides, which cause the deposition of acidic compounds, leading to a decrease in soil fertility, damage to the leaf surface of crops, disruption of transpiration and photosynthesis, and weakening of crop immunity to harmful organisms.

It should be noted that the regional adaptation measures we have outlined largely correspond to those used in foreign agricultural regions. For example, such a correspondence in a changing climate occurs for agricultural landscapes similar to the European Non-Black Earth in the middle and northern parts of the Canadian provinces of Quebec and Ontario [51] and northern European countries [52, 53], as well as for excessively humid areas in Central Europe [54-56]. This can serve as the basis for expanding opportunities for adaptation through optimal management decisions.

So, changes in the thermal conditions and the nature of atmospheric moisture are having an increasingly noticeable impact on field cultivation in the zone of drained lands of the European Non-Black Earth Region. An increase in the sum of active temperatures that satisfy the thermal needs of plants contributes to the expansion of more productive varieties of hay and silage crops, as well as the expansion of some moisture-loving forages towards the northern territories. However, the increasing loss of abundant and super-abundant amounts of atmospheric moisture due to an increase in the precipitation of advective and convective origin leads to a sharp waterlogging of crops. Particularly, the crop losses occure which in excessively wet years exceed losses in dry years with a simultaneous reduce in the quality of crop products. In the context of increasing anthropogenic influence on the climate, there is an expansion of agricultural areas that are at risk of sudden waterlogging. The isolines on the map with frequency of years with definite HTC values, indicating the effects of very sharp waterlogging, shows that with ongoing climate changes, vulnerable territories are expanding due to the inclusion of regions located in the northern part of the southern taiga subzone and in the middle taiga subzone. In the future, the most sensitive to the effects of sudden waterlogging will be the northernmost part of the zone of drained lands, the territories lying north of 60°N latitude and belonging to the middle taiga subzone. This fact can be explained by the presence of spaces with waterlogged soils and wetlands. Increased frequency of high temperatures leads to increased evaporation from large areas, followed by the formation of convective thunderclouds and heavy rainfall.

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