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Integrated assessment of change in contribution of excessive moisture to farming risks in the humid zone of Western Russia

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ABSTRACT. This paper is devoted to assessing the farming risks associated with excessive moisture effects in the Humid Zone of Western Russia over the past seven decades. The proposed spatiotemporal monitoring of the areas of this zone vulnerable to over-wetting allows us to evaluate the aggregate impact of climate variability and change on the degree of risk to farming over time. Furthermore, the detailed scale of the G.T. Selyaninov Hydrothermal Index (HTC) (with high values in July) is proposed to identify the recurrence and intensity of such risks as crop lodging under ongoing climate change (by comparing two 35-yr time intervals: 1945-1979 and 1980-2014). The functional analysis of HTC helps to show an increasing contribution of extreme precipitation totals to lodging intensity in comparison with cumulative air temperature contribution in recent decades, even in cases when air temperature sums have a tendency to increase. Moreover, the regression relationships between high precipitation totals and high HTC values are revealed more distinctly in the time interval of 1980-2014 due to a decrease in the residual variance. The comparative analysis of empirical distributions of total seasonal precipitation deviations from trends within time intervals 1946-1980 and 1981-2015 also confirmed the increasing recurrence of marginal positive anomalies in summer and autumn precipitation totals in the time interval of 1981-2015. In conclusion, the effects of excess moisture on the sustainability of regional crop production are assessed, and adaptation strategies are discussed.

KEYWORDS: Humid zone, climate change, excessive moisture effects, farming risks.

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1. INTRODUCTION

The Humid Zone (HZ) of Western Russia comprises the European territory of the Russian Federation between 52-63°N and 28-53°E. This zone is characterized by flat relief and predominantly podzolic soils with high moisture content. In recent years, a sharp increase in precipitation totals, especially in summer, has led to significant losses in the crop production in this zone due to crop over-wetting across large areas, including drained lands.

According to the climate change scenarios for European regions with cool temperate climate, further increase in annual precipitation totals accompanied by rising mean annual air temperature is predicted (Kjellstrom et al. 2011; IPCC 2014; Katssov et al. 2017). Thus, crop production is expected to be very vulnerable to the impending climatic changes in the HZ. This research has been conducted primarily to assess the observed changes in precipitation and also to evaluate impacts on the sustainability of regional cropping systems given the increasing recurrence and degree of farming risks caused by excessive moisture.

Here, the focus is put on the assessment of such risks during the warm period of the year. Some earlier efforts to assess climate change impacts on crop yield risk have been partially used in this research (Eitzinger et al. 2007; Nikolaev 2010, 2015a, b, 2016, 2017, 2018).

2. MATERIALS AND METHODS

The 70-yr monthly precipitation and mean monthly air temperature data (1945-2015) were obtained from the stations located within the territory under study. These data were transformed into agroclimatic variables for the intensive growth season, i.e. May, June, and July. The following aspects were considered in developing our methodology: selecting the agroclimatic indicators and time intervals; development of spatiotemporal monitoring of at-risk farming areas; comparison of the changing contribution of precipitation and thermal conditions to the intensity of farming risks, etc. The principal methods are functional and statistical analysis, including trend and residual analysis.

3. APPROACHES AND RESULTS

3.1. SPATIOTEMPORAL MONITORING OF FARMING RISKS

Among climatic indicators are those based on long-term agrometeorological observations of growth conditions during the vegetation season. Table 1 presents the agroclimatic indicators of emerging farming risks associated with excessive moisture effects during the warm months, as proposed by I.A. Gol'tsberg and A.D. Pasechnjuk (Sinitsina et al. 1973; Pasechnjuk 1990).

Based on these indicators, spatiotemporal monitoring of crop areas with different percentages of years with crop waterlogging and lodging effects in the changing climate conditions has been conducted, using a 5-yr step shift with-

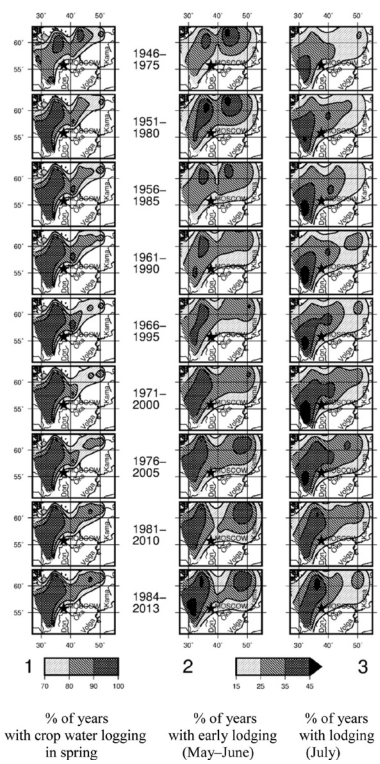

Fig. 1. Monitoring of crop areas vulnerable to excessive moisture effects during warm period (HZ of Western Russia)

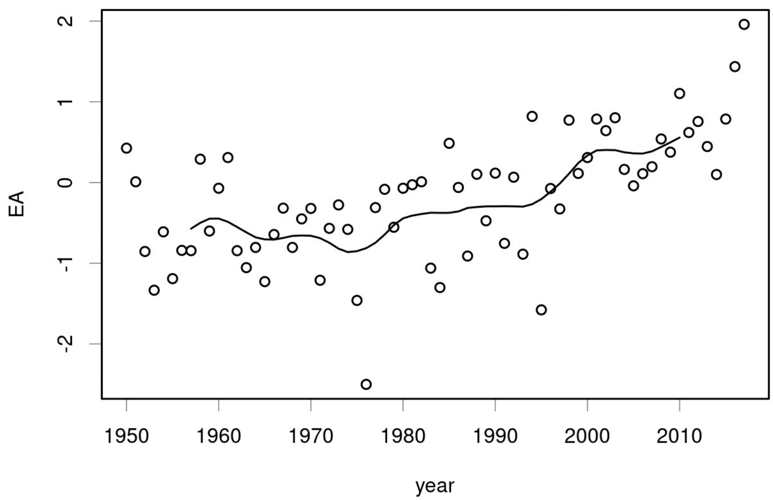

Fig. 2. Dynamics of the summertime EA indices (June-August) from 1950 to 2017 and 7-yr moving averages (the Gaussian filter is used)

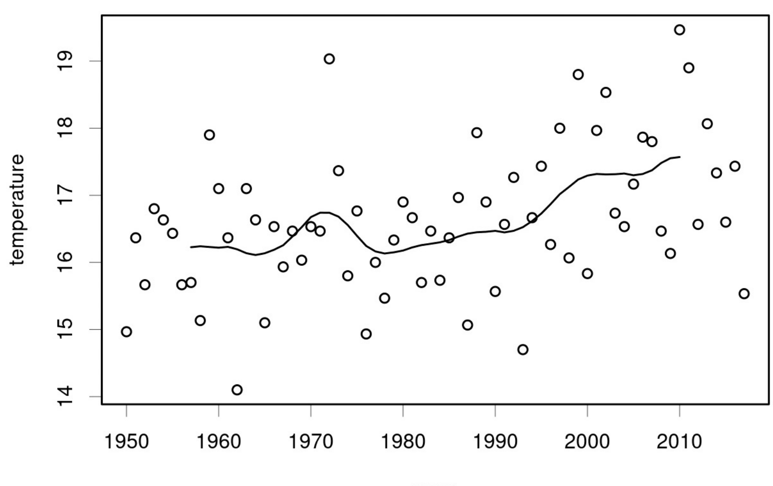

Fig. 3. Dynamics of summer air temperature (June-August) since 1950 to 2017 and 7-yr moving averages (the Gaussian filter is used) at Pskov: 57.8°N, 28.4°E

in the 30-yr observed period beginning in 1946 (Nikolaev 2017). Figure 1 illustrates the spatial dynamics of the vulnerable areas.

The optimal configuration of isoline-contoured areas with varied recurrence of farming risks employed GIS interpolation methods, such as kriging (Silkin 2008). This technique enables visualization of temporal changes in the boundaries of vulnerable areas relative to those for the baseline climate conditions (in the observed period 1961-1990). Obviously, the most extensive vulnerable areas are noticeable within the recent 30-yr period (predominantly the years after 1980) in comparison with the earlier 30-yr period. The occurrence of areas most vulnerable to the risk of early lodging in the northern regions of the HZ within the 30-yr periods 1946-1975 and 1951-1980 is explained by the prevalence of low air temperatures in May-June, along with precipitation amounts close to the long-term mean value. At the same time, there was some reduction in the size of areas vulnerable to the risk of lodging for the period 1984-2013. This observation is accounted for by the diminishing number of years with excessively wet conditions after 2005, and emergence of extremely dry conditions in July 2010 and July 2012 in the southwestern and central parts of the HZ.

3.2. COMPARATIVE ANALYSIS OF FARMING RISKS CAUSED BY EXCESSIVE MOISTURE EFFECTS IN THE CHANGING CLIMATE CONDITIONS

For comparative analysis of farming risks within the HZ, it is convenient to subdivide the period from 1945 to 2014 into two 35-yr intervals: 1945-1979 and 1980-2014. The rationale for this subdivision includes: (1) the increase in cyclonic activity at the middle-high latitudes in recent decades, and (2) upward trends in the mean annual air temperature, observed for Russian regions since the 1980s (Nesterov 2003, 2009; Franzke, Feldstein 2005; Drozdov, Smirnov 2011; Murav'ev, Kulikova 2011; Katssov, Semenov 2014; Kulikova et al. 2015; Polonskij, Kibal'chich 2015; Kiktev et al. 2018). Moreover, according to our recent study, there is strong agreement between the dynamics of 7-yr moving averages of the summer East Atlantic pattern (EA) indices and 7-yr moving averages of summer air temperatures in the time interval 1981-2017 (see Figures 2 and 3). It should be noted that the 68-yr dynamics of summer EA indices include an inflection point observed in approximately 1980.

This inflection point is very important as it is related to the northern expansion of crop areas of small cereals, maize hybrids, sunflower and fiber flax, as well as highly productive seed grasses.

Selyaninov Hydrothermal Index values for July (HTC_{VII}) are proposed for identifying the intensity and recurrence of farming risk from root and stem lodging in the changing climate conditions:

- $1.8 \leq HTC_{VII} \leq 2.5$ (perceptible root-stem lodging);
- $2.5 < HTC_{VII} \leq 3.5$ (severe root-stem lodging);
- $3.5 < HTC_{VII} \leq 4.5$ (very severe root-stem lodging);
- $HTC_{VII} > 4.5$ (extremely severe root- stem lodging)

The proposed scale reflects the increasing effects of both incessant and heavy rain on the lodging rate of example crops and their varieties due to the emerging conditions that lead to thinning of the soil surface and increasing mechanical load on stems, despite the application of short-statured cultivars in some regions (Gringof 1986). Simultaneously, the percentage of crop areas subjected to root-stem lodging increases with time.

Table 2 demonstrates an increase in the percentage of years with greater intensity of root-stem lodging during 1980-2014 compared to 1945-1979.

Table 1. Farming risks associated with excessive moisture effects during the warm period

Farming risk	Agroclimatic indicator of occurrence
Crop water logging in spring	$\sum P_{IX-III} \geq 230$ mm
Early root-stem lodging	$HTC_{V-VI} \geq 1.8$
Root-stem lodging in ordinary dates	$HTC_{VII} \geq 1.8$

Note: $\sum P_{IX-III}$ is precipitation totals for September-March; HTC_{V-VI} is the G.T. Selyaninov's Hydrothermal Index for May-June; HTC_{VII} is the G.T. Selyaninov's Hydrothermal Index for July; HTC is a ratio of precipitation sums to air temperature sums with proportional coefficient equals 10 (Selyaninov 1958)

Table 2. Recurrence of root-stem lodging with different intensity [% of years] in the time intervals of 1945-1979 and 1980-2014 in the HZ of Western Russia

Station name with geographic coordinates	Root-stem lodging category							
	Perceptible $1.8 \leq HTC_{VII} \leq 2.5$		Severe $2.5 < HTC_{VII} \leq 3.5$		Very severe $3.5 < HTC_{VII} \leq 4.5$		Extremely severe $HTC_{VII} > 4.5$	
	1945-1979	1980-2014	1945-1979	1980-2014	1945-1979	1980-2014	1945-1979	1980-2014
Pskov 57.8°N; 28.4°E	29%	9%	**9%**	**11%**	0%	0%	0%	0%
Smolensk 54.5°N; 32.3°E	**20%**	**26%**	17%	9%	6%	6%	**0%**	**3%**
Trubchevsk 52.6°N; 33.8°E	**14%**	**23%**	20%	9%	**0%**	**3%**	0%	0%
Kostroma 57.7°N; 40.8°E	**17%**	**23%**	9%	6%	6%	3%	0%	0%
Petrozavodsk 61.8°N; 34.3°E	**17%**	**20%**	11%	9%	**0%**	**3%**	0%	0%
Vytegra 61.0°N; 36.4°E	**17%**	**29%**	11%	11%	**0%**	**3%**	0%	0%
Vologda 59.3°N; 39.9°E	17%	9%	**9%**	**20%**	0%	0%	0%	0%
Shenkursk 62.1°N; 42.9°E	**9%**	**17%**	9%	9%	0%	0%	0%	0%
Kotlas 61.2°N; 46.7°E	**14%**	**17%**	11%	6%	3%	3%	0%	0%
Syktyvkar 61.7°N; 50.8°E	**14%**	**23%**	**6%**	**14%**	3%	0%	0%	0%

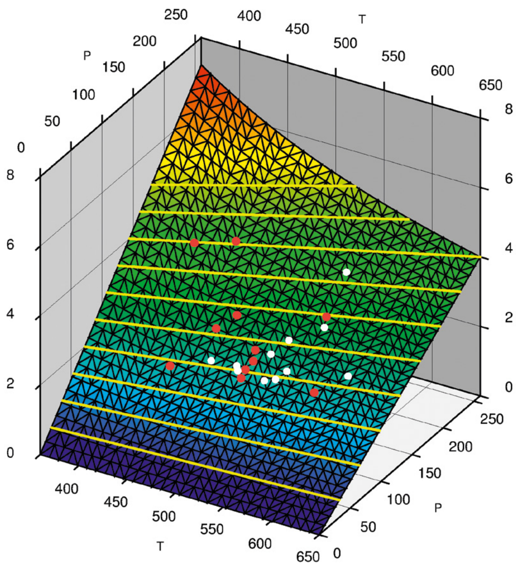

Fig. 4. Three-dimensional representation of the *HTC* values ≥1.8 for July; Kostroma: 57.7°N, 40.8°E (forest belt of the HZ); red dots – time interval of 1945-1979, white dots – time interval of 1980-2014

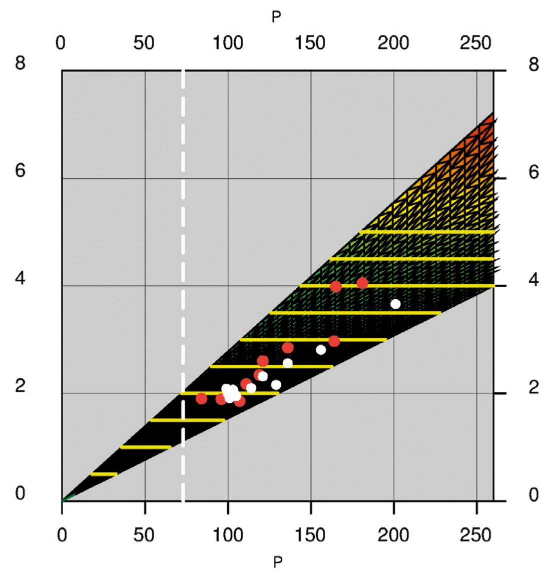

Fig. 5. Change in contribution of abundant precipitation in July to high HTC_{VII} values Kostroma: 57.7°N, 40.8°E (forest belt of the HZ); horizontal axis: precipitation sums for July [mm], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of precipitation amounts for July equals of $\sum P_{VII}$ = 73 mm

This table also shows a number of cases where the percentage of years with perceptible and severe root-stem lodging in the northern regions during 1980-2014 is similar to that in the southern regions during 1945-1979. This fact has been analyzed in detail previously to establish the spatiotemporal analogue within the HZ (Nikolaev 2015a).

3.3. ASSESSMENT OF THE CHANGING CONTRIBUTIONS OF PRECIPITATION AND THERMAL CONDITIONS TO THE INTENSITY OF FARMING RISKS

Functional analysis (Kolmogorov, Fomin 1976; Nikolaev 2016) has been applied to assess the changing contributions of precipitation and thermal conditions to the intensity of farming risks. The *HTC* index is a function of two variables: the precipitation totals and the cumulative air temperatures (degree-days), i.e. a surface with two horizontal axes – the precipitation sums and air temperature sums and a vertical axis – the *HTC* index. For example, Figure 4 shows the 3-dimensional representation of the *HTC* index with the plotted *HTC* index values ≥1.8 for the two time intervals of 1945-1979 and 1980-2014 at Kostroma. For convenient visual assessment of how the dot clouds shift, the isolines are plotted with intervals of 0.5 in the *HTC* index.

The contribution of each factor to high *HTC* values can be assessed, as well as the variation in *HTC*, by means of this surface projection. The criterion of this assessment is based on the proximity of relationships shown in Figures 5-9. The conclusion may be made that the July precipitation totals make a governing contribution to the lodging intensity, compared to the July air temperature totals. Simultaneously, Figures 5-7 demonstrate the increasing contribution of the extreme precipitation totals in July to the lodging intensity during 1980-2014 in different parts of the HZ. This contribution accounts for the fact that the dots are located on a straight line, reflecting the decrease in the residual variance.

Figures 8 and 9 show the changing contribution of cumulative air temperatures to the high HTC_{VII} values at Smolensk and at Vytegra. A general drift of dot clouds towards the air temperature totals less than their 70-yr mean values is observed, which corresponds to the usual conditions when lodging occurs. Nevertheless, the dots related to 1980-2014 are plotted a bit to the right, i.e. high and very high HTC_{VII} values are observed at the higher air temperature totals. Figure 9 also shows that in the northern regions of the HZ extremely high HTC_{VII} values are observed even at air temperature totals noticeably higher than their 70-yr mean values during 1980-2014.

For example, at Kotlas (61.2°N, 46.7°E) the extremely high HTC_{VII} value of 4.14 occurred in 2000 when the air temperature totals exceeded the 70-yr mean value (515°C) by almost 100°C, and exceptionally high total precipitation in July exceeded the 70-yr mean value (72 mm) by 177 mm.

3.4. ASSESSMENT OF THE CHANGING CONTRIBUTION OF SEASONAL PRECIPITATION TOTALS TO RECURRENCE OF FARMING RISKS

It is known that crop farming in the HZ often is subjected to adverse effects due to the abundant precipitation over the year. Therefore, statistical methods are used for analyzing the empirical distributions of the deviations of seasonal precipitation totals around the trends (Kovalenko, Filippova 1982). Linear trend models (Anderson 1971) are applied to account for the high interannual and intra-seasonal variability in the precipitation totals. A comparison is made for the periods 1946-1980 and 1981-2015 (Nikolaev 2018). Figures 10-12 are histograms of deviations in seasonal precipitation totals from trends in both time intervals for several stations located in different parts of the HZ. For each histogram, both the equation of the linear trend and parameters of the empirical distribution of residuals, i.e. standard deviation (*s*), skewness (s) and kurtosis (k), are presented.

A significant increase in *s* for summer precipitation totals is observed for 1981-2015 (1.6 greater than *s* for 1946-1980) because of the marginal positive anomalies caused by the extremely high precipitation totals

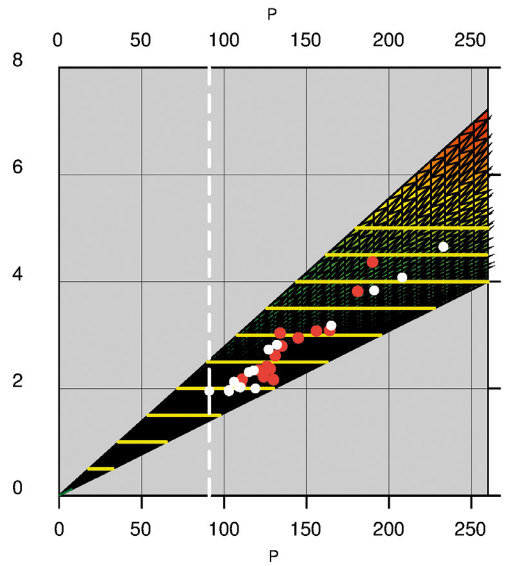

Fig. 6. Change in contribution of abundant precipitation in July to high HTC_{VII} values Smolensk: 54.5°N, 32.3°E (forest belt of the HZ); horizontal axis: precipitation sums for July [mm], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of precipitation amounts for July equals of $\sum P_{VII}$ = 91 mm

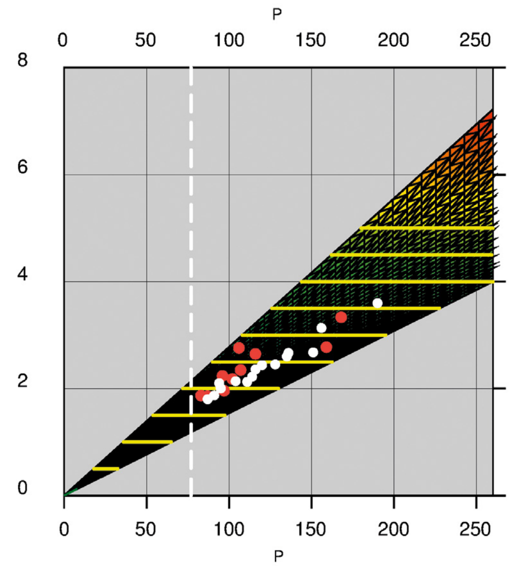

Fig. 7. Change in contribution of abundant precipitation in July to high HTC_{VII} values Vytegra: 61.0°N, 36.4°E (subboreal forest belt of the HZ); horizontal axis: precipitation sums for July [mm], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of precipitation amounts for July equals of $\sum P_{VII}$ = 77 mm

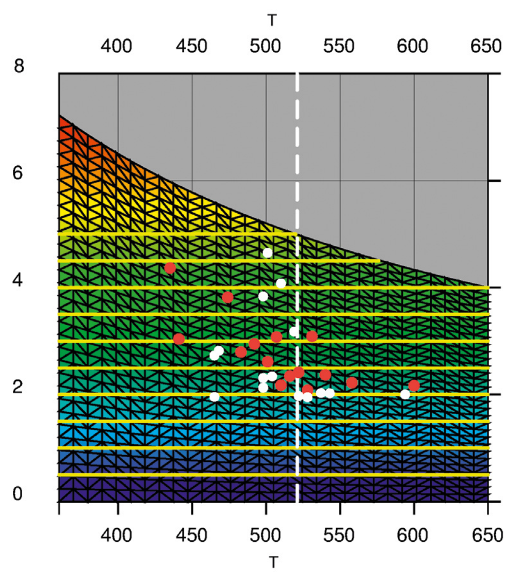

Fig. 8. Change in contribution of cumulative air temperatures for July to high HTC_{VII} values; Smolensk: 54.5°N, 32.3°E (forest belt of the HZ); horizontal axis: cumulative air temperatures for July [°C], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of cumulative air temperatures for July equals of $\sum T_{VII}$ = 521°C

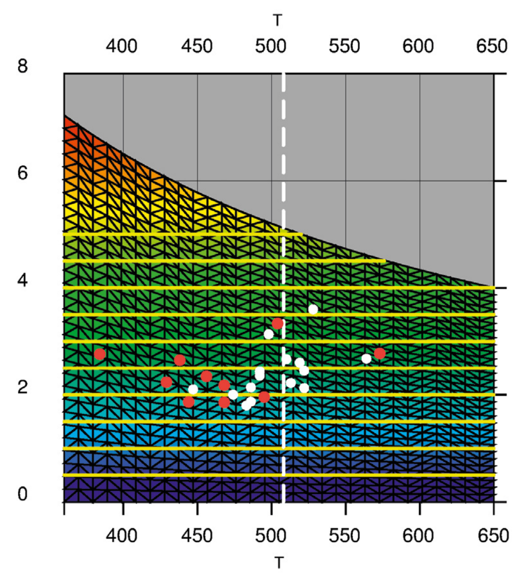

Fig. 9. Change in contribution of cumulative air temperatures for July to high HTC_{VII} values; Vytegra: 61.0°N, 36.4°E (sub-boreal forest belt of the HZ); horizontal axis: cumulative air temperatures for July [°C], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of cumulative air temperatures for July equals of $\sum T_{VII}$ = 508°C

in summer at Pskov (western part of the HZ), see Figure 10. At the same time, the skewness of all distributions for the 2nd interval is positive and larger, excluding the spring season. The kurtosis is also larger, excluding the spring season.

For the same reason, the high *s* for summer precipitation totals is observed for 1981-2015 (1.3 greater than *s* for 1946-1980) at Vologda (eastern part of the HZ); see Figure 11. Meanwhile, the skewness changes sign between the winter and autumn seasons. Thus, the skewness is positive for the distribution of autumn precipitation in the second time interval (with increasing *s*), whereas the skewness is negative for the 1st time interval. The kurtosis differs insignificantly for all distributions, except for summer.

Although *s* values are greater for all seasons during 1981-2015 in comparison with those during 1945-1980 at Syktyvkar (the northeastern part of the HZ), the skewness is negative for summer precipitation totals in the 2nd time interval; see Figure 12. The kurtosis is greater in the 2nd time interval, except for winter.

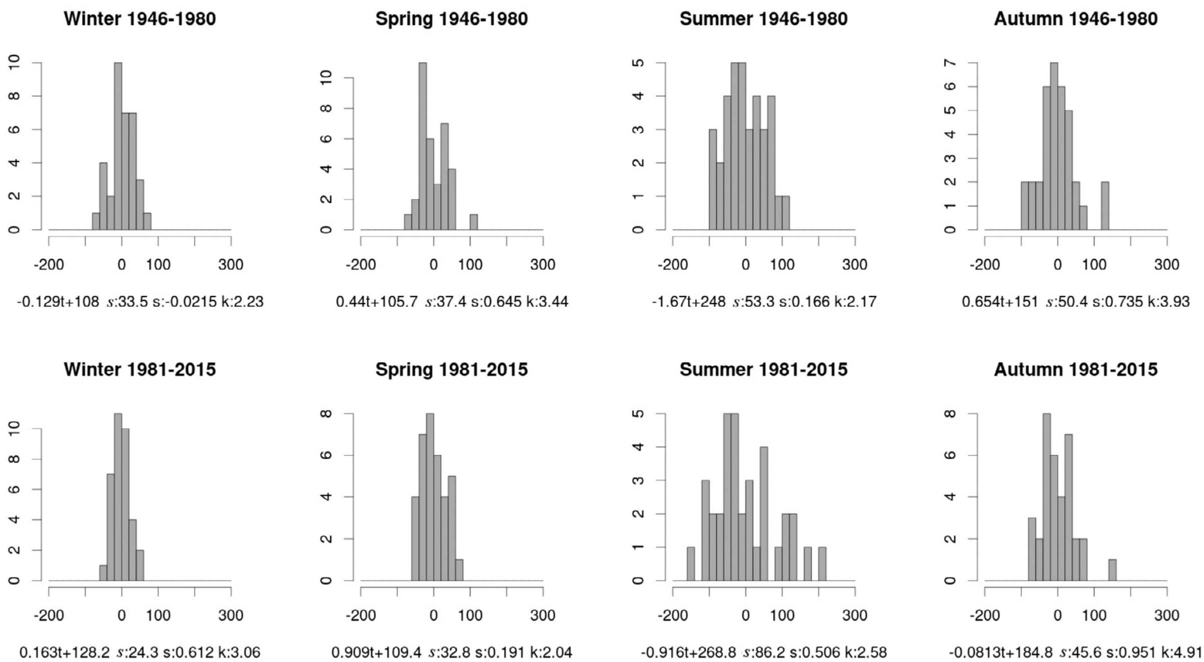

Fig. 10. Empirical distributions of seasonal precipitation totals in the time intervals of 1946-1980 and 1981-2015; Pskov: 57.8°N, 28.4°E (forest belt of the HZ)

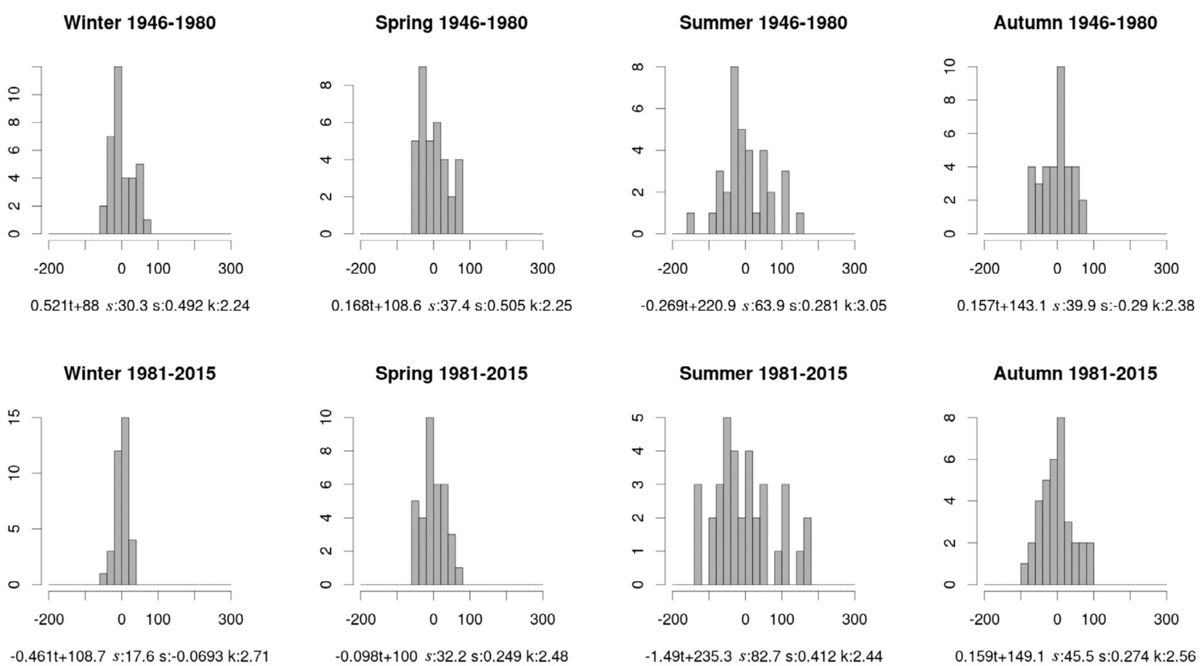

Fig. 11. Empirical distributions of seasonal precipitation totals in the time intervals of 1946-1980 and 1981-2015; Vologda: 59.3°N, 39.9°E (forest belt of the HZ)

3.5. ASSESSMENT OF EXCESSIVE MOISTURE EFFECTS ON THE SUSTAINABILITY OF CROP PRODUCTION

To assess excessive moisture effects on sustainability of crop production in the HZ of Western Russia, we analyzed the dynamics of yield losses with respect to technological trends in crop yields. Among small cereals, such crops as winter rye and winter wheat were revealed to be the most vulnerable. Then, yield losses of these crops were compared with several moisture indicators such as summer precipitation totals, HTC_{V-VI}, HTC_{VII}, $HTC_{VII-VIII}$ and summer EA indices. Thus, during 1945-1979 there were significant yield losses, corresponding to the excessively wet years 1950, 1958, and 1961. These yield losses were 10-15% greater than yield losses in extremely dry years such as 1972 and 1975. For example, in 1958 yield losses of winter rye at Shenkursk exceeded 29% (summer precipitation was 383 mm, HTC_{V-VI} = 3.09, HTC_{VII} = 1.58, $HTC_{VII-VIII}$ = 1.96, summer EA index value = 0.29); in 1961 yield losses of winter rye at Vytegra exceeded 36% (summer precipitation was 462 mm, HTC_{V-VI} = 1.40, HTC_{VII} = 3.33, $HTC_{VII-VIII}$ = 4.22, summer EA index value = 0.31).

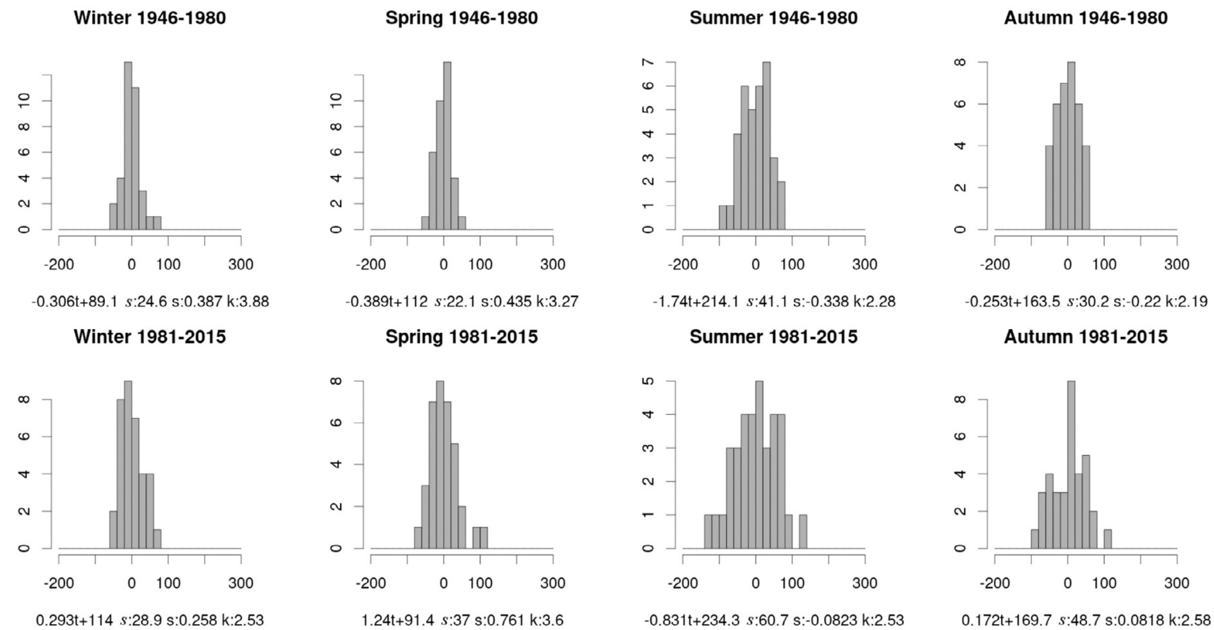

Fig. 12. Empirical distributions of seasonal precipitation totals in the time intervals of 1946-1980 and 1981-2015; Syktyvkar: 61.7°N, 50.8°E (sub-boreal forest belt of the HZ)

For 1980-2014 the absolute yield losses related to excessively wet years were noticeably greater than those during 1945-1979. This effect was a result of large upward trends in crop yields and also of a significant increase in precipitation amounts in the 1993-2008 period. Significant yield losses of indicated crops were recorded at Vologda in 1993 (35%), at Kotlas in 2000 (37%), at Kostroma in 2003 (22%) and at Petrozavodsk in 2008 (31%). The year 1998 was the wettest since 1945, and this agricultural year was considered most unfavorable for regional crop production. For example, yield losses of winter rye at Smolensk exceeded 54% (summer precipitation was 459 mm, $HTC_{V\text{-}VI}$ = 2.19, HTC_{VII} = *4.64*, $HTC_{VII\text{-}VIII}$ = 4.29, summer EA index = 0.77); yield losses of winter rye at Pskov reached up to 37% (summer precipitation was 457 mm, $HTC_{V\text{-}VI}$ = 3.32, HTC_{VII} = 3.42, $HTC_{VII\text{-}VIII}$ = 2.79, summer EA index = 0.77). It is noted that these losses are greater than yield losses observed in the extremely dry year 2010 (at Smolensk in 2010 yield losses of winter rye amounted to 24%, at Pskov in 2010 yield losses of winter rye amounted to 20%). According to available data, the year 2017 was an exceptionally wet year. For instance, yield losses of winter rye in this year at Vytegra exceeded 40% (summer precipitation was 406 mm, $HTC_{V\text{-}VI}$ = 2.40, HTC_{VII} = 4.61, $HTC_{VII\text{-}VIII}$ = 3.15, summer EA index = 1.96). It is characteristic that during past decades the most significant yield losses were observed in years with very high *HTC* values in July.

For soils of the HZ of Western Russia, the flushing type of water regime is typical, and the water table is near the surface in the northern and central parts of this zone. Field crops are mainly cultivated in the areas with sandy loam soils, medium-textured loam soils, and clay loam soils, due to limited distribution of sandy- and loamy-sand soils. Loam soils are less permeable than sandy soils, a fact reflected in greater yield loss at Smolensk (modal gleysolic podzol, medium-textured loam soil), than at Pskov (weak podzol, loamy sand soil) in 1998 as a result of over-wetting of the root layer.

The effects of water logging on winter crops in the early spring period typically are caused by the presence of lowlands and subnormal relief. However, these effects have been observed in recent decades more frequently, especially in the north-eastern part of this zone, i.e., in the sub-region with loam soils with expressed gley horizon (e.g., at Vytegra, at Kotlas, and at Syktyvkar).

4. CONCLUSIONS

The results reported above give evidence of the increasingly negative effect of abundant precipitation on crop production in the HZ of Western Russia under ever-increasing climatic changes.

Spatiotemporal monitoring of the areas vulnerable to crop over-wetting reflects the aggregate impact of climate variability and change in the degree of risk for farming in the humid regions considered here. The change in the configuration of the vulnerable areas in recent decades is in good agreement with the increasing cyclonic activity over the North Atlantic. Meanwhile, a shift of the boundaries of the vulnerable area northward is observed, despite the concurrent rise in the surface air temperature. Specifically, the increase in the percentage of years characterized by emerging risks of different-intensity lodging in the HZ conforms with the specific features of such spatiotemporal modes as the North Atlantic Oscillation and the East Atlantic pattern.

The functional analysis enables us to distinctly differentiate the changing contribution of precipitation and thermal conditions to the intensity of risks associated with excessive moisture. Evidently, the graphs plotted show the ever-increasing contribution of the extreme precipitation totals to the lodging risk intensity compared to cumulative air temperature contribution, even in the cases when air temperature sums tend to increase (likely due to the increased contribution of both advective and convective types of precipitation).

The statistical analysis also confirmed the significant contribution of extreme summer precipitation to the emerging crop over-wetting risks. This fact demonstrates the increasing recurrence of the notable positive anomalies in the summer precipitation totals in different parts of the HZ during 1981-2015. At the same time, due to the more frequent occurrence of such anomalies in autumn, the harvest is made difficult or completely hindered, while unfavorable pre-wintering conditions for winter crops are also created.

It should be noted that the reliable regression relationships revealed during this research, in turn, make it possible to introduce more reliable extrapolation of the increasing lodging risks from predicted precipitation conditions in the nearest future. Furthermore, the observed trends in the changing precipitation and thermal conditions agree with the changes in air temperature and precipitation based on the transient GCM simulation for the long term. It provides the opportunity for better choices of the most probable scenarios for the climate in the future for further investigations.

On the other hand, the assessment presented serves as a basis for developing regional adaptation strategies. Specifically:

- improving tillage practice, namely: wide application of ridge and close-bed plowing in order to reduce the distance between the furrows to accelerate surplus water flow, as well as shallow plowing with rolling in the autumn to intensify surface runoff in the early spring;
- effective application of drainage systems: adjustment of pipe drainage capacity, use of surface drainage due to more frequent summer rains (in the waterlogged areas the creation of more frequent network of deep channels);
- smoothing and leveling of agricultural fields (in case of subnormal relief, displacement of crop areas from depressions to more high relief area);
- switching to more wet- and warm-weather crops and varieties in some sub-regions within the HZ (e.g., enlarging the crop areas under buckwheat as well as certain fodder and vegetable crops);
- enhancing disease control as well as pest- and weed control, especially for the species that are well adapted to wet conditions (e.g., the lodged crops are usually subjected to rust and mildew, and there are many aphids encountered in them)

In turn, these strategies may be expanded to the intra-regional levels, taking into consideration the local features of the crop production practice. Particularly, the results may be used in crop insurance; in decision-making for improving the water regime control in the agricultural fields; and in selective research related to prospective zoning of highly productive crops and their hybrids, etc.

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