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Climatically driven yield variability of major crops in Khakassia (South Siberia)

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RESPONSE TO THE REVIEWER'S COMMENTS

We found the comments of the Reviewer to be very useful in making our manuscript more precise. Here all the numbers considering lines, tables etc. correspond to the numbers in the version of the R1 version of manuscript (i.e. version after first revision).

Reviewer #1

In response to the review process of the first submission, several issues were improved and were answered. However some minor reviews are still needed, as follows:

Line 86-91 - the abbreviations of the territories should be inserted to facilitate the visualization of Figure 1.

The abbreviations have been inserted.

Table 2 - the variables names should be inserted in the title of the table as explained in the lines 226-228.

The variables and their meanings have been inserted as the footnote.

Line 163-167 - Please, indicate table to consult

This information was not shown in table form previously. New table have been formed and inserted in Supplementary Materials as Table S4 (Old Table S4 currently has number S5). In the text also abbreviations of districts were added to make it clearer.

Line 236-237 - I can´t see these values in cited table

These lines are referring to the summarily contribution of temperature and HTC in the crops yield variation for the Northern zone, and to the contribution of temperature in the yield variation for the Central zone. In the previous version of manuscript these values were rounded to the integer values of %, which could be confusing. Now not rounded values, consistent with table, are showed.

Line 250-252 - Please, indicate table to consult

Authors deemed not necessary to show these values in table form, as it would consist from only one line. Therefore, they were just listed in the text.

Climatically driven yield variability of major crops in Khakassia (South Siberia)

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ABSTRACT We investigated the variability of yield of the three main crop cultures in the Khakassia Republic: spring wheat, spring barley and oats. In terms of yield values, variability characteristics, and climatic response, the agricultural territory of Khakassia can be divided into three zones: 1) the Northern Zone, where crops yield has a high positive response to the amount of precipitation, May-July, and a moderately negative one to the temperatures of the same period; 2) the Central Zone, where crops yield depends mainly on temperatures; and 3) the Southern Zone, where climate has the least expressed impact on yield. The dominant pattern in the crops yield is caused by water stress during periods of high temperatures and low moisture supply with heat stress as additional reason. Differences between zones are due to combinations of temperature latitudinal gradient, precipitation altitudinal gradient and presence of a well-developed hydrological network and the irrigational system as moisture sources in the Central Zone. More detailed analysis shows differences in the climatic sensitivity of crops during phases of their vegetative growth and grain development and, to a lesser extent, during harvesting period. Multifactor linear regression models were constructed to estimate climate- and autocorrelation-induced variability of the crops yield. These models allowed prediction of the possibility of yield decreasing by at least 2-11% in the next decade due to increasing of the regional summer temperatures.

Keywords: crops yield variability, temperature, precipitation, hydrothermal coefficient, South Siberia

Introduction

The global warming leads to crops yield increasing at high latitudes whereas at low latitudes the situation is reversed (Bindi, Olesen, 2011; Wang et al., 2016b). Significant long-term climatic trends influence agro- and natural ecosystems in a similar pattern. Therefore studying climatic dependencies in the productivity of cultivated plants is relevant for estimating the general productivity of the regional terrestrial ecosystems (Wu et al., 2014). An important factor influencing productivity of regional agriculture is the climatic regime with the crucial role of climate extremes (Ceglar et al., 2016; Wang et al., 2016b; Zhang et al., 2016 and references therein). The influence of global and regional climate change on the crops yield and its variability was investigated recently (Lobell and Field, 2007; Iizumi, Ramankutty, 2016). Studies of crops yield variability driven by climate change, reveal shifts of boundaries for the zones considered optimal for cultivation of various cultures and their cultivars (i.e. “zones of agroclimatic division”, see Novikova, 2012).

With regard to agricultural potential, steppe and forest-steppe zones are the most prominent territories of the Siberia, characterized by the dominance of grain crops. In South Siberia these zones form a wide continuous band excluding mountain regions, supplying grain to entire Siberia and the Far East of Russia. Similarly to many other mid-latitude regions the quantitative and qualitative characteristics of grain production in South Siberia are determined chiefly by the deficit of moisture during the growing season (Ozturk and Aydin, 2004; Sivakumar et al., 2005; Lobell and Field, 2007; Hlavinka et al., 2009). In the sharply continental temperate climate conditions the availability of moisture for cultivated plants depends on two factors. First being the moisture sources, i.e. quantity and seasonal distribution of precipitation and presence and specification of irrigation system. The second is the dependence of soil moisture loss from temperature.

In this study we carried out spatial analysis of climate-induced variability of grain crops yield in Khakassia. The results can be extrapolated to other territories with similar environmental conditions. The aims of this study were: 1) comparing the long-term dynamics of grain crop yield series using the available data averaged for administrative districts of Khakassia and additional data from crop variety trial stations, 2) determining distinct territories within Khakassia using the patterns of climate-induced dynamics of crops yield, 3) performing a detailed climate sensitivity analysis for grain varieties at various stages of plant development, 4) making probable predictions for the dynamics of crop yield with the assumption of continuation of the current climatic trends.

Materials and Methods

The agriculture in the Republic of Khakassia (Fig. 1) is concentrated in the Khakass-Minusinsk Depression, where climatic conditions are described as sharply continental (Agroclimatic Resources, 1974). Daily and seasonal temperature variations in this region display very large amplitudes. The annual pattern in the precipitation depicts high interannual variability, strong summer maximums and dry, low-snow winters. The typical snow depth by the end of the winter is only 20 cm or less in the steppe zone. Early spring is characterized by rapid increase in temperature. Crossing the +5°C value occurs 30-35 days earlier than the beginning of the frost-free period. Therefore spring frosts delay growth of the vegetation and effectively reduce the duration of the vegetative season. Beginning of the third decade of May can be considered a start of the summer season. The duration of the period with temperatures above +10°C does not exceed 120 days. The Selyaninov hydrothermal coefficient ($HTC = 10 \cdot \sum P / \sum T$ for period of $T > 10°C$; Selyaninov, 1937) is unstable and varies within the range from 0.5 to 2.0, where values < 1.0 indicate insufficient moisture supply. It points to the presence of periods of insufficient moisture supply during the warm season. The temperature distribution over the Khakass-Minusinsk Depression during the vegetative period is characterized by a latitudinal gradient with gradual increase in temperature towards south. Similarly, precipitation varies in altitudinal gradient with decrease in its amount from base to top of the mountainous region. For example, precipitation decreases from the base of Kuznetsk Alatau Mountains to the East towards the Yenisei River and from the base of the Western Sayan Mountains to the North in Tashtyp and Beya districts.

Monthly and daily data of average temperature and total precipitation over the period 1938-2012 were obtained from the meteorological stations Tashtyp (52°48’N 89°53’E), Shira (54°30’N 89°56’E), and Minusinsk (53°41’N 91°40’E) (Table 1). The HTC value has been calculated based on temperature and precipitation data.

According to the conventional agroclimatic division (Agroclimatic Resources, 1974; Vedrov, Lazarev, 1997), the agricultural territory of Khakassia is divided into three soil-climatic zones: 1) the subtaiga at the foothills (mostly Tashtyp district – TA), 2) the steppes on ordinary and southern chernozem, which consists of Ordzhonikidzevskiy, Shira, Bograd and partially Beya district (OR, SH, BO, BE), and 3) the steppes on chestnut and dark chestnut soils, consisting of Altaiskiy, Ust-Abakan and partially Beya district (AL, AS, BE).

The subtaiga zone occupies a narrow strip adjacent to the mountainous part of Khakassia. Soils in this zone are dark grey and alfisol and agricultural areas are restricted mainly to the more gently slopes. The steppes on the ordinary chernozem soils and southern medium chernozem ones are located in the northern part of the depression. They are characterized by insufficient moisture supply. However, there is insufficient hydrological network to develop irrigating system. The driest zone is located in central Khakassia steppe areas on chestnut and dark-chestnut soils, where irrigation is required for sustained agriculture. Therefore most of this territory (except part of the Ust-Abakan district) is covered by an advanced network of irrigation canals passively fed by Yenisei and Abakan rivers and their tributaries (Territorial planning scheme, 2011).

In spite of moisture deficit the climatic conditions of Khakassia allow cultivation of a broad set of crops. In this study we used the grain crops annual yield statistical series of two types: 1) the yield data generalized for cultivated areas of each administrative district over the period 1960-2012 and 2) the yield data from the crop variety trial stations Bograd (54°17'N 91°06'E), Tashtyp (52°52'N 89°55'E), Ust-Abakan (53°40'N 91°17'E), and Shira (54°42'N 89°46'E) over the period 1939-1995. We used relative yield, i.e. the weight of obtained grain in metric hundredweights per hectare of cultivated area (1 cwt/ha = 100 kg/ha). It allows to eliminate from consideration the cultivated area dynamics (Therrell et al., 2006) and to consider massive crops death occurrences.

We considered yield dynamics of spring wheat, spring barley and oats. These three crops occupy about 95% of all crops cultivated area of Khakassia (Online Resource Fig. S1). To estimate the plant growth and grain development phases we employed the decimal Zadoks scale (Zadoks et al., 1974). Approximate timing for various grain development phases and harvesting in the region was obtained from the unpublished state archival records of Khakassia.

Following statistical characteristics of time series were used: arithmetic (interannual) mean over all time period, minimum and maximum values, standard deviation, variation coefficient (the ratio of standard deviation to arithmetic mean), the sensitivity coefficient (the ratio of the difference between two adjacent values to their arithmetical mean, averaged over all time period), and the first order autocorrelation coefficient as measure of the yield of current year dependence on the yield of previous year (Fritts 1976; Wigley et al., 1984).

We applied Pearson correlation coefficients and carried out cluster analysis (hierarchical classification). In the cluster analysis the correlation coefficients were used as a measure of closeness between crop yield series. More generalized series of the crop yield were calculated as the first principal component (PC1) of the series set for each cluster and for the full set of series. This type of generalizing was used because it allows highlighting common external signal, including climatic one, if it is similar in all series of the generalized set (compare with Peters et al., 1981; Frank, Esper, 2004 for the tree growth on the different scales). The long-term trends in the raw crop yield series were seen to be not distinct; hence procedure of their removing was not necessary. We used linear multiple-factor regression models and linear long-term trends.

Results

The main statistical characteristics were calculated for all yield series (Online Resource Table S1, S2). The maximum and mean yield was the highest in the Tashtyp district and the lowest in the Ust-Abakan and Askiz districts. In general the coefficient of variation decreases from the West to the East. The sensitivity coefficient decreases from the South to the North.

Wheat was characterized by the highest values for the mean and maximum yield but the lowest characteristics of variability. In the steppe zone the oats were characterized by the lowest values of mean and maximum yield. However, with sufficient moisture supply in the foothills oats had higher mean and maximum yield than others. The oats also had the highest characteristics of variability.

The spatial analysis of correlation relationships between the district yield series (Online Resource Table S3) shows the predominance of the latitudinal gradient. Thus the greater the latitudinal difference between districts, the weaker is the observed correlation between their series. But we found no longitudinal gradient. This agricultural territory is divided into three zones with a high similarity of crop yield dynamics. The first is the Northern Zone that includes Ordzhonikidzevskiy, Shira, Bograd, and Ust-Abakan districts. The second being the Central Zone includes the Altaiskiy, Askiz, and Beya districts. The final zone is the Southern Zone, which includes only Tashtyp district (Fig. 1). This classification resonates with the outcome of the cluster analysis (Online Resource Fig. S2).

In comparison with the corresponding district series, the trial station series are characterized by higher mean yield (by 1.6-1.8 times) and maximum yield (by 1.8-2.3 times) and by lower coefficients of variation and first-order autocorrelations. The sensitivity is similar for the district series and the trial station series. Correlations between the trial station series and district series are in the range $r = 0.57 \ldots 0.89$, despite rather short common time period (Online Resource Fig. S3, S4). Comparing the yield series for one crop culture between different trial stations has revealed that the similarity between them decreases along the precipitation gradient for all three crops, taking into account the distances between the trial stations. The highest similarity is observed between Bograd and Shira stations ($r = 0.47 \ldots 0.65$) and between Bograd and Ust-Abakan stations ($r = 0.40 \ldots 0.69$). The lowest similarity is observed between Ust-Abakan and Shira stations ($r = 0.21 \ldots 0.44$) and between Ust-Abakan and Tashtyp stations ($r = 0.16 \ldots 0.48$).

The correlation showed positive and significant relationship between yield series of different crops within a given district (Online Resource Table S4). The intensity of relationship changes along the altitudinal gradient. In the eastern districts adjacent to the Yenisei River (SH, BO, AL and BE) the correlations are in the range r = 0.71 … 0.93, in more western districts (OR, UA and AS) r = 0.50 … 0.73 while in the Tashtyp district r = 0.33 … 0.52.

The three zones of yield dynamics in Khakassia are having distinct climatic influence on individual zones. The climatic influence was found from the preliminary analysis of correlations of the districts yield series with precipitation, temperature and HTC (Online Resource Fig. S5). The climatic response in the trial stations series is generally weaker than in the district series. But it is characterized by qualitatively similar patterns and gradients. The climatic conditions of the period preceding the sowing do not exert significant impact on the yield. Therefore the climatic response of zonal yield series during the period of May-August was considered in the present study (Fig. 2). We used PC1 of each district crops yield series zonal set as generalized zonal yield series, since for these zones it explains 80.8 … 89.9% of general crops yield variability within zone and 73.1 … … 85.4% of yield variability for separate crop cultures. On the other hand, for the Khakassia as a whole the first principal component explains 67.9% for crops in general and 51.6 … 67.3% for separate cultures, that is less by 12.2…25.1% than within zones, thus their integration in the one regional yield series is unreasonable.

In the Northern Zone, yield positively correlates with precipitation and HTC, but negatively correlates with temperature. Significant correlations are observed during all period from May to July. In the Central Zone the relationships between yield and precipitation and HTC are lower and not significant on $p<0.05$ in June and July, whereas correlations with temperatures, on the contrary, are higher. Negative response of yield to August precipitation is observed and is significant for wheat and barley. In the Tashtyp district the response of yield to temperature is weak, while the response to precipitation and HTC is not significant.

We also considered the pointer years, when yield is outside the mean ± standard deviation range for a half or more of raw series. For the period 1970-1995 (common for all series) high-yield pointer years are 1972, 1988 and 1991; low-yield pointer years are 1974, 1981 and 1994 (Online Resource, Fig. S6). The low-yield pointer years are characterized with higher temperatures and very low amounts of precipitation from the second half of May until July. The high-yield pointer years record smaller amount of precipitation in August and September.

To refine the crucial periods of climatic influence on yield we carried out correlation analysis of zonal yield series with climatic series calculated for moving 10-day intervals with a one-day step for May-September period (Fig. 3). There are common patterns observed for all crops and zones. Response to precipitation is positive and response to temperature is negative within the period from May to the middle of August. In the end of the warm season the climatic response becomes weak, unstable, and change sign. Nevertheless, the response intensity variation during the season depends on zone.

In the Northern Zone the maximum correlation of yield with temperature for all three crops is observed during the period from the end of June to the end of July, which corresponds to the reproductive period – phases of flowering and grain maturation. The peak of correlations at the end of May is less pronounced. That period corresponds to the phases of stem elongation and awn emergence. Correlations with precipitation are positive during the entire period of plants development from May 1 until August 10 and reach a maximum in the medium of July. The influence of precipitation on yield of wheat is weaker. For the Central Zone, the response to temperature and especially to precipitation is less expressed than for the Northern Zone. The positive response to precipitation sharply weakens in the middle of June, when most of the vegetative mass of plants has already been formed. In the response to temperature there is a third maximum at the end of July – beginning of August, which corresponds to the final phase of grain development. In the Southern Zone the correlations of yield with climatic factors are unstable and less pronounced, . Nevertheless, for all crops there is a significant response to precipitation in the middlbut have the same general patterns as in other zones.

Sowing areas in Khakassia are distributed as follows (average for all time period): 62.9% in the Northern Zone, 33.6% in the Central Zone, and only 3.6% for the Tashtyp district. Therefore it is sufficient to consider only Northern and Central Zones for the analysis of climate-induced dynamics of crops yield in Khakassia.

When calculating the linear multifactor regression models of yield dynamics we employed the following independent variables: May-July temperature, HTC of the same period (since the yield has stronger response to it in comparison to precipitation) and an autocorrelation component. For modeling zonal series were presented in form of standard indices (i.e. ratio of current yield value to the mean zonal yield). The following general equation was obtained as a result:

$$Y = a_0 + a_1 \cdot Y_{-1} + a_2 \cdot T + a_3 \cdot H + \varepsilon, \quad (1)$$

where, Y is standard yield index for the current year, $a_0 \dots a_3$ are numerical coefficients, Y_{-1} is standard yield index for the previous year, T is the mean May-July temperature, H is the mean May-July HTC, ε is the yield component caused by unaccounted factors, including random variability. In the Central Zone, HTC does not have sufficient influence on the yield (it’s coefficients in regression function are not significant). Therefore for this zone HTC was excluded from the equation and yield was calculated as function of Y_{-1} and T (Table 2, Online Resource Fig. S7). Climatic data from Shira and Minusinsk stations were used for the Northern and Central zones respectively. Correlations between T and H variables are negative, but not significant.

Based on the partial correlations and on the general determination coefficients of the regression models we found that the climatic conditions of May-July explain 33.8 … 40.8% of yield variability in the Northern Zone and 24.9 … 31.8% in the Central Zone (Online Resource Table S5). In the Northern Zone the variability of barley and oats yield depends on moisture to a much greater extent than on temperature. The relative importance of these factors differs for wheat. In the Central Zone the contribution of temperature to the yield variability is considerable for all the three grain crop cultures. The autocorrelation makes large contribution to the yield variability for barley and especially for wheat, whereas for oats this component is smaller. Overall the presented models explain about a half of the yield variability with the exception of the model for oats yield in the Central Zone.

During the climatic observation period within the Khakass-Minusinsk Depression there are no significant long-term trends in precipitation and HTC of the warm period. On the other hand, summer temperatures increase significantly from around 1970th (Online Resource Fig. S8). Thus, using this trend it is possible to predict that with the growth of temperature by 0.4 °C over the next decade. The mean precipitation level and the hydrothermal coefficient stay approximately constant. Thus the cumulative result may be a decrease in long-term average crops yield by about 2.4 … 6.0% in the Northern Zone and about 8.5 … 10.7% in the Central Zone. This estimation of the yield loss can be further increased due to nonlinear components, not included in this model.

Discussion

The influence of climatic characteristics of winter and early spring on crops yield is typical for many regions of the world, e.g. agricultural territories of Europe (Hlavinka et al., 2009; Wu et al., 2014). However in Khakassia snow melting ends at the end of March – beginning of April, i.e. approximately one month prior to the start of the sowing campaign. This is related to high amplitude of daily temperature oscillations typical for sharply continental climate. This and the low snow quantities during winters in the Khakass-Minusinsk Depression lead to not significant influence of winter precipitation and early spring temperatures on the crops yield.

The climatic response in the crops yield for Khakassia is typical for moisture-lacking steppe and forest-steppe conditions of continental climate (Dong et al., 2016). This response is comparable to other regions of temperate latitudes (e.g. Ceglar et al., 2016; Liu et al., 2016). However, even across the rather small Khakassia territory it is not uniform. This is due to the existence of pronounced climatic gradients and also due to the usage of irrigated agriculture in the central districts. Obviously the latter leads to the suppression of the precipitation response (Hlavinka et al., 2009; Ceglar et al., 2016).

One of the factors causing the differences between crop cultures in the mean yield values and in the yield variability parameters may be higher sensitivity of oats to adverse factors in comparison to barley and especially to wheat. The adverse factors include climatic variables. Higher yield values and rather low variability in the trial stations series in comparison to the district series is related to some specifics. Stations are characterized by uniform landscape and soil characteristics. The new cultivars of grain crops are tested there under controlled conditions and the complex of agro-technical techniques may differ from those used in mass agriculture (Lobell and Burke, 2010). The difference in the levels of autocorrelation is caused by the dependence of yield on the quality of sowing material (Mohan, Gupta, 2015), the fact of using grain from the previous year harvest in mass agriculture for that purpose, and the positive interrelations between grain quality and yield of the same season (Abd El-Kareem, El-Saidy, 2011).

It is clear that distinguishing three zones in Khakassia based on similarities in yield characteristics matches the existing agro-climatic division with the exception of Ust-Abakan district. That district belongs to the central agro-climatic zone, but our classification based on yield characteristics assigns it in the Northern zone in spite of differences in soils. This points to the more significant role of such factors as the climatic gradients of the vegetative period and especially the existence of an irrigational system than the soil type factor. Classification into these three zones is confirmed by the three main methods that were employed. They were confirmed firstly by the ranges of inter-series correlations within each zone and between the zones. Secondly by the results of cluster analysis and thirdly based on the patterns of climatic response in the yield series. The principal components analysis showed higher proportion of common yield variability within zones than that for total agricultural territory of Khakassia. This fact points to the existence of a strong common signal related to the unified landscape/climatic, hydrological conditions and agricultural techniques within each zone. This allows using the first principal component as a chronology of crops yield in each zone as the analysis and modeling of climatic response are performed.

The analysis of statistical characteristics of the crops yield series shows pronounced regularities in their geographical distribution. Inter-annual fluctuations of yield are very high across the entire territory of region. This is probably because Khakassia, as well as the majority of the regions of Russia, are considered as a risky agriculture zone, where the crop yield depends mainly on the current environmental conditions and catastrophically decreases by their unfavorable combination (Agroclimatic Resources, 1974).

The range of variability and the mean yield value for all considered grain crops depend primarily on the agro-climatic conditions. The productivity is highest in the foothills and lowest in the dry steppes (Online Resource Table S1). However, despite the Altaiskiy district belonging to dry steppes, the yield here is comparable to the foothills. This may be attributable to the location of Altaiskiy district between the two largest rivers of the Republic – the Abakan and the Yenisei. These rivers mediate the climate and significantly simplify irrigation (this district is characterized by the most developed network of irrigation canals in Khakassia). The relative variability of the yield series has the prevailing altitudinal gradient, i.e. it increases in the direction from the foothills to steppes near the Yenisei river. In the interannual variability component (sensitivity) the latitudinal gradient is observed, i.e. increase from Ordzhonikidzevskiy to Askiz district. It is reduced in the Altaiskiy, Beya, and Tashtyp districts by the increase in moisture caused by the landscape and hydrological conditions.

In the northern regions of Khakassia the warm period precipitation is a crucial climatic factor since it is the main source of moisture. A poorly developed hydrological network (prevalence of drainless areas, lack of large rivers) hampers the development of irrigated agriculture. On the contrary, temperature increases strengthen evapotranspiration, dry up the soil and cause water stress in plants. During the highest temperature period from June 20 until July 25 the crossing of day temperatures over the threshold level (for the considered grain crops it is about 30°C) leads to heat stress and suppression of growth and development of plants (Koehler et al., 2013; Liu et al., 2016). The impact of temperature and precipitation is accumulated during the period from May to July, i.e., at all stages of plants growth and development. The highest influence of precipitation is observed at stages of seeding growth and tillering (May) and during the reproductive period (end of June – July). The Selyaninov hydrothermal coefficient correspondingly unifies the influence of temperature and precipitation on the humidity of air and soil. In the Northern Zone, it has a strong correlation with crops yield in May, July and for the entire vegetative period.

Despite moisture deficit in the Central Zone the positive influence of precipitation and HTC on the yield is low. On the other hand the negative response of yield to temperature is more considerable. We believe that such climatic response is related to the presence of a developed river system on this territory (basins of the Abakan and the Yenisei rivers) as well as the irrigation channels network as a significant moisture sources (Territorial planning scheme, 2011; Ceglar et al., 2016). This network of channels can serve for temporary depository of moisture from precipitation discharge even in the absence of irrigation costs. It is also promoted by a more flat topography and the relatively high level of ground waters in the Central Zone, compared to the Northern Zone. In some years (e.g., 1994, see Online Resource Fig. S6b) strong rains during harvesting period cause stems lodging and harvest loss (Mukula and Rantanen, 1989).

In the foothills in the South Zone the agroclimatic conditions are most optimal for grain crop cultivation, which is evidenced by a practically total absence of significant climatic response in yield. However this territory is not characterized by high significance for the economy of Khakassia, since the nature of its topography leads to the severe limitation of possible cultivation area.

Less pronounced climatic response in crops yield on the trial stations can be attributed to the following reasons: 1) when averaging all the cultivated areas of a territory non-climatic features (e.g. soil, landscape, differences in agricultural techniques and sowing material between the farms) are leveled off; on the other hand on the trial stations landscapes and soil conditions are uniform and optimal for cultivation of grain crops; 2) special attention to the quality of sowing material and agrotechnical practices, frequent changes of cultivars not only increase the productivity at the trial stations in comparison with common agricultural areas, but also partially compensate for adverse weather conditions thereby weakening the climatic limitation (Therrell et al., 2006; Lobell and Burke, 2010). It should also be mentioned that the Ust-Abakan station and especially the Tashtyp station unlike the majority of cultivated areas in the respective districts are located near the boundary with the Central Zone. Thus the agroclimatic conditions and the observed crops yield climatic response at these stations are in-between of the Central Zone and their respective zones.

Climatic variables that are generalized over a month and especially over a season do not reflect the details of the short-term oscillations within that period. Importantly, these oscillations can exert a great influence on growth and development of plants and consequently on the yield (Fishman, 2016). The importance of short-term climatic oscillations is also related to the small duration of growth phases of grain crops (various phases last from 5-10 to 15-20 days; Fig. 3) and to the changing moisture, heat and light demands of the plants that depends on the phase. Therefore, it was of interest to conduct an analysis of the oscillations of weather conditions over 10-day intervals during the vegetative period.

Moisture is the crucial factor for plant development in the Northern Zone during the first phases of vegetative growth of grain crops (from sowing to the beginning of tillering). Subsequently until the beginning of awn emergence the limiting factor is mainly the temperature. As was noted earlier, in hot and arid climate grain crops are most vulnerable to climatic fluctuations during the reproductive period, when there is a possibility of simultaneously occurring water stress and heat stress (e.g. Wang et al., 2016a). The water level in irrigation network of central districts of Khakassia at the beginning of vegetative growth is insufficient for providing the fields with complete supply of moisture. Thus the first peak of positive influence of precipitation is observed during that period. The second peak corresponds to the phase of awn emergence, when the moisture demands of plants are the highest and all available sources of moisture are important (White, Edwards, 2008). The irrigation moderates the deficit of moisture during the other phases of plant development, reducing the reaction to precipitation. High air temperatures create deficit of moisture (regardless of its sources) in the middle of the vegetative growth period. It suppresses plant growth and leads to a decrease in the yield. Further added during the development of the grain is the probability of the suppression of plants by overheating, i.e. the heat stress. Both temperature and precipitation have significant influence in the south for 10-day periods in contrast to the monthly data. This influence although similar is much less pronounced in comparison with the rest of Khakassia territory due to the location of the zone in the foothills, which moderates the climate.

The fraction of variation of the yield explained by the climatic variables is high enough for practical use in the regression models that were obtained and is comparable to the existing models for other regions (e.g. Therrell et al., 2006; Wu et al., 2014; Zhang et al., 2016). Application of these models in the conditions of regional climate change allows to predict the yield changes and to account for them during planning in agriculture and economy of the Republic of Khakassia in general.

In the long-term perspective warm season temperatures of the study area are steadily increasing and rate of this increase is consistent with other works (e.g. Tchebakova et al., 1995; Nazimova et al., 2010; Kattsov, Semenov, 2014). Even with stable amount of precipitation this warming will lead to the higher frequency and duration of the heat stress occurrences during hottest period of season. It will form additional nonlinear negative component in the influence of temperature on the plants growth and increase estimation of the yield loss due to climate change. Another possible source of nonlinearity in the climatic response is volatility of the plants heat tolerance due to acclimation (e.g., Yamori et al., 2014). Therefore further consideration of warming of future regional climate and associated risks for agriculture due to increasing of probability of water and heat stresses is necessary.

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Figure captions

Fig. 1 Map of the study area. Districts with similar climatic response in the crops yield are marked with the same shade. Territories suitable for the crops agriculture are marked with hatching. Circles are meteostations and diamonds are crop variety trial stations. Climatic diagrams (mean air temperature and amount of precipitation for every month) correspond to the averages over the entire period of instrumental measurements on each meteostations

Fig. 2 Correlation coefficients of crops yield zonal series with precipitation (P), temperature (T) and hydrothermal coefficient (H) of May-August. Coefficients marked with “+” sign are significant on level $p<0.05$

Fig. 3 Correlation coefficients of crops yield zonal series with moving (10-day window, 1-day step) mean temperatures (solid lines) and total precipitation (areas) from May to September. Dashed lines mark $p = 0.05$ significance level of the correlation coefficients. The average timing of harvesting and the Zadoks decimal growth stages of crops (Zadoks et al., 1974) in the study area are marked as follows: Z0 – germination; 1 – seeding growth; 2 – tillering; 3 – stem elongation; 4 – booting; 5 – awn emergence; 6 – flowering (anthesis); 7 – milk grain development; 8 - dough grain development; 9 – hard grain

Climatically driven yield variability of major crops in Khakassia (South Siberia)

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ABSTRACT We investigated the variability of yield of the three main crop cultures in the Khakassia Republic: spring wheat, spring barley and oats. In terms of yield values, variability characteristics, and climatic response, the agricultural territory of Khakassia can be divided into three zones: 1) the Northern Zone, where crops yield has a high positive response to the amount of precipitation, May-July, and a moderately negative one to the temperatures of the same period; 2) the Central Zone, where crops yield depends mainly on temperatures; and 3) the Southern Zone, where climate has the least expressed impact on yield. The dominant pattern in the crops yield is caused by water stress during periods of high temperatures and low moisture supply with heat stress as additional reason. Differences between zones are due to combinations of temperature latitudinal gradient, precipitation altitudinal gradient and presence of a well-developed hydrological network and the irrigational system as moisture sources in the Central Zone. More detailed analysis shows differences in the climatic sensitivity of crops during phases of their vegetative growth and grain development and, to a lesser extent, during harvesting period. Multifactor linear regression models were constructed to estimate climate- and autocorrelation-induced variability of the crops yield. These models allowed prediction of the possibility of yield decreasing by at least 2-11% in the next decade due to increasing of the regional summer temperatures.

Keywords: crops yield variability, temperature, precipitation, hydrothermal coefficient, South Siberia

Introduction

The global warming leads to crops yield increasing at high latitudes whereas at low latitudes the situation is reversed (Bindi, Olesen, 2011; Wang et al., 2016b). Significant long-term climatic trends influence agro- and natural ecosystems in a similar pattern. Therefore studying climatic dependencies in the productivity of cultivated plants is relevant for estimating the general productivity of the regional terrestrial ecosystems (Wu et al., 2014). An important factor influencing productivity of regional agriculture is the climatic regime with the crucial role of climate extremes (Ceglar et al., 2016; Wang et al., 2016b; Zhang et al., 2016 and references therein). The influence of global and regional climate change on the crops yield and its variability was investigated recently (Lobell and Field, 2007; Iizumi, Ramankutty, 2016). Studies of crops yield variability driven by climate change, reveal shifts of boundaries for the zones considered optimal for cultivation of various cultures and their cultivars (i.e. “zones of agroclimatic division”, see Novikova, 2012).

With regard to agricultural potential, steppe and forest-steppe zones are the most prominent territories of the Siberia, characterized by the dominance of grain crops. In South Siberia these zones form a wide continuous band excluding mountain regions, supplying grain to entire Siberia and the Far East of Russia. Similarly to many other mid-latitude regions the quantitative and qualitative characteristics of grain production in South Siberia are determined chiefly by the deficit of moisture during the growing season (Ozturk and Aydin, 2004; Sivakumar et al., 2005; Lobell and Field, 2007; Hlavinka et al., 2009). In the sharply continental temperate climate conditions the availability of moisture for cultivated plants depends on two factors. First being the moisture sources, i.e. quantity and seasonal distribution of precipitation and presence and specification of irrigation system. The second is the dependence of soil moisture loss from temperature.

In this study we carried out spatial analysis of climate-induced variability of grain crops yield in Khakassia. The results can be extrapolated to other territories with similar environmental conditions. The aims of this study were: 1) comparing the long-term dynamics of grain crop yield series using the available data averaged for administrative districts of Khakassia and additional data from crop variety trial stations, 2) determining distinct territories within Khakassia using the patterns of climate-induced dynamics of crops yield, 3) performing a detailed climate sensitivity analysis for grain varieties at various stages of plant development, 4) making probable predictions for the dynamics of crop yield with the assumption of continuation of the current climatic trends.

Materials and Methods

The agriculture in the Republic of Khakassia (Fig. 1) is concentrated in the Khakass-Minusinsk Depression, where climatic conditions are described as sharply continental (Agroclimatic Resources, 1974). Daily and seasonal temperature variations in this region display very large amplitudes. The annual pattern in the precipitation depicts high interannual variability, strong summer maximums and dry, low-snow winters. The typical snow depth by the end of the winter is only 20 cm or less in the steppe zone. Early spring is characterized by rapid increase in temperature. Crossing the +5°C value occurs 30-35 days earlier than the beginning of the frost-free period. Therefore spring frosts delay growth of the vegetation and effectively reduce the duration of the vegetative season. Beginning of the third decade of May can be considered a start of the summer season. The duration of the period with temperatures above +10°C does not exceed 120 days. The Selyaninov hydrothermal coefficient ($HTC = 10 \cdot \sum P / \sum T$ for period of $T > 10°C$; Selyaninov, 1937) is unstable and varies within the range from 0.5 to 2.0, where values < 1.0 indicate insufficient moisture supply. It points to the presence of periods of insufficient moisture supply during the warm season. The temperature distribution over the Khakass-Minusinsk Depression during the vegetative period is characterized by a latitudinal gradient with gradual increase in temperature towards south. Similarly, precipitation varies in altitudinal gradient with decrease in its amount from base to top of the mountainous region. For example, precipitation decreases from the base of Kuznetsk Alatau Mountains to the East towards the Yenisei River and from the base of the Western Sayan Mountains to the North in Tashtyp and Beya districts.

Monthly and daily data of average temperature and total precipitation over the period 1938-2012 were obtained from the meteorological stations Tashtyp (52°48’N 89°53’E), Shira (54°30’N 89°56’E), and Minusinsk (53°41’N 91°40’E) (Table 1). The HTC value has been calculated based on temperature and precipitation data.

According to the conventional agroclimatic division (Agroclimatic Resources, 1974; Vedrov, Lazarev, 1997), the agricultural territory of Khakassia is divided into three soil-climatic zones: 1) the subtaiga at the foothills (mostly Tashtyp district – TA), 2) the steppes on ordinary and southern chernozem, which consists of Ordzhonikidzevskiy, Shira, Bograd and partially Beya district (OR, SH, BO, BE), and 3) the steppes on chestnut and dark chestnut soils, consisting of Altaiskiy, Ust-Abakan and partially Beya district (AL, AS, BE).

The subtaiga zone occupies a narrow strip adjacent to the mountainous part of Khakassia. Soils in this zone are dark grey and alfisol and agricultural areas are restricted mainly to the more gently slopes. The steppes on the ordinary chernozem soils and southern medium chernozem ones are located in the northern part of the depression. They are characterized by insufficient moisture supply. However, there is insufficient hydrological network to develop irrigating system. The driest zone is located in central Khakassia steppe areas on chestnut and dark-chestnut soils, where irrigation is required for sustained agriculture. Therefore most of this territory (except part of the Ust-Abakan district) is covered by an advanced network of irrigation canals passively fed by Yenisei and Abakan rivers and their tributaries (Territorial planning scheme, 2011).

In spite of moisture deficit the climatic conditions of Khakassia allow cultivation of a broad set of crops. In this study we used the grain crops annual yield statistical series of two types: 1) the yield data generalized for cultivated areas of each administrative district over the period 1960-2012 and 2) the yield data from the crop variety trial stations Bograd (54°17’N 91°06’E), Tashtyp (52°52’N 89°55’E), Ust-Abakan (53°40’N 91°17’E), and Shira (54°42’N 89°46’E) over the period 1939-1995. We used relative yield, i.e. the weight of obtained grain in metric hundredweights per hectare of cultivated area (1 cwt/ha = 100 kg/ha). It allows to eliminate from consideration the cultivated area dynamics (Therrell et al., 2006) and to consider massive crops death occurrences.

We considered yield dynamics of spring wheat, spring barley and oats. These three crops occupy about 95% of all crops cultivated area of Khakassia (Online Resource Fig. S1). To estimate the plant growth and grain development phases we employed the decimal Zadoks scale (Zadoks et al., 1974). Approximate timing for various grain development phases and harvesting in the region was obtained from the unpublished state archival records of Khakassia.

Following statistical characteristics of time series were used: arithmetic (interannual) mean over all time period, minimum and maximum values, standard deviation, variation coefficient (the ratio of standard deviation to arithmetic mean), the sensitivity coefficient (the ratio of the difference between two adjacent values to their arithmetical mean, averaged over all time period), and the first order autocorrelation coefficient as measure of the yield of current year dependence on the yield of previous year (Fritts 1976; Wigley et al., 1984).

We applied Pearson correlation coefficients and carried out cluster analysis (hierarchical classification). In the cluster analysis the correlation coefficients were used as a measure of closeness between crop yield series. More generalized series of the crop yield were calculated as the first principal component (PC1) of the series set for each cluster and for the full set of series. This type of generalizing was used because it allows highlighting common external signal, including climatic one, if it is similar in all series of the generalized set (compare with Peters et al., 1981; Frank, Esper, 2004 for the tree growth on the different scales). The long-term trends in the raw crop yield series were seen to be not distinct; hence procedure of their removing was not necessary. We used linear multiple-factor regression models and linear long-term trends.

Results

The main statistical characteristics were calculated for all yield series (Online Resource Table S1, S2). The maximum and mean yield was the highest in the Tashtyp district and the lowest in the Ust-Abakan and Askiz districts. In general the coefficient of variation decreases from the West to the East. The sensitivity coefficient decreases from the South to the North.

Wheat was characterized by the highest values for the mean and maximum yield but the lowest characteristics of variability. In the steppe zone the oats were characterized by the lowest values of mean and maximum yield. However, with sufficient moisture supply in the foothills oats had higher mean and maximum yield than others. The oats also had the highest characteristics of variability.

The spatial analysis of correlation relationships between the district yield series (Online Resource Table S3) shows the predominance of the latitudinal gradient. Thus the greater the latitudinal difference between districts, the weaker is the observed correlation between their series. But we found no longitudinal gradient. This agricultural territory is divided into three zones with a high similarity of crop yield dynamics. The first is the Northern Zone that includes Ordzhonikidzevskiy, Shira, Bograd, and Ust-Abakan districts. The second being the Central Zone includes the Altaiskiy, Askiz, and Beya districts. The final zone is the Southern Zone, which includes only Tashtyp district (Fig. 1). This classification resonates with the outcome of the cluster analysis (Online Resource Fig. S2).

In comparison with the corresponding district series, the trial station series are characterized by higher mean yield (by 1.6-1.8 times) and maximum yield (by 1.8-2.3 times) and by lower coefficients of variation and first-order autocorrelations. The sensitivity is similar for the district series and the trial station series. Correlations between the trial station series and district series are in the range r = 0.57 … 0.89, despite rather short common time period (Online Resource Fig. S3, S4). Comparing the yield series for one crop culture between different trial stations has revealed that the similarity between them decreases along the precipitation gradient for all three crops, taking into account the distances between the trial stations. The highest similarity is observed between Bograd and Shira stations (r = 0.47 … 0.65) and between Bograd and Ust-Abakan stations (r = 0.40 … 0.69). The lowest similarity is observed between Ust-Abakan and Shira stations (r = 0.21 … 0.44) and between Ust-Abakan and Tashtyp stations (r = 0.16 … 0.48).

The correlation showed positive and significant relationship between yield series of different crops within a given district (Online Resource Table S4). The intensity of relationship changes along the altitudinal gradient. In the eastern districts adjacent to the Yenisei River (SH, BO, AL and BE) the correlations are in the range r = 0.71 … 0.93, in ~~the~~ more western districts (OR, UA and AS) r = 0.50 … 0.73 while in the Tashtyp district r = 0.33 … 0.52.

The three zones of yield dynamics in Khakassia are having distinct climatic influence on individual zones. The climatic influence was found from the preliminary analysis of correlations of the districts yield series with precipitation, temperature and HTC (Online Resource Fig. S5). The climatic response in the trial stations series is generally weaker than in the district series. But it is characterized by qualitatively similar patterns and gradients. The climatic conditions of the period preceding the sowing do not exert significant impact on the yield. Therefore the climatic response of zonal yield series during the period of May-August was considered in the present study (Fig. 2). We used PC1 of each district crops yield series zonal set as generalized zonal yield series, since for these zones it explains 80.8 … 89.9% of general crops yield variability within zone and 73.1 … … 85.4% of yield variability for separate crop cultures. On the other hand, for the Khakassia as a whole the first principal component explains 67.9% for crops in general and 51.6 … 67.3% for separate cultures, that is less by 12.2…25.1% than within zones, thus their integration in the one regional yield series is unreasonable.

In the Northern Zone, yield positively correlates with precipitation and HTC, but negatively correlates with temperature. Significant correlations are observed during all period from May to July. In the Central Zone the relationships between yield and precipitation and HTC are lower and not significant on $p<0.05$ in June and July, whereas correlations with temperatures, on the contrary, are higher. Negative response of yield to August precipitation is observed and is significant for wheat and barley. In the Tashtyp district the response of yield to temperature is weak, while the response to precipitation and HTC is not significant.

We also considered the pointer years, when yield is outside the mean ± standard deviation range for a half or more of raw series. For the period 1970-1995 (common for all series) high-yield pointer years are 1972, 1988 and 1991; low-yield pointer years are 1974, 1981 and 1994 (Online Resource, Fig. S6). The low-yield pointer years are characterized with higher temperatures and very low amounts of precipitation from the second half of May until July. The high-yield pointer years record smaller amount of precipitation in August and September.

To refine the crucial periods of climatic influence on yield we carried out correlation analysis of zonal yield series with climatic series calculated for moving 10-day intervals with a one-day step for May-September period (Fig. 3). There are common patterns observed for all crops and zones. Response to precipitation is positive and response to temperature is negative within the period from May to the middle of August. In the end of the warm season the climatic response becomes weak, unstable, and change sign. Nevertheless, the response intensity variation during the season depends on zone.

In the Northern Zone the maximum correlation of yield with temperature for all three crops is observed during the period from the end of June to the end of July, which corresponds to the reproductive period – phases of flowering and grain maturation. The peak of correlations at the end of May is less pronounced. That period corresponds to the phases of stem elongation and awn emergence. Correlations with precipitation are positive during the entire period of plants development from May 1 until August 10 and reach a maximum in the medium of July. The influence of precipitation on yield of wheat is weaker. For the Central Zone, the response to temperature and especially to precipitation is less expressed than for the Northern Zone. The positive response to precipitation sharply weakens in the middle of June, when most of the vegetative mass of plants has already been formed. In the response to temperature there is a third maximum at the end of July – beginning of August, which corresponds to the final phase of grain development. In the Southern Zone the correlations of yield with climatic factors are unstable and less pronounced, . Nevertheless, for all crops there is a significant response to precipitation in the middlbut have the same general patterns as in other zones.

Sowing areas in Khakassia are distributed as follows (average for all time period): 62.9% in the Northern Zone, 33.6% in the Central Zone, and only 3.6% for the Tashtyp district. Therefore it is sufficient to consider only Northern and Central Zones for the analysis of climate-induced dynamics of crops yield in Khakassia.

When calculating the linear multifactor regression models of yield dynamics we employed the following independent variables: May-July temperature, HTC of the same period (since the yield has stronger response to it in comparison to precipitation) and an autocorrelation component. For modeling zonal series were presented in form of standard indices (i.e. ratio of current yield value to the mean zonal yield). The following general equation was obtained as a result:

$$Y = a_0 + a_1 \cdot Y_{-1} + a_2 \cdot T + a_3 \cdot H + \varepsilon, \tag{1}$$

where, Y is standard yield index for the current year, $a_0 \dots a_3$ are numerical coefficients, Y_{-1} is standard yield index for the previous year, T is the mean May-July temperature, H is the mean May-July HTC, ε is the yield component caused by unaccounted factors, including random variability. In the Central Zone, HTC does not have sufficient influence on the yield (it's coefficients in regression function are not significant). Therefore for this zone HTC was excluded from the equation and yield was calculated as function of Y_{-1} and T (Table 2, Online Resource Fig. S7). Climatic data from Shira and Minusinsk stations were used for the Northern and Central zones respectively. Correlations between T and H variables are negative, but not significant.

Based on the partial correlations and on the general determination coefficients of the regression models we found that the climatic conditions of May-July explain 33.8~~4~~ … 40.8~~1~~% of yield variability in the Northern Zone and 24.9~~5~~ … 31.8~~2~~% in the Central Zone (Online Resource Table S5~~4~~). In the Northern Zone the variability of barley and oats yield depends on moisture to a much greater extent than on temperature. The relative importance of these factors differs for wheat. In the Central Zone the contribution of temperature to the yield variability is considerable for all the three grain crop cultures. The autocorrelation makes large contribution to the yield variability for barley and especially for wheat, whereas for oats this component is smaller. Overall the presented models explain about a half of the yield variability with the exception of the model for oats yield in the Central Zone.

During the climatic observation period within the Khakass-Minusinsk Depression there are no significant long-term trends in precipitation and HTC of the warm period. On the other hand, summer temperatures increase significantly from around 1970th (Online Resource Fig. S8). Thus, using this trend it is possible to predict that with the growth of temperature by 0.4 °C over the next decade. The mean precipitation level and the hydrothermal coefficient stay approximately constant. Thus the cumulative result may be a decrease in long-term average crops yield by about 2.4 … 6.0% in the Northern Zone and about 8.5 … 10.7% in the Central Zone. This estimation of the yield loss can be further increased due to nonlinear components, not included in this model.

Discussion

The influence of climatic characteristics of winter and early spring on crops yield is typical for many regions of the world, e.g. agricultural territories of Europe (Hlavinka et al., 2009; Wu et al., 2014). However in Khakassia snow melting ends at the end of March – beginning of April, i.e. approximately one month prior to the start of the sowing campaign. This is related to high amplitude of daily temperature oscillations typical for sharply continental climate. This and the low snow quantities during winters in the Khakass-Minusinsk Depression lead to not significant influence of winter precipitation and early spring temperatures on the crops yield.

The climatic response in the crops yield for Khakassia is typical for moisture-lacking steppe and forest-steppe conditions of continental climate (Dong et al., 2016). This response is comparable to other regions of temperate latitudes (e.g. Ceglar et al., 2016; Liu et al., 2016). However, even across the rather small Khakassia territory it is not uniform. This is due to the existence of pronounced climatic gradients and also due to the usage of irrigated agriculture in the central districts. Obviously the latter leads to the suppression of the precipitation response (Hlavinka et al., 2009; Ceglar et al., 2016).

One of the factors causing the differences between crop cultures in the mean yield values and in the yield variability parameters may be higher sensitivity of oats to adverse factors in comparison to barley and especially to wheat. The adverse factors include climatic variables. Higher yield values and rather low variability in the trial stations series in comparison to the district series is related to some specifics. Stations are characterized by uniform landscape and soil characteristics. The new cultivars of grain crops are tested there under controlled conditions and the complex of agro-technical techniques may differ from those used in mass agriculture (Lobell and Burke, 2010). The difference in the levels of autocorrelation is caused by the dependence of yield on the quality of sowing material (Mohan, Gupta, 2015), the fact of using grain from the previous year harvest in mass agriculture for that purpose, and the positive interrelations between grain quality and yield of the same season (Abd El-Kareem, El-Saidy, 2011).

It is clear that distinguishing three zones in Khakassia based on similarities in yield characteristics matches the existing agro-climatic division with the exception of Ust-Abakan district. That district belongs to the central agro-climatic zone, but our classification based on yield characteristics assigns it in the Northern zone in spite of differences in soils. This points to the more significant role of such factors as the climatic gradients of the vegetative period and especially the existence of an irrigational system than the soil type factor. Classification into these three zones is confirmed by the three main methods that were employed. They were confirmed firstly by the ranges of inter-series correlations within each zone and between the zones. Secondly by the results of cluster analysis and thirdly based on the patterns of climatic response in the yield series. The principal components analysis showed higher proportion of common yield variability within zones than that for total agricultural territory of Khakassia. This fact points to the existence of a strong common signal related to the unified landscape/climatic, hydrological conditions and agricultural techniques within each zone. This allows using the first principal component as a chronology of crops yield in each zone as the analysis and modeling of climatic response are performed.

The analysis of statistical characteristics of the crops yield series shows pronounced regularities in their geographical distribution. Inter-annual fluctuations of yield are very high across the entire territory of region. This is probably because Khakassia, as well as the majority of the regions of Russia, are considered as a risky agriculture zone, where the crop yield depends mainly on the current environmental conditions and catastrophically decreases by their unfavorable combination (Agroclimatic Resources, 1974).

The range of variability and the mean yield value for all considered grain crops depend primarily on the agro-climatic conditions. The productivity is highest in the foothills and lowest in the dry steppes (Online Resource Table S1). However, despite the Altaiskiy district belonging to dry steppes, the yield here is comparable to the foothills. This may be attributable to the location of Altaiskiy district between the two largest rivers of the Republic – the Abakan and the Yenisei. These rivers mediate the climate and significantly simplify irrigation (this district is characterized by the most developed network of irrigation canals in Khakassia). The relative variability of the yield series has the prevailing altitudinal gradient, i.e. it increases in the direction from the foothills to steppes near the Yenisei river. In the interannual variability component (sensitivity) the latitudinal gradient is observed, i.e. increase from Ordzhonikidzevskiy to Askiz district. It is reduced in the Altaiskiy, Beya, and Tashtyp districts by the increase in moisture caused by the landscape and hydrological conditions.

In the northern regions of Khakassia the warm period precipitation is a crucial climatic factor since it is the main source of moisture. A poorly developed hydrological network (prevalence of drainless areas, lack of large rivers) hampers the development of irrigated agriculture. On the contrary, temperature increases strengthen evapotranspiration, dry up the soil and cause water stress in plants. During the highest temperature period from June 20 until July 25 the crossing of day temperatures over the threshold level (for the considered grain crops it is about 30°C) leads to heat stress and suppression of growth and development of plants (Koehler et al., 2013; Liu et al., 2016). The impact of temperature and precipitation is accumulated during the period from May to July, i.e., at all stages of plants growth and development. The highest influence of precipitation is observed at stages of seeding growth and tillering (May) and during the reproductive period (end of June – July). The Selyaninov hydrothermal coefficient correspondingly unifies the influence of temperature and precipitation on the humidity of air and soil. In the Northern Zone, it has a strong correlation with crops yield in May, July and for the entire vegetative period.

Despite moisture deficit in the Central Zone the positive influence of precipitation and HTC on the yield is low. On the other hand the negative response of yield to temperature is more considerable. We believe that such climatic response is related to the presence of a developed river system on this territory (basins of the Abakan and the Yenisei rivers) as well as the irrigation channels network as a significant moisture sources (Territorial planning scheme, 2011; Ceglar et al., 2016). This network of channels can serve for temporary depository of moisture from precipitation discharge even in the absence of irrigation costs. It is also promoted by a more flat topography and the relatively high level of ground waters in the Central Zone, compared to the Northern Zone. In some years (e.g., 1994, see Online Resource Fig. S6b) strong rains during harvesting period cause stems lodging and harvest loss (Mukula and Rantanen, 1989).

In the foothills in the South Zone the agroclimatic conditions are most optimal for grain crop cultivation, which is evidenced by a practically total absence of significant climatic response in yield. However this territory is not characterized by high significance for the economy of Khakassia, since the nature of its topography leads to the severe limitation of possible cultivation area.

Less pronounced climatic response in crops yield on the trial stations can be attributed to the following reasons: 1) when averaging all the cultivated areas of a territory non-climatic features (e.g. soil, landscape, differences in agricultural techniques and sowing material between the farms) are leveled off; on the other hand on the trial stations landscapes and soil conditions are uniform and optimal for cultivation of grain crops; 2) special attention to the quality of sowing material and agrotechnical practices, frequent changes of cultivars not only increase the productivity at the trial stations in comparison with common agricultural areas, but also partially compensate for adverse weather conditions thereby weakening the climatic limitation (Therrell et al., 2006; Lobell and Burke, 2010). It should also be mentioned that the Ust-Abakan station and especially the Tashtyp station unlike the majority of cultivated areas in the respective districts are located near the boundary with the Central Zone. Thus the agroclimatic conditions and the observed crops yield climatic response at these stations are in-between of the Central Zone and their respective zones.

Climatic variables that are generalized over a month and especially over a season do not reflect the details of the short-term oscillations within that period. Importantly, these oscillations can exert a great influence on growth and development of plants and consequently on the yield (Fishman, 2016). The importance of short-term climatic oscillations is also related to the small duration of growth phases of grain crops (various phases last from 5-10 to 15-20 days; Fig. 3) and to the changing moisture, heat and light demands of the plants that depends on the phase. Therefore, it was of interest to conduct an analysis of the oscillations of weather conditions over 10-day intervals during the vegetative period.

Moisture is the crucial factor for plant development in the Northern Zone during the first phases of vegetative growth of grain crops (from sowing to the beginning of tillering). Subsequently until the beginning of awn emergence the limiting factor is mainly the temperature. As was noted earlier, in hot and arid climate grain crops are most vulnerable to climatic fluctuations during the reproductive period, when there is a possibility of simultaneously occurring water stress and heat stress (e.g. Wang et al., 2016a). The water level in irrigation network of central districts of Khakassia at the beginning of vegetative growth is insufficient for providing the fields with complete supply of moisture. Thus the first peak of positive influence of precipitation is observed during that period. The second peak corresponds to the phase of awn emergence, when the moisture demands of plants are the highest and all available sources of moisture are important (White, Edwards, 2008). The irrigation moderates the deficit of moisture during the other phases of plant development, reducing the reaction to precipitation. High air temperatures create deficit of moisture (regardless of its sources) in the middle of the vegetative growth period. It suppresses plant growth and leads to a decrease in the yield. Further added during the development of the grain is the probability of the suppression of plants by overheating, i.e. the heat stress. Both temperature and precipitation have significant influence in the south for 10-day periods in contrast to the monthly data. This influence although similar is much less pronounced in comparison with the rest of Khakassia territory due to the location of the zone in the foothills, which moderates the climate.

The fraction of variation of the yield explained by the climatic variables is high enough for practical use in the regression models that were obtained and is comparable to the existing models for other regions (e.g. Therrell et al., 2006; Wu et al., 2014; Zhang et al., 2016). Application of these models in the conditions of regional climate change allows to predict the yield changes and to account for them during planning in agriculture and economy of the Republic of Khakassia in general.

In the long-term perspective warm season temperatures of the study area are steadily increasing and rate of this increase is consistent with other works (e.g. Tchebakova et al., 1995; Nazimova et al., 2010; Kattsov, Semenov, 2014). Even with stable amount of precipitation this warming will lead to the higher frequency and duration of the heat stress occurrences during hottest period of season. It will form additional nonlinear negative component in the influence of temperature on the plants growth and increase estimation of the yield loss due to climate change. Another possible source of nonlinearity in the climatic response is volatility of the plants heat tolerance due to acclimation (e.g., Yamori et al., 2014). Therefore further consideration of warming of future regional climate and associated risks for agriculture due to increasing of probability of water and heat stresses is necessary.

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Figure captions

Fig. 1 Map of the study area. Districts with similar climatic response in the crops yield are marked with the same shade. Territories suitable for the crops agriculture are marked with hatching. Circles are meteostations and diamonds are crop variety trial stations. Climatic diagrams (mean air temperature and amount of precipitation for every month) correspond to the averages over the entire period of instrumental measurements on each meteostations

Fig. 2 Correlation coefficients of crops yield zonal series with precipitation (P), temperature (T) and hydrothermal coefficient (H) of May-August. Coefficients marked with "+" sign are significant on level $p<0.05$

Fig. 3 Correlation coefficients of crops yield zonal series with moving (10-day window, 1-day step) mean temperatures (solid lines) and total precipitation (areas) from May to September. Dashed lines mark $p = 0.05$ significance level of the correlation coefficients. The average timing of harvesting and the Zadoks decimal growth stages of crops (Zadoks et al., 1974) in the study area are marked as follows: Z0 – germination; 1 – seeding growth; 2 – tillering; 3 – stem elongation; 4 – booting; 5 – awn emergence; 6 – flowering (anthesis); 7 – milk grain development; 8 - dough grain development; 9 – hard grain

Table 1

Table 1. Administrative districts of Khakassia and corresponding climatic characteristics of the average period from sowing to the end of grain development (May-July)

Administrative district	**Meteorological station**	**May-July climate characteristics (mean value ± standard deviation)**		
		Mean temperature , °C	Total precipitation, mm	HTC
Ordzhonikidzevskiy (OR)	Shira 1937-2012 monthly data 1966-2000 daily data	14.6 ± 1.0	145.4 ± 45.8	1.07 ± 0.35
Shira (SH)				
Bograd (BO)				
Ust-Abakan (UA)				
Altaiskiy (AL)	Minusinsk 1915-2012 monthly & daily data	16.3 ± 1.0	158.8 ± 44.8	1.06 ± 0.31
Askiz (AS)				
Beya (BE)				
Tashtyp (TA)	Tashtyp 1929-2012 monthly data 1929-2010 daily data	14.5 ± 0.9	214.5 ± 70.3	1.67 ± 0.54

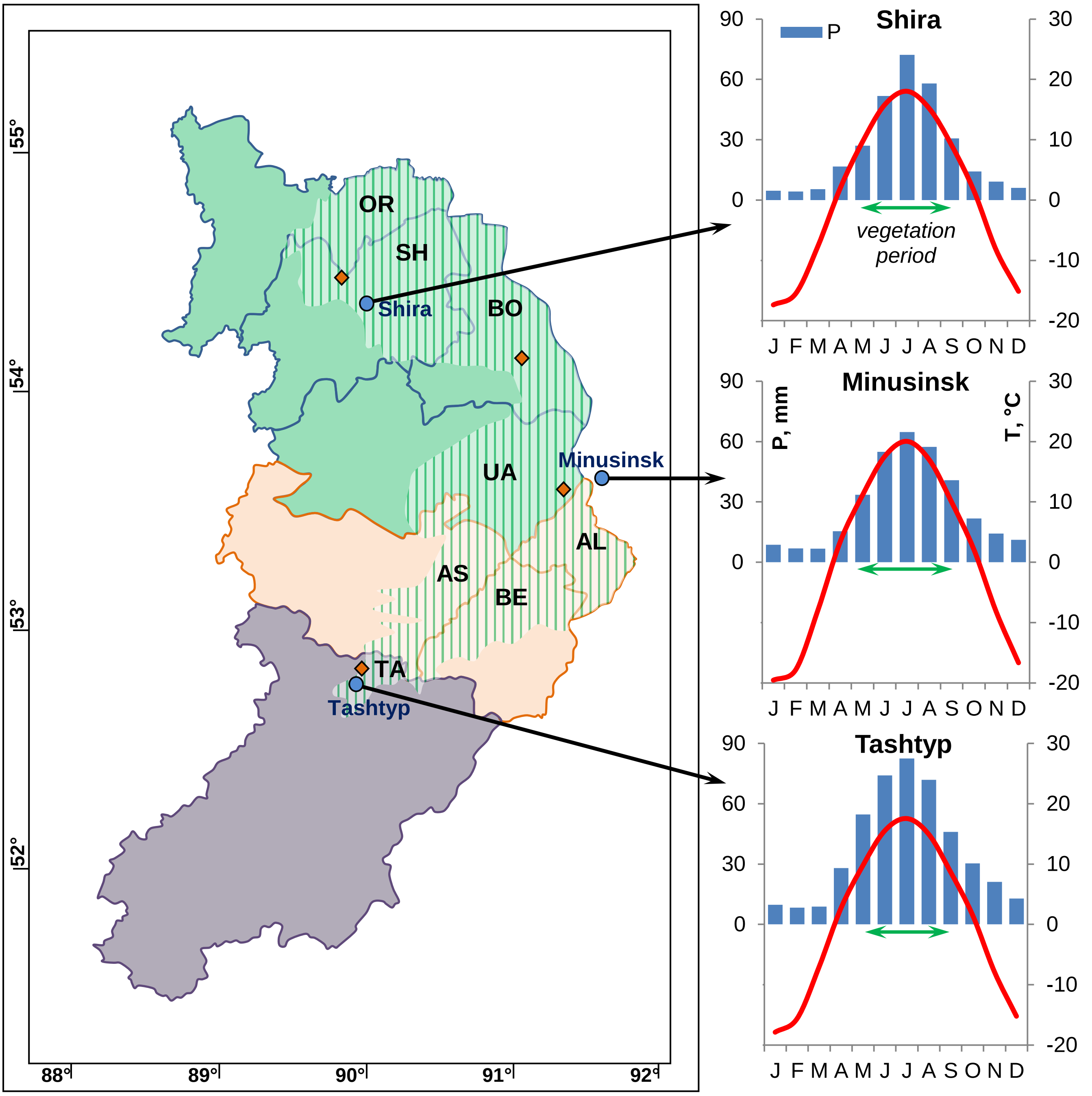
Table 2 revised

Table 2. Regression models of the crops yield for Northern and Central Zones of Khakassia

Crop	**Regression function**	**R**	**R^2**	**F**	**p**	**SEE**
Northern Zone						
Wheat	$2.51 + 0.27 \cdot Y_{-1} - 0.14 \cdot T + 0.30 \cdot H$	0.69	0.47	11.4	<0.001	0.29
Barley	$0.87 + 0.25 \cdot Y_{-1} - 0.06 \cdot T + 0.68 \cdot H$	0.70	0.49	12.3	<0.001	0.35
Oats	$1.14 + 0.16 \cdot Y_{-1} - 0.07 \cdot T + 0.73 \cdot H$	0.68	0.46	10.8	<0.001	0.38
Central Zone						
Wheat	$4.78 + 0.51 \cdot Y_{-1} - 0.26 \cdot T$	0.79	0.63	24.5	<0.001	0.32
Barley	$5.42 + 0.33 \cdot Y_{-1} - 0.29 \cdot T$	0.67	0.45	15.8	<0.001	0.39
Oats	$4.57 + 0.19 \cdot Y_{-1} - 0.23 \cdot T$	0.54	0.30	8.2	0.001	0.39

Y_{-1} – standard yield index for the previous year, T – mean May-July temperature, H – the mean May-July HTC

Figure 1


55°
54°
53°
52°
88°
89°
90°
91°
92°
OR
SH
Shira
BO
UA
Minusinsk
AL
AS
BE
TA
Tashtyp
Shira
P
vegetation
period
Minusinsk
P, mm
T, °C
Tashtyp
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60
30
0
30
20
10
0
-10
-20
J F M A M J J A S O N D

Figure 2

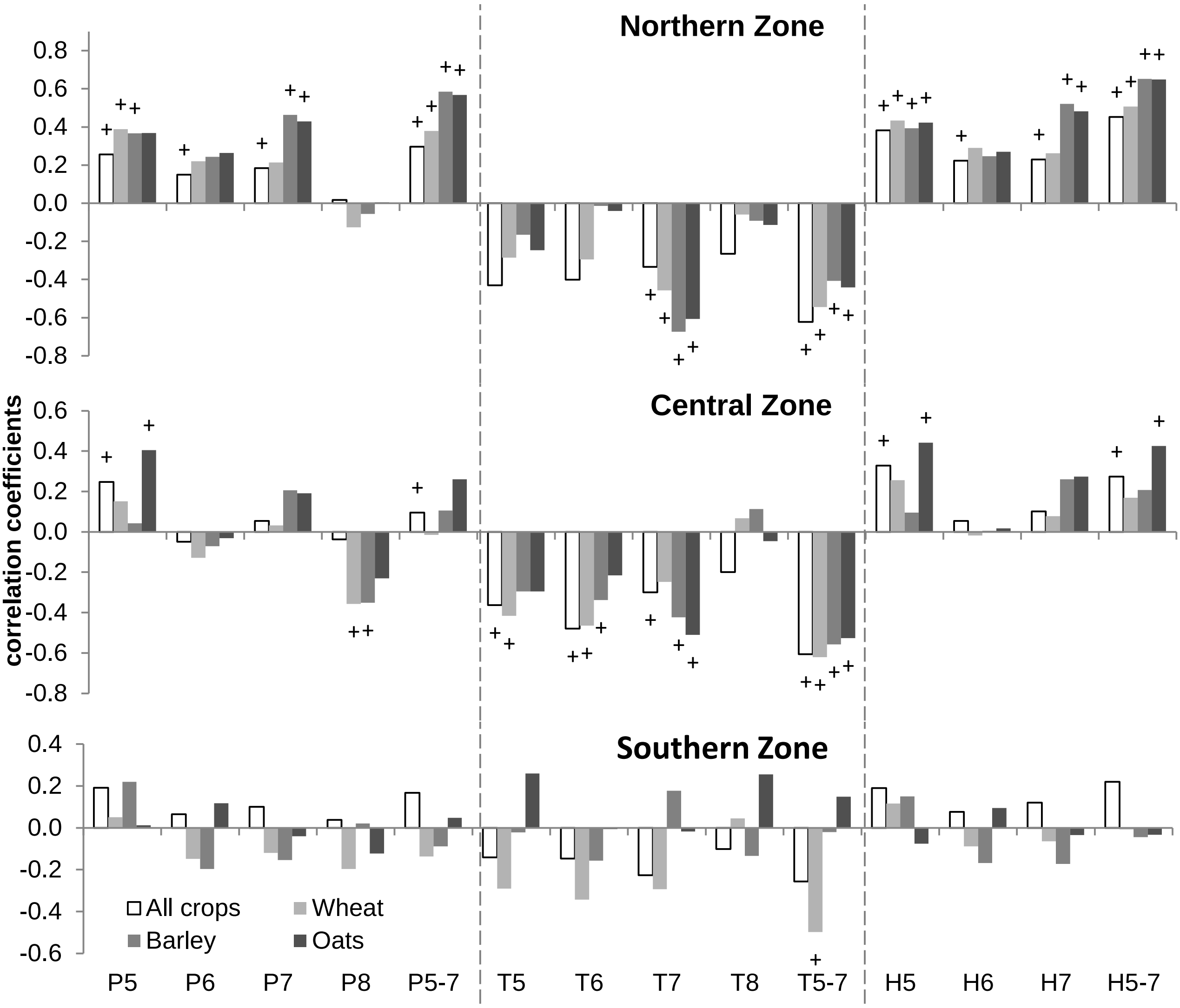
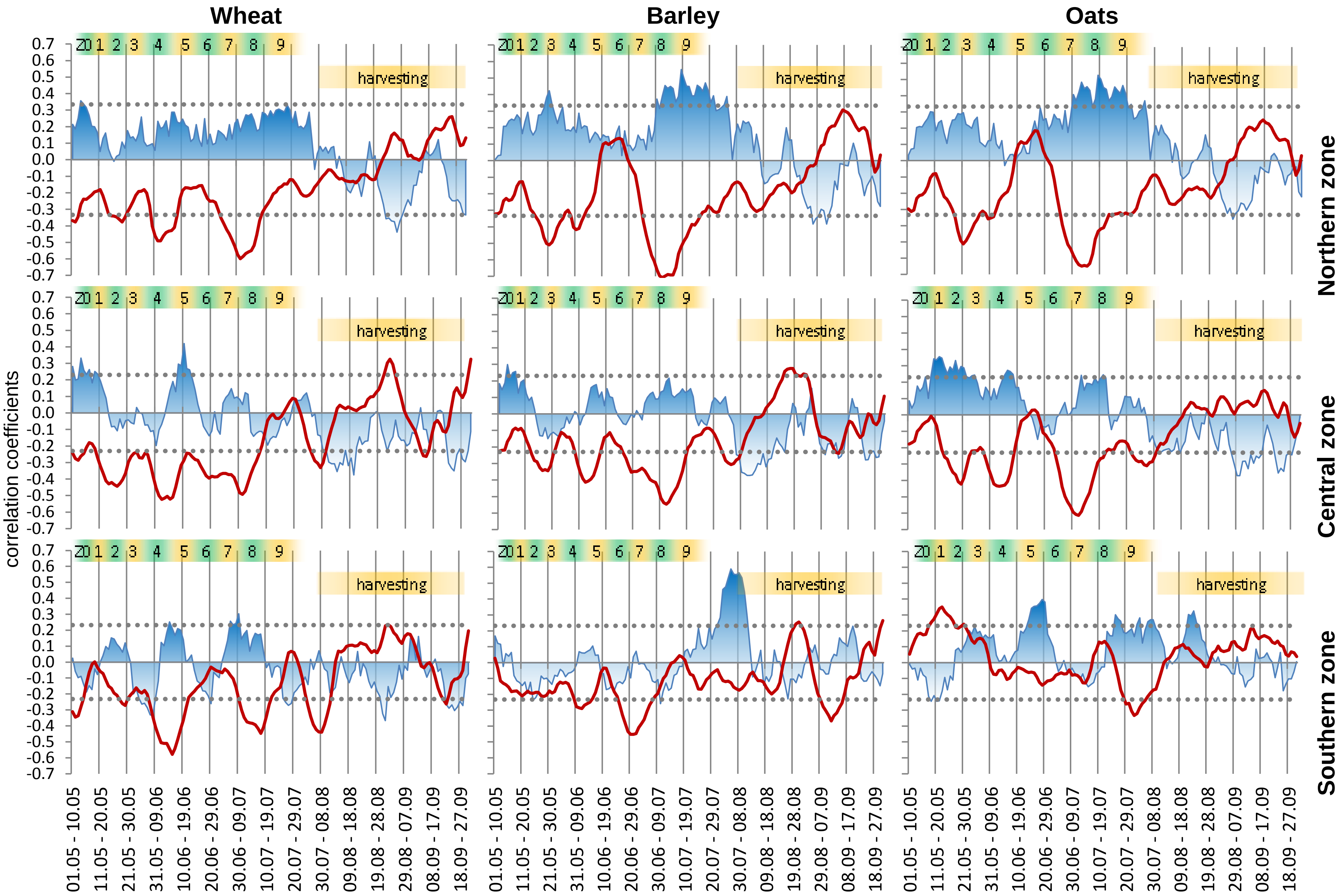

Northern Zone
Central Zone
Southern Zone
correlation coefficients
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
All crops
Wheat
Barley
Oats
P5
P6
P7
P8
P5-7
T5
T6
T7
T8
T5-7
H5
H6
H7
H5-7
+

Figure 3


Wheat
Barley
Oats
Northern zone
Central zone
Southern zone
correlation coefficients
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
20 1 2 3 4 5 6 7 8 9
harvesting
01.05 - 10.05
11.05 - 20.05
21.05 - 30.05
31.05 - 09.06
10.06 - 19.06
20.06 - 29.06
30.06 - 09.07
10.07 - 19.07
20.07 - 29.07
30.07 - 08.08
09.08 - 18.08
19.08 - 28.08
29.08 - 07.09
08.09 - 17.09
18.09 - 27.09

Supplementary Material revised