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Past crops yield dynamics reconstruction from tree-ring chronologies in the forest-steppe zone based on low- and high-frequency components

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Corresponding Author:	Elena A. Babushkina, Candidate Siberian Federal University Abakan, RUSSIAN FEDERATION
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Siberian Federal University
Corresponding Author's Secondary Institution:	
First Author:	Elena A. Babushkina, Candidate
First Author Secondary Information:	
Order of Authors:	Elena A. Babushkina, Candidate
	Liliana V. Belokopytova
	Santosh K. Shah, PhD
	Dina F. Zhirnova, Candidate
Order of Authors Secondary Information:	
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Abstract:	Interrelations of the yield variability of the main crops (wheat, barley, and oats) with hydrothermal regime and growth of conifer trees (Pinus sylvestris and Larix sibirica) in forest-steppes were investigated in Khakassia, South Siberia. An attempt has been made to understand the role and mechanisms of climatic impact on plants productivity. It was found that amongst variables describing moisture supply, wetness index had maximum impact. Strength of climatic response and correlations with tree growth are different for rain-fed and irrigated crops yield. Separated high-frequency variability components of yield and tree-ring width have more pronounced relationships between each other and with climatic variables than their chronologies per se. Corresponding low-frequency variability components are strongly correlated with maxima observed after 1 to 5 years time shift of tree-ring width. Results of analysis allowed us to develop original approach of crops yield dynamics reconstruction on the base of high-frequency variability component of the growth of pine and low-frequency one of larch.

RESPONSE TO THE REVIEWER'S COMMENTS

We found the comments of the reviewer to be very helpful to make our paper more clear and precise.

Reviewer #2

The title: I recommend avoiding the use of words like estimation, analysis, etc. It is obvious that you estimate, analyze, study, etc when you make any research.

In the original title “estimation” was used as the synonym of “reconstruction”. We corrected the title: “Past crops yield dynamics reconstruction from tree-ring chronologies in the forest-steppe zone based on low- and high-frequency components”

Key words: tree ring as a noun is without hyphen, as a modifier is tree-ring with a hyphen. Please correct it.

The use of the “tree ring” term with and without hyphen throughout all files of the manuscript was checked and corrected where it is necessary.

The figures have to be self-explanatory that means you can understand them without reading the text. In figure 2 you have many abbreviations as Cr Av Br that even though they are well described in the text it is better if you describe them in the bottom of the figure.

Abbreviations of the 5-year smoothing (Av5) and of the crops series (CrN, WrN, CrC etc) were described in the figure caption.

Line 126. Pearson's correlation coefficient.

The text was corrected.

How many trees did you sample for the dendrochronological analysis? Even though the Rbar value suggests that the values are accurate when you mention any dendrochronological study is important to point out the sample's number.

The number of trees in each tree-ring width chronology was added to the Table 2.

Past crops yield dynamics reconstruction from tree-ring chronologies in the forest-steppe zone based on low- and high-frequency components

Elena A. Babushkina[1], Liliana V. Belokopytova[1], Santosh K. Shah[2] and Dina F. Zhirnova[1]

[1]Khakass Technical Institute, Siberian Federal University, 27 Shchetinkina St., Abakan, 655017, Russia

[2]Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow, 226007, India

Corresponding author: Elena A. Babushkina, <babushkina70@mail.ru>

Abstract

Interrelations of the yield variability of the main crops (wheat, barley, and oats) with hydrothermal regime and growth of conifer trees (*Pinus sylvestris* and *Larix sibirica*) in forest-steppes were investigated in Khakassia, South Siberia. An attempt has been made to understand the role and mechanisms of climatic impact on plants productivity. It was found that amongst variables describing moisture supply, wetness index had maximum impact. Strength of climatic response and correlations with tree growth are different for rain-fed and irrigated crops yield. Separated high-frequency variability components of yield and tree-ring width have more pronounced relationships between each other and with climatic variables than their chronologies per se. Corresponding low-frequency variability components are strongly correlated with maxima observed after 1 to 5 years time shift of tree-ring width. Results of analysis allowed us to develop original approach of crops yield dynamics reconstruction on the base of high-frequency variability component of the growth of pine and low-frequency one of larch.

Keywords crops yield, tree-ring width, South Siberia, climate, reconstruction model.

Introduction

Hydrothermal regime of a territory is determined by hydrological and climatic factors that strongly influence the productivity of the both natural and agricultural ecosystems (Seneviratne et al. 2006; Challinor et al. 2014; Lipper et al. 2014; Porter et al. 2014; Iizumi and Ramankutty 2016). Current climatic trends of global warming include not only increasing temperatures, but also changes of water balance and frequency/severity of droughts (Easterling et al. 2000; Rosenzweig et al. 2002, 2014; Lobell et al. 2011; Mueller and Seneviratne 2012; Kattsov and Semenov 2014; Porter et al. 2014; IPCC 2015). Its impact on ecosystems has certain pattern on global scale. In the low and medium latitudes warming leads to more frequent droughts and increases vulnerability of plants to moisture shortage. In the high latitudes with sufficient moisture level warming lengthens vegetative season and intensifies growth and development of plants. Overall, geographic range of most plants species and cultivars shifts to the higher latitudes (Bindi and Olesen 2011; Peltonen-Sainio et al. 2016; Wang et al. 2016).

Understanding the regional mechanisms of this impact will provide more effective adaptation of the agriculture to the climate change, allowing to obtain more stable spatiotemporally yield (Zhirnova 2005; Hlavinka et al. 2009; Holman et al. 2017). Investigation of the yield dynamics can provide crucial information about its vulnerability to the climate change and estimation of the possible risks for food security (Myglan et al. 2007; Sauchyn et al. 2009; Pfister 2010; Qureshi et al. 2013; Wu et al. 2014; Huhtamaa et al. 2015; IPCC 2015).

However this field of research is highly restricted by short cover periods of the factual data of instrumental environmental measurements and especially statistics of yield (Therrell et al. 2006; Sauchyn et al. 2009). Use of proxy records in various natural objects allows overcoming this limitation (Wang and Liu 2016; Huhtamaa and Helama 2017). In particular, tree-ring width (*TRW*) chronologies are available in many regions and reflect environmental variations on multi-centennial scale with annual/seasonal resolution (Fritts 1976). Both *TRW* and yield are productivity indicators of the terrestrial ecosystems and results of plants growth and development processes. Thus common patterns in their dynamics and climatic responses are to be expected (Vaganov 1989; Wu et al. 2014). There are several recent studies investigating these two variables jointly, including tree-ring based reconstructions of yield itself or climatic factors crucial for it (Myglan et al. 2007; Helama et al. 2013; Rygalova et al. 2014; Sun and Liu 2014; Huhtamaa et al. 2015; Yadav et al. 2015).

The Republic of Khakassia (Siberia, Russia) is a typical example of a region in need of evaluation of the agricultural productivity. Small grain crops production is important part of the regional economy (Agroclimatic resources 1974; Surin and Lyakhova 1993). In this study we aimed to investigate variability of the main crops yield in Khakassia using instrumental environmental data and *TRW* chronologies of two prevalent conifer species in forest-steppe zone of the region. To achieve this goal the following objectives were set: (1) to reveal relationships between yield and *TRW* per se and between their components, (2) to analyze regional environmental factors and their extremes as driving forces for plants productivity indicators and their relationships, and (3) to obtain and verify tree-ring based reconstruction of the yield.

Materials and methods

Study area

The Republic of Khakassia is situated in the South Siberia, on the left bank of Yenisei river in its middle reaches. Montane part (south and east) of the republic belongs to the Altai-Sayan mountain system, whereas remaining territory is represented by plains of the Minusinsk Depression and is more appropriate for agriculture (Fig. 1 a) (Agroclimatic resources 1974). Climate of the study area is sharply continental (Alisov 1956). Minusinsk Depression is a wide valley surrounded by mountain ranges from all sides except North. Region is situated far from the ocean, but has broad Yenisei river with its two reservoirs (Chlebovich and Bufal 1976). The temperature during the vegetative season on plains increases from North to South. The precipitation decreases from the mountain ranges on the East and South towards the main rivers.

In spring rapidly increasing temperature have high daily variation. It causes delay of the frost-free period about 30-35 days after date of daily temperature crossing +5°C threshold. As a result spring frosts inhibit plant growth on the first development stages, thus shortening length of the vegetative season. The period of temperatures higher than +10°C starts around mid May and lasts up to 120 days. Precipitation has maximum in July-August, winter precipitation is scarce (maximal snow depth on plains is about 20 sm). Its interannual variation is very high, attaining 45-57% of mean value in summer and 56-90% of mean value in winter. Main reason of precipitation shortage is location of the Minusinsk Depression in the rain-shadow of mountain ranges. Due to this fact and spatiotemporally uneven precipitation the drought indices on the plains are unstable.

Regional hydrographic network is also uneven. Most of the water bodies are concentrated in the mountain part; northern half of Minusinsk depression has the lowest hydrographic density. Water bodies are mainly rain-fed, thus their runoff (*Q*) depends on climatic conditions. Most of the rivers belong to the Yenisei basin. In the centre of region main rivers and their tributaries form the base of irrigational network (Territorial planning scheme 2015).

Agrarian territory of Khakassia can be divided into three agroclimatic zones (Fig. 1): subtaiga zone with dark gray soils as narrow strip along mountain foothills, rain-fed steppes on chernozems in the north, and dry steppes on chestnut soils in the centre of republic, where irrigated agriculture is dominating (Agroclimatic resources 1974; Semenov et al. 2004). Agricultural area on the foothills is small (~4% of total area in republic) and has the least climatic impact, hence it was not investigated in the study.

Data sources

Monthly data of average temperature (*T*) and sum of precipitation (*P*) for 1938-2012 were obtained from Shira and Minusinsk stations (Fig. 1). Two indices characterizing moisture regime were computed from *T* and *P* data: Selyaninov hydrothermal coefficient ($HTC = 10 \cdot \sum P / \sum T$ for period of $T > 10°C$, based on daily data) and wetness index ($WI = \sum \log P / \sum T$, based on monthly data) (Selyaninov 1958; Lei et al. 2014). Additionally monthly *PDSI* and *SPEI* indices were used from open datasets (Beguería et al. 2010; van der Schrier et al. 2013). Runoff of Yenisei and Abakan rivers (*QY* and *QA*) obtained from Ust-Abakan and Raikov stations respectively were used as hydrological characteristic.

Crops yield measured as obtained grain weight per unit of sowing area (*Y*, kg/ha) was used as indicator of agricultural productivity (Therrell et al. 2006). Yield series averaged for every administrative district for 1960-2012 were obtained from unpublished records of the Federal State Statistics Service. Sufficient data are available for crops in total and for three main crops: spring wheat, spring barley and oats. For this study yield series of every crop were united into two zonal chronologies (Northern and Central) in regards to agroclimatic conditions and irrigation.

The samples of Scots pine (*Pinus sylvestris* L. – PS) and Siberian larch (*Larix sibirica* Ledeb. – LS) were collected in the foothills forest-steppes (BER, TUI, BID, KAZ sites) and insular forest in steppe (MIN). The processing of samples, measurement and cross-dating of *TRW* were carried out using standard dendrochronological techniques (Cook and Kairiukstis 1990; Speer 2010). All individual series were standardized by fitting exponential/linear functions to remove age related trends. Then individual indices were combined into single standard chronology per site/species using bi-weight robust mean (Cook and Krusic 2005).

Mathematical and statistical techniques

In this study we used following statistics of time series: arithmetic mean (*mean*), standard deviation (*stdev*), variation coefficient ($var = stdev/mean$), sensitivity coefficient (for time series *X* it is $sens = \mathrm{mean}(2 \cdot |X_t - X_{t-1}|/(X_t + X_{t-1}))$), first-order autocorrelation coefficient (*ar-1*). For *TRW* chronologies also average interseries correlation coefficient (*r-bar*) was calculated to check quality (Fritts 1976; Wigley et al. 1984; Cook 1985).

Pearson's correlation coefficients were used to evaluate relationships between time series. High-frequency component of variation was calculated as first differences (for time series *X* in year *t* first difference is $\Delta X_t = X_t - X_{t-1}$). This approach was successfully used in some previous analyses of climate-yield relationships (Nicholls 1997; Lobell et al. 2005; Lobell and Field 2007). Low-frequency component of variation was estimated as time series smoothed with 5-year moving average centered to the middle year ($Av5X_t = \mathrm{mean}(X_{t-2}, \cdots, X_{t+2})$).

Linear regression functions were used for reconstruction of the crops yield variation components. Quality of reconstruction models was estimated with the following statistics: coefficient of multiple correlation (*R*), coefficient of determination (R^2), adjusted coefficient of determination (R^2_{adj}), Fisher test (*F*), significance level *p* and standard error of estimation (*SEE*).

Results

Chronologies and relationships between them

Four regional crops yield chronologies were developed for each zone: crops in total – CrN and CrC in Northern and Central zones respectively, wheat – WrN and WrC, barley – BrN and BrC, oats – OrN and OrC. Their statistics are shown in Table 1. In the study area wheat yield has the highest mean values, and oats yield has the lowest ones. There are no significant differences in mean yield between zones. Variability of yield reaches 38-51% of mean values with substantial proportion of year-to-year changes, indicated by high sensitivity ($sens = 0.39 - 0.54$). Nevertheless, yield chronologies have also significant autocorrelations. The *TRW* chronologies range from 124 to 272 years (Table 1). *TRW* has lower variability per se and sensitivity ($sens = 0.19 - 0.47$), but higher autocorrelation than yield.

Within each zone yields of different crops are highly correlated ($r = 0.80 - 0.95$ in Northern zone and $r = 0.81 - 0.96$ in Central zone). The correlations between zones are moderate ($r = 0.49 - 0.78$) (Online Resource Table S1). The correlations between *TRW* chronologies are low to moderate. The highest correlations are observed within one site ($\mathrm{r} = 0.40 - 0.71$). Most of yield-*TRW* relationships are weak, 50% of correlations are not significant on level $p < 0.05$. However, we can note some relatively high correlations both in Northern (yield and BER_PS have $r = 0.34 - 0.54$, yield and BID_LS have $r = 0.35 - 0.47$) and Central zone (yield and BER_LS have $r = 0.45 - 0.63$, yield and BER_PS have $r = 0.36 - 0.47$).

Comparison of the smoothed *TRW* and yield series (Fig. 2 a-f) was performed by cross-correlation, i.e. correlations were calculated with different time shift (lag) of *TRW* (Online Resource Fig. S1). More pronounced similarity of low-frequency variation is revealed between yield and *TRW* of larch: BID_LS has the highest correlation with the yield in Northern zone, BER_LS has the highest one in Central zone, and TUI_LS has second-best correlations with the yield in both zones. The highest values of cross-correlation coefficients are observed with lag +1 to +2 years for BID_LS ($r = 0.54 - 0.79$) and for BER_LS ($r = 0.66 - 0.92$), and with lag +3 to +5 years for TUI_LS ($r = 0.43 - 0.65$ for Northern zone and $r = 0.54 - 0.80$ for Central zone). The cross-correlations are quasiperiodic. The distance between consequent maxima / consequent minima for cross-correlations of yield with BID_LS is 19 to 20 years and for cross-correlations of yield with BER_LS and TUI_LS is 26 to 33 years. Relationships between smoothed series of yield and pine *TRW* are considerably less pronounced. The extremal cross-correlations are unstable and not exceeding 0.50. Smoothed yield series correlations between themselves are high, viz., $r = 0.86 - 0.97$ in Northern zone, $r = 0.90 - 0.98$ in Central zone, and $r = 0.57 - 0.87$ between zones.

Climatic response in the chronologies

Significant correlations between *TRW* chronologies and monthly temperatures and precipitation were observed from previous July to current July (Online Resource, Fig. S2). Climatic response of all *TRW* chronologies has similar pattern. During the previous July-September and current May-July, response of *TRW* on *P* is positive and response on *T* is negative. Also there is positive response on both factors in the late autumn. Strength of the climatic response varies between species.

Crops yield chronologies have significant climatic response only during May-July (period of crops growth and development in the region). Therefore this period was selected for comparison of influence of the ecological factors on the natural and agro-ecosystems productivity (Table 2). Temperatures have strong negative relationships with crops yield in both zones. In Northern zone yield have also high positive correlations with precipitation. All drought indices have significant correlations with yield too, especially high in Northern zone. The wetness index has the strongest relationship with yield amongst ecological variables. The Yenisei runoff has no relationships with yield, whereas the Abakan runoff's correlations with yield are weak but partially significant. Correlations of *TRW* chronologies with ecological conditions of May-July are weaker than yield's ones. But there are similar patterns of strongest reaction on precipitation and *WI* and minimal response on rivers runoff. Overall pine has more pronounced dependence of growth on May-July conditions than larch.

Extremal events and plants productivity

As unfavorable extremal events (e.g. droughts) we considered years when ecological factors in May-July have high deviations from mean values (Online Resource Table S2). Specifically, combination of low moisture supply and high temperatures was observed in 1945, 1965 and 1999; in 1974 and 1981 precipitation and drought indices also were low but temperatures were on average level. These years were characterized by significant decrement of the tree growth, especially for pine. Crop failures were observed too with the most pronounced ones in 1965 and 1999. In 1994 high temperatures and normal moisture supply resulted in poor harvest and some low *TRW* values. Two-year drought in 1945-1946 was associated with low *TRW* values, but yield chronologies do not cover these years.

First differences of time series

Correlation analysis of the first differences of yield showed relationships and patterns similar to the chronologies per se (Online Resource Table S3): for ΔY correlations between each other in Northern zone $r = 0.75 - 0.94$, in Central zone $r = 0.77 - 0.95$, and between zones $r = 0.34 - 0.62$. For ΔTRW it is true as well. They have maximal correlations within the site ($r = 0.43 - 0.60$) and basically the same range of correlations among themselves as *TRW* chronologies per se. Though correlations between ΔY yield and ΔTRW are substantially higher than between their chronologies, 81% of them are significant on level $p < 0.05$ (Online Resource Fig. S3). These relationships are more pronounced for TRW of pine (Fig. 2 g, h). ΔY series in Northern zone have maximal correlations with ΔMIN_PS ($r = 0.47 - 0.61$) and the second-best correlations with ΔKAZ_PS ($r = 0.35 - 0.44$). In Central zone ΔY series have maximal correlations with ΔKAZ_PS ($r = 0.51 - 0.62$).

Relationships of ΔY and ΔTRW with first differences of environmental factors are also higher than corresponding relationships of original time series (Table 2). For example, ΔY has higher correlations with first differences of *T*, *PDSI*, *SPEI* and rivers runoff; ΔTRW has higher correlations with first differences of *T*, *WI*, *PDSI* and *QA*. Amongst indicators of moisture regime *WI* has closest relationship with both *TRW* and yield when first differences are considered, as well as for original time series.

Tree-ring based reconstructions of the crops yield

Yield series have the highest correlations with pine *TRW* in first differences and with larch *TRW* after smoothing. Therefore we made separate tree-ring based models of hith- and low-frequency variability of yield. Detailed procedure of reconstruction is presented in Online Resource.

For high-frequency yield variation component the highest statistics of regression model were retrieved with using MIN_PS chronology for Northern zone and KAZ_PS chronology for Central zone. Due to relatively short cover period of MIN_PS we also constructed estimations for Northern zone on base of KAZ_PS chronology, which have ~80 year longer cover period but lower statistics (Table 3, Online Resource Fig. S4). For low-frequency yield variation component the highest statistics were retrieved with using smoothed BID_LS and TUI_LS for Northern zone, and BER_LS and TUI_LS for Central zone. For Northern zone also model on the base of BER_LS and TUI_LS was constructed, which have ~150 year longer cover period but lower statistics (Table 3, Online Resource Fig. S5).

Both yield and *TRW* chronologies contain fluctuations of different frequency. Thus a hypothesis was postulated that these two types of models could be used together to obtain one combined model of yield dynamics estimation as a whole. We obtained combined models with cover periods 122 and 237 years for Northern zone and 238 years for Central zone (Table 3, Fig. 3). Combined models with shorter cover period for Northern zone have higher statistics then corresponding ΔY models. At the same time most statistics of combined models with longer cover period for Northern zone are similar to ones of corresponding ΔY models, but *F*-test and significance level are lower due to higher amount of predictors. For Central zone statistics of combined models are lower than ones of ΔY models.

Verification of reconstruction

Combined models have the same extremes as actual yield chronologies within observation period. There are set of years of extremal low yield outside the observation period which are confirmed by regional data from other sources (Fig. 3). According to instrumental data, moisture deficit was observed in 1910, 1917, 1945-46 and 1951. Low yields of all three main crops were registered at the state variety testing stations of Khakassia in 1945-46, 1949 and 1951 (Zhirnova 2005).

There are also confirming historic evidences in the South of Siberia (Myglan 2010). For instance, in the opinion of Vatin (1922), "since 1837 crop failures have begun in the Yenisei Gubernia and completely ruined it in 2-3 years". There is also stated that in 1838 "sown cereals and meadow grass have a mediocre growth on the occasion of the absence of rains until this time"; in 1852 "worms appeared in the crops. During the crops ripening there was no rain; the yield was less than in previous 1851 year". In the work of Latkin (1890) the repeated crop failures in the Minusinsk depression during 1856-1868 were described: "since 1856 due to repeated poor harvest and gold mining, prices began to rise (up to 60 kopecks for pood of rye flour and oats)"; "in 1868 again prices have risen, thanks to some years with poor harvest". In a monograph of Butanayev (2002) drought in Khakassia in 1900-1902 was mentioned: "A severe drought gave rise to lack of fodder. Up to half of draught horses have died in the Abakan and Askiz establishments".

Discussion

Comparison of the plants productivity indicators response to the hydrothermal regime characteristics showed that the wetness index *WI* most explicitly expresses limiting by moisture supply. Its advantage is that this index not only combines the impact of precipitation as a source of moisture and temperature as a withering factor, but also highlights the contribution of drought events, as it contains logarithm of precipitation (Lei et al. 2014). The relationships between productivity indicators and river runoff are weak primarily due to their large catchment basins, especially for the Yenisei river. The Abakan river is supplied by the precipitation in the Minusinsk depression to a greater extent, and is the main water source for the irrigation system. These facts ensure the pronounced response to *QA*. Irrigation also significantly weakens yield climatic response on precipitation in the Central zone.

As many other regions, study area characterizes by frequent simultaneous temperature raising and precipitation deficit (Bazhenova and Tyumentseva 2010; Prasad et al. 2011; Nouri et al. 2017), Our analysis showed that both indicators of plant productivity are accurately capturing such unfavorable combinations, as well as extremes of one of these factors. It means that drought events lead to synchronicity of negative extremes in yield and *TRW*, which is partially reason for the positive, though not always significant, correlations between them. Therefore, it should be expected that the *TRW* chronologies and the yield dynamics reconstructed on their basis will allow also restoring regional climatic extremes history (Touchan et al. 2016).Growth and development of plants has common regularities due to the unity of resources and physiological mechanisms (e.g. nutrition, respiration, water balance), so we should expect them to be limited by the same environmental factors typical for the semi-arid continental climatic zone (Myglan et al. 2007; Sun and Liu 2014). Moreover, both grains for agricultural crops and wood for trees are the main targets of resources storage processes during their growth and development. For instance, wheat has about 50% ratio of grain mass to above ground biomass (Schulze et al. 2005). Also one more common trait is adaptation to the moisture deficit. Climatypes of the tree species in forest-steppe are adapted to the semiarid conditions by natural selection. At the same time, regional crop cultivars are adapted to these conditions by human activity, i.e. breeding.

Differences in the variability of yield and *TRW* chronologies follow primarily from their life forms and cycles. Most of yield variability of crops, as annual plants, is due to current conditions, including high-frequency climatic fluctuations. Significant autocorrelation is associated with using the previous harvest as source of grain for sowing, because grain quality usually has positive relationship with yield (Ozturk and Aydin 2004; Meng et al. 2016). Long-term yield variability is influenced by both climatic trends and changes in farming practices and cultivars. Conifer trees as perennials, especially evergreens, are characterized by stronger autocorrelation and less sensitivity of growth. On the one hand, the variability of tree growth is constrained by the slowness of changes in morphometric parameters (the size and structure of stem&root system) determining the access to resources. On the other hand, woody plants are characterized by active storage of nutrients for using in the next season. Moreover, evergreen trees have needles of previous years participating in photosynthesis processes (Chapin et al. 1990; Schulze et al. 2005). Thus trees respond to the hydrothermal regime not only of the current vegetative season, but also of the previous months. In regard to long-term tree growth dynamics, the impact of human activity is much less pronounced than in agroecosystems. Thereby the long-term variation of *TRW* is mainly due to a combination of climatic trends, aging and changes in the stand structure. Also it is necessary to take into account using of standardized *TRW* data, from which most of the age trend was removed during processing. Since the crops yield does not have such trends, its standardizing was not necessary.

As a result of all aforementioned differences, despite the similarity of the growth conditions *TRW* chronologies per se have limited relationships with crops yield, as well as with climate of May-July. Therefore instead of head-on approach we proposed other methods to make tree-ring-based yield reconstruction. Separation of plants production variability into high- and low-frequency components and their analysis allowed us to circumvent these restrictions.

Low-frequency variation in the yield and *TRW* has much in common due to its dependence on climatic trends. More pronounced similarity with yield is observed in larch *TRW* smoothed series then in pine ones. It might be caused by need to re-grow all needles every spring for larch. Pine as evergreen has needles with overlapping life spans, which complicates autocorrelation component and low-frequency variation of growth in general. The delay in decadal oscillations of the tree growth in comparison with crops is associated with the more pronounced autocorrelation described above.

Main non-climatic factors affecting variation of the both plant productivity indicators (the age changes of trees and the development of agricultural technologies) are low frequency. Thus transition to the first differences reduces their contribution and highlights role of the climate and the hydrological regime, as they have considerable high-frequency variation component. It should be noted that, unlike the smoothed series, the similarity between year-to-year dynamics of pine growth and the crops yield is more pronounced. This is due to the fact that the response to the May-July conditions is higher for pine than for larch.

As both components of yield variability have more close relationships with the tree growth than yield chronologies per se, we can reconstruct these components separately. Both reconstructions have their advantages and disadvantages. The reconstructed first differences easily allow one-year crops failures to be revealed, but do not allow to receive information about longer periods of high/low yield. Conversely, the reconstruction of the smoothed series describes long-term trends well, but there is no information about the extreme years. Therefore, it was proposed to reconstruct the entire yield variability by combining these two models. Use of a recursive equation for obtaining yields from the model of the first differences leads to the accumulation of errors in long-term trends. To erase these errors, low-frequency variation was completely removed from the resulting series by subtracting their smoothed series. Then year-to-year yield fluctuations were threaded onto the reconstructed separately long-term oscillations. The advantage of this approach in our case is also in the use of tree-ring chronologies of different species and habitats, which reduces the correlations between predictors.

The obtained yield estimations are quite close to the factual series, especially extremal values. However, the limits of the *TRW* chronologies cover periods restricting the length of the most qualitative yield reconstruction in the Northern zone. The use of longer chronologies makes it possible to significantly extend this period at the expense of the quality reducing. Despite this, the relevance of models is confirmed by their comparison with other data sources –instrumental records, historical documents, and yield data of regional variety testing stations.

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Table 1. Statistical characteristics of crops yield and *TRW* chronologies

	Crops yield								Tree-ring width							
	Nothern zone				Central zone				*Pinus sylvestris*				*Larix sibirica*			
	CrN	WrN	BrN	OrN	CrC	WrC	BrC	OrC	BER PS	BID PS	MIN PS	KAZ PS	BER LS	TUI LS	BID LS	KAZ LS
N, years	53	43	43	43	53	33	43	43	257	164	166	246	272	294	124	178
period, years	1960-2012	1970-2012	1970-2012	1970-2012	1960-2012	1980-2012	1970-2012	1970-2012	1752-2008	1849-2012	1847-2012	1767-2012	1737-2008	1719-2012	1889-2012	1835-2012
Number of trees	-	-	-	-	-	-	-	-	14	15	40	23	14	57	16	20
mean*	9.34	10.40	10.00	9.27	9.73	11.31	9.87	9.76	-	-	-	-	-	-	-	-
stdev*	4.06	3.96	4.68	4.56	4.45	5.57	5.00	4.46	0.29	0.35	0.23	0.43	0.32	0.47	0.32	0.62
var*	0.43	0.38	0.47	0.49	0.46	0.49	0.51	0.46	-	-	-	-	-	-	-	-
sens	0.43	0.39	0.48	0.54	0.45	0.39	0.52	0.51	0.25	0.33	0.19	0.40	0.30	0.43	0.26	0.47
ar-1	0.36	0.41	0.44	0.34	0.39	0.62	0.40	0.27	0.48	0.44	0.45	0.51	0.44	0.49	0.50	0.62
r-bar	-	-	-	-	-	-	-	-	0.56	0.51	0.43	0.60	0.58	0.57	0.42	0.48

**mean* and *stdev* of the crops yield are in 10^2 kg/ha; standard *TRW* chronologies have *mean* = 1 and *var* = *stdev*

Table 2. Correlation coefficients of crops yield and *TRW* chronologies with climatic and hydrological variables, averaged for the crops growth period – May-July (calculated for time series / chronologies per se and for their first differences)

	T	P	HTC	WI	PDSI	SPEI	QE	QA		ΔT	ΔP	ΔHTC	ΔWI	ΔPDSI	ΔSPEI	ΔQE	ΔQA
	time series per se									first differences							
CrN	-0.48	0.48	0.56	0.72	0.50	0.52	0.20	0.26	ΔCrN	-0.57	0.32	0.41	0.67	0.70	0.56	0.32	0.29
WrN	-0.54	0.38	0.46	0.66	0.31	0.32	0.17	0.21	ΔWrN	-0.58	0.23	0.30	0.56	0.48	0.40	0.26	0.28
BrN	-0.41	0.58	0.63	0.68	0.48	0.55	0.33	0.40	ΔBrN	-0.43	0.47	0.52	0.65	0.63	0.58	0.44	0.40
OrN	-0.44	0.57	0.63	0.71	0.48	0.57	0.23	0.34	ΔOrN	-0.43	0.46	0.52	0.65	0.61	0.57	0.32	0.31
CrC	-0.58	0.30	0.40	0.61	0.41	0.45	0.20	0.28	ΔCrC	-0.59	0.45	0.51	0.66	0.55	0.52	0.39	0.54
WrC	-0.62	-0.02	0.12	0.45	0.14	0.16	0.22	0.14	ΔWrC	-0.63	0.18	0.26	0.49	0.35	0.22	0.32	0.51
BrC	-0.56	0.11	0.21	0.43	0.29	0.27	0.08	0.23	ΔBrC	-0.63	0.29	0.36	0.53	0.39	0.35	0.24	0.58
OrC	-0.53	0.26	0.36	0.56	0.37	0.42	0.21	0.28	ΔOrC	-0.46	0.37	0.42	0.58	0.49	0.43	0.38	0.55
BER PS	-0.32	0.26	0.25	0.37	0.15	0.21	-0.01	0.22	ΔBER PS	-0.45	0.33	0.33	0.50	0.26	0.25	0.00	0.37
BID PS	-0.21	0.33	0.23	0.29	0.32	0.26	0.20	0.37	ΔBID PS	-0.36	0.09	0.04	0.25	0.36	0.16	0.31	0.50
MIN PS	-0.35	0.45	0.47	0.51	0.40	0.38	0.27	0.45	ΔMIN PS	-0.46	0.45	0.49	0.61	0.63	0.43	0.46	0.58
KAZ PS	-0.16	0.17	0.19	0.27	0.08	0.17	0.12	0.54	ΔKAZ PS	-0.36	0.23	0.29	0.45	0.46	0.20	0.32	0.70
BER LS	-0.36	0.28	0.17	0.36	0.16	0.19	-0.21	0.04	ΔBER LS	-0.32	0.25	0.16	0.31	0.14	0.14	-0.22	0.22
TUI LS	-0.14	0.35	0.17	0.22	0.29	0.24	-0.24	0.11	ΔTUI LS	-0.27	0.32	0.20	0.31	0.32	0.16	0.03	0.31
BID LS	-0.16	0.32	0.25	0.28	0.41	0.27	0.18	0.18	ΔBID LS	-0.15	0.10	0.06	0.17	0.40	0.21	0.19	0.36
KAZ LS	-0.06	0.01	0.00	0.12	-0.10	0.03	0.16	0.17	ΔKAZ LS	-0.11	0.02	0.03	0.20	0.34	0.03	0.28	0.53

T – temperatures; P – precipitation; HTC – hydrothermal coefficient of Selyaninov; WI – wetness index (Lei et al. 2014); QE – runoff of Yenisei river; QA – runoff of Abakan river.

Marked with shade correlation coefficients are significant at $p<0.05$

Table 3. Regression reconstruction models of crops yield high- and low- frequency variation components and combined models on base of *TRW* chronologies and their statistical characteristics

Yield models	Function / predictors	R	R^2	R^2_{adj}	F	p	SEE	Period
high-frequency variability component								
ΔCrN1	-1.31 + 13.16·MIN_PS – 11.63·MIN_PS$_{-1}$	0.65	0.42	0.40	17.8	<0.001	3.56	1848-2012
ΔWrN1	-3.16 + 13.55·MIN_PS – 10.18·MIN_PS$_{-1}$	0.67	0.45	0.43	16.2	<0.001	3.27	
ΔBrN1	-1.38 + 13.89·MIN_PS – 12.50·MIN_PS$_{-1}$	0.63	0.40	0.36	9.5	<0.001	4.05	
ΔOrN1	-0.58 + 12.58·MIN_PS – 12.00·MIN_PS$_{-1}$	0.56	0.31	0.26	6.5	0.004	4.56	
ΔCrN2	0.21 + 6.45·KAZ_PS – 6.50·KAZ_PS$_{-1}$	0.60	0.36	0.34	14.0	<0.001	3.72	1768-2012
ΔWrN2	-0.19 + 6.24·KAZ_PS – 5.92·KAZ_PS$_{-1}$	0.60	0.36	0.33	11.1	<0.001	3.53	
ΔBrN2	1.10 + 5.31·KAZ_PS – 6.51·KAZ_PS$_{-1}$	0.51	0.26	0.22	6.9	0.003	4.42	
ΔOrN2	0.74 + 5.49·KAZ_PS – 6.32·KAZ_PS$_{-1}$	0.48	0.23	0.19	5.9	0.006	4.75	
ΔCrC	-0.03 + 9.29·KAZ_PS – 9.14·KAZ_PS$_{-1}$	0.80	0.64	0.62	42.7	<0.001	3.04	
ΔWrC	0.43 + 10.41·KAZ_PS – 10.71·KAZ_PS$_{-1}$	0.92	0.85	0.84	82.9	<0.001	1.96	
ΔBrC	-0.39 + 9.47·KAZ_PS – 8.84·KAZ_PS$_{-1}$	0.72	0.51	0.49	20.6	<0.001	3.92	
ΔOrC	0.45 + 9.18·KAZ_PS – 9.61·KAZ_PS$_{-1}$	0.75	0.56	0.54	25.3	<0.001	3.63	
low-frequency variability component								
Av5Y_N1	-1.09 + 3.50·Av5TUI_LS$_4$ + 7.39·Av5BID_LS$_1$	0.81	0.66	0.65	43.1	<0.001	1.52	1890-2009
Av5Y_N2	3.55 + 4.17·Av5TUI_LS$_3$ + 1.91·Av5BER_LS$_2$	0.62	0.39	0.36	14.1	<0.001	2.05	1737-2004
Av5Y_C	-2.40 + 4.02·Av5TUI_LS$_5$ + 8.54·Av5BER_LS$_1$	0.85	0.73	0.72	59.5	<0.001	1.67	1734-2005
combined models								
CrN	MIN_PS, MIN_PS$_{-1}$, Av5TUI_LS$_4$, Av5BID_LS$_1$	0.76	0.57	0.53	15.1	<0.001	2.82	1890-2011
WrN		0.68	0.46	0.40	7.4	<0.001	3.15	
BrN		0.70	0.49	0.43	8.5	<0.001	3.65	
OrN		0.68	0.46	0.40	7.6	<0.001	3.83	
CrN	KAZ_PS, KAZ_PS$_{-1}$, Av5TUI_LS$_3$, Av5BER_LS$_2$	0.55	0.30	0.23	4.3	0.006	3.83	1768-2004
WrN		0.60	0.36	0.27	4.2	0.009	3.71	
BrN		0.54	0.29	0.20	3.1	0.030	4.65	
OrN		0.54	0.29	0.20	3.1	0.030	4.52	
CrC	KAZ_PS, KAZ_PS$_{-1}$, Av5TUI_LS$_5$, Av5BER_LS$_1$	0.56	0.31	0.25	4.7	0.003	4.05	1768-2005
WrC		0.75	0.56	0.47	6.6	0.001	4.33	
BrC		0.59	0.35	0.27	4.2	0.008	4.38	
OrC		0.53	0.28	0.19	3.1	0.031	4.20	

Fig1

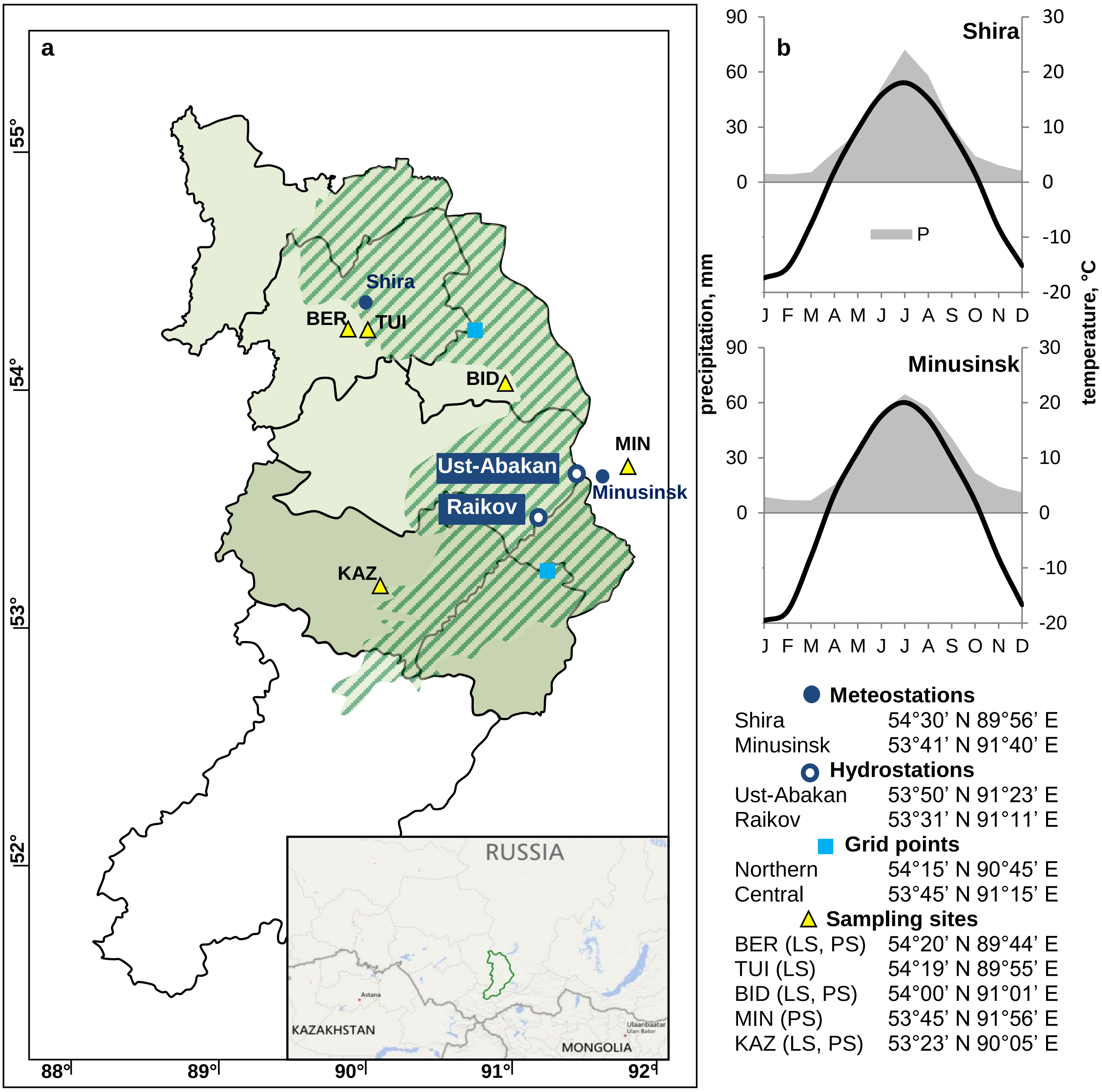

Fig. 1 Study region. On the map (a) Northern zone is marked with light shade, Central zone is marked with dark shade. Territory suitable for agriculture is marked with hatching. Climatic diagrams (b) of mean air temperature and amount of precipitation for every month are average for all period of instrumental measurements

Fig2 - corrected

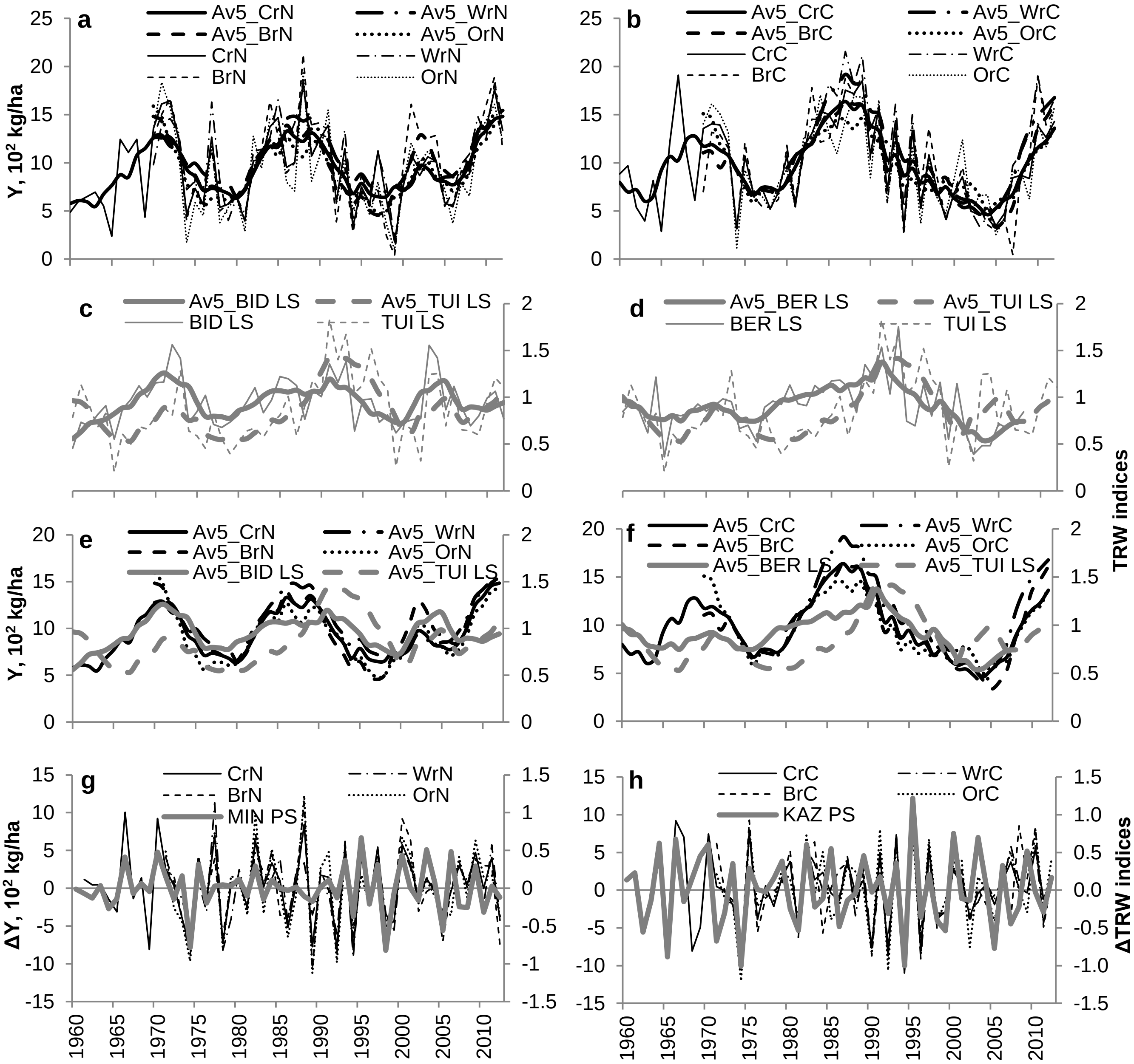

Fig. 2 Low- and high-frequency variation components of the crops yield and *TRW* chronologies: smoothing (Av5 – 5-year moving average) of yield chronologies, where CrN/CrC – crops in total, WrN/WrC – wheat, BrN/BrC – barley, OrN/OrC – oats regional yield series for Northern (a) and Central (b) zones respectively; smoothing (Av5) of *TRW* chronologies, low-frequency variation of which is the best-fitting for Northern (c) and Central (d) zones; comparison of the yield and *TRW* low-frequency variation in Northern (e) and Central (f) zones; high-frequency variation (first differences) of yield in comparison with the best-fitting high-frequency *TRW* variation in Northern (g) and Central (h) zones

Fig3

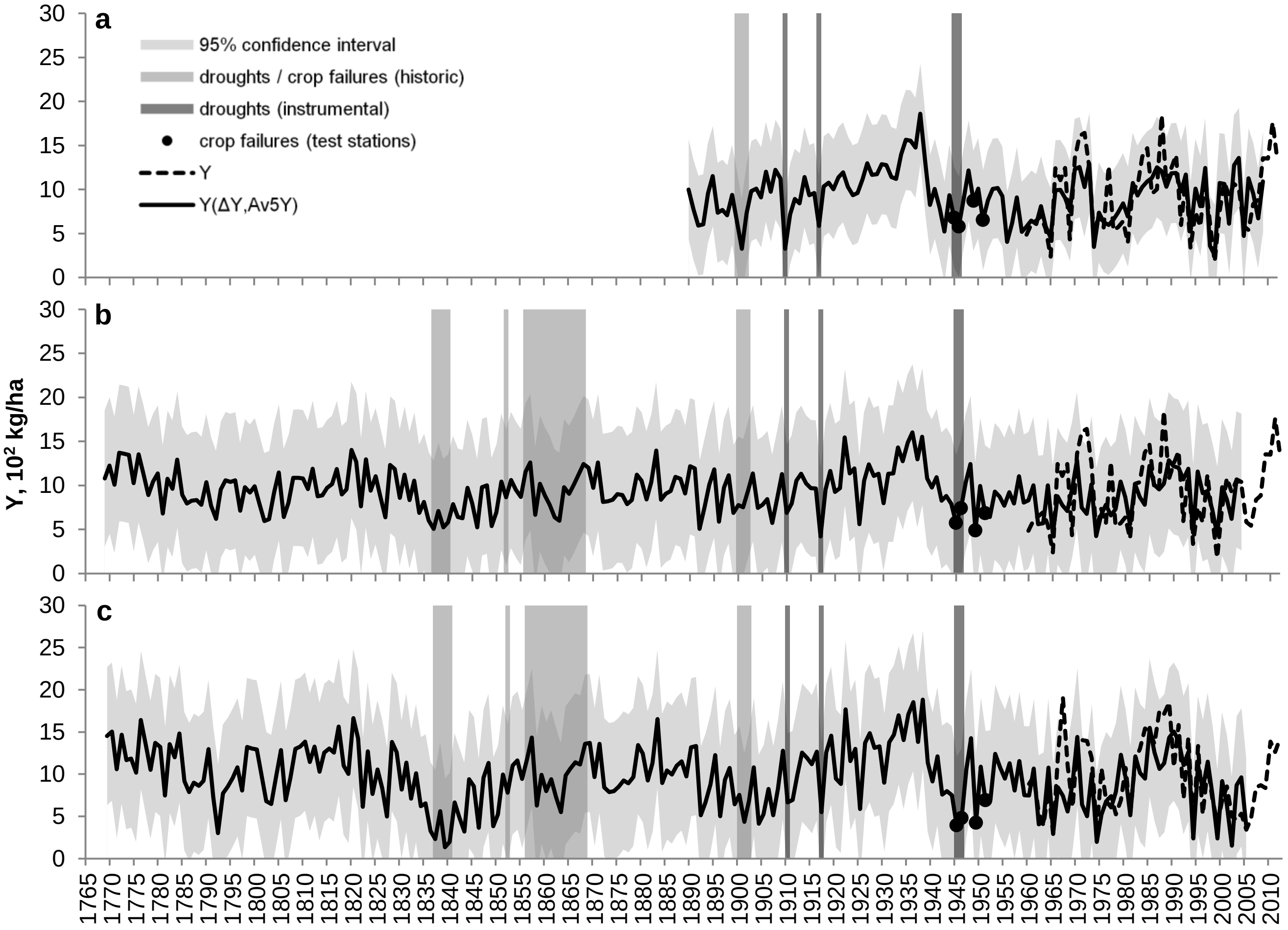

Fig. 3 Combined tree-ring based yield reconstruction models, actual series of CrN and CrC yield chronologies and evidences of droughts and crop failures from other sources. In Northern zone two models were constructed with different length and quality: best-fitted model (a) and second best-fitted model (b); in Central zone one model (c) was constructed

~~Estimation of past~~Past crops yield dynamics reconstruction from tree~~-~~-ring chronologies in the forest-steppe zone based on low- and high-frequency components

Elena A. Babushkina[1], Liliana V. Belokopytova[1], Santosh K. Shah[2] and Dina F. Zhirnova[1]
[1]Khakass Technical Institute, Siberian Federal University, 27 Shchetinkina St., Abakan, 655017, Russia
[2]Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow, 226007, India
Corresponding author: Elena A. Babushkina, <babushkina70@mail.ru>

Abstract

Interrelations of the yield variability of the main crops (wheat, barley, and oats) with hydrothermal regime and growth of conifer trees (*Pinus sylvestris* and *Larix sibirica*) in forest-steppes were investigated in Khakassia, South Siberia. An attempt has been made to understand the role and mechanisms of climatic impact on plants productivity. It was found that amongst variables describing moisture supply, wetness index had maximum impact. Strength of climatic response and correlations with tree growth are different for rain-fed and irrigated crops yield. Separated high-frequency variability components of yield and tree-ring width have more pronounced relationships between each other and with climatic variables than their chronologies per se. Corresponding low-frequency variability components are strongly correlated with maxima observed after 1 to 5 years time shift of tree-ring width. Results of analysis allowed us to develop original approach of crops yield dynamics reconstruction on the base of high-frequency variability component of the growth of pine and low-frequency one of larch.

Keywords crops yield, tree~~-~~-ring width, South Siberia, climate, reconstruction model.

Introduction

Hydrothermal regime of a territory is determined by hydrological and climatic factors that strongly influence the productivity of the both natural and agricultural ecosystems (Seneviratne et al. 2006; Challinor et al. 2014; Lipper et al. 2014; Porter et al. 2014; Iizumi and Ramankutty 2016). Current climatic trends of global warming include not only increasing temperatures, but also changes of water balance and frequency/severity of droughts (Easterling et al. 2000; Rosenzweig et al. 2002, 2014; Lobell et al. 2011; Mueller and Seneviratne 2012; Kattsov and Semenov 2014; Porter et al. 2014; IPCC 2015). Its impact on ecosystems has certain pattern on global scale. In the low and medium latitudes warming leads to more frequent droughts and increases vulnerability of plants to moisture shortage. In the high latitudes with sufficient moisture level warming lengthens vegetative season and intensifies growth and development of plants. Overall, geographic range of most plants species and cultivars shifts to the higher latitudes (Bindi and Olesen 2011; Peltonen-Sainio et al. 2016; Wang et al. 2016).

Understanding the regional mechanisms of this impact will provide more effective adaptation of the agriculture to the climate change, allowing to obtain more stable spatiotemporally yield (Zhirnova 2005; Hlavinka et al. 2009; Holman et al. 2017). Investigation of the yield dynamics can provide crucial information about its vulnerability to the climate change and estimation of the possible risks for food security (Myglan et al. 2007; Sauchyn et al. 2009; Pfister 2010; Qureshi et al. 2013; Wu et al. 2014; Huhtamaa et al. 2015; IPCC 2015).

However this field of research is highly restricted by short cover periods of the factual data of instrumental environmental measurements and especially statistics of yield (Therrell et al. 2006; Sauchyn et al. 2009). Use of proxy records in various natural objects allows overcoming this limitation (Wang and Liu 2016; Huhtamaa and Helama 2017). In particular, tree-ring width (*TRW*) chronologies are available in many regions and reflect environmental variations on multi-centennial scale with annual/seasonal resolution (Fritts 1976). Both *TRW* and yield are productivity indicators of the terrestrial ecosystems and results of plants growth and development processes. Thus common patterns in their dynamics and climatic responses are to be expected (Vaganov 1989; Wu et al. 2014). There are several recent studies investigating these two variables jointly, including tree-ring based reconstructions of yield itself or climatic factors crucial for it (Myglan et al. 2007; Helama et al. 2013; Rygalova et al. 2014; Sun and Liu 2014; Huhtamaa et al. 2015; Yadav et al. 2015).

The Republic of Khakassia (Siberia, Russia) is a typical example of a region in need of evaluation of the agricultural productivity. Small grain crops production is important part of the regional economy (Agroclimatic resources 1974; Surin and Lyakhova 1993). In this study we aimed to investigate variability of the main crops yield in Khakassia using instrumental environmental data and *TRW* chronologies of two prevalent conifer species in forest-steppe zone of the region. To achieve this goal the following objectives were set: (1) to reveal relationships between yield and *TRW* per se and between their components, (2) to analyze regional environmental factors and their extremes as driving forces for plants productivity indicators and their relationships, and (3) to obtain and verify tree-ring based reconstruction of the yield.

Materials and methods

Study area

The Republic of Khakassia is situated in the South Siberia, on the left bank of Yenisei river in its middle reaches. Montane part (south and east) of the republic belongs to the Altai-Sayan mountain system, whereas remaining territory is represented by plains of the Minusinsk Depression and is more appropriate for agriculture (Fig. 1 a) (Agroclimatic resources 1974). Climate of the study area is sharply continental (Alisov 1956). Minusinsk Depression is a wide valley surrounded by mountain ranges from all sides except North. Region is situated far from the ocean, but has broad Yenisei river with its two reservoirs (Chlebovich and Bufal 1976). The temperature during the vegetative season on plains increases from North to South. The precipitation decreases from the mountain ranges on the East and South towards the main rivers.

In spring rapidly increasing temperature have high daily variation. It causes delay of the frost-free period about 30-35 days after date of daily temperature crossing +5°C threshold. As a result spring frosts inhibit plant growth on the first development stages, thus shortening length of the vegetative season. The period of temperatures higher than +10°C starts around mid May and lasts up to 120 days. Precipitation has maximum in July-August, winter precipitation is scarce (maximal snow depth on plains is about 20 sm). Its interannual variation is very high, attaining 45-57% of mean value in summer and 56-90% of mean value in winter. Main reason of precipitation shortage is location of the Minusinsk Depression in the rain-shadow of mountain ranges. Due to this fact and spatiotemporally uneven precipitation the drought indices on the plains are unstable.

Regional hydrographic network is also uneven. Most of the water bodies are concentrated in the mountain part; northern half of Minusinsk depression has the lowest hydrographic density. Water bodies are mainly rain-fed, thus their runoff (Q) depends on climatic conditions. Most of the rivers belong to the Yenisei basin. In the centre of region main rivers and their tributaries form the base of irrigational network (Territorial planning scheme 2015).

Agrarian territory of Khakassia can be divided into three agroclimatic zones (Fig. 1): subtaiga zone with dark gray soils as narrow strip along mountain foothills, rain-fed steppes on chernozems in the north, and dry steppes on chestnut soils in the centre of republic, where irrigated agriculture is dominating (Agroclimatic resources 1974; Semenov et al. 2004). Agricultural area on the foothills is small (~4% of total area in republic) and has the least climatic impact, hence it was not investigated in the study.

Data sources

Monthly data of average temperature (*T*) and sum of precipitation (*P*) for 1938-2012 were obtained from Shira and Minusinsk stations (Fig. 1). Two indices characterizing moisture regime were computed from *T* and *P* data: Selyaninov hydrothermal coefficient ($HTC = 10 \cdot \sum P / \sum T$ for period of $T > 10°C$, based on daily data) and wetness index ($WI = \sum \log P / \sum T$, based on monthly data) (Selyaninov 1958; Lei et al. 2014). Additionally monthly *PDSI* and *SPEI* indices were used from open datasets (Beguería et al. 2010; van der Schrier et al. 2013). Runoff of Yenisei and Abakan rivers (*QY* and *QA*) obtained from Ust-Abakan and Raikov stations respectively were used as hydrological characteristic.

Crops yield measured as obtained grain weight per unit of sowing area (*Y*, kg/ha) was used as indicator of agricultural productivity (Therrell et al. 2006). Yield series averaged for every administrative district for 1960-2012 were obtained from unpublished records of the Federal State Statistics Service. Sufficient data are available for crops in total and for three main crops: spring wheat, spring barley and oats. For this study yield series of every crop were united into two zonal chronologies (Northern and Central) in regards to agroclimatic conditions and irrigation.

The samples of Scots pine (*Pinus sylvestris* L. – PS) and Siberian larch (*Larix sibirica* Ledeb. – LS) were collected in the foothills forest-steppes (BER, TUI, BID, KAZ sites) and insular forest in steppe (MIN). The processing of samples, measurement and cross-dating of *TRW* were carried out using standard dendrochronological techniques (Cook and Kairiukstis 1990; Speer 2010). All individual series were standardized by fitting exponential/linear functions to remove age related trends. Then individual indices were combined into single standard chronology per site/species using bi-weight robust mean (Cook and Krusic 2005).

Mathematical and statistical techniques

In this study we used following statistics of time series: arithmetic mean (*mean*), standard deviation (*stdev*), variation coefficient ($var = stdev/mean$), sensitivity coefficient (for time series *X* it is $sens = \mathrm{mean}(2 \cdot |X_t - X_{t-1}| / (X_t + X_{t-1}))$), first-order autocorrelation coefficient (*ar-1*). For *TRW* chronologies also average interseries correlation coefficient (*r-bar*) was calculated to check quality (Fritts 1976; Wigley et al. 1984; Cook 1985).

~~Pearson~~Pearson's correlation coefficients were used to evaluate relationships between time series. High-frequency component of variation was calculated as first differences (for time series *X* in year *t* first difference is $\Delta X_t = X_t - X_{t-1}$). This approach was successfully used in some previous analyses of climate-yield relationships (Nicholls 1997; Lobell et al. 2005; Lobell and Field 2007). Low-frequency component of variation was estimated as time series smoothed with 5-year moving average centered to the middle year ($Av5X_t = \mathrm{mean}(X_{t-2}, \cdots, X_{t+2})$).

Linear regression functions were used for reconstruction of the crops yield variation components. Quality of reconstruction models was estimated with the following statistics: coefficient of multiple correlation (R), coefficient of determination (R^2), adjusted coefficient of determination (R^2_{adj}), Fisher test (F), significance level p and standard error of estimation (SEE).

Results

Chronologies and relationships between them

Four regional crops yield chronologies were developed for each zone: crops in total – CrN and CrC in Northern and Central zones respectively, wheat – WrN and WrC, barley – BrN and BrC, oats – OrN and OrC. Their statistics are shown in Table 1. In the study area wheat yield has the highest mean values, and oats yield has the lowest ones. There are no significant differences in mean yield between zones. Variability of yield reaches 38-51% of mean values with substantial proportion of year-to-year changes, indicated by high sensitivity ($sens = 0.39 - 0.54$). Nevertheless, yield chronologies have also significant autocorrelations. The *TRW* chronologies range from 124 to 272 years (Table 1). *TRW* has lower variability per se and sensitivity ($sens = 0.19 - 0.47$), but higher autocorrelation than yield.

Within each zone yields of different crops are highly correlated ($r = 0.80 - 0.95$ in Northern zone and $r = 0.81 - 0.96$ in Central zone). The correlations between zones are moderate ($r = 0.49 - 0.78$) (Online Resource Table S1). The correlations between *TRW* chronologies are low to moderate. The highest correlations are observed within one site ($\mathrm{r} = 0.40 - 0.71$). Most of yield-*TRW* relationships are weak, 50% of correlations are not significant on level $p < 0.05$. However, we can note some relatively high correlations both in Northern (yield and BER_PS have $r = 0.34 - 0.54$, yield and BID_LS have $r = 0.35 - 0.47$) and Central zone (yield and BER_LS have $r = 0.45 - 0.63$, yield and BER_PS have $r = 0.36 - 0.47$).

Comparison of the smoothed *TRW* and yield series (Fig. 2 a-f) was performed by cross-correlation, i.e. correlations were calculated with different time shift (lag) of *TRW* (Online Resource Fig. S1). More pronounced similarity of low-frequency variation is revealed between yield and *TRW* of larch: BID_LS has the highest correlation with the yield in Northern zone, BER_LS has the highest one in Central zone, and TUI_LS has second-best correlations with the yield in both zones. The highest values of cross-correlation coefficients are observed with lag +1 to +2 years for BID_LS ($r = 0.54 - 0.79$) and for BER_LS ($r = 0.66 - 0.92$), and with lag +3 to +5 years for TUI_LS ($r = 0.43 - 0.65$ for Northern zone and $r = 0.54 - 0.80$ for Central zone). The cross-correlations are quasiperiodic. The distance between consequent maxima / consequent minima for cross-correlations of yield with BID_LS is 19 to 20 years and for cross-correlations of yield with BER_LS and TUI_LS is 26 to 33 years. Relationships between smoothed series of yield and pine *TRW* are considerably less pronounced. The extremal cross-correlations are unstable and not exceeding 0.50. Smoothed yield series correlations between themselves are high, viz., $r = 0.86 - 0.97$ in Northern zone, $r = 0.90 - 0.98$ in Central zone, and $r = 0.57 - 0.87$ between zones.

Climatic response in the chronologies

Significant correlations between *TRW* chronologies and monthly temperatures and precipitation were observed from previous July to current July (Online Resource, Fig. S2). Climatic response of all *TRW* chronologies has similar pattern. During the previous July-September and current May-July, response of *TRW* on *P* is positive and response on *T* is negative. Also there is positive response on both factors in the late autumn. Strength of the climatic response varies between species.

Crops yield chronologies have significant climatic response only during May-July (period of crops growth and development in the region). Therefore this period was selected for comparison of influence of the ecological factors on the natural and agro-ecosystems productivity (Table 2). Temperatures have strong negative relationships with crops yield in both zones. In Northern zone yield have also high positive correlations with precipitation. All drought indices have significant correlations with yield too, especially high in Northern zone. The wetness index has the strongest relationship with yield amongst ecological variables. The Yenisei runoff has no relationships with yield, whereas the Abakan runoff's correlations with yield are weak but partially significant. Correlations of *TRW* chronologies with ecological conditions of May-July are weaker than yield's ones. But there are similar patterns of strongest reaction on precipitation and *WI* and minimal response on rivers runoff. Overall pine has more pronounced dependence of growth on May-July conditions than larch.

Extremal events and plants productivity

As unfavorable extremal events (e.g. droughts) we considered years when ecological factors in May-July have high deviations from mean values (Online Resource Table S2). Specifically, combination of low moisture supply and high temperatures was observed in 1945, 1965 and 1999; in 1974 and 1981 precipitation and drought indices also were low but temperatures were on average level. These years were characterized by significant decrement of the tree growth, especially for pine. Crop failures were observed too with the most pronounced ones in 1965 and 1999. In 1994 high temperatures and normal moisture supply resulted in poor harvest and some low *TRW* values. Two-year drought in 1945-1946 was associated with low *TRW* values, but yield chronologies do not cover these years.

First differences of time series

Correlation analysis of the first differences of yield showed relationships and patterns similar to the chronologies per se (Online Resource Table S3): for ΔY correlations between each other in Northern zone $r = 0.75 - 0.94$, in Central zone $r = 0.77 - 0.95$, and between zones $r = 0.34 -$

0.62. For ΔTRW it is true as well. They have maximal correlations within the site ($r = 0.43 - 0.60$) and basically the same range of correlations among themselves as *TRW* chronologies per se. Though correlations between ΔY yield and ΔTRW are substantially higher than between their chronologies, 81% of them are significant on level $p < 0.05$ (Online Resource Fig. S3). These relationships are more pronounced for *TRW* of pine (Fig. 2 g, h). ΔY series in Northern zone have maximal correlations with ΔMIN_PS ($r = 0.47 - 0.61$) and the second-best correlations with ΔKAZ_PS ($r = 0.35 - 0.44$). In Central zone Δ*Y* series have maximal correlations with ΔKAZ_PS ($r = 0.51 - 0.62$).

Relationships of Δ*Y* and Δ*TRW* with first differences of environmental factors are also higher than corresponding relationships of original time series (Table 2). For example, Δ*Y* has higher correlations with first differences of *T*, *PDSI*, *SPEI* and rivers runoff; Δ*TRW* has higher correlations with first differences of *T*, *WI*, *PDSI* and *QA*. Amongst indicators of moisture regime *WI* has closest relationship with both *TRW* and yield when first differences are considered, as well as for original time series.

Tree-ring based reconstructions of the crops yield

Yield series have the highest correlations with pine *TRW* in first differences and with larch *TRW* after smoothing. Therefore we made separate tree-ring based models of hith- and low-frequency variability of yield. Detailed procedure of reconstruction is presented in Online Resource.

For high-frequency yield variation component the highest statistics of regression model were retrieved with using MIN_PS chronology for Northern zone and KAZ_PS chronology for Central zone. Due to relatively short cover period of MIN_PS we also constructed estimations for Northern zone on base of KAZ_PS chronology, which have ~80 year longer cover period but lower statistics (Table 3, Online Resource Fig. S4). For low-frequency yield variation component the highest statistics were retrieved with using smoothed BID_LS and TUI_LS for Northern zone, and BER_LS and TUI_LS for Central zone. For Northern zone also model on the base of BER_LS and TUI_LS was constructed, which have ~150 year longer cover period but lower statistics (Table 3, Online Resource Fig. S5).

Both yield and *TRW* chronologies contain fluctuations of different frequency. Thus a hypothesis was postulated that these two types of models could be used together to obtain one combined model of yield dynamics estimation as a whole. We obtained combined models with cover periods 122 and 237 years for Northern zone and 238 years for Central zone (Table 3, Fig. 3). Combined models with shorter cover period for Northern zone have higher statistics then corresponding ΔY models. At the same time most statistics of combined models with longer cover period for Northern zone are similar to ones of corresponding Δ*Y* models, but *F*-test and significance level are lower due to higher amount of predictors. For Central zone statistics of combined models are lower than ones of Δ*Y* models.

Verification of reconstruction

Combined models have the same extremes as actual yield chronologies within observation period. There are set of years of extremal low yield outside the observation period which are confirmed by regional data from other sources (Fig. 3). According to instrumental data, moisture deficit was observed in 1910, 1917, 1945-46 and 1951. Low yields of all three main crops were registered at the state variety testing stations of Khakassia in 1945-46, 1949 and 1951 (Zhirnova 2005).

There are also confirming historic evidences in the South of Siberia (Myglan 2010). For instance, in the opinion of Vatin (1922), "since 1837 crop failures have begun in the Yenisei Gubernia and completely ruined it in 2-3 years". There is also stated that in 1838 "sown cereals and meadow grass have a mediocre growth on the occasion of the absence of rains until this time"; in 1852 "worms appeared in the crops. During the crops ripening there was no rain; the yield was less than in previous 1851 year". In the work of Latkin (1890) the repeated crop failures in the Minusinsk depression during 1856-1868 were described: "since 1856 due to repeated poor harvest and gold mining, prices began to rise (up to 60 kopecks for pood of rye flour and oats)"; "in 1868 again prices have risen, thanks to some years with poor harvest". In a monograph of Butanayev (2002) drought in Khakassia in 1900-1902 was mentioned: "A severe drought gave rise to lack of fodder. Up to half of draught horses have died in the Abakan and Askiz establishments".

Discussion

Comparison of the plants productivity indicators response to the hydrothermal regime characteristics showed that the wetness index *WI* most explicitly expresses limiting by moisture supply. Its advantage is that this index not only combines the impact of precipitation as a source of moisture and temperature as a withering factor, but also highlights the contribution of drought events, as it contains logarithm of precipitation (Lei et al. 2014). The relationships between productivity indicators and river runoff are weak primarily due to their large catchment basins, especially for the Yenisei river. The Abakan river is supplied by the precipitation in the Minusinsk depression to a greater extent, and is the main water source for the irrigation system. These facts ensure the pronounced response to *QA*. Irrigation also significantly weakens yield climatic response on precipitation in the Central zone.

As many other regions, study area characterizes by frequent simultaneous temperature raising and precipitation deficit (Bazhenova and Tyumentseva 2010; Prasad et al. 2011; Nouri et al. 2017), Our analysis showed that both indicators of plant productivity are accurately capturing such unfavorable combinations, as well as extremes of one of these factors. It means that drought events lead to synchronicity of negative extremes in yield and *TRW*, which is partially reason for the positive, though not always significant, correlations between them. Therefore, it should be expected that the

TRW chronologies and the yield dynamics reconstructed on their basis will allow also restoring regional climatic extremes history (Touchan et al. 2016).Growth and development of plants has common regularities due to the unity of resources and physiological mechanisms (e.g. nutrition, respiration, water balance), so we should expect them to be limited by the same environmental factors typical for the semi-arid continental climatic zone (Myglan et al. 2007; Sun and Liu 2014). Moreover, both grains for agricultural crops and wood for trees are the main targets of resources storage processes during their growth and development. For instance, wheat has about 50% ratio of grain mass to above ground biomass (Schulze et al. 2005). Also one more common trait is adaptation to the moisture deficit. Climatypes of the tree species in forest-steppe are adapted to the semiarid conditions by natural selection. At the same time, regional crop cultivars are adapted to these conditions by human activity, i.e. breeding.

Differences in the variability of yield and *TRW* chronologies follow primarily from their life forms and cycles. Most of yield variability of crops, as annual plants, is due to current conditions, including high-frequency climatic fluctuations. Significant autocorrelation is associated with using the previous harvest as source of grain for sowing, because grain quality usually has positive relationship with yield (Ozturk and Aydin 2004; Meng et al. 2016). Long-term yield variability is influenced by both climatic trends and changes in farming practices and cultivars. Conifer trees as perennials, especially evergreens, are characterized by stronger autocorrelation and less sensitivity of growth. On the one hand, the variability of tree growth is constrained by the slowness of changes in morphometric parameters (the size and structure of stem&root system) determining the access to resources. On the other hand, woody plants are characterized by active storage of nutrients for using in the next season. Moreover, evergreen trees have needles of previous years participating in photosynthesis processes (Chapin et al. 1990; Schulze et al. 2005). Thus trees respond to the hydrothermal regime not only of the current vegetative season, but also of the previous months. In regard to long-term tree growth dynamics, the impact of human activity is much less pronounced than in agroecosystems. Thereby the long-term variation of *TRW* is mainly due to a combination of climatic trends, aging and changes in the stand structure. Also it is necessary to take into account using of standardized *TRW* data, from which most of the age trend was removed during processing. Since the crops yield does not have such trends, its standardizing was not necessary.

As a result of all aforementioned differences, despite the similarity of the growth conditions *TRW* chronologies per se have limited relationships with crops yield, as well as with climate of May-July. Therefore instead of head-on approach we proposed other methods to make tree-ring-based yield reconstruction. Separation of plants production variability into high- and low-frequency components and their analysis allowed us to circumvent these restrictions.

Low-frequency variation in the yield and *TRW* has much in common due to its dependence on climatic trends. More pronounced similarity with yield is observed in larch *TRW* smoothed series then in pine ones. It might be caused by need to re-grow all needles every spring for larch. Pine as evergreen has needles with overlapping life spans, which complicates autocorrelation component and low-frequency variation of growth in general. The delay in decadal oscillations of the tree growth in comparison with crops is associated with the more pronounced autocorrelation described above.

Main non-climatic factors affecting variation of the both plant productivity indicators (the age changes of trees and the development of agricultural technologies) are low frequency. Thus transition to the first differences reduces their contribution and highlights role of the climate and the hydrological regime, as they have considerable high-frequency variation component. It should be noted that, unlike the smoothed series, the similarity between year-to-year dynamics of pine growth and the crops yield is more pronounced. This is due to the fact that the response to the May-July conditions is higher for pine than for larch.

As both components of yield variability have more close relationships with the tree growth than yield chronologies per se, we can reconstruct these components separately. Both reconstructions have their advantages and disadvantages. The reconstructed first differences easily allow one-year crops failures to be revealed, but do not allow to receive information about longer periods of high/low yield. Conversely, the reconstruction of the smoothed series describes long-term trends well, but there is no information about the extreme years. Therefore, it was proposed to reconstruct the entire yield variability by combining these two models. Use of a recursive equation for obtaining yields from the model of the first differences leads to the accumulation of errors in long-term trends. To erase these errors, low-frequency variation was completely removed from the resulting series by subtracting their smoothed series. Then year-to-year yield fluctuations were threaded onto the reconstructed separately long-term oscillations. The advantage of this approach in our case is also in the use of tree-ring chronologies of different species and habitats, which reduces the correlations between predictors.

The obtained yield estimations are quite close to the factual series, especially extremal values. However, the limits of the *TRW* chronologies cover periods restricting the length of the most qualitative yield reconstruction in the Northern zone. The use of longer chronologies makes it possible to significantly extend this period at the expense of the quality reducing. Despite this, the relevance of models is confirmed by their comparison with other data sources –instrumental records, historical documents, and yield data of regional variety testing stations.

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Table 1. Statistical characteristics of crops yield and *TRW* chronologies

	Crops yield								Tree-ring width							
	Nothern zone				Central zone				*Pinus sylvestris*				*Larix sibirica*			
	CrN	WrN	BrN	OrN	CrC	WrC	BrC	OrC	BER PS	BID PS	MIN PS	KAZ PS	BER LS	TUI LS	BID LS	KAZ LS
N, years	53	43	43	43	53	33	43	43	257	164	166	246	272	294	124	178
period, years	1960-2012	1970-2012	1970-2012	1970-2012	1960-2012	1980-2012	1970-2012	1970-2012	1752-2008	1849-2012	1847-2012	1767-2012	1737-2008	1719-2012	1889-2012	1835-2012
Number of trees	-	-	-	-	-	-	-	-	14	15	40	23	14	57	16	20
mean[*]	9.34	10.40	10.00	9.27	9.73	11.31	9.87	9.76	-	-	-	-	-	-	-	-
stdev[*]	4.06	3.96	4.68	4.56	4.45	5.57	5.00	4.46	0.29	0.35	0.23	0.43	0.32	0.47	0.32	0.62
var[*]	0.43	0.38	0.47	0.49	0.46	0.49	0.51	0.46	-	-	-	-	-	-	-	-
sens	0.43	0.39	0.48	0.54	0.45	0.39	0.52	0.51	0.25	0.33	0.19	0.40	0.30	0.43	0.26	0.47
ar-1	0.36	0.41	0.44	0.34	0.39	0.62	0.40	0.27	0.48	0.44	0.45	0.51	0.44	0.49	0.50	0.62
r-*bar*	-	-	-	-	-	-	-	-	0.56	0.51	0.43	0.60	0.58	0.57	0.42	0.48

[*] *mean* and *stdev* of the crops yield are in 10^2 kg/ha; standard *TRW* chronologies have *mean* = 1 and *var* = *stdev*

Table 2. Correlation coefficients of crops yield and *TRW* chronologies with climatic and hydrological variables, averaged for the crops growth period – May-July (calculated for time series / chronologies per se and for their first differences)

	T	P	HTC	WI	PDSI	SPEI	QE	QA		ΔT	ΔP	ΔHTC	ΔWI	ΔPDSI	ΔSPEI	ΔQE	ΔQA
	time series per se									first differences							
CrN	-0.48	0.48	0.56	0.72	0.50	0.52	0.20	0.26	ΔCrN	-0.57	0.32	0.41	0.67	0.70	0.56	0.32	0.29
WrN	-0.54	0.38	0.46	0.66	0.31	0.32	0.17	0.21	ΔWrN	-0.58	0.23	0.30	0.56	0.48	0.40	0.26	0.28
BrN	-0.41	0.58	0.63	0.68	0.48	0.55	0.33	0.40	ΔBrN	-0.43	0.47	0.52	0.65	0.63	0.58	0.44	0.40
OrN	-0.44	0.57	0.63	0.71	0.48	0.57	0.23	0.34	ΔOrN	-0.43	0.46	0.52	0.65	0.61	0.57	0.32	0.31
CrC	-0.58	0.30	0.40	0.61	0.41	0.45	0.20	0.28	ΔCrC	-0.59	0.45	0.51	0.66	0.55	0.52	0.39	0.54
WrC	-0.62	-0.02	0.12	0.45	0.14	0.16	0.22	0.14	ΔWrC	-0.63	0.18	0.26	0.49	0.35	0.22	0.32	0.51
BrC	-0.56	0.11	0.21	0.43	0.29	0.27	0.08	0.23	ΔBrC	-0.63	0.29	0.36	0.53	0.39	0.35	0.24	0.58
OrC	-0.53	0.26	0.36	0.56	0.37	0.42	0.21	0.28	ΔOrC	-0.46	0.37	0.42	0.58	0.49	0.43	0.38	0.55
BER PS	-0.32	0.26	0.25	0.37	0.15	0.21	-0.01	0.22	ΔBER PS	-0.45	0.33	0.33	0.50	0.26	0.25	0.00	0.37
BID PS	-0.21	0.33	0.23	0.29	0.32	0.26	0.20	0.37	ΔBID PS	-0.36	0.09	0.04	0.25	0.36	0.16	0.31	0.50
MIN PS	-0.35	0.45	0.47	0.51	0.40	0.38	0.27	0.45	ΔMIN PS	-0.46	0.45	0.49	0.61	0.63	0.43	0.46	0.58
KAZ PS	-0.16	0.17	0.19	0.27	0.08	0.17	0.12	0.54	ΔKAZ PS	-0.36	0.23	0.29	0.45	0.46	0.20	0.32	0.70
BER LS	-0.36	0.28	0.17	0.36	0.16	0.19	-0.21	0.04	ΔBER LS	-0.32	0.25	0.16	0.31	0.14	0.14	-0.22	0.22
TUI LS	-0.14	0.35	0.17	0.22	0.29	0.24	-0.24	0.11	ΔTUI LS	-0.27	0.32	0.20	0.31	0.32	0.16	0.03	0.31
BID LS	-0.16	0.32	0.25	0.28	0.41	0.27	0.18	0.18	ΔBID LS	-0.15	0.10	0.06	0.17	0.40	0.21	0.19	0.36
KAZ LS	-0.06	0.01	0.00	0.12	-0.10	0.03	0.16	0.17	ΔKAZ LS	-0.11	0.02	0.03	0.20	0.34	0.03	0.28	0.53

T – temperatures; P – precipitation; HTC – hydrothermal coefficient of Selyaninov; WI – wetness index (Lei et al. 2014); QE – runoff of Yenisei river; QA – runoff of Abakan river.

Marked with shade correlation coefficients are significant at $p<0.05$

Table 3. Regression reconstruction models of crops yield high- and low- frequency variation components and combined models on base of *TRW* chronologies and their statistical characteristics

Yield models	Function / predictors	R	R^2	R^2_{adj}	F	p	SEE	Period
high-frequency variability component								
ΔCrN1	-1.31 + 13.16·MIN_PS – 11.63·MIN_PS$_{-1}$	0.65	0.42	0.40	17.8	<0.001	3.56	1848-2012
ΔWrN1	-3.16 + 13.55·MIN_PS – 10.18·MIN_PS$_{-1}$	0.67	0.45	0.43	16.2	<0.001	3.27	
ΔBrN1	-1.38 + 13.89·MIN_PS – 12.50·MIN_PS$_{-1}$	0.63	0.40	0.36	9.5	<0.001	4.05	
ΔOrN1	-0.58 + 12.58·MIN_PS – 12.00·MIN_PS$_{-1}$	0.56	0.31	0.26	6.5	0.004	4.56	
ΔCrN2	0.21 + 6.45·KAZ_PS – 6.50·KAZ_PS$_{-1}$	0.60	0.36	0.34	14.0	<0.001	3.72	1768-2012
ΔWrN2	-0.19 + 6.24·KAZ_PS – 5.92·KAZ_PS$_{-1}$	0.60	0.36	0.33	11.1	<0.001	3.53	
ΔBrN2	1.10 + 5.31·KAZ_PS – 6.51·KAZ_PS$_{-1}$	0.51	0.26	0.22	6.9	0.003	4.42	
ΔOrN2	0.74 + 5.49·KAZ_PS – 6.32·KAZ_PS$_{-1}$	0.48	0.23	0.19	5.9	0.006	4.75	
ΔCrC	-0.03 + 9.29·KAZ_PS – 9.14·KAZ_PS$_{-1}$	0.80	0.64	0.62	42.7	<0.001	3.04	
ΔWrC	0.43 + 10.41·KAZ_PS – 10.71·KAZ_PS$_{-1}$	0.92	0.85	0.84	82.9	<0.001	1.96	
ΔBrC	-0.39 + 9.47·KAZ_PS – 8.84·KAZ_PS$_{-1}$	0.72	0.51	0.49	20.6	<0.001	3.92	
ΔOrC	0.45 + 9.18·KAZ_PS – 9.61·KAZ_PS$_{-1}$	0.75	0.56	0.54	25.3	<0.001	3.63	
low-frequency variability component								
Av5Y_N1	-1.09 + 3.50·Av5TUI_LS$_4$ + 7.39·Av5BID_LS$_1$	0.81	0.66	0.65	43.1	<0.001	1.52	1890-2009
Av5Y_N2	3.55 + 4.17·Av5TUI_LS$_3$ + 1.91·Av5BER_LS$_2$	0.62	0.39	0.36	14.1	<0.001	2.05	1737-2004
Av5Y_C	-2.40 + 4.02·Av5TUI_LS$_5$ + 8.54·Av5BER_LS$_1$	0.85	0.73	0.72	59.5	<0.001	1.67	1734-2005
combined models								
CrN	MIN_PS, MIN_PS$_{-1}$, Av5TUI_LS$_4$, Av5BID_LS$_1$	0.76	0.57	0.53	15.1	<0.001	2.82	1890-2011
WrN		0.68	0.46	0.40	7.4	<0.001	3.15	
BrN		0.70	0.49	0.43	8.5	<0.001	3.65	
OrN		0.68	0.46	0.40	7.6	<0.001	3.83	
CrN	KAZ_PS, KAZ_PS$_{-1}$, Av5TUI_LS$_3$, Av5BER_LS$_2$	0.55	0.30	0.23	4.3	0.006	3.83	1768-2004
WrN		0.60	0.36	0.27	4.2	0.009	3.71	
BrN		0.54	0.29	0.20	3.1	0.030	4.65	
OrN		0.54	0.29	0.20	3.1	0.030	4.52	
CrC	KAZ_PS, KAZ_PS$_{-1}$, Av5TUI_LS$_5$, Av5BER_LS$_1$	0.56	0.31	0.25	4.7	0.003	4.05	1768-2005
WrC		0.75	0.56	0.47	6.6	0.001	4.33	
BrC		0.59	0.35	0.27	4.2	0.008	4.38	
OrC		0.53	0.28	0.19	3.1	0.031	4.20	

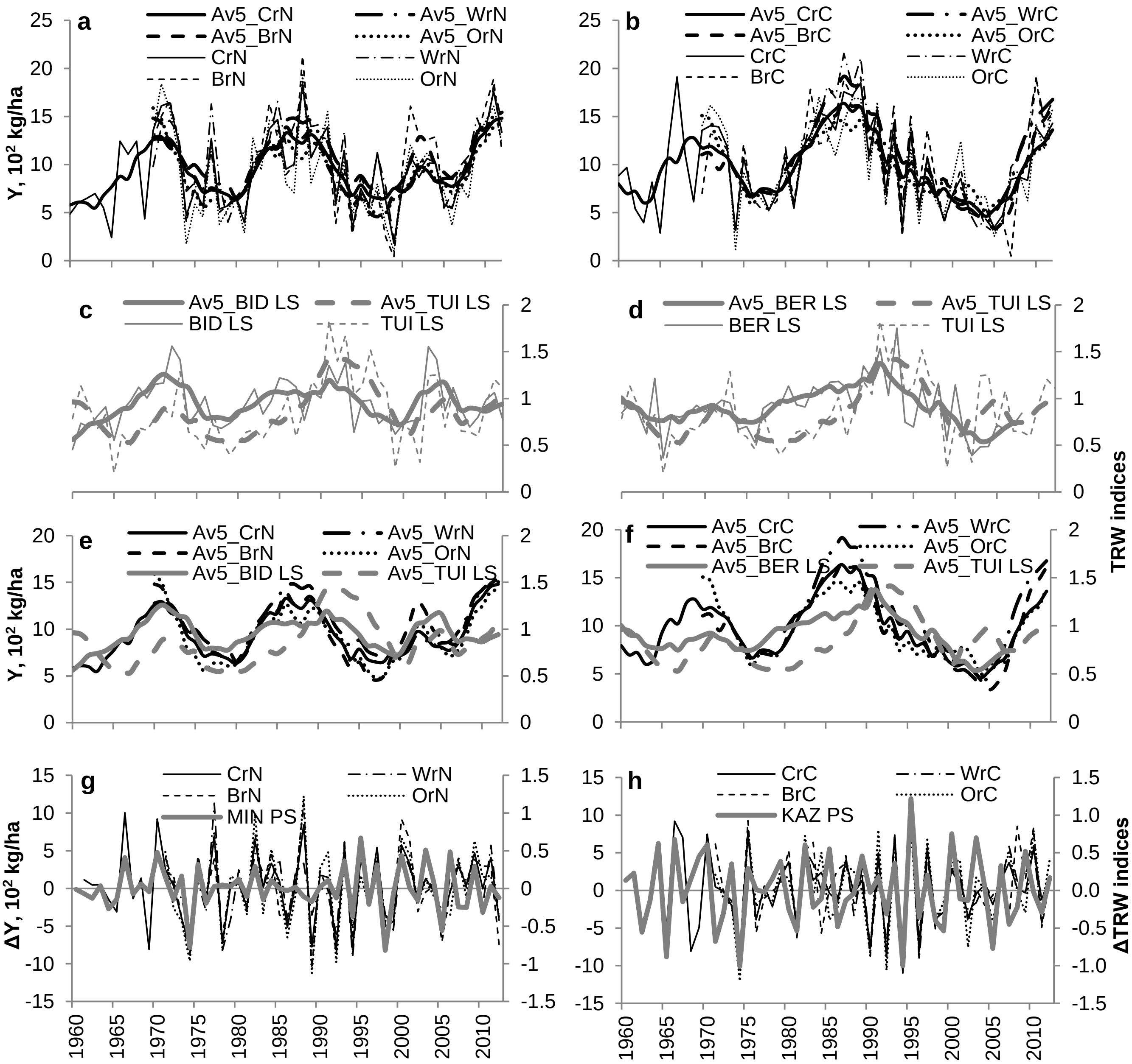

Fig. 2 Low- and high-frequency variation components of the crops yield and *TRW* chronologies: smoothing (Av5 – 5-year moving average) of yield chronologies, where CrN/CrC – crops in total, WrN/WrC – wheat, BrN/BrC – barley, OrN/OrC – oats regional yield series for Northern (a) and Central (b) zones respectively; smoothing (Av5) of *TRW* chronologies, low-frequency variation of which is the best-fitting for Northern (c) and Central (d) zones; comparison of the yield and *TRW* low-frequency variation in Northern (e) and Central (f) zones; high-frequency variation (first differences) of yield in comparison with the best-fitting high-frequency *TRW* variation in Northern (g) and Central (h) zones