forests

MDPI

Article

Wild Apple Growth and Climate Change in Southeast Kazakhstan

Irina P. Panyushkina [1,*], Nurjan S. Mukhamadiev [2], Ann M. Lynch [1,3], Nursagim A. Ashikbaev [2], Alexis H. Arizpe [1], Christopher D. O'Connor [4], Danyar Abjanbaev [2], Gulnaz Z. Mengdbayeva [2] and Abay O. Sagitov [2]

1 Laboratory of Tree-Ring Research, University of Arizona, 1215 W. Lowell St., Tucson, AZ 85721, USA; lyncha@email.arizona.edu (A.M.L.); alexisa@email.arizona.edu (A.H.A.)
2 Z.H. Zhiembaev Research Institute of Plant Protections and Quarantine, Almaty 050070, Kazakhstan; nurzhan-80@mail.ru (N.S.M.); ms.ank141@gmail.com (N.A.A.); abjanbaev@mail.ru (D.A.); www.gulnaz87.kz@mail.ru (G.Z.M.); a_sagitov@mail.ru (A.O.S.)
3 U.S. Forest Service, Rocky Mountain Research Station, Tucson, AZ 85721, USA; alynch@fs.fed.us
4 U.S. Forest Service, Rocky Mountain Research Station, Missoula, MT 59801, USA; christopheroconnor@fs.fed.us
* Correspondence: ipanyush@email.arizona.edu

Received: 31 August 2017; Accepted: 22 October 2017; Published: 26 October 2017

Abstract: Wild populations of *Malus sieversii* [Ldb.] M. Roem are valued genetic and watershed resources in Inner Eurasia. These populations are located in a region that has experienced rapid and on-going climatic change over the past several decades. We assess relationships between climate variables and wild apple radial growth with dendroclimatological techniques to understand the potential of a changing climate to influence apple radial growth. Ring-width chronologies spanning 48 to 129 years were developed from 12 plots in the Trans-Ili Alatau and Jungar Alatau ranges of Tian Shan Mountains, southeastern Kazakhstan. Cluster analysis of the plot-level chronologies suggests different temporal patterns of growth variability over the last century in the two mountain ranges studied. Changes in the periodicity of annual ring-width variability occurred ca. 1970 at both mountain ranges, with decadal-scale variability supplanted by quasi-biennial variation. Seascorr correlation analysis of primary and secondary weather variables identified negative growth associations with spring precipitation and positive associations with cooler fall-winter temperatures, but the relative importance of these relationships varied spatially and temporally, with a shift in the relative importance of spring precipitation ca. 1970 at Trans-Ili Alatau. Altered apple tree radial growth patterns correspond to altered climatology in the Lake Balkhash Basin driven by unprecedented intensified Arctic Oscillations after the late 1970s.

Keywords: wild fruit wood forest; *Malus sieversii*; dendrochronology; climate change; Central Asia

1. Introduction

The relict fruit wood forests of Inner Eurasia are highly treasured as genetic reserves for cultivated fruit species, especially apple (*Malus* spp.), and for the ecosystem services that they provide [1–3]. All domesticated apple varieties around the world originate in part from *Malus sieversii* (*M. sieversii*) [4–6]. Wild populations of *M. sieversii* are genetically more diverse than cultivated populations, exhibiting a much wider range of adaptation to drought and temperature extremes and to pathogens [7,8]. *M. sieverii* (known as Siever's apple, Asian apple, and Almaty apple) is the dominant species in the relict wild fruit wood forests in southeast Kazakhstan. The natural range of relict fruit wood forests spreads across many mountain ranges of the Tian Shan and Pamyr Mountains through the neighboring countries: Kyrgyzstan and China, as well as Russian Siberia (e.g., Lake Baykal region). It is believed that mesophyllic flora of the wild fruitwood forests originated in the Tertiary period and survived extinction in isolated refugia during the last Quaternary glaciation [9,10].

The fruit forests surrounded by semi-desert landscapes are also valued for watershed preservation, as well-developed and interlaced apple root systems protect mountain soils from erosion and landslides [7] in a region prone to extreme landslide and river outflow events [11]. These forests have not been inventoried in any systematic fashion, and the frequency and extent of insect outbreaks and pathogen conditions are unknown, but extensive forest health issues are clearly evident in that large portions of tree crowns are dead and foliage is sparse (Figure 1). It is unknown if this condition is short-term or reflective of long-term decline. Suggested causes of poor forest health range from post-seral stage succession, other natural ecological process such as insect outbreaks or pathogens, air pollution, or changing climate conditions [7,12].

(**a**) (**b**)

Figure 1. General view of wild apple stand (**a**) and tree-ring sampling with increment borer (**b**).

Apple has been studied extensively as a cultivated orchard tree, but its ecology in wild forests is less-well studied [13]. Dzhangaliev (2003) provides a comprehensive synthesis of literature through the late 1970s, especially as it relates to fruit production, life history traits, and response to extreme weather events such as frosts, excessive snow, and seasonal drought [7]. Apple reproduces by both seed and root suckering [7], forming stands composed of both independent trees and surculose biogroups. Self-grafting root systems and the surculose habit enable biogroups to maintain dominance and persist on individual sites, resist defoliator damage, and contribute to soil stability.

Though there is an understanding of fruiting response to extreme weather events [7], the relationships between apple tree growth and climate variables are poorly known. Understanding how trees respond to the full range of seasonal precipitation and temperature variables is a necessary first step for determining if declining forest health is related to ecological succession, pest dynamics, climate change, or a combination of various factors. Here we develop tree-ring chronologies for wild apple and assess the relationships between wild apple radial growth and climate variables.

Tree rings have long been used to evaluate the environmental and climate impacts on tree growth. Past tree-ring studies from the Tian Shan Mountains demonstrated strong relationships between climate and spruce and juniper growth, which facilitated reconstructions of summer temperature and moisture variability [14–18]. The tree-ring based reconstructions indicate increased drought stress on conifer tree growth in the mountains of Central Asia. Rapid increase in the rate of warming occurred in the last two decades, which caused the increase of summer aridity [14,17]. Juniper and spruce growing at the lower elevations are most sensitive to the drought stress, while conifers from the upper elevation showed significantly increased response to the temperature trend [15–17].

Tree-ring crossdating was recently used to determine stand demography of wild apple forests and the age of old orchards [19,20]. Yet to the best of our knowledge, the relationship between radial growth of apple trees and climate with dendrochronology has not been evaluated. We collected tree-ring samples from the Jungar Alatau (Figure 1) and Trans-Ili Alatau to evaluate the relationships between climate conditions and annually resolved variations of wild apple tree growth in southern Kazakhstan.

2. Materials and Methods

2.1. Study Areas

Large contiguous wild apple forests survive in a few locations of Eurasia, including the foothills of the Tian Shan Mountains in southeast Kazakhstan. Wild apple forests cover about 1463 km^2 in Kazakhstan [7]. Trees form regular stands in five mountain ranges, with 49 and 25% of the Kazakh relict fruitwood forest area in the Jungar Alatau and Trans-Ili Alatau, respectively, and lesser amounts in the Karatau (12.1%), Talass Alatau (11.7%) and Tarbagatay (2%). Our study sites are located in the Semirechye (also known as Jetisu or Seven Rivers) Region of the Jungar Alatau and Trans-Ili (Figure 2) in areas where *M. sieversii* was first identified in 1929 [21]. Conservation management of wild apple groves has been active in this region for at least 80 years. Geographically, the Semirechye is the middle part of the Lake Balkhash Basin between the northern margins of Tian Shan Mountains and Saryesik-Atyrau desert. The landscape closely conforms to the Tian Shan mountainous ranges of Kyrgyzstan and the Chinese province of Xinjiang where wild apple growth occur as well.

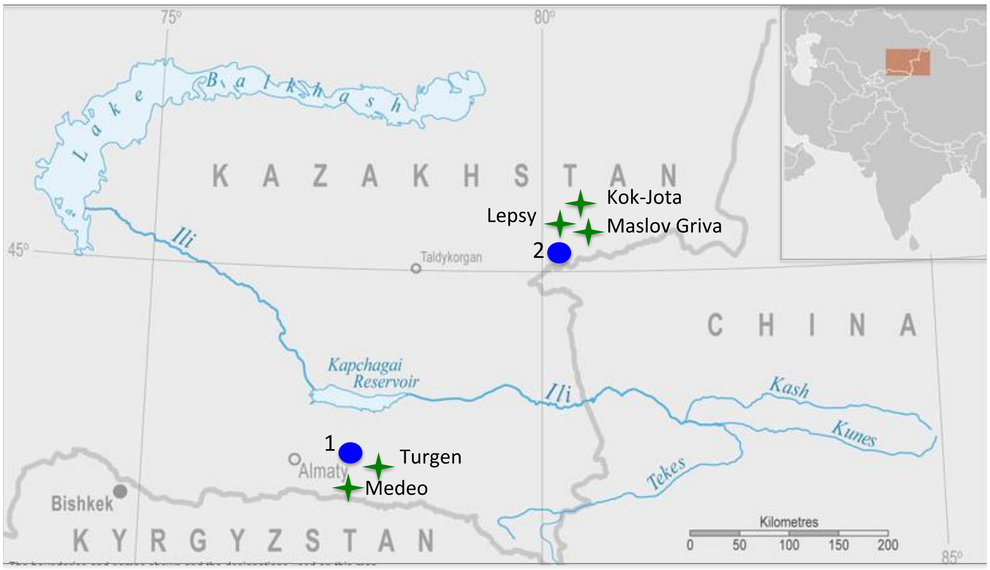


Figure 2. Map of study area with insert (upper right) showing the Semirechye, southeast Kazakhstan, in Eurasia. Circles mark positions of the Almaty (1) and Panfilov (2) weather stations used in the analyses. Stars show five primary locations of 12 sampled plots. Sample plot statistics are provided in Table S1.

Apple forms relatively pure open to relatively dense stands with understories of *Populus tremula*, *Sorbus* tianschanica, *Padus racemosa*, *Crataegus songarica* (C. Koch), *Armeniaca vulgaris* Lamarck, Acer semenovii and *Rosa fedtschenkoana*. *M. sieversii* usually occurs on the slopes of wide river valleys and on lower mountain slopes between steppe vegetation and spruce forest (primarily *Picea schrenkiana*).

We sampled trees on 12 plots in five locations at an elevation range 1200–1600 m *a.s.l.* of the Trans-Ili Alatau and Jungar Alatua Ranges, Tian Shan Mountains. A full list of the tree-ring sites can be found in Supplementary Materials Table S1. Sampled plots covered a good range of geographical settings, spanning ca. 400 m of elevation, a wide range of aspect, and slope gradients from 7% to 58% (Table S1). Apple tree size varied considerably, with average diameter at root collar ranging from 40 to 130 cm, and diameter at breast height (1.37 m above ground level) ranging from 20 to 130 cm. The height of sampled mature trees varied from 7 to 13 m.

2.2. Weather Data

Instrumental weather data were not available at the study plots, so we used weather data from Almaty (WMO#36870, 43°23′. N, 76°93′ E) and Panfilov (WMO# 36859, 44°17′ N, 80°07′ E). The Almaty station record begins in the late 1880s and is the longest recording station in the region. We used it to evaluate seasonal weather patterns and to calculate climate response functions over the 1920–2014 period. The Panfilov weather station period of observations is relatively short but typical for the region, from 1960 to 1992. We compared Panfilov data to Almaty data to determine if climate patterns near the Jungar Alatau differed from the Trans-Ili Alatau. Both weather stations are at lower elevations than the study sites and located on the steppe-forest boundary (Almaty is at 895 m *a.s.l.*, and the Trans-Ili sites are at 1490–1540 m *a.s.l.*; Panfilov is at 953 m *a.s.l.*, 60 km northeast of the Jungar Alatau sites, which are at 1245–1475). Generally, the Jungar Alatau has less precipitation and slightly colder winters than the Trans-Ili Alatau. At Almaty, the average monthly temperatures are +24 °C and −6 °C in July and January, respectively, and annual precipitation is near 650 mm. The growing season at Almaty (T_{min} > 5 °C) is between April and October, and precipitation peaks in spring (April–May) with a second much smaller peak in autumn (October–November) (Figure 3). July–September is the hottest and driest period with precipitation less than 50 mm per month. At Panfilov, the average monthly temperatures are +24 and −8 °C in July and January, respectively, and annual precipitation is about 250 mm. Climate conditions at the weather stations are warmer and dryer than at the study sites due to the 500–800 m elevation difference, but represent the climate variability of Semirechye foothills.

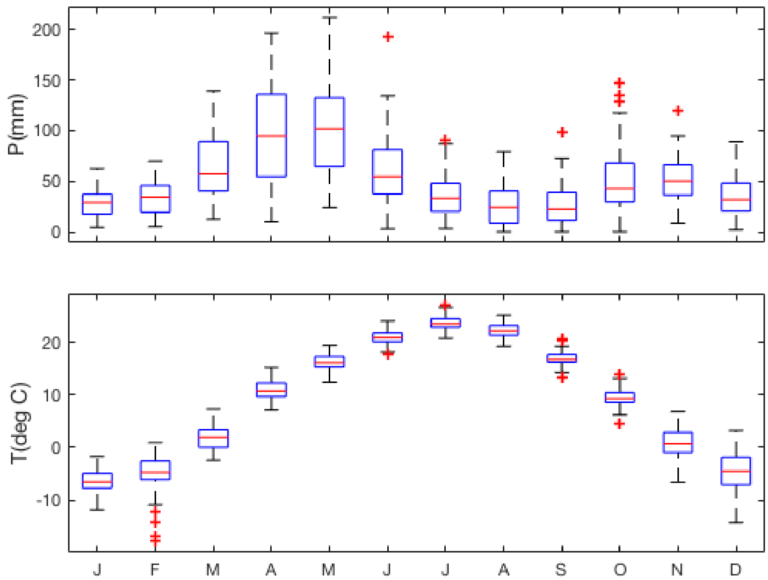


Figure 3. Climagraph calculated from monthly observations of the Almaty weather station for 1920–2014. Distributions for individual months are displayed as box plots with a horizontal line at the median, a box over the interquartile range, and plus signs at values more than 1.5 times the interquartile range above or below the box. If there are no such outliers, the bracket marks the data extremes.

2.3. Tree-Ring Data

We sampled 10–12 live apple trees on ca. 0.4 ha plots at 12 sites (Table S1). Increment core samples were taken at 1.37 m (breast height) or lower. We selected the oldest-appearing and relatively healthiest trees to obtain the longest possible dendrochronological record. Sampled cores were mounted and sanded with progressively finer grits until individual cell structure was observable [22]. Ring widths were measured on a Lintab stage system with 0.01-mm precision. Samples were crossdated visually and the crossdating was verified with correlation analyses of the measured ring widths using COFECHA [23].

Tree-ring index chronologies were developed using standard methodology, whereby crossdated ring-width series are detrended by the ratio method after first fitting the data with a cubic smoothing spline with frequency response 0.50 at a wavelength of 2/3 the sample series length, which preserves at least 50% of ring-width variance [24]. The individual detrended series were combined into standard plot-level chronologies using a bi-weight robust mean using ARSTAN [25]. Variance of the plot-level chronologies was analyzed using cluster analysis [26] in STATISTICA [27] to determine which plot series should be combined in composite chronologies. Individual-tree ring-width series were screened within each cluster and series with weak inter-series correspondence (Pearson correlation less than 95% confidence) or shorter than 55 years were removed. Remaining individual ring index series within each cluster were composited as above using a bi-weight robust mean using ARSTAN. The composite chronologies were used in statistical response functions of climate and ring growth (Table 1).

Table 1. Statistics * of composite tree-ring chronologies representing the wild apple growth at Jungar Alatau and Trans-Ili Alatau. Short series (<50 years) and low-correlated series were removed from the composite chronologies. EPS statistic (Expressed Population Signal) is above 0.85 for the full length of ring records.

Mountain Range	Grid Coordinates	Elevation m *a.s.l.*	Number of Series	Period	Length	*R*	SD	AR Lag1 Lag2
Jungar	45° N, 80° E	1254–1475	81	1899–2014	116	0.57	0.21	0.10 0.18
Trans-Ili	43° N, 77° E	1540–1600	42	1886–2014	129	0.59	0.28	0.31 0.14

* *R*, Correlation of time series in chronology, SD, Standard deviation, AR, Autocorrelation coefficient.

2.4. Statistical Analysis

Linear relationships between apple ring indices and monthly precipitation and mean temperatures were estimated using Seascorr, which applies interserial correlations and partial correlations with a Monte Carlo simulation approach to assess correlation significance of primary and secondary weather variables [28,29]. Seascorr calculates correlations between tree-rings and user-specified primary weather variable, and then calculates partial correlations with a second weather variable after controlling the influence of the primary variable. We alternately specified precipitation and temperature variables as primary in multiple Seascorr analyses for different sub-periods in the tree-ring records. The season-length of climate signals in the tree-ring series was identified with monthly moving windows for 56 seasons. Temporal instability of the relationships was estimated with the difference-of-correlation test [30], which divides the interval of climatic observations into two sub-periods. The Seascorr functions were calculated with historical observations of monthly temperature and precipitation from the Almaty station.

Time series variations were summarized in the frequency domain by smoothed periodogram spectral analysis [31] and wavelet analysis [32]. The raw periodogram was smoothed with a succession of Daniell filters such that main spectral features emerged with known bandwidth confidence intervals. Confidence intervals were not adjusted for multiple comparisons (e.g., no Bonferroni adjustment). In wavelet calculation, the applied Morlet wavelet (6.0/6) estimates the relative power at a certain scale and a certain time, and summarizes changes in amplitude of or frequency oscillations as a function of time.

Self-calibrated Palmer Drought Severity Index (PDSI) downloaded from GHCN-M v.2/v.3 data set (www.climexp.knmi.nl) was used to evaluate variations on the soil moisture at two grid points 43° N–77° E and 45° N–81° E [33]. Monthly time series of the Arctic Oscillation index (AO) were downloaded from the NOAA/ESRL website (www.esrl.noaa.gov). The monthly series were averaged for winter (December–February) and spring (March–April) seasons, and smoothed for comparison with climatic instrumental variables.

3. Results

3.1. Apple Growth Variations

Individual-tree ring-width chronologies were developed from 12 plots spanning 48 to 129 years in length. Inter-serial correlations were from 0.42 to 0.64 ($p < 0.01$). Growth patterns from CH and TP were distinct from all other plots (Figure 2) and were excluded from the composite chronologies. Our field observations indicate that they contained hybrids of wild and inter-planted cultivated varieties. The hybrids may reflect selection for specific growth traits not represented in the larger wild population. CH and TP are located in the vicinity of former collective-farm gardens and cultivated apple tree plantations where records indicate the use of hybrids. The Jungar and Trans-Ili plots formed distinct clusters of ring-width variations. While some between-plot differences are evident these differences were not statistically significant (Figure 4). The Jungar cluster includes 7 plots from the Kok-Jota, Maslov Griva and Lepsy Valleys, and the Trans-Ili cluster includes 3 plots from Turgen Valley (Figure 2). Little variance in apple ring-width variance was associated with slope and elevation gradients. The tree-ring series from highly correlated plots resulted in two composite tree-ring records, Jungar and Trans-Ili (Figure 5). Length of the Jungar and Trans-Ili chronologies are 116 and 129 years, respectively.

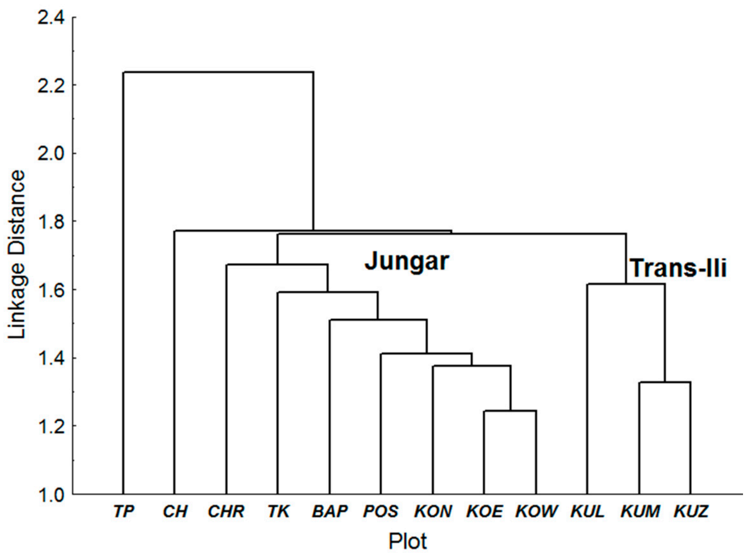


Figure 4. Dendrogram derived from cluster analysis of 12 plot chronologies of apple ring widths (Table S1) calculated with single linkage of Ward minimum variance method.

Comparison of the Almaty and Panfilov instrumental data show similar climate patterns for the common period of record (1960–1992) (Figure S2). Both stations are warm or cold, wet or dry, in the same years, though as expected spring is warmer in Panfilov than in Almaty. This indicates that the two stations are subject to the same regional variation, and that the much longer instrumental record from Almaty can be used in the response function analyses for both Trans-Ili and Jungar.

Both composite chronologies show considerable annual variation in apple growth and longer-period variance changes frequency in the late 1970s (Figure 5). Wavelet analysis confirms that prominent decadal variability is lost in both chronologies in the late 1970s, with a corresponding increase in quasi-biennial (2–3 and 3–4 year) variation. Spectral analyses indicate significant ($\alpha = 0.05$) peaks at 11.6 year, 7.1 year and 3.3 year in the Jungar, and at 21.8 year and 6.3 year in the Trans-Ili ring variance. The spectral peaks are in agreement with significant modes of variability seen in winter atmospheric oscillations such as the Siberian High index (SH), East Asian Winter Monsoon (EAWM) and Arctic Oscillation [34–36].

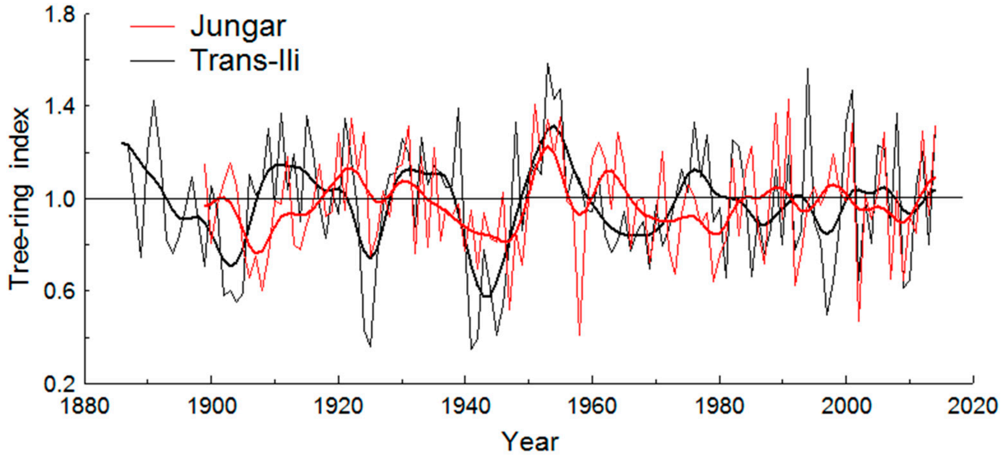


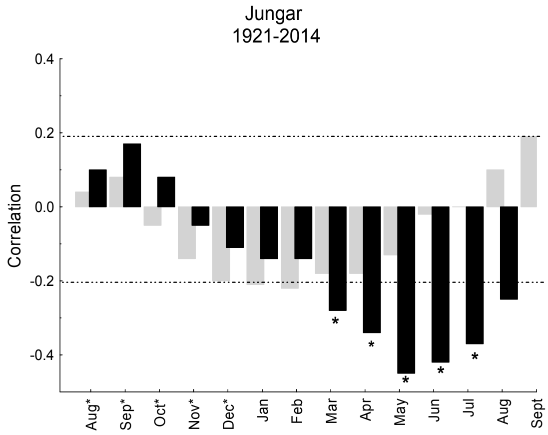
Figure 5. Composite tree-ring chronologies of wild apples from the Jungar Alatau (red) and Trans-Ili Alatau (black). The chronologies correlate significantly for common interval 1899–2014, $r = 0.30$ $p < 0.05$. Thick line is 10-year Tukey filter smoothed curve emphasizing the decadal variability. Sample size of the composite chronologies is shown in Figure S1. Table 1 shows main statistics of the composite chronologies.

Neither chronology incurred persistent growth suppression coincidental to the change in periodicity. Radial growth was low in the 1900s, 1920s, and 1940s in both regions, and in the 1960s at Jungar. The highest observed growth was between 1950–1960. Temporal variations of annual apple growth are more pronounced in the Trans-Ili region. General correspondence of apple ring growth variations ($r = 0.30$, $p < 0.05$ for the common period 1899–2014) suggests that one or more common factors limit apple growth across the studied 400-km span, but that local factors also influence tree growth.

3.2. Apple Growth Response to Climate

The Seascorr analysis indicates that annual variability of apple radial growth is sensitive to fall-winter temperatures and spring precipitation (Figure 6). Both temperature and moisture significantly impact apple tree growth, yet the relationship between these two limiting factors in the Trans-Ili Alatau shows a shift ca. 1970 (Table 2). The instability is temporally coincidental with changes in periodicity of tree-ring indices described in the section above. Growth at Jungar for the entire record is negatively associated with spring (April–May) precipitation (Figure 6A). Similarly, growth at Trans-Ili over the entire period of record is negatively associated with spring precipitation, but is also negatively associated with warm fall-winter temperature (Figure 6B). However, the Trans-Ili relationships are not stable, and closer examination revealed that the strong negative association between radial growth and warm winters identified in the pre-1970s period switches to a strong negative association with spring precipitation in the 1970s, which aligns the growth response in the Trans-Ili with that of Jungar (Figure 6A). Consequently, the spring weather conditions became more and more influential to the apple ecology in recent decades. The growth rates of apple after ca. 1970 change faster from one year to another (Figure 5) when the importance of spring moisture increases.

(**A**)



(**B**)

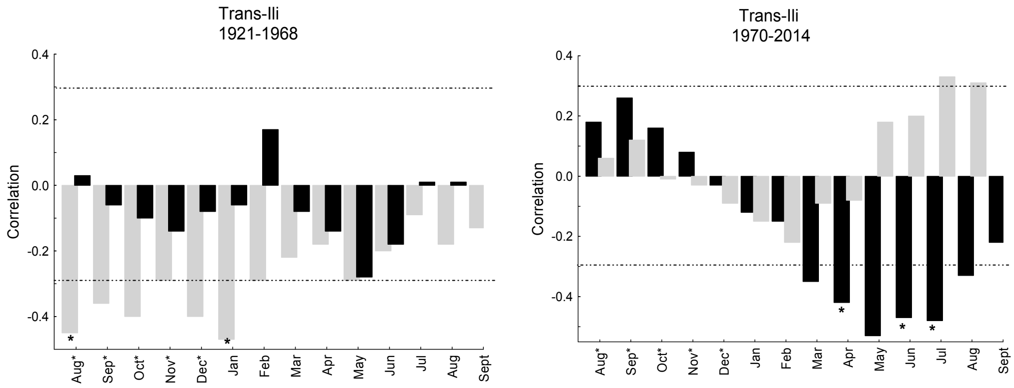


Figure 6. Primary and partial correlation of 3-month seasons calculated in Seascorr program. (**A**) TRW index of the Jungar composite chronology with Almaty temperature (T) and precipitation (P) for interval 1921–2014 (full period); (**B**) TRW index of Trans-Ili composite chronology correlated with Almaty T and P for interval 1921–1968 (early period) and 1970–2014 (late period). Black shows primary P-variable and grey is secondary T-variable (partial correlation). For the interval 1921–1968, T is primary variable and P is secondary with the same color-coding of climatic variables. Dash line marks significant level of correlation at $p < 0.05$, and * denotes season of the highest correlation at $p < 0.01$. *Y*-axis labels the end month of 3-month grouping season.

Table 2. Strength of seasonal climate signals the composite tree-ring chronology estimated with the instrumental record at Almaty station. Statistics are shown for the full instrumental period and two instrumental periods of equal length, early (1921–1967) and late (1968–2014), as our analyses show that the temporal structure of the signal changed shortly after ca. 1970 and Seascorr splits series into periods of equal length. Furthermore, the Trans-Ili subperiod comparisons assess how the signals behave within the 1921–1967 (early) and 1968–2014 (late) periods. Correlations are computed in Seascorr with precipitation (P) and partial correlations for temperature (T), except one case where the asterisk denotes temperature is primary and precipitation is secondary. ΔZ is the difference between transformed correlations for the early and late periods [29]. The *p*-value tests the null hypothesis that the population sample correlations for the early and late period are the same. Bold marks ΔZ with significant difference between the correlations of investigated subperiods.

Season	Correlation Intervals			Test Statistics	
	Full	Early	Late	ΔZ	*p*
Jungar					
March–May P	1921–2014 −0.45	1921–1967 −0.37	1968–2014 −0.52	0.19	0.37
Trans-Ili					
March–May P	1921–2014 −0.33	1921–1967 −0.16	1968–2014 −0.55	0.46	0.03
Trans-Ili Subperiods					
* November$_{year1}$–January T	1921–1968 −0.47	1921–1944 −0.49	1945–1968 −0.46	−0.04	0.89
March–May P	1970–2014 −0.53	1970–1992 −0.54	1993–2014 −0.55	0.01	0.99

4. Discussion

The frequency of annual ring-width variability at both Jungar and Trans-Ili locations has changed after ca. 1970. The Trans-Ili ring widths showed clear evidence for associating this variance shift to the change in climate. Prominent decadal variability was lost in the 1970s, with a corresponding increase in quasi-biennial variation. Tree radial growth in the Trans-Ili region shifted from being primarily negatively associated warm winter temperature prior to ca. 1970 (i.e., warm winters are unfavorable) to being primarily negatively associated with increased spring precipitation after ca. 1970 (i.e., wet spring conditions are unfavorable). Radial growth at Jungar was consistently negatively associated with spring precipitation amounts.

Apple radial growth shows high sensitivity to spring precipitation. The negative relationship is most likely related to delayed growth initiation caused by cooler soil temperatures and reduced oxygen availability maintained by excessive spring moisture [7]. The negative effects of excess soil moisture counteract the effects of warming spring ambient temperatures on springtime growth.

Growth sensitivity to warmer fall and winter temperatures is harder to explain, especially given that the negative association with winter temperature was diminished at Trans-Ili as winter temperature increased. Possible explanations include (a) effects on spring vegetative phenology and (b) relative changes in variability of winter temperatures and spring precipitation. Springtime apple vegetative phenology has both chilling and heat requirements and is favored by the combined effects of fall/winter cold and spring heat [37–39]. For example, if cooler than normal conditions occur during years with increased spring precipitation, the onset of radial growth could be delayed. The genetic and physiological processes occurring in trees during winter chill accumulation are poorly understood, and chilling requirements and phenological responses of a given species can vary between regions [40,41]. The shift in the climatic response of apple rings from temperature to precipitation in recent decades is only pronounced in the Trans-Ili Alatau (west) region where plot growth conditions are wetter than in the Jungar Alatau plots. After the 1970s, spring precipitation corresponds with temperature decreases, and a positive trend slows significantly until ca. 2002 (Figure 7). The combination of decreased spring precipitation and rapidly warming winter temperatures is concurrent with the shift in apple growth response to climate, but additional study is necessary to determine the mechanisms involved.

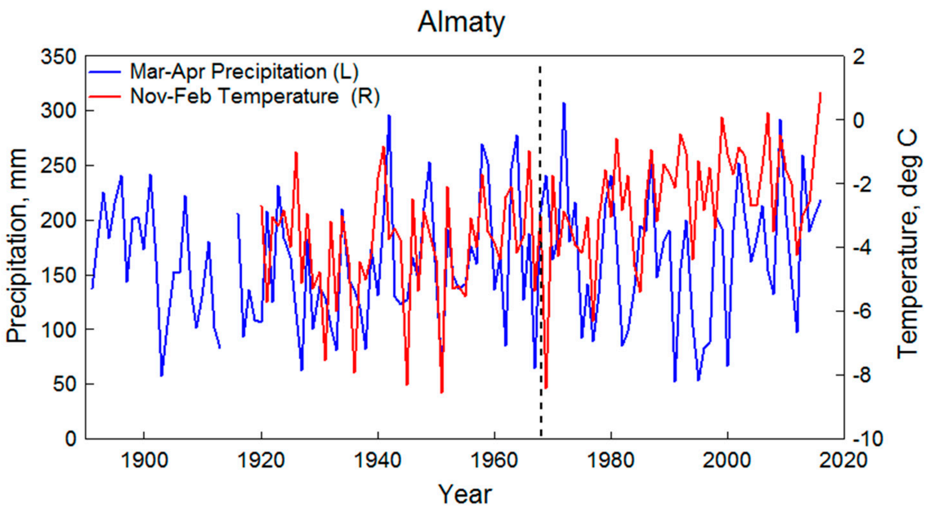


Figure 7. Variations of spring precipitation (blue line) and fall-winter temperature (red line) recorded at Almaty station. Blue line is precipitation and dashed line is temperature. Consistent discrepancy between these variables occurred after 1969 and is marked with dashed vertical line.

Greater variability in moisture with warmer climate is associated with the shift in ring-width variability response from temperature to moisture. Moisture was more consistent prior to 1960 when fall-winter temperature was the primary variable associated with tree growth. Variable moisture after ca. 1970, under a warmer regime, could have caused the shift in which variable tree growth is primarily responsive to precipitation, since trees respond to both climatic variables; tree growth will vary with the variable exhibiting the greatest variance. This would be especially true if there is a threshold limiting tree response to winter temperatures.

We cannot compare site-specific moisture and temperature conditions because of the lack of weather station data at the study sites. However, the Almaty (in the Trans-Ili but at a lower elevation) weather station shows that temperature increases and soil moisture availability decreases as indicated by PDSI after 1970 in both winter and spring (Figure S2). Although there are obvious signs of poor forest health in that large portions of tree crowns are dead and foliage is sparse, the onset of any decline is not evident in radial growth patterns and our data does not show a corresponding long-term suppression. Lack of a persistent decline in the composite chronologies is not surprising because we analyzed data from the most vigorous trees.

Recent changes in climatology of springtime and wintertime in the Lake Balkhash Basin are implicated in the apple growth observations. Instrumental weather observations show that the climate of southeastern Kazakhstan has been warming significantly over the last century. Fall-winter temperature (November–February) has increased 3 °C (Figure S2a), and the rate of warming does not vary much across the studied region. Spring temperature (March–May) shows a slightly smaller warming trend for the same time period. Since the 1920s, spring temperature increased 2.2 °C at Almaty (Figure S2b) and 1 °C at Panfilov. The long-term anomalies of winter precipitation indicate decreasing snow depth almost everywhere between 1940 and 1990 [42,43]. Snow depth decreased about 8–14 cm below 2000 m *a.s.l.* in the studied region [42]. Moisture was more consistent prior to 1960 when winter temperatures were the primary influence on growth variability. Inconsistent moisture after ca. 1970 could have caused the switch to moisture as a driver, especially in the wetter Trans Ili region (Figure S2c,d).

Wintertime and springtime precipitation characteristics are spatially variable over Inner Eurasia. Variations of winter snow in the Lake Balkhash Basin appear to be opposite to those in western and southern Siberia [44]. Yet spring precipitation is more homogeneous across Inner Eurasia, with a gradual increase from the northwest to the southeast across China. Variability of winter-spring hydroclimate is controlled by the Arctic Oscillation (AO), and its teleconnections with the Siberian High-Pressure System (SH) and the East Asian winter monsoon (EAWM). The intensity of SH and EAWM were considerably weakened from the late 1970s to 1990s, which was associated with a steady decrease of snow cover and warmer winters over Northern Eurasia and increased intensity of the AO [34,35]. A positive phase of AO is associated with decreasing winter snow over Northern Eurasia [45,46]. In springtime, a positive AO represents increasing precipitation. Numerical modeling and instrumental observations indicate a strong shift in the AO decadal variability in the late 1980s, which resulted in decreased snow cover over Siberia for the next decade but increased spring rainfall in Inner Eurasia [44–46]. In our context, both winter precipitation and spring precipitation contribute to the increased moisture variability during the growth onset after the late 1980s (Figure S2c,d).

Shifts seen in periodicity of annual ring-width variability at both Jungar and Trans-Ili, and in the climatic response that is primarily associated with ring width at Trans-Ili correspond to changes in atmospheric circulation patterns over Northern and Inner Eurasia during the winter and spring periods [47]. The highest positive AO anomaly for the instrumental interval occurred between 1990 and 2000 for both seasons (Figure 8). Thus, our tree-ring analyses suggest that changes in wild apple forest growth may be linked to changes in winter-spring climatology driven by the changes in decadal variability of atmospheric circulation in the Northern Hemisphere. Implications of our results to forest health are unclear. Data and analyses presented here were designed to identify climate variables and patterns associated with radial growth, not to assess disturbance-related declines.

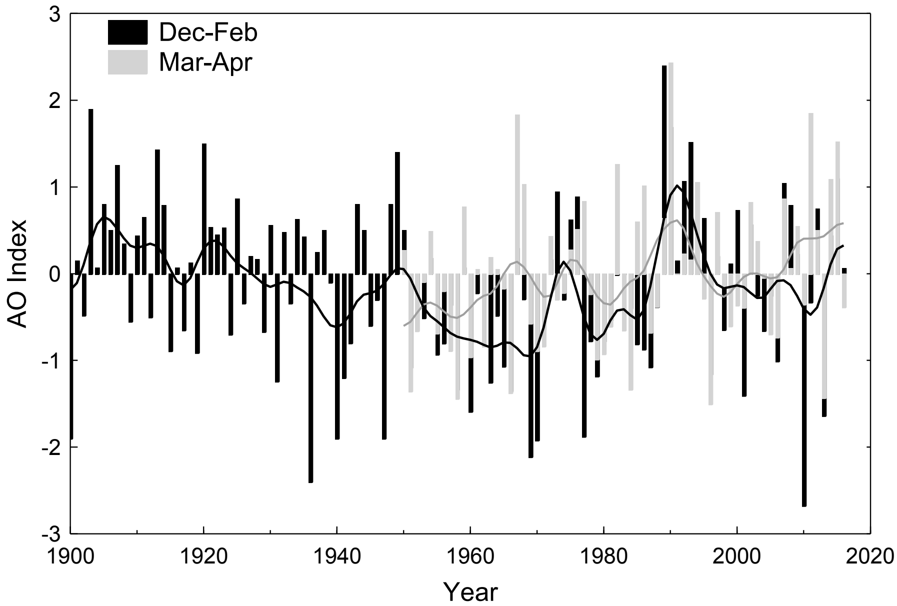


Figure 8. Arctic Oscillation index for winter (December–February) and spring (March–April) seasons from 1900 or 1950 to 2016 (black and grey bars, respectively). Decadal variability of the index is shown with a 10-year Turkey filter smoothed curve (black for winter and grey for spring).

5. Conclusions

The *M. sieversii* tree-ring chronologies are the first developed for wild apple. They characterize spatial–temporal patterns of apple growth variability over the last century in southeast Kazakhstan. Growth variability is similar in two mountain ranges located 400 km apart. Growth was greatest in 1950–1965, and least in 1938–1950. The spectral properties of growth variability changed in response to climate change, with decadal variability dominant before the late 1970s and quasi-biennial (2–3 year) variability prevailing in more recent decades. The change of signal occurred around the same time that the climatic response of apple growth in the Trans-Ili Alatau shifted from one climate variable (negative association with warm winter temperatures) to another (increased negative association with spring precipitation). The apple occupies a wide range of environmental conditions, and radial growth is highly sensitive to the combined effects of both fall/winter temperature and spring precipitation. Thus, wild apple growth patterns are associated with changes of winter and spring climatology in the Lake Balkhash Basin driven by unprecedented intensified Arctic Oscillation in winter-spring time after the late 1970s.

It is important to be aware of linkages between large-scale atmospheric circulation patterns and regional scales of climate change, and of the forest growth response to the regional climate variability. Drought conditions are obviously important to forest ecology in the arid Central Asia, but spring moisture surpluses also have an important influence on wild fruit wood forests of mountain foothills and this needs to be better understood.

Supplementary Materials: The following are available online at www.mdpi.com/1999-4907/8/11/406/s1, Figure S1: Number of tree samples averaged into the composite ring chronologies. Red line is Jungar and black line is Trans-Ili series; Figure S2: Trends in variability of temperature and moisture at the studied locations of Jungar Alatau and Trans-Ili Alatau. Plotted instrumental data show (**a**) Fall-winter temperature (November–February) and (**b**) Spring temperature (March–May) observed at the Panfilov station (Blue line) in Jungar and the Almaty weather station (Red line) in Trans-Ili; (**c**) Winter PDSI and (**d**) Spring PDSI series from grid 44° N–80° E (Jungar) and grid 43° N–77° E (Trans-Ili) measuring the variations of soil moisture. Red and blue lines show variables for the full interval. Grey line shows the early period of observations and black line—the late period (see related Seascorr calculation results in Table 2). Solid straight line shows linear regression fit with 95% confidence intervals (dash line); Table S1: Statistics of 12 plots sampled to study wild apple growth across the Jungar Alatau and Trans-Ili Alatau in the southern Kazakhstan. Plot locations are shown in Figure 1.

Acknowledgments: The research was support by Science Committee of Ministry of Education and Science of Republic of Kazakhstan (Program 217, Section 1.8 "Efficient use of natural resources, raw materials and products", award 4165/GF4) and the U.S. Forest Service, Rocky Mountain Research Station Research Joint Venture Agreement 12-JV-11221633-161 with the University of Arizona. We are thankful to field assistance and support to administration and foresters of the Jungar and Trans-Ili Alatau National Parks, and Forestry Committee of the Ministry of Agriculture, Republic of Kazakhstan.

Author Contributions: Irina P. Panyushkina, Ann M. Lynch, Nurjan S. Mukhamadiev and Abay O. Sagitov conceived, designed and analyzed the experiment; Christopher D. O'Connor, Nursagim A. Ashikbaev, Danyar Abjanbaev and Gulnaz Z. Mengdbayeva were primarily responsible for field data collection; Alexis H. Arizpe performed crossdating and ring-width measurements and contributed to data interpretation; Irina P. Panyushkina wrote the first draft and made the revisions, Ann M. Lynch and Christopher D. O'Connor completed the final version of manuscript. All authors took a part in the data analysis.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cornille, A.; Giraud, T.; Smulders, M.J.M.; Roldán-Ruiz, I.; Gladieux, P. The domestication and evolutionary ecology of apples. *Trends Genet.* **2014**, *30*, 57–65. [CrossRef] [PubMed]
2. Forte, A.V.; Ignatov, A.N.; Ponomarenko, V.V.; Dorokhov, D.B.; Saveleyev, N.I. Phylogeny of the *Malus* (apple tree) species, inferred from the morphological traits and molecular DNA analysis. *J. Genet.* **2002**, *38*, 1150–1160.
3. Maxted, N.; Kell, S. Establishment of a Global Network for the. In *Situ Conservation of Crop Wild Relatives: Status and Needs*; FAO Commission on Genetic Resources for Food and Agriculture: Rome, Italy, 2009.
4. Duan, N.; Bai, Y.; Sun, H.; Wang, N.; Ma, Y.; Li, M.; Wang, X.; Jiao, C.; Legall, N.; Mao, L.; et al. Genome re-sequencing reveals the history of apple and supports a two-stage model for fruit enlargement. *Nat. Commun.* **2017**, *8*, 249. [CrossRef] [PubMed]
5. Velasco, R.; Zharkikh, A.; Affourtit, J.; Dhingra, A.; Cestaro, A.; Kalyanaraman, A.; Fontana, P.; Bhatnagar, S.K.; Troggio, M.; Pruss, D.; et al. The genome of the domesticated apple (*Malus* × *domestica* Borkh.). *Nat. Genet.* **2010**, *42*, 833–839. [CrossRef] [PubMed]
6. Zhukovsky, P.A. *Cultivated Plants and Their Ancestors*; Nauka: Leningrad, USSR, Russia, 1971; p. 79.

7. Dzhangaliev, A. The wild apple tree of Kazakhstan. *Hortic. Rev.* **2003**, *29*, 63–304.
8. Luby, J.; Forsline, P.; Aldwinckle, H.; Bus, V.; Geibel, M. Silk road apples—Collection, evaluation, and utilization of *Malus sieversii* from Central Asia. *HortScience* **2001**, *36*, 225–231.
9. Baranov, V.I. *Development of Tertiary Flora on the Territory of USSR*; Scientific Bulletin of Kazan University: Botany, Kazan, Russia, 1954; Volumes 3, p. 362.
10. Beer, R.; Kaiser, F.; Schmidt, K.; Ammann, B.; Carraro, G.; Grisa, E.; Tinner, W. Vegetation history of the walnut forests in Kyrgyzstan (Central Asia): Natural or anthropogenic origin? *Quat. Sci. Rev.* **2008**, *27*, 621–632. [CrossRef]
11. Aizen, V.B.; Aizen, E.M.; Melack, J.M. Precipitation, melt and runoff in the northern Tien Shan. *J. Hydrol.* **1996**, *186*, 229–251. [CrossRef]
12. World Conservation Monitoring Centre. *IUCN Red List of Threatened Plants*; Walter, K.S., Gillett, H.J., Eds.; World Conservation Union: Gland, Switzerland; Cambridge, UK, 1998; p. 862.
13. Cornille, A.; Gladieux, P.; Smulders, M.J.M.; Roldan-Ruiz, I.; Laurens, F.; Le Cam, B.; Nersesyan, A.; Clavel, J.; Olonova, M.; Feugey, L.; et al. New insight into the history of domesticated apple: Secondary contribution of the European wild apple to the genome of cultivated varieties. *PLoS Genet.* **2012**, *8*, e1002703. [CrossRef] [PubMed]
14. Esper, J.; Schweingruber, F.H.; Winiger, M. 1300 years of climatic history for Western Central Asia inferred from tree-rings. *Holocene* **2002**, *12*, 267–277. [CrossRef]
15. Solomina, A.; Maximova, A.; Cook, A. Picea Schrenkian ring width and density at the upper and lower tree limits in the Tien Shan Mountains (Kirgizstan Republic) as a source of paleoclimatic information. *Geogr. Environ. Sustain.* **2014**, *7*, 66–79. [CrossRef]
16. Zhang, T.; Yuan, Y.; He, Q.; Wei, W.; Diushen, M.; Shang, H.; Zhang, R. Development of tree-ring width chronologies and tree-growth response to climate in the mountains surrounding the Issyk-Kul Lake, Central Asia. *Dendrochronologia* **2014**, *32*, 230–236. [CrossRef]
17. Seim, A.; Omurova, G.; Azisov, E.; Musuraliev, K.; Aliev, K.; Tulyaganov, T.; Nikolyai, L.; Botman, E.; Helle, G.; Dorado Liñan, I.; et al. Climate Change Increases Drought Stress of Juniper Trees in the Mountains of Central Asia. *PLoS ONE* **2016**, *11*, e0153888. [CrossRef] [PubMed]
18. Feng, T.; Zhang, Y.; Chen, X. Study on the age structure and density of the wild apple forest of *Malus sieversii*. *J. Fruit Sci.* **2007**, *24*, 571–573.
19. Routson, K.J.; Routson, C.C.; Sheppard, P.R. Dendrochronology reveals planting dates of historic apple trees in the southwestern United States. *J. Am. Pomol. Soc.* **2012**, *66*, 9–15.
20. Sagitov, A.O.; Mukhamadiev, N.S.; Ashikbaev, N.J.; Mendibaeva, G.J.; Panyushkina, I.P.; Lynch, A.M.; O'Connor, C.D. Toward dendrochronological research of wild apple forests in the southeastern Kazakhstan. In Proceedings of the Innovative and Environmentally Friendly Technologies for Plant Protection, Almaty, Kazakhstan, 24–25 September 2015; pp. 171–175.
21. Vavilov, N. Wild relatives of fruit trees in the Asian part of USSR and the origin of fruit trees. In *Works on the Applied Botany, Genetics, Artificial Selection*; USSR: Frunze, The Republic of Kyrgyzstan, 1931; pp. 3–44.
22. Stokes, M.A.; Smiley, T.L. *An Introduction to Tree-Ring Dating*; University of Chicago Press: Chicago, IL, USA, 1968; p. 73.
23. Holmes, R.L. Computer-Assisted Quality Control in Tree-Ring Dating and Measurement. *Tree-Ring Bull.* **1983**, *43*, 69–78.
24. Cook, E.R.; Kairiūkštis, L. *Methods of Dendrochronology: Applications in the Environmental Sciences*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1992; p. 394.
25. Cook, E.R.; Holmes, R.L. User's manual for Program ARSTAN. In *Tree-Ring Chronologies of Western North America: California, Eastern Oregon and Northern Great Basin with Procedures Used in the Chronology Development Work Including Users Manuals for Computer Programs COFECHA and ARSTAN*; Holmes, R.L., Adams, R.K., Fritts, H.C., Eds.; University of Arizona: Tucson, AZ, USA, 1986; pp. 50–65.
26. Ward, J.H. Hierarchical Grouping to Optimize an Objective Function. *J. Am. Stat. Assoc.* **1963**, *58*, 236–244. [CrossRef]
27. StatSoft, Inc. STATISTICA (Data Analysis Software System), Version 8.0. 2007. Available online: www.statsoft.com (accessed on 24 October 2017).
28. Haan, C.T. *Statistical Methods in Hydrology*, 2nd ed.; Iowa State Press: Ames, IA, USA, 2002; p. 496.

29. Meko, D.M.; Touchan, R.; Anchukaitis, K.J. Seascorr: A MATLAB program for identifying the seasonal climate signal in an annual tree-ring time series. *Comput. Geosci.* **2011**, *37*, 1234–1241. [CrossRef]
30. Snedecor, G.W.; Cochran, W.G. *Statistical Methods*, 8th ed.; Iowa State University Press: Ames, IA, USA, 1989; p. 503.
31. Bloomfield, P. *Fourier Analysis of Time Series: An Introduction*, 2nd ed.; Wiley: New York, NY, USA, 2000; p. 261.
32. Torrence, C.; Compo, G.P. A Practical Guide to Wavelet Analysis. *Bull. Am. Meteorol. Soc.* **1998**, *79*, 61–78. [CrossRef]
33. Harris, I.; Jones, P.D.; Osborn, T.J.; Lister, D.H. Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 Dataset. *Int. J. Climatol.* **2014**, *34*, 623–642. [CrossRef]
34. Wu, B.; Wang, J. Winter Arctic Oscillation, Siberian High and East Asian Winter Monsoon. *Geophys. Res. Lett.* **2002**, *29*, 3-1–3-4. [CrossRef]
35. Jhun, J.; Lee, E. A New East Asian Winter Monsoon Index and Associated Characteristics of the Winter Monsoon. *J. Clim.* **2004**, *17*, 711–726. [CrossRef]
36. D'Arrigo, R.; Jacoby, G.; Wilson, R.; Panagiotopoulos, F. A reconstructed Siberian High index since A.D. 1599 from Eurasian and North American tree rings. *Geophys. Res. Lett.* **2005**, *32*. [CrossRef]
37. Kalmykov, S.S. *Wild Fruit Trees of Western Tien Shan*; Alma-Ata: Almaty, Kazakhstan, 1956; p. 101.
38. Linkosalo, T. Mutual regularity of spring phenology of some boreal tree species: Predicting with other species and phenological models. *Can. J. For. Res.* **2000**, *30*, 667–673. [CrossRef]
39. Luedeling, E.; Zhang, M.; Girvetz, E.H. Climatic changes lead to declining winter chill for fruit and nut trees in California during 1950–2099. *PLoS ONE* **2009**, *4*, e6166. [CrossRef] [PubMed]
40. Luedeling, E.; Brown, P.H. A global analysis of the comparability of winter chill models for fruit and nut trees. *Int. J. Biometeorol.* **2011**, *55*, 411–421. [CrossRef] [PubMed]
41. Menzel, A.; Sparks, T. Temperature and plant development: Phenology and seasonality. In *Plant Growth Climate Change*; Blackwell Publ.: Oxford, UK, 2006; pp. 70–95.
42. Aizen, V.B.; Aizen, E.M.; Melack, J.M.; Dozier, J. Climatic and Hydrologic Changes in the Tien Shan, Central Asia. *J. Clim.* **1997**, *10*, 1393–1404. [CrossRef]
43. Shiklomanov, A.I.; Lammers, R.B.; Lettenmaier, D.P.; Polischuk, Y.M.; Savichev, O.G.; Smith, L.C.; Chernokulsky, A.V. Hydrological changes: Historical analysis, contemporary status, and future projections. In *Regional Environmental Changes in Siberia and Their Global Consequences*; Springer: New York, NY, USA, 2013; pp. 111–154.
44. Zuo, Z.; Zhang, R.; Wu, B.; Rong, X. Decadal variability in springtime snow over Eurasia: Relation with circulation and possible influence on springtime rainfall over China. *Int. J. Climatol.* **2012**, *32*, 1336–1345. [CrossRef]
45. Cohen, J.; Saito, K.; Entekhabi, D. The role of the Siberian high in northern hemisphere climate variability. *Geophys. Res. Lett.* **2001**, *28*, 299–302. [CrossRef]
46. Panagiotopoulos, F.; Shahgedanova, M.; Hannachi, A.; Stephenson, D.B. Observed Trends and Teleconnections of the Siberian High: A Recently Declining Center of Action. *J. Clim.* **2005**, *18*, 1411–1422. [CrossRef]
47. Zhou, S.; Miller, A.J.; Wang, J.; Angell, J.K. Trends of NAO and AO and their associations with stratospheric processes. *Geophys. Res. Lett.* **2001**, *28*, 4107–4110. [CrossRef]