

## Article

# Growth Rates of Poplar Cultivars across Central Asia

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**Abstract:** *Research Highlights:* Despite a long tradition of using poplars as wood source across Central Asia, recent international breeding developments have not penetrated that region yet. This study therefore explored growth performance of 30 local and international poplar cultivars. *Background and Objectives:* The Central Asian countries are forest poor countries, which need to cover the domestic wood demand through costly imports. Therefore, fast growing trees, such as poplars, are gaining increasing attention as option to grow wood domestically. The most common cultivars date back to Soviet Union times. As recent breeding developments have not reached the region, this study aims at investigate the growth performance of a number of newly developed poplar cultivars. *Materials and Methods:* The investigated cultivars were planted as cuttings across nine sites in Kyrgyzstan, Kazakhstan, and Tajikistan between 2018 and 2020. *Results:* Under warm climate conditions, i.e., low elevations, *P. deltoides x nigra* hybrids attained highest stem volumes and biomass yields, up to 16.9 t/ha\*a after two years, followed by *P. nigra x maximoviczii* hybrids. One of the *P. deltoides x nigra* hybrids reached a tree height of 10.5 m after three years. On higher elevations, e.g., in the Pamirs and in Naryn, *P. maximoviczi x trichocarpa* hybrids and *P. trichocarpa* cultivars grew faster than the former hybrids. *Conclusions:* The cultivars explored in this study should be included into plantations or agroforestry systems that are being established, provided that land users are able to thoroughly control weeds and ensure nutrient and water supply. If sufficient weed control, nutrient supply, or water supply cannot be ensured, then land users should opt for local cultivars (e.g., Mirza Terek) or the *P. nigra x maximoviczii* hybrids or *P. trichocarpa*, in order to avoid failure.

**Keywords:** fast growing trees; poplar hybrids; poplar clones; tree height; DBH; stem volume; yield; agroforestry; Kyrgyzstan; Kazakhstan; Tajikistan

## 1. Introduction

Poplars are a major agroforestry tree across Central Asia and increasingly gain attention for fast growing tree woodlots and plantations [1]. Traditionally, poplars were planted along field borders and irrigation ditches to gain wood as construction material, without occupying much space of adjacent crop fields. During Soviet Union times, those poplar rows along field borders were propagated as tree wind breaks to reduce wind speed,

improve the micro climate, and help to increase crop yields [2–5]. Thereby, the effects on the microclimate and crop yields were the main target rather than the wood resources potentially provided from such tree wind breaks [6–8]. After disintegration of the Soviet Union, a large share of those tree wind breaks was cut down primarily for fuel wood and secondarily for timber, as the energy supply system had broken down in the course of the disintegration of the Soviet Union [1]. Now, in parts of Central Asia, e.g., in the Ferghana Valley, poplars are being planted as tree wind breaks and plantations to gain wood as a resource and as an additional income source [9]. This is in line with policy programs or strategies of the Central Asian countries, e.g., the Green Economy Program in Kyrgyzstan, the recent Strategy to Develop the Agriculture in the Republic of Uzbekistan 2020–2030, or under the Kazakhstan 2050 strategy as reviewed by [1].

During Soviet Union times, *P. bolleana*, *P. nigra*, and *P. deltoides* cultivars were brought into Central Asia to be planted in agroforestry systems and plantations [10]. Though, today the most widely distributed poplar in agroforestry systems and plantations across Central Asia is *Populus nigra* var. *pyramidalis*, in particular the local cultivar Mirza Terek, according to own field observations and personnel communications across the region. This *Populus nigra* var. *pyramidalis* originated from an area comprising Afghanistan, the Western Pamirs, and the Western Tianshan. Standardized Mirza Terek planting material was brought from Sochi into Central Asia in 1952 [11]. Until today, Mirza Terek is the typical poplar that is planted across most parts of Central Asia, while only in the northern part of Kyrgyzstan and SE Kazakhstan, *P. alba* is planted as well. Starting in the 1980s and 1990s, the knowledge on the physiology and genetics of poplars has been increasing (e.g., [12] and further literature there), which resulted in the development of new cultivars. Globally, a number of new poplar cultivars have been developed and released during the last decades through public breeding programs and developments by private businesses as listed by [13] and reviewed by [14]. In Asia, breeding programs have been carried out and are ongoing in China, India, Japan, Korea, and Kazakhstan. In Russia, poplar research and breeding are being carried out in a number of institutes in the European part of Russia. So far, these recent breeding developments of new cultivars have not entered Central Asia on a larger scale.

Against this background, this study aims at addressing that gap by starting to plant and monitor the survival and growth rates of a number of poplar cultivars across the different climates and elevations of Central Asia to take genotype  $\times$  location interactions into account [15]. This study sees itself as a first step to explore which of the cultivars or parentages, which are listed in Table 1 below, might be selected for further more systematic in-depth field trials. Yet, as a report of work in progress this study is able to report results on the survival rates after planting, growth rates immediately after planting, and during the youth development of the planted cultivars.

**Table 1.** List of poplar cultivars, corresponding parent species, and distribution across sites. Parentages refer to the following species and hybrids: PN—*P. nigra* (section Aigeiros), PD—*P. deltoides* (section Aigeiros), PT—*P. trichocarpa* (section Tacamahaca), PA—*P. alba* (section Populus), Psi—*P. simonii* (section Tacamahaca), PPa—*P. pamirica* (section Tacamahaca), PDN—*P. x canadensis* (intra-sectional), PMT—*P. maximoviczii x trichocarpa* (intra-sectional), PNM—*P. nigra x maximoviczii* (inter-sectional), and PLfND—*P. laurifolia x canadensis* (inter-sectional). The geographical location, elevation, and climate zone are given in Table 2.

Cultivar	Parentage	Almaty	Bishkek I	Bishkek II	Jalalabad	Osh	Lavar	Tup	Khorog	Naryn
Mirza Terek	PN			•	•	•	•	•		•
Pyramidalis <sup>1</sup>	PN								•	
Samsun	PD			•	•			•		
89M060	PD			•	•			•		
Oudenberg	PDN	•	•	•	•	•	•	•	•	•
Orion	PDN	•	•	•	•	•	•	•	•	•
H-8	PDN	•		•	•	•	•	•	•	
H-11	PDN	•		•	•	•	•	•	•	

Table 1. Cont.

Cultivar	Parentage	Almaty	Bishkek I	Bishkek II	Jalalabad	Osh	Lavar	Tup	Khorog	Naryn
H-17	PDN	•	•	•	•	•	•	•	•	•
H-33	PDN	•	•	•	•	•	•	•	•	•
Tiepolo	PDN			•	•			•		
Bellini	PDN			•	•			•		
Veronese	PDN			•	•			•		
Vesten	PDN	•	•			•				•
Kazakhstani	PLfND	•		•	•	•		•		
Kyzyl-Tan	PLfND						•			
H-275	PMT	•	•	•	•	•	•	•		•
Matrix-11	PMT	•	•	•	•	•	•	•		•
Matrix-49	PMT	•								
Matrix-24	PMT	•								
Fastwood 1	PMT			•	•			•	•	
Fastwood 2	PMT			•	•			•	•	
Max-3	PNM	•	•	•	•	•	•	•	•	•
Max-4	PNM	•	•			•				•
Max-1	PNM	•								
Muhle Larsen	PT			•	•		•	•	•	
Fritzi Pauley	PT	•	•	•	•	•	•	•	•	•
Trichobel	PT	•	•	•	•	•	•	•	•	•
Ozolin	PA			•	•			•		
<i>P. pamirica</i>	PPa								•	
<i>P. simonii</i>	PSi			•	•			•		

<sup>1</sup> Possibly this is also Mirza Terek.

Table 2. List of sites with their geographical location, elevation, and climate zone.

Site Name	Country	Geographical Position	Elevation [m a.s.l.]	Climate Zone <sup>1</sup>
Almaty	Kazakhstan	43.18° N 76.87° E	1014	Dfa
Bishkek I and II	Kyrgyzstan	42.92° N 74.62° E	701	Dsa
Jalalabad	Kyrgyzstan	40.94° N 72.97° E	779	Dsa
Osh	Kyrgyzstan	40.54° N 72.89° E	1022	Dsa
Lavar	Kazakhstan	43.57° N 78.09° E	572	BSk
Tup	Kyrgyzstan	42.8° N 78.49° E	1771	Dfb
Khorog	Tajikistan	37.46° N 71.61° E	2183	BSk
Naryn	Kyrgyzstan	41.42° N 75.74° E	1938	BSk

<sup>1</sup> Climate zone after [www.climate-data.org](http://www.climate-data.org) (accessed on 16 March 2021): Dfa, Dsa, Dfb—humid and hot continental climate, BSk—cold semiarid climate.

## 2. Materials and Methods

### 2.1. Planting Material

In total, 31 cultivars were planted on nine sites in 2018, 2019, and 2020, as listed in Table 1 underneath. This set of cultivars included *P. nigra* (PN, section Aigeiros), *P. deltoides* (PD, section Aigeiros), *P. trichocarpa* (PT, section Tacamahaca), *P. alba* (PA, section Populus), and *P. simonii* (Psi, section Tacamahaca), *P. pamirica* (PPa, section Tacamahaca) cultivars as well as *P. x canadensis* (PDN, intra-sectional), *P. maximoviczii x trichocarpa* (PMT, intra-sectional), *P. nigra x maximoviczii* (PNM, inter-sectional) and *P. laurifolia x canadensis* (PLfND, inter-sectional) hybrids.

All the PT, PMT, and PNM cultivars were purchased from Wald21, Germany, while the PDN cultivars H-8, H-11, H-17, H-33, Orion, Oudenberg, and Vesten were purchased from Biopoplar, Italy. The cultivars Samsun, 89M060, Tiepolo, Bellini, Ozolin, and Veronese were obtained from the Academy of Sciences in Uzbekistan. The remaining cultivars were obtained locally from project partners. All the planting material was planted in spring as cuttings with a length of 20 cm.

## 2.2. Study Sites

The study sites were distributed across Central Asia from SE Kazakhstan over Kyrgyzstan, including the Ferghana Valley, into Tajikistan (Figure 1), with the aim to capture different growth rates of the cultivars across the climate zones and elevation range relevant for the potential use of those poplar cultivars in agroforestry or plantations [15]. The final selection of the particular sites here and their different management, as explained below, are partly owed to the availability of sites and resources.

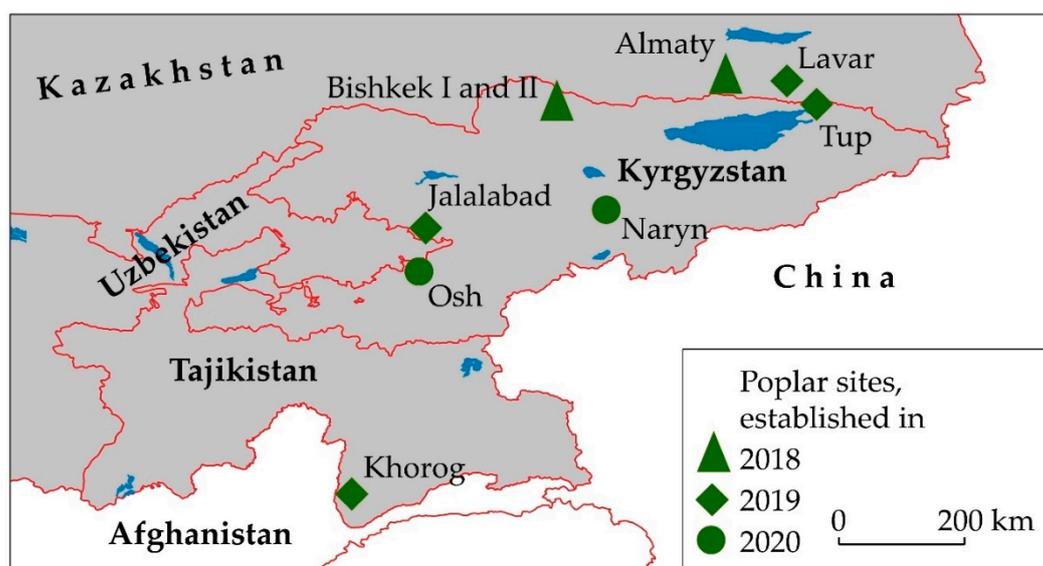


Figure 1. Location of the poplar testing sites.

The sites Almaty, Bishkek I and II, and Lavar represent the hot continental climate (Tables 2 and 3) with a pronounced rainy season in spring along the northern slopes of the Tianshan Mountains with its agricultural areas there. The sites Jalalabad and Osh represent the Ferghana Valley with a hot continental climate, too, but warmer and with a longer growing season compared to the former three sites (Tables 2 and 3). The Ferghana Valley is the area with the highest population density and a major agricultural region of whole Central Asia. The three latter sites, Tup, Khorog, and Naryn, represent higher elevations with colder climates and a shorter growing season compared to the former sites (Tables 2 and 3). Khorog and Naryn, in addition to their high elevation, are considered semiarid (Tables 2 and 3).

Table 3. Climate features at the sites ([www.weatherbase.com](http://www.weatherbase.com), accessed on 16 March 2021).

Site	Average January Temperature [°C]	Average July Temperature [°C]	Annual Precipitation [mm]	First Month of the Year with >5 °C
Almaty	−4.7	23.8	570	April: 11.5 °C
Bishkek	−2.6	24.9	452	March: 5.3 °C
Jalalabad	−1	25	430	March: 8 °C
Osh	−3.4	25.1	378	March: 6.9 °C
Lavar	−9.4	23.1	198	April: 14.9 °C
Tup	−10.7	18.5	423	April: 7.6 °C
Khorog	−6	22	260	April: 10 °C
Naryn	−16	16	300	April: 7 °C

On each site, at least one soil profile was drilled down to 100 cm. The soils of all sites are silt and loam dominated through the first 50 cm of the soil profiles. Below 50 cm, the soil profiles contain sand and loam in Bishkek I and Jalalabad, but continue with silty horizons under the other sites. All those sites are well drained. On the site Bishkek I, there

is a gradient from sandy loam to silty loam with the humus content also increasing along that gradient. The soil profile of the site Bishkek II is silty clay throughout the first 100 cm, which is not well drained. The soil in Lavar is slightly saline. According to [13], the former sites offer good to very good soil properties for poplars, while Bishkek II and Lavar offer fair to poor conditions due to their soil texture and salinity, respectively.

### 2.3. Site Management

This planting experiment was started in 2018 with the sites Almaty and Bishkek I. In 2019, the sites Khorog, Lavar, Bishkek II, Jalalabad, and Tup were started. Finally, in 2020 the sites in Osh and Naryn were added. The planting schemes and site management differed according to land, water, fertilizer, and labor availability for each of the sites (Tables 4 and 5). The site area Almaty was part of a nursery, while the two site areas in Bishkek had been unused land before starting this experiment. The sites in Tup, Jalalabad, Naryn, and Lavar belong to nursery areas of forestry enterprises and research institutes. The sites in Khorog and Osh were cropland before using them as sites within this study.

**Table 4.** Planting dates, planting schemes, and number of cuttings initially planted per site.

Site	Planting Date	Planting Scheme	Total Number of Cuttings	Cuttings Planted per ha
Almaty	18 April 2018	0.8 m × 0.2 m	242	62,500
Bishkek I	7 April 2018	0.6 m × 0.6 m to 1.2 m × 0.6 m	309	27,700 to 13,800
Bishkek II	6 April 2019	1 m × 0.6 m	743	16,700
Jalalabad	10 April 2019	0.7 m × 1.5 m	580	9500
Osh	27 May 2020	0.7 m × 0.6 m	535	23,800
Lavar	29 March 2019	1.6 m × 0.6 m	284	10,400
Tup	16 April 2019	1.4 m × 0.6 m	828	11,900
Khorog	20 March 2019	0.5 m × 0.2 m	352	100,000
Naryn	9 May 2020	1 m × 0.4 m	379	25,000

**Table 5.** Water supply, weed control, and plant nutrition by site. Ammophos contained 12% N and 52% P<sub>2</sub>O<sub>5</sub>. The NPK fertilizer contained 25.6% N, 6.6% P<sub>2</sub>O<sub>5</sub>, and 21% K<sub>2</sub>O.

Site	Water Supply	Weed Control	Plant Nutrition
Almaty	Manually by water can: Every 2–3 days from mid-May through September.	Site was covered with geo-textile.	None
Bishkek I	Drip irrigation: Every 2–3 days from mid-May to mid-September, 3rd season once per week from June to mid-September.	Manual: 1st season: every 3 weeks until July. 2nd season: once in May and June.	1st season: 3 g Ammophos and 6 g NPK fertilizer per tree. 2nd season: 16 g NPK fertilizer per tree.
Bishkek II	Drip irrigation: 1st season every 2–3 days from mid-May to mid-September, 2nd season no irrigation.	Manual: 1st season: every 3 weeks until July. 2nd season: no weed control.	1st season: 16 g NPK fertilizer per tree. 2nd season: no fertilizer.
Lavar	Furrow irrigation: 1st season: once in April, once per week in May, twice per week end of July to mid-Sep. 2nd season: every 2 weeks.	Manual: Once per month from April to July	none
Jalalabad	Furrow irrigation: 1st season: once in April, once per week in May, twice per week end of July to mid-September 2nd season: every 2 weeks during summer.	Once per month from April to July. Manual in April, May, and July, herbicide in June.	1st season: 3 g Ammophos and 6 g NPK fertilizer per tree. 2nd season: none.

Table 5. Cont.

Site	Water Supply	Weed Control	Plant Nutrition
Osh	Furrow irrigation: Twice per month from June to September.	Once per month from April to June. Manual in April, May, herbicide in June.	Manure before planting. 3 g Ammophos and 6 g NPK fertilizer per tree.
Tup	Furrow irrigation: Once per week from July to September	Mowing and manual: 1st season: 22 April and once per week during July. 2nd season: once per month.	1st and 2nd season: 3 g Ammophos and 6 g NPK fertilizer per tree.
Khorog	Furrow irrigation: Once per week from June to August.	Manual: Twice per week from June to August.	1st season: 3 g Ammophos per tree.
Naryn	Flood irrigation: Every 10 days in June, July, and August.	Manual: Once per month in June, July, and August.	None

Leaf beetles (*Chrysomela populi*) were observed to feed on the leaves of the poplars on the sites Bishkek I and Tup during their second and third season and were treated once per season with the pesticide Doxin 100 EC from Dogal Agro, Turkey. With regard to weeds, the sites in Jalalabad and Osh suffered from a higher weed coverage throughout compared to the other site, despite the use of herbicides.

On the site Almaty, all trees were cut on October 2019, except for one tree per cultivar. In Bishkek I, all trees were cut in March 2020, except for three trees per cultivar. Therefore, Almaty and Bishkek I offer data for two seasons with a higher number of trees per cultivar, but data for the third season are only based on small numbers per cultivar.

#### 2.4. Data Collection and Analysis

During the first season, the tree heights were measured at least three times during the season. These tree height measurements were continued through the second season. At the end of the second season, in addition to heights, the basal diameter, the diameters at 1 m, at 1.30 m (DBH), and at 2 m were measured to calculate the stem volume and stem biomass of each individual tree. Thereby, all trees were measured, including those on boundary rows of the sites.

The stem volumes were calculated as the sum of the volumes of the following stem sections: basis—1 m, 1 m to 1.30 m, 1.30 m to 2 m, and 2 m to the tip of the stem (or from a lower cross section to the tip of the stem for trees smaller than 2 m). The tree height was taken as stem height. The volumes of the former sections were calculated as follows:

$$V_{section} = \frac{A_{bottom} + A_{top}}{2} l$$

with  $V_{section}$ —volume of the given section,  $A_{bottom}$  and  $A_{top}$ —cross section areas at the bottom and top of the given section,  $l$ —length of the given section.

The volume of the top section was calculated as a cone volume:

$$V_{section} = \frac{1}{3} \pi r^2 l$$

with  $V_{section}$ —volume of the given section,  $r$ —radius of the cross section at the basis of this section,  $l$ —length of the given section.

The yield of dry woody biomass (BM) was calculated as follows:

$$BM = V \delta D$$

with  $V$ —stem volume,  $\delta$ —wood density, and  $D$ —tree density (number of plants per hectare).

For data analysis, mean and standard deviations were calculated by site and cultivar and analyzed by an analysis of variance in SPSS (Tukey-2 post hoc test),  $\alpha < 0.05$ ; for significant differences between cultivars by sites.

### 3. Results

The survival rates at the end of the first season were highest on the site Bishkek I with rates between 73% to 100%, followed by the sites Almaty, Lavar, and Naryn (Table S1). Thereby, on the latter three sites most cultivars had high survival rates of 70% and more, but a limited number of cultivars showed very low survival rates of below 30%, which reduced the overall survival rates per site compared to Bishkek I. For example, H-17 and H-33 had survival rates of 60% and more in Lavar and Bishkek I, but only 31% in Almaty. Also, Fritzi-Pauley had survival rates of 70% and more in Bishkek I, Almaty, and Naryn, but none of the Fritzi-Pauley cuttings survived in Lavar. On the site Bishkek I, most of the trees that did not survive were the ones planted in the sandy loam part of the site.

The survival rates on the sites Bishkek II, Jalalabad, and Tup exhibited high variability between cultivars. On those three sites, while only 10% or less of the cuttings of Orion, H-8, H-11, H-17, H-33, and Ozolin survived until the end of the first season, the cultivar Samsun showed a survival rate of 70% and more across those three sites. Other cultivars showed different survival rates across those three sites, such as Fastwood 2 with survival rates of 76%, 40%, and 30% in Bishkek II, Jalalabad, and Tup, respectively.

Survival rates by cultivar, when examined among plots, was highest for the cultivars Samsun, Max-4, and Max-3. The locally used cultivars Mirza Terek, Pyramidalis, and Pamir Poplar had survival rates of 19–100%, 64%, and 14%, respectively.

Most trees that had survived until end of the first season also survived the winter and the following second season (Table S2). On the sites Almaty, Bishkek I, Khorog, Lavar, and Tup the survival rates from the first to the second season were 90% and more by cultivar. In Jalalabad, none of the H-275, Matrix-11, Fastwood 1, and Oudenberg trees survived the winter and following second season. Less than 20% of Kazakhstani and Fritzi-Pauley survived until end of the second season. On the site Bishkek II, less than 10% of H-275, Matrix-11, Fastwood 1, Fastwood 2, Muhle-Larsen, Trichobel, and Fritzi-Pauley survived from the end of the first through the end of the second season. In addition, none of the *P. pamirica* survived the winter between the first and the second season.

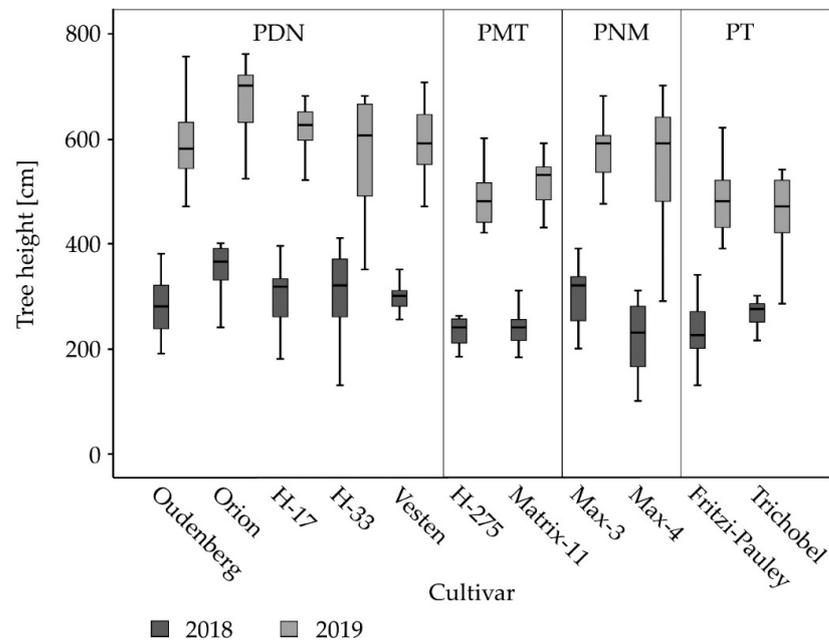
The trees, all cultivars pooled together, grew tallest on the sites Bishkek I and Almaty at the end of the first and second season (Table 6). The smallest trees at the end of the first and second season were found in Khorog, Bishkek II, and Lavar.

**Table 6.** Means  $\pm$  standard deviations of tree heights [m] of all trees per site at the end of the first and second growing season. Letters here indicate groups of sites that do not differ significantly at  $\alpha < 0.05$ .

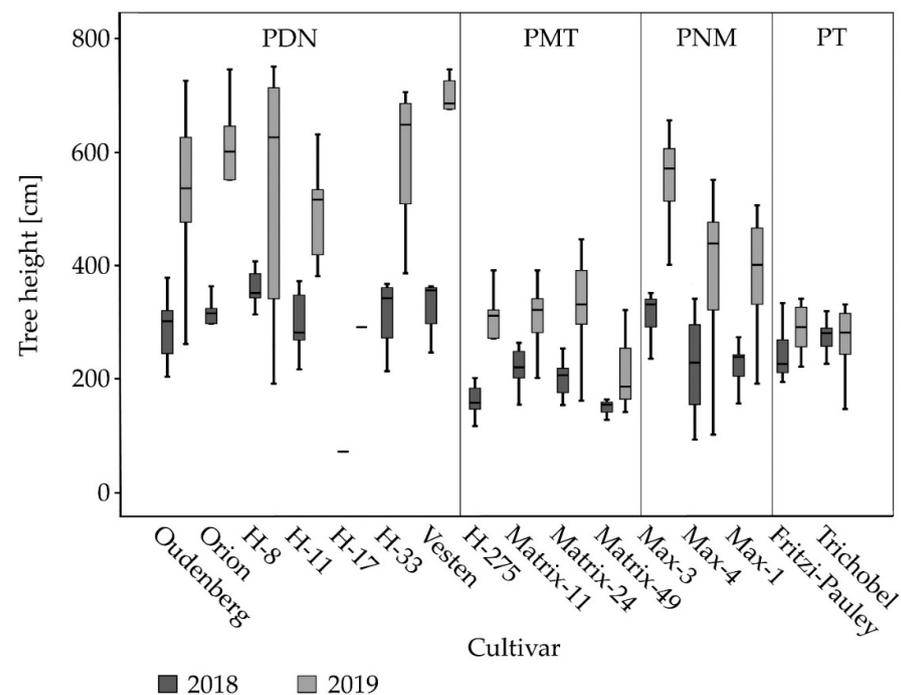
Site	Tree Height [m] at the End of the 1st Season	Tree Height [m] at the End of the 2nd Season
Almaty	254 $\pm$ 75 a	424 $\pm$ 169 b
Bishkek I	260 $\pm$ 86 a	550 $\pm$ 106 a
Bishkek II	73 $\pm$ 43 e	142 $\pm$ 55 e
Jalalabad	167 $\pm$ 68 b	334 $\pm$ 63 c
Osh	104 $\pm$ 42 d	
Lavar	48 $\pm$ 28 f	79 $\pm$ 55 f
Tup	131 $\pm$ 45 c	281 $\pm$ 61 d
Khorog	74 $\pm$ 45 e	169 $\pm$ 66 e
Naryn	107 $\pm$ 35 d	

The tree heights at the end of the first season for the sites Bishkek I and Almaty are shown in Figures 2 and 3 (dark grey bars), where the cultivars grew into the highest trees

compared across sites. On both sites, *P. x canadensis* (PDN) hybrids grew highest, followed by the *P. nigra x maximoviczii* (PNM) hybrids Max-3 and -4 as well as the *P. trichocarpa* (PT) cultivars Fritzi-Pauley and Trichobel. Of the PNM hybrids in Almaty, Max-3 attained heights comparable with the PDN hybrids. The *P. maximoviczii x trichocarpa* (PMT) hybrids ranked lowest regarding tree height at the end of the first season in these two sites.

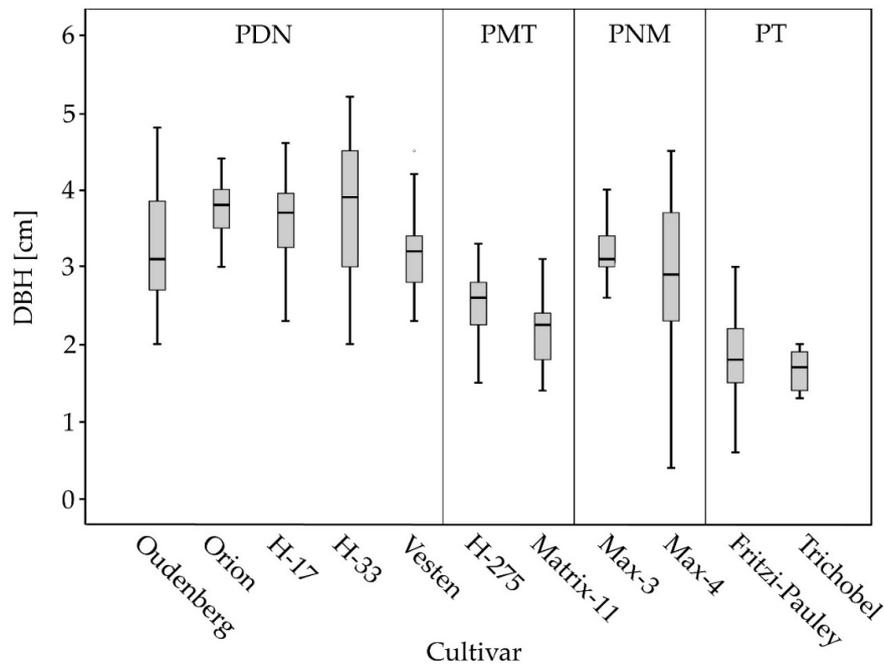


**Figure 2.** Box plots of tree heights in Bishkek I at the end of the growing seasons 2018 (dark grey) and 2019 (light grey). Parentages: PDN—*P. deltooides x nigra*, PMT—*P. maximoviczii x trichocarpa*, PNM—*P. nigra x maximoviczii*, PT—*P. trichocarpa*.

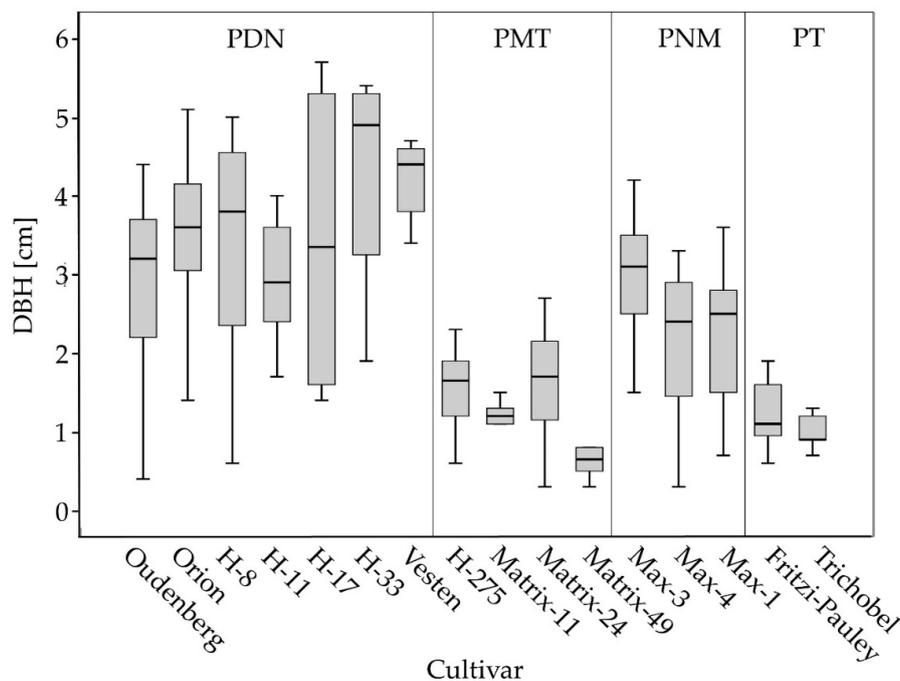


**Figure 3.** Box plots of tree heights in Almaty at the end of the growing seasons 2018 (dark grey) and 2019 (light grey). Parentages: PDN—*P. deltooides x nigra*, PMT—*P. maximoviczii x trichocarpa*, PNM—*P. nigra x maximoviczii*, PT—*P. trichocarpa*.

At the end of the second season (Figures 2 and 3, light grey bars), the PDN hybrids continued to grow highest and attained the largest stem volumes, followed by the PNM hybrids. In contrast to the first season, the PT cultivars ranked lowest with regard with tree heights and stem volumes on the site Bishkek I and similarly with the PMT hybrids in Almaty. The DBH values at the end of the second season behaved like the tree heights, with the PDN hybrids attaining the largest DBH, followed by PNM, PMT, and PT (Figures 4 and 5).

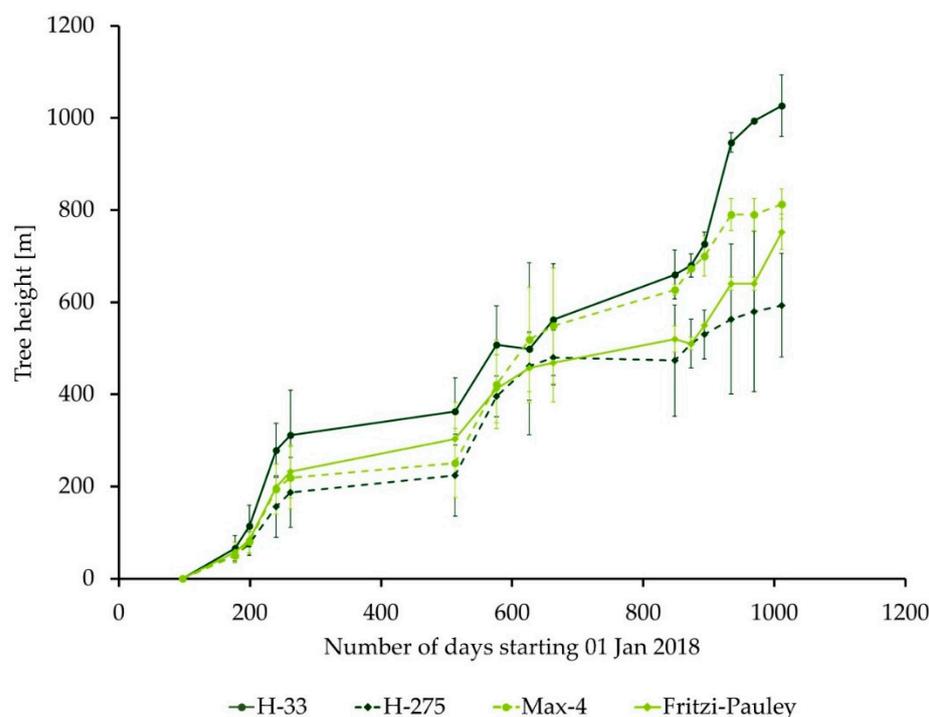


**Figure 4.** Box plots of DBH in Bishkek I at the end of the growing season 2019. Parentages: PDN—*P. deltooides x nigra*, —*P. maximoviczii x trichocarpa*, PNM—*P. nigra x maximoviczii*, PT—*P. trichocarpa*.



**Figure 5.** Box plots of DBH in Almaty at the end of the growing season 2019. Parentages: PDN—*P. deltooides x nigra*, PMT—*P. maximoviczii x trichocarpa*, PNM—*P. nigra x maximoviczii*, PT—*P. trichocarpa*.

Among the trees, which were carried on through the third season (2020), H-33, Orion, and H-17 (all PDN hybrids) clearly reached the largest stem volumes, tree heights, and DBH in Bishkek I (Figure 6, Table 7) as was already at the end of the second season (Table 8). At the end of the third season, H-33 had an average stem volume of 47.4 dm<sup>3</sup> at an average tree height of 10.2 m, and DBH 10.5 cm (Table 7). Max-4 and Max-3 attained average stem volumes of 16.1 dm<sup>3</sup> and 12.3 dm<sup>3</sup> and average tree heights of 8.1 m and 8 m, respectively, which placed Max-4 and Max-3 among the PDN hybrids Oudenberg and Vesten (Table 7).



**Figure 6.** Mean tree heights by parentage groups, expressed by one cultivar per parentage (H-33—PDN, H-275—PMT, Max-4—PNM, and Fritzi-Pauley—PT) from planting time in April 2018 to end of the third season (Oct. 2020) on the site Bishkek I.

**Table 7.** Means  $\pm$  standard deviations of tree heights [m], and DBH [cm] and stem volumes [dm<sup>3</sup>] at the end of the growing season 2020 for the site Bishkek I. From all cultivars, except for Trichobel, three trees were measured. Only one Trichobel survived until end of the growing season 2020.

Cultivar	Tree Height [m]	DBH [cm]	Stem Volume [dm <sup>3</sup> ]
Oudenberg	8 $\pm$ 0.1	5.2 $\pm$ 0.5	9.9 $\pm$ 2.3
Orion	9.5 $\pm$ 0.05	7.5 $\pm$ 0.4	21.4 $\pm$ 2.2
H-33	10.2 $\pm$ 0.5	10.5 $\pm$ 1.5	47.4 $\pm$ 12.7
H-17	8.9 $\pm$ 0.7	7.2 $\pm$ 0.6	20.5 $\pm$ 5.1
Vesten	9.3 $\pm$ 0.2	6.2 $\pm$ 0.2	14.7 $\pm$ 1.6
Max-3	8.5 $\pm$ 0.4	5.9 $\pm$ 0.9	12.6 $\pm$ 3.9
Max-4	8.1 $\pm$ 0.3	6.8 $\pm$ 0.2	16.1 $\pm$ 1.3
H-275	5.9 $\pm$ 0.9	4.2 $\pm$ 1.3	6.1 $\pm$ 3.2
Matrix-11	7.1 $\pm$ 0.3	4.8 $\pm$ 0.5	8.3 $\pm$ 2.3
Fritzi-Pauley	7.5 $\pm$ 0.3	3.7 $\pm$ 0.6	5.7 $\pm$ 2
Trichobel	3.8	1.8	0.9

**Table 8.** Means  $\pm$  standard deviations of stem volumes [ $\text{dm}^3$ ] after two growing seasons for the sites Bishkek I and II, Almaty, Jalalabad and Tup. Sample sizes, minima, and maxima are listed in Table S3. Letters indicate groups of values that do not differ significantly at  $\alpha < 0.05$ . The last row contains means  $\pm$  standard deviations by sites with all cuttings pooled together by site. Letters here indicate groups of sites that do not differ significantly at  $\alpha < 0.05$ .

Cultivar	Volume [ $\text{dm}^3$ ]. Average $\pm$ Standard Deviation				
	Almaty (2019)	Bishkek I (2019)	Bishkek II (2020)	Jalalabad (2020)	Tup (2020)
Mirza Terek			$0.14 \pm 0.03^a$	$1.8 \pm 1.2^a$	$0.7 \pm 0.5^b$
Samsun			$0.22 \pm 0.31^a$	$1.7 \pm 0.8^a$	$1.2 \pm 1^{ab}$
89M060			$0.24 \pm 0.15^a$	$1.7 \pm 0.7^a$	$1.2 \pm 0.6^{ab}$
Oudenberg	$2.5 \pm 1.7^{bcd}$	$2.9 \pm 1.5^{bc}$	$0.18 \pm 0.14^a$		$2.4 \pm 0.6^a$
Orion	$3.4 \pm 2.2^{abc}$	$4.1 \pm 1.1^a$			
H-8	$3.4 \pm 2.5^{abc}$				
H-11	$2.2 \pm 1.2^{bcd}$			$1.4 \pm 0.3^a$	
H-17	$4.1 \pm 4^{ab}$	$3.7 \pm 1.3^{ab}$	$0.07 \pm 0.03^a$		
H-33	$5.6 \pm 3.4^a$	$4.6 \pm 2.6^a$	$0.06 \pm 0.01^a$	$0.6 \pm 0.06^a$	
Tiepolo			$0.07 \pm 0.01^a$	$0.9 \pm 0.3^a$	
Bellini			$0.19 \pm 0.17^a$		
Veronese			$0.14 \pm 0.11^a$		$1.5 \pm 0.8^{ab}$
Vesten	$5.1 \pm 2^a$	$2.7 \pm 1.3^{bc}$			
Kazakhstani					$1.4 \pm 0.6^{ab}$
H-275	$0.7 \pm 0.4^d$	$1.8 \pm 0.7^{cd}$			$1.7 \pm 0.8^{ab}$
Matrix-11	$0.3 \pm 0.2^d$	$1.4 \pm 0.6^d$			$2.2 \pm 1.2^a$
Matrix-49	$0.3 \pm 0.5^d$				
Matrix-24	$0.8 \pm 0.5^d$				
Fastwood 1					$1.7 \pm 0.7^{ab}$
Fastwood 2				$0.9 \pm 0.3^a$	$2.6 \pm 0.9^a$
Max-3	$2.4 \pm 1.3^{bcd}$	$2.7 \pm 1^{bc}$	$0.34 \pm 0.34^a$	$2 \pm 0.8^a$	$1.7 \pm 0.8^{ab}$
Max-4	$1.1 \pm 0.9^d$	$2.7 \pm 1.6^{bc}$			
Max-1	$1.3 \pm 0.8^{cd}$				
Fritzi-Pauli	$0.5 \pm 0.3^d$	$1 \pm 0.5^d$	$0.13 \pm 0.05^a$	$0.6 \pm 0.3^a$	$1.2 \pm 0.4^{ab}$
Trichobel	$0.3 \pm 0.2^d$	$0.8 \pm 0.3^d$		$1.4 \pm 0.7^a$	$1.2 \pm 0.4^{ab}$
Ozolin			$0.12 \pm 0.12^a$		
P. simonii					$1.6 \pm 0.6^{ab}$
All cuttings	$1.9 \pm 2^b$	$2.6 \pm 1.7^a$	$0.2 \pm 0.2^c$	$1.5 \pm 0.8^b$	$1.4 \pm 0.8^b$

In Almaty and Bishkek I, Max-1, Max-3, and Max-4 developed leaves two to three weeks earlier than the PDN hybrids. In 2019 and 2020, a number of those trees were bent down by rain or late snow falls, but reverted back to upright trees during summer.

Annual biomass yields extrapolated to a hectare basis are listed for Bishkek I in Table 9. Only the PDN and PNM hybrids attained biomass values above the threshold of  $8 \text{ t/ha}^*a$ , which was set for being economically viable. Among the PDN hybrids, H-33 ranked first with  $14.8 \text{ t/ha}^*a$  (at a wood density of  $0.35 \text{ t/m}^3$  and tree density of 18,500 per ha), followed by Orion and H-17. Thereby, survival rates of 100% were assumed.

**Table 9.** Yield expectation table [t/ha\*a] for different tree densities between 10,000 and 20,000 trees per hectare and wood densities between 0.3 to 0.4 t/m<sup>3</sup> for each cultivar for the site Bishkek 1. The stem volumes used to calculate yields were measured at the end of the growing season 2019 as listed in Table 8. The values for wood densities were taken from own observations and center around the value of 0.35 t/m<sup>3</sup>, which is given by FAO (<http://www.fao.org/3/j2132s/J2132S16.htm>, assessed on 10 January 2021). Grey boxes mark economically viable values of more than 8 t biomass per hectare and year. The total of 18,500 plants per hectare represents the real planting density of this site. For the calculations here, a survival rate of 100% was assumed for all cultivars.

Trees per ha		10,000			15,000			18,500			20,000		
Wood Density in t/m <sup>3</sup>		0.3	0.35	0.4	0.3	0.35	0.4	0.3	0.35	0.4	0.3	0.35	0.4
Cultivar	Stem Volume [dm <sup>3</sup> ]												
Oudenberg	2.9	4.4	5.1	5.9	6.6	7.7	8.8	8.1	9.5	10.9	8.8	10.3	11.7
Orion	4.1	6.2	7.2	8.3	9.3	10.8	12.4	11.5	13.4	15.3	12.4	14.4	16.5
H-33	4.6	6.8	8.0	9.1	10.3	12.0	13.7	12.6	14.8	16.9	13.7	15.9	18.2
H-17	3.7	5.5	6.5	7.4	8.3	9.7	11.1	10.2	12.0	13.7	11.1	12.9	14.8
Vesten	2.7	4.1	4.8	5.5	6.2	7.2	8.2	7.6	8.9	10.2	8.2	9.6	11.0
Max-3	2.7	4.0	4.6	5.3	6.0	7.0	8.0	7.4	8.6	9.8	8.0	9.3	10.6
Max-4	2.7	4.1	4.8	5.4	6.1	7.1	8.2	7.5	8.8	10.1	8.2	9.5	10.9
H-275	1.8	2.7	3.1	3.6	4.0	4.7	5.4	5.0	5.8	6.6	5.4	6.3	7.2
Matrix-11	1.4	2.1	2.5	2.8	3.2	3.7	4.2	3.9	4.6	5.2	4.2	4.9	5.6
Fritzi-Pauley	1	1.5	1.7	2.0	2.2	2.6	3.0	2.8	3.2	3.7	3.0	3.5	4.0
Trichobel	0.76	1.1	1.3	1.5	1.7	2.0	2.3	2.1	2.5	2.8	2.3	2.7	3.0

In Jalalabad, with a climate warmer than Bishkek and Almaty, also the PDN hybrids were among the highest trees at the end of the first season, e.g., H-33 with an average tree height of 2.2 m. The tallest trees, though, were Veronese with an average height of 2.6 m followed by the *P. deltooides* cultivar Samsun with an average height of 2.3 m (Table S4). On the other side, the *P. deltooides* cultivar 89M060 and the PDN hybrid H-11 only attained 1.2 m and 1.6 m, respectively, as average tree heights (Table S4). By the end of the second season, Max-3 (PNM) and Mirza Terek (PN) became the tallest and largest trees with average tree heights of 3.8 m and 3.5 m and average stem volumes of 2 dm<sup>3</sup> and 1.8 dm<sup>3</sup>, respectively (Table S5). By end of the second season, the average stem volume of Max-3 (2 dm<sup>3</sup>), which was lower, but still the same range, than the corresponding stem volumes of Max-3 in Almaty (2.4 dm<sup>3</sup>) and Bishkek I (2.7 dm<sup>3</sup>). H-11 only attained an average stem volume of 1.4 dm<sup>3</sup>, which was only about two thirds of the corresponding stem volume of H-11 in Almaty at the end of the second season (Table 8 and Table S3).

H-33, which clearly attained the largest stem volume in Bishkek I and Almaty (Table 8) and was among the tallest in Jalalabad at the end of the first season, yielded the smallest stem volume in Jalalabad at the end of the second season with only 0.58 dm<sup>3</sup> (Tables S3 and S5).

In Osh, which has a similar climate as Jalalabad, the trees remained smaller at the end of first season compared to Jalalabad (Table S4). In Osh, the PDN hybrids H-8 and H-17 grew highest at the end of the first season (average tree heights of 1.4 m and 1.3 m, respectively), while other PDN hybrids were among the smallest with Vesten being the smallest with 0.7 m. Like in Bishkek I and Almaty, the PMT hybrids H-275 and Matrix-11 were among the smallest cultivars as well. Kazakhstani and the locally used Mirza Terek grew to average tree heights of 1.2 m and 1.1 m, respectively, which was almost as high as H-8 and H-17 (Table S4).

The site Lavar, which is saline, trees grew smaller across cultivars compared with nearby Almaty or Bishkek I, but also compared to Jalalabad and Osh, e.g., H-11, the tallest cultivar in Lavar in the middle of the second season, grew in average 1.80 m tall, which falls short more than 1 m compared to H-11 in Almaty already at the end of the first season. When comparing the different cultivars with each other on the site Lavar, the PDN hybrids also grew tallest (e.g., H-11 with 1 m average tree height) and the PMT hybrids H-275 and

Matrix-11 being among the smallest with 52 cm and 26 cm, respectively (Table S4). Max-3, which was among the tallest cultivars in Bishkek I and Almaty at the end of the second season, remained among the smallest cultivars in Lavar with an average height of 26 cm at the end of the second season. The locally developed cultivars Kazakhstani and Kyzyl-Tan also reached average heights of 26 cm only (Table S5).

On the site Bishkek II, the tree heights at the end of the first season were in a similar range as in Osh (Table S4), but less than half as tall as on the neighboring Bishkek I site or in Almaty (Tables 7 and 8). Though, the ranking between the cultivar groups was similar as in Bishkek I, Almaty, Jalalabad, or Lavar, with PD-cultivar 89M060, and the PDN hybrids Veronese, Oudenberg, H-33, Tiepolo, Bellini, and H-11 (average tree heights between 1 m and 1.6 m) being the tallest and Matrix-11, H-275, and the PT cultivars Muhle-Larsen and Trichobel being the smallest with average tree heights below 51 cm (Table S4). Mirza Terek, Fritzi-Pauley, Fastwood 1 and Fastwood 2 attained medium average tree heights with 90 cm, 89 cm, 71 cm, and 67 cm, respectively. In contrast to the other PDN hybrids, H-17 and H-8 remained small with 70 cm and 51 cm height. During the second season, Fritzi-Pauley showed the highest increment in terms of height, from 0.5 m to 1.8 m, while Max-3 attained the largest stem volume at the end of second season ( $0.34 \text{ dm}^3$ ). With regard to stem volume, the PD cultivar 89M060 and the PDN hybrids Samsun, Bellini, and Oudenberg ranked behind Max-3, followed by the locally used Mirza Terek (Table 8). Like in Jalalabad, but in stark contrast to neighboring Bishkek I, H-33 remained the smallest with only  $0.06 \text{ dm}^3$  stem volume (Tables S3 and S5). Most of the trees across all parentages showed signs of phosphorus deficiency, which became visible through yellowish and partly reddish leaves at the top of the stems, while basal leaves remained green. These signs did not completely disappear after fertilizer application. On the neighboring Bishkek I site, such signs of phosphorus deficiency became visible as well, but disappeared quickly after fertilizer application.

In contrast to the previous sites, the PMT hybrids (Fastwood 1, Fastwood 2, and Matrix-11) were the tallest (in Khorog) or among the tallest (in Tup) cultivars on the two sites Khorog and Tup at the end of the first season. The average tree height of Fastwood 1 was 1.6 m in Tup and 1.3 m in Khorog at the end of the first season. At the end of the second season, Fastwood 1 and 2 were still the tallest or among the tallest cultivars with 3.2 m and 3.7 m in Tup and 2.4 m and 2.3 m in Khorog, respectively). In Tup, Fastwood 2 attained the largest stem volume ( $2.6 \text{ dm}^3$ ), followed by Oudenberg (PDN), Matrix-11 (PMT), and Max-3 (PNM) as listed in Table 7. The stem volume of Oudenberg of  $2.3 \text{ dm}^3$  is lower than, but still in the range of the corresponding stem volumes in Almaty ( $2.5 \text{ dm}^3$ ) and Bishkek I ( $2.9 \text{ dm}^3$ ) at the end of their second seasons (Table S3 and Tables 8 and 9). The other PDN hybrids that had been planted in Tup had smaller stem volumes and were less tall than the PMT hybrids in Tup. In Khorog, by end of the second season the PDN hybrid Orion grew into trees as tall as Fastwood 1 and 2, while the PDN hybrids H-17 and H-11 remained among the smallest trees. On both sites, the locally used cultivars, Mirza Terek and *P. nigra* (*pyramidalis*) were among the smallest trees by end of the first and second season.

In Naryn, the third site under a cold semiarid climate, the results regarding tree heights at the end of the first season differed from the two former sites Tup and Khorog, as Orion, a PDN hybrid, grew highest (1.5 m), followed by Max-4 (PNM) with 1.2 m, and Fritzi-Pauley (PT) with 1.2 m. The PDN hybrids Oudenberg, Vesten, H-8, and Mirza Terek remained the shortest trees with average heights of 71 cm, 76 cm, 92 cm, and 60–70 cm, respectively (Table S4).

#### 4. Discussion

The survival rates at the end of the first season in Bishkek I and Almaty are similar to survival rates reported by [16] and further literature there. The sites established in 2019 partly showed very low survival rates, in particular the PDN cultivars purchased from Italy on the sites Jalalabad, Bishkek II, and Tup. That can be explained by the long storage time between delivery and planting, as survival rates of those cultivars were higher in

Khorog and Lavar, where planting took place two to three weeks earlier than on the former sites. The high survival rates from the first season through winter into the second season is confounded by the findings by [16].

The annual stem biomass yields as calculated in Table 9 for Bishkek I are the same range as the annual yields published by [17] for a PDN hybrid in the Po Valley in Italy. The stem biomass yields of the PDN hybrids H-33, Orion, and H-17 after two years in Bishkek I are in the same range as *P. x canadensis* with biomass yields of 12.9 to 13.6 t/ha\*a as reported by [18] from Idaho and California, but lower than NPP of 12 to 24 t/ha\*a for *P. x canadensis* as listed by [13]. The lower values of Bishkek I compared to [13] can be explained as follows: in this study, stem biomass yields are presented so that branch and leaf biomass, which are a part of NPP, are ignored here. Secondly, the soil in Bishkek I had a low nutrient status, in particular with regard to phosphorus, as was visible during the first season. The fertilizer application listed for Bishkek I in Table 5 met the phosphorus requirements (20–36 kg P/ha\*a), but not the nitrogen (182–246 kg N/ha\*a) and potassium requirements (113–171 kg K/ha\*a) as given by [13]. The tree heights and DBH values after the third season in Bishkek I are in the same range as the tree heights of 8.7–9.7 m and DBH of 6.3–7.8 cm, which were reported by [19] for PD and PDN cultivars from North Carolina. In Bishkek I, Max-3 reached an annual biomass yield which was in the same range as the 10.6 t/ha\*a as published by [20] for PNM hybrid studied in Quebec, Canada. At the end of the second season, the hybrid Kazakhstani planted in Tup attained tree heights in the same range, 1.5–3.2 m, as that hybrid attained after four to five years on a site in northern Kazakhstan [21]. The slower growth in northern Kazakhstan can be explained by the colder climate and shorter growing season there compared to Tup. According to [22] local *P. nigra* var *pyramidalis* reached tree heights of 18–20 m and DBH of 11–13 cm after 20 years, while Max-3 and -4 and the PDN hybrids in Bishkek I reached DBH averages of 5.2 cm and more after three years. Therefore, it is to expect that the latter cultivars will need a shorter time to reach those heights and DBH as given for the local *P. nigra* var *pyramidalis*.

The finding that PMT and PT cultivars performed better under a colder climate than most of the PDN cultivars was confirmed by [23] on a site in Poland. There, PMT (H-275) and Fritzi-Pauley performed better than PDN hybrids. [24] reported much better growth of PDN cultivars in Italy compared to a site in Northern France. [25] studied growth and biomass yields of PDN and PNM hybrids along an elevation and climate gradient in Quebec, Canada. There, the growth and biomass yields decreased with elevation and a cooler climate across all cultivars, but the PDN hybrids exhibited the steepest decrease. The PDN hybrid attained almost the same stem volume as PNM on the site on the lowest elevation, but quickly fell onto the last rank with an increasing elevation. Next to the elevation, soil fertility impacted more strongly on growth of the PDN hybrids than on the PNM hybrid [26]. This is in line with the data of this study, as Max-3 performed better than the PDN hybrids in Jalalabad, where conditions were less favorable (less water was available and weed prevalence was higher) than in Bishkek I or Almaty.

Max-3 and Max-4 in Bishkek I reached similar tree heights, DBH, and biomass yields as Max- and Max-4 on a plantation in NE Germany published by [16]. Though, Fritzi-Pauley performed much better in that study in NE Germany compared to Bishkek I and also Almaty. Fritzi-Pauley in Almaty and Bishkek I grew slightly higher than the tree height of 2.1 m as published by [27] for Northern France after the first season. While Fritzi-Pauley grew taller than the PDN hybrids in Northern France, Fritzi-Pauley was significantly smaller than the PDN hybrids in Almaty and Bishkek I underlining that PDN hybrids have a higher potential than PT cultivars under hot continental climates.

The overall smaller tree heights and stem volumes in Lavar, the saline site, are in line with a study on growth rates of different poplar cultivars on saline soils in North Dakota [21]. There, the PDN and PNM cultivars were least affected, which reflects the results of this study regarding the PDN cultivars on the site Lavar. In contrast to [28], the PNM hybrid Max-3 remained among the smallest in Lavar.

The tree data from Bishkek II are significantly smaller than from the neighboring site Bishkek I. This stark difference can be explained by the soil properties, as the clayey texture, coupled with bad drainage, impacts negatively on poplar growth [13,29]. At the end of the second season, the pure species Fritzi-Pauley and Mirza Terek showed the largest increments, while a number of the otherwise high performing PDN hybrids (H-8, H-11, H-33) remained very small. This is particularly noteworthy, as those two cultivars grew, although the site was not irrigated throughout the whole second season. This can be explained by the better root development of the pure species compared to the PDN hybrids [12].

The lower growth performance in Jalalabad and Osh compared to Bishkek I and Almaty can be explained by the higher weed coverage on the former sites compared to the latter. This is in line with [30], who found a negative correlation between weed prevalence and stem wood production for poplars in Saskatchewan, Canada. The weeds outcompete the cuttings and trees for water, in particular during the first season after planting. Under such more adverse conditions, Mirza Terek and the PNM hybrids (Max-3) attained average tree heights in Osh and highest values in Jalalabad, while the otherwise high performing PDN hybrids (e.g., H-33) perform poorly.

The wide range of tree densities between sites might partly explain the differences with regard to grow rates between Khorog and Naryn. By end of the first season, trees in Naryn grew slightly higher compared to Khorog, though Khorog received fertilizer and weeds were controlled more intensively. The high tree density of 100,000 trees/ha in Khorog, as opposed to 25,000 trees/ha in Naryn, might have led to competition between trees, which impacted on their grow. In contrast, tree heights, dbh, and stem volumes were similar on the two sites Almaty and Bishkek I, despite the huge difference in tree densities, which were 62,500 in Almaty versus 13,800 to 27,700 trees per hectare in Bishkek I. Possibly the much better nutrient and water supply on those two sites outweighed effects of tree density at least in this young stage of tree development.

The leaf beetles did not impact on growth performance, as those beetles were controlled rapidly. Trees in Bishkek I, which was affected by pests, and in Almaty, which was not affected, attained similarly high growth rates. The two sites in Bishkek and Tup, which suffered from those beetles, were located close to other woodlands, which according to field observations harbored those beetles.

The preceding paragraphs described qualitatively relationships between the different environments of the sites, such as soil properties, climate, and weed prevalence, and resulting growth rates of the poplar cultivars included in this study. Initially, this study aimed at addressing genotype  $\times$  location interactions. Though, different soil properties, e.g., the higher clay content of Bishkek II in comparison to the neighboring site Bishkek I, and differences in site management, which resulted in varying degrees of weed prevalence, water supply, and plant nutrition made it necessary to discuss the results in the light of genotype  $\times$  environment interactions [15]. The design of this study, in particular the absence of control plots and replicates on the sites, e.g., with regard to different fertilizer doses or water supply, is a clear weakness of this study and needs to be addressed in further studies on local and promising new cultivars to be able to systematically describe genotype  $\times$  environment interactions. These interactions are important for sound cultivar recommendations, in particular if cultivars are to be recommended under sub-optimal conditions where land users cannot guarantee optimal site management. Despite its weakness, this study is able to provide basic information to land users in the region Central Asia with regard to which group of cultivars has most promising potentials in the lower elevation versus high elevation areas. Furthermore, this study highlights to land users the most urgent operations, which are weed control, water supply, and the ability to react to nutrient deficiencies and pests, that need to be ensured to be able to tap the potentials of high yielding poplar cultivars.

## 5. Conclusions

This study investigated the growth rates of a number of poplar cultivars, *P. nigra* (PN), *P. deltoides* (PD), *P. trichocarpa* (PT), *P. alba* (PA), and *P. simonii* cultivars as well as *P. x canadensis* (PDN), *P. maximoviczii x trichocarpa* (PMT), *P. nigra x maximoviczii* (PNM), and *P. laurifolia x canadensis* (PLfND) hybrids, on experimental sites, ranging from hot continental climate to cold semiarid climate on higher elevations in Central Asia. The PDN hybrids, in particular H-33 and H-17, followed by Orion, Vesten, and Oudenberg grew tallest and yielded the highest biomass on the sites under a hot continental climate, provided that weeds were controlled thoroughly, sufficient water and plant nutrients were available, and pests were controlled. If these favorable conditions were not met, those high performing cultivars would not be able to unfold their potential. Under poor soil and management conditions, traditional and obviously more robust cultivars, as Fritzi-Pauley, Mirza Terek, or Max-3 perform better than the high yielding PDN cultivars. This implies that land users who wish to attain high growth rates and biomass yields from poplars should use high yielding PDN hybrids, but have to ensure intensive site management through the first and second season to tap the potential of those cultivars. If such intensive site management cannot be ensured, the more robust cultivars, as Fritzi-Pauley, Mirza Terek, or Max-3 should be used to avoid failure. Even if intensive site management can be ensured, Max-3 and Max-4 could be considered to be included into plantations of agroforestry systems, in order to reduce the risk of failure.

On sites on higher elevation and under a colder climate, the PMT and PT cultivars performed better than the PDN hybrids. In particular, H-8, H-11, H-17, and H-33 grew smaller than the PMT and PT cultivars, while Oudenberg and Orion only grew slightly smaller than the PMT and PT cultivars. In addition, the locally used cultivars performed worse on the higher elevation sites than the new cultivars investigated through this study.

In general, poplar-based agroforestry systems and plantations can increase their productivity by including cultivars investigated in this study. Furthermore, new cultivars, such as *P. trichocarpa x maximoviczii* or *P. deltoides x trichocarpa*, should be tested in Central Asia as well.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/1999-4907/12/3/373/s1>, Table S1: survival rates [%] by sites and cultivars at the end of the first season, Table S2: survival rates [%] by sites and cultivars from the first season to the second season, Table S3: Tables of stem volumes at the end of the second growing season. The columns indicate the cultivar, average  $\pm$  standard deviation, N—number of measured trees, and Min and Max—minima and maxima of tree heights. Letters indicate significant differences at  $\alpha < 0.05$ , Table S4: tables of tree heights at the end of the first growing season. The columns indicate the cultivar, average  $\pm$  standard deviation, N—number of measured trees, and Min and Max—minima and maxima of tree heights. Letters indicate significant differences at  $\alpha < 0.05$ , Table S5: tables of tree heights at the end of the second growing season. The columns indicate the cultivar, average  $\pm$  standard deviation, N—number of measured trees, and Min and Max—minima and maxima of tree heights. Letters indicate significant differences at  $\alpha < 0.05$ .

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