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Accelerated formation of Siberian pine (*Pinus sibirica* Du Tour) stands: a case study from Siberia

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Abstract: Under natural conditions, Siberian pine *Pinus sibirica* begins to produce commercial cone yields of nuts relatively late (after more than 100 years). The aim of this study was to summarise the experience of the directed formation of Siberian pine forests in Siberia. Experimental objects included plots with traditional thinning of varying intensity and frequency as well as chemical treatment. We assessed the parameters of the stand and its seed production dynamics. Only stands with a minimum density (395–435 trees·ha^{-1}) had a normal seed production energy (1.5 or more cones per shoot). Over-dense stands (830–930 trees·ha^{-1}) were characterised by a low seed production energy (two times or more below the threshold value). In all plots, there were Siberian pine trees with absent or unacceptable seed production energy, which should be removed (DBH up to 28 cm). Seed production energy positively correlated with most tree parameters (age, height, diameter, volume, length and width of crown).

Keywords: thinning; seed orchards; radial growth; seed production energy; middle taiga

On a global scale, there is a change in the forest use paradigm from large-scale clear-cuttings to various types of selective logging (Puettmann et al. 2015), with the greatest importance attached to thinning. As a result of thinning, growth space increases and competition for resources decreases, stimulating an intensive increase in growth in the remaining trees (Štefančík 2013). Depending on the method, thinning can change the diameter of trees, homogenise the horizontal or vertical structure of the canopy and increase the mixing of tree species (Barbeito et al. 2009).

Siberian pine *Pinus sibirica* Du Tour belongs to the five-needle stone pine species. Most of its range is located within Russia, where it covers an area of about 40 million ha (Semechkin et al. 1985). However, this applies only to forests, where its share is at least 30%, and its actual range is 2.5 times larger (Debkov 2018). In 1989, a moratorium on cutting of Siberian pine forests with *Pinus sibirica* participation from 30% was introduced (Debkov, Krivets 2017). However, its natural dynamics is characterised by the complexity and duration of its development (Sedykh 2014). Under natural conditions, *Pinus sibirica* starts producing commercial cone yields of nuts at the age of 180–220 years, when it first forms communities (Danchenko, Bekh 2010). This feature has also been noted for other species of five-needle stone pine (Shelef et al. 2017).

Pine nut is a very important and valuable food product not only for communities of those places where Siberian pine grows, for example, nuts from Siberia are in demand in the USA (Shelef et al. 2017).

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In Western Siberia, many ancient villages are growing Siberian pine stands, which provided in the past and provide today's periodic income for local communities (Debkov 2014). It is noteworthy that in order to maximize the nut production, the local population sought to form a mono-breed stands. At the same time, thinning began to be done as early as possible to form a crown from a young age, thereby ensuring the early fruiting of Siberian pine trees.

In this study, we investigated the accelerated formation of Siberian pine stands in the plain taiga of Western Siberia with the objective to reach commercially profitable cone production per tree and per hectare in a shorter time.

MATERIAL AND METHODS

Study area

The objects of research were located within the middle- and southern taiga subzone of Western Siberia [on the territory of the Khanty-Mansiysk Autonomous Okrug (region) – Yugra and Tyumen Oblasts (region)] (Fig. 1). Objects 1 and 2 were located on the territory of the scientific station "Trenka" [Khanty-Mansiysk Autonomous Okrug (region) – Yugra], object 3 in the vicinity of the village of Chembakchino [Khanty-Mansiysk Autonomous Okrug (region) – Yugra] and object 4 in the vicinity of the village of Burtas [Tyumen Oblasts (region)].

Background Siberian pine forests are distinguished by a multi-species composition, where the share of *Pinus sibirica* participation ranges from 10 to 50% (Debkov 2017). The ground cover is represented mainly by green mosses and small grasses (Sedykh 2014). By origin, most Siberian pine forests of post-fire genesis with a relatively even-aged structure (Sedykh 2014).

Object 1 is a series of sample plots (SPs) with different histories of silvicultural impacts and different stand structures (Table 1):

(*i*) SP 1_a – accompanying species were removed by thinning in 1985, and the density of Siberian pine trees was reduced to 500 trees·ha^{-1};

(*ii*) SP 1_b – only accompanying species were cut (Siberian spruce *Picea obovata* Ledeb., Silver birch *Betula pubescens* Ehrh.) in 1985;

Fig. 1. Range of *Pinus sibirica* and locations of the study objects (1, 2, 3, 4)

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Table 1. Characteristics of experimental stands

Plot	Stand composition (%)	Height (m)	DBH (cm)	Age (years)	Density (trees·ha^{-1})	Volume** (m^3·ha^{-1})	Crown length (m/%)	Crown width (m/%)
SP 1_a	90P	15.8 ± 0.3	32.6 ± 0.7	50.0 ± 2.1	375	307.5	8.2 ± 0.3/52 ± 2	3.9 ± 0.3/25 ± 2
	10B	13.7 ± 0.9	9.4 ± 0.3	31.3 ± 2.6	335	20.1		
	*Sp	10.5 ± 1.0	10.0 ± 0.6	31.0 ± 0.6	127	5.1		
SP 1_b	90P	13.9 ± 0.5	21.9 ± 0.8	42.9 ± 2.7	930	204.6	5.4 ± 0.3/39 ± 2	2.2 ± 0.1/16 ± 1
	10B	12.8 ± 0.1	9.9 ± 0.8	27.5 ± 2.6	270	16.2		
	*Sp	9.8 ± 1.3	10.5 ± 0.6	27.2 ± 1.2	80	2.4		
SP 1_c	100P	15.0 ± 0.2	34.3 ± 0.6	48.9 ± 2.2	435	356.7	8.2 ± 0.3/55 ± 2	3.1 ± 0.1/21 ± 1
SP 1_d	100P	16.4 ± 0.4	23.8 ± 0.4	48.5 ± 1.6	920	331.2	7.2 ± 0.3/44 ± 2	2.8 ± 0.2/17 ± 1
SP $2_{control}$	70P	15.6 ± 1.4	19.8 ± 1.5	91.1 ± 17.7	1,046	251.0	5.0 ± 0.3/32 ± 2	2.5 ± 0.3/16 ± 2
	20Sp	18.8 ± 1.9	24.1 ± 2.5	80.2 ± 19.7	324	77.8		
	10B	20.5 ± 2.5	25.3 ± 4.8	89.0 ± 25.5	103	24.7		
SP $2_{25\%}$	70P	17.3 ± 1.0	22.8 ± 1.2	80.0 ± 14.2	1,008	241.9	6.4 ± 0.5/37 ± 3	2.6 ± 0.3/15 ± 2
	20B	20.5 ± 2.5	23.4 ± 2.0	89.0 ± 25.5	331	79.4		
	10Sp	18.8 ± 1.9	19.3 ± 1.7	80.2 ± 19.7	101	24.2		
SP $2_{50\%}$	100P	16.0 ± 1.5	23.3 ± 0.9	60.7 ± 5.7	915	283.6	6.4 ± 0.5/40 ± 3	2.4 ± 0.3/15 ± 2
SP $2_{75\%}$	100P	15.1 ± 0.5	21.2 ± 0.9	46.4 ± 2.8	830	258.6	6.2 ± 0.3/41 ± 2	2.3 ± 0.1/15 ± 1
SP 3_{Utal}	90P	15.0 ± 1.2	22.7 ± 1.7	81.2 ± 3.4	625	206.2	5.8 ± 0.1/39 ± 2	2.1 ± 0.1/14 ± 1
	10F	12.7 ± 4.5	11.6 ± 1.7	64.5 ± 6.5	225	15.3		
	*B	19.1 ± 1.5	24.2 ± 1.9	85.3 ± 14.4	25	9.2		
	*Sp	7.8 ± 0.5	8.2 ± 0.9	52.1 ± 12.2	100	2.3		
SP 4	100P	16.2 ± 1.1	29.1 ± 1.5	67.4 ± 6.8	355	181.0	9.9 ± 0.6/61 ± 4	2.9 ± 0.2/18 ± 1
	*B	10.7 ± 0.9	9.3 ± 1.0	15.5 ± 0.5	40	2.0		
	*Sp	10.5 ± 1.5	10.0 ± 0.9	19.5 ± 1.5	40	1.6		
	20B	20.5 ± 2.5	23.4 ± 2.0	89.0 ± 25.5	331	79.4		

SP 1_a – accompanying species were removed by thinning in 1985, and the density of Siberian pine trees was reduced to 500 trees·ha–1; SP 1_b – only accompanying species were cut (Siberian spruce, Silver birch) in 1985; SP 1_c – thinning was conducted in 1981, later in 2012, accompanying species (Siberian spruce, Silver birch) and dead trees of Siberian pine were cut; SP 1_d – only accompanying species were cut (Siberian spruce, Silver birch) in 1985, and untargeted Siberian pine trees were cut in 2007; SP $2_{25\%}$ – thinning in 1987, 25% of trees was removed; SP $2_{50\%}$ – thinning in 1987, 50% of trees was removed; SP $2_{75\%}$ – thinning in 1987, 75% of trees was removed; SP $2_{control}$ – in the control section, thinning was not performed; SP 3_{Utal} – laid in place of the secondary mature aspen-birch stands, treated with the chemical preparation "Utal"; SP 4 – permanent forest seed orchard (PFSO)

P – Siberian pine *Pinus sibirica* Du Tour, B – Silver birch *Betula pubescens* Ehrh., Sp – Siberian spruce *Picea obovata* Ledeb., F – Siberian fir *Abies sibirica* L.; *sporadic, ** volume of trees was calculated on the basis of height and DBH according to official standards (Zagreev 2005)

(*iii*) SP 1_c – thinning was conducted in 1981, later in 2012, accompanying species (Siberian spruce, Silver birch) and dead trees of Siberian pine were cut;

(*iv*) SP 1_d – only accompanying species were cut (Siberian spruce, Silver birch) in 1985, and untargeted Siberian pine trees were cut in 2007.

Object 2 is a series of SPs, where in 1987, thinning of different intensities was carried out in three sections according to the number of trees to be removed: 25% (SP $2_{25\%}$), 50% (SP $2_{50\%}$) and 75% (SP $2_{75\%}$). In the control section, thinning was not performed (SP $2_{control}$).

Object 3 – SP 3, laid in place of the secondary mature aspen-birch stands, treated with the chemical

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preparation "Utal" (SP 3_{Utal}). The active substance used glyphosate 36% concentration. The dose of herbicide for one tree depended on its size. Notches 10 cm wide and 1 cm deep (in wood, not counting the thickness of the bark) were applied with an axe at equal distances (20 cm) around the perimeter of the trunk at a convenient height (about 1 m) from the root collar. By 1986, the total treatment area was about 9 ha. As a result of chemical drying, the trees of soft-leaved species died almost completely and were decomposed by the time of this study.

Object 4 – SP 4 is a certified permanent forest seed orchard (PFSO). Siberian pine PFSO was laid on an area of 5 ha in 1994 from a natural young stand. The first two thinnings were carried out in 1987–1988, with a total intensity of 50%. Subsequently, thinning was repeated in 1994, 1995 and 1998. After 5 years, the thinning cycle was repeated from 2003–2006. Each of the 4 years was accompanied by a seizure of 8–10 $m^3 \cdot ha^{-1}$ of Silver birch wood and deadwood of Siberian pine.

Data measurement

The sample plots were delimited by a Compass KB-14/360 (Suunto, Finland), using a Walktax thread distance measurer (Haglöf, Sweden); the trees were measured with an Aluminium measuring fork (Haglöf, Sweden). On the basis of this data, according to the method of proportional-step representation, 20 to 30 model trees were selected for core sampling with an Incremental borer (Haglöf, Sweden) and for height measurements with an Electronic altimeter Forestry PRO (Nikon, Japan). For Siberian pine trees, crown parameters such as length and width were measured using the Kondratiev crown gauge (Taxator, Russia).

Data analysis

To determine the seed production energy (SPE) on the basis of a continuous measurement of trees in the SP, the average DBH was determined for three model trees. In total, we surveyed 15 model trees. To build chronological rows, for each model tree, three long-term seeding branches of medium size were selected from different parts of the female tier of the crown. The number of external (on the bark of shoots) traces of cones on each annual shoot of branches of the I–III orders was sequentially restored by retrospective methods. According to the approved method (Nekrasova, Zemlyanoy 1980), a cones·shoot^{-1} ratio of 1.5 was taken as the threshold value of the seed production energy.

For data analysis, we used the software package STATISTICA (Version 10, 2011), applying standard descriptive statistics, non-parametric tests for estimating the reliability of the difference for independent (two – Mann-Whitney test, several – Kruskal-Wallis test) variables, correlation and regression analyses. The width of the tree rings was measured using the LINTAB-5 complex with the TSAP software package with an accuracy of 0.01 mm (Rinn, Germany).

RESULTS

Effect of thinning on the radial growth of Siberian pine stands

The response of Siberian pine at the stand level to thinning showed that, despite the great oppression of growth of young stands under the canopy of derived (soft-leaved) forests as compared to the young ones in clear cuttings, they are characterised by a more pronounced positive response (SP 3_{Utal}, Fig. 2).

A weak response was found for SP $2_{25\%}$. More impressive was the increase in radial growth at SP $2_{50\%}$ and $2_{75\%}$. At SP $2_{50\%}$, due to the fact that at the time of thinning, Siberian pine trees were on the upward growth curve, thinning created optimal conditions, which led to an increase of the period of increased stem growth.

In plots with more rare (less dense) (SP $1_{a,c}$ and 4) forest stands, a more aligned dynamics was observed, which shows that thinning provided growth without significant oppression. More dense stands (SP 1_b, 1_d) are characterised by a dome-shaped form of the radial growth dynamics. The effects of thinning 2 and further treatments did not have such a stimulating effect on the growth of Siberian pine trees when compared to thinning 1 (for example, see SP 4).

Crown structure of Siberian pine

Targeting the formation of Siberian pine seed orchards can maximise the development of tree

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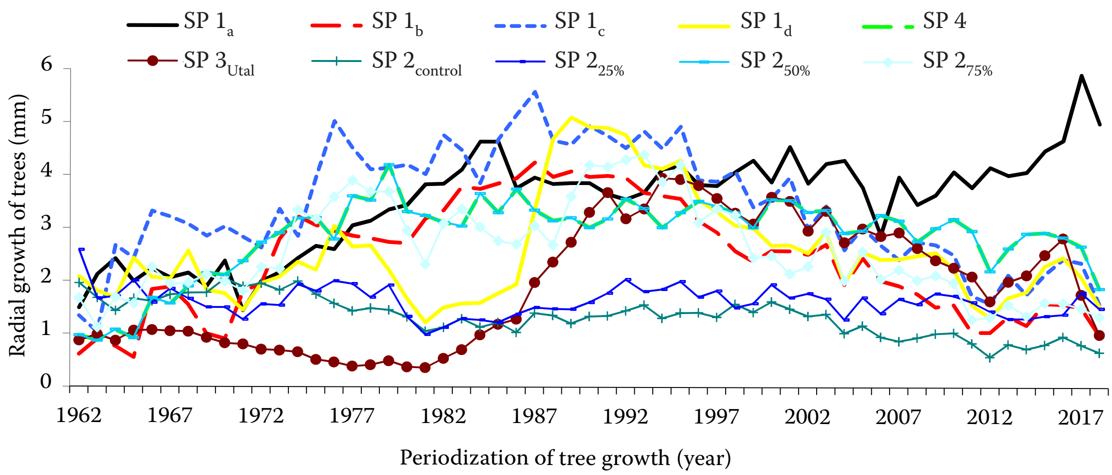

Fig. 2. Dynamics of radial growth of Siberian pine forests, formed by thinning of natural young stands

SP 1_a – accompanying species were removed by thinning in 1985, and the density of Siberian pine trees was reduced to 500 trees·ha–1; SP 1_b – only accompanying species were cut (Siberian spruce, Silver birch) in 1985; SP 1_c – thinning was conducted in 1981, later in 2012, accompanying species (Siberian spruce, Silver birch) and dead trees of Siberian pine were cut; SP 1_d – only accompanying species were cut (Siberian spruce, Silver birch) in 1985, and untargeted Siberian pine trees were cut in 2007; SP $2_{25\%}$ – thinning in 1987, 25% of trees was removed; SP $2_{50\%}$ – thinning in 1987, 50% of trees was removed; SP $2_{75\%}$ – thinning in 1987, 75% of trees was removed; SP $2_{control}$ – in the control section, thinning was not performed; SP 3_{Utal} – laid in place of the secondary mature aspen-birch stands, treated with the chemical preparation "Utal"; SP 4 – permanent forest seed orchard (PFSO)

crowns and their entry into early seed bearing. As a rule, this requires an acceptable tree density. According to our data, the most developed trees grow in SP $1_{a,\ c}$ and 4 (Table 1). Crown length in more rare (less dense) plots, on average, is about 50–60%, while in more dense plots, it is reduced to 40–45%. Crown width showed a similar dynamics, with wider crowns (3–4 m) being more characteristic for rarer (denser) stands, while in overly dense stands, the trees mostly have narrow crowns (2–2.5 m).

The relationships between crown and trunk indicators were considerable (Fig. 3), based on the correlation coefficients (about 0.70–0.80). At the same time, the relation equations were reliable (P < 0.05), with coefficients of determination of about 0.50–0.60.

The most significant relationships were found for crown width and length Siberian pine trees with trunk diameter, which makes it possible to consider the dynamics of crown parameters by DBH class (Table 2).

There was a clear relationship between these indicators. In the DBH classes up to 24 cm, crown length varied from 33 to 43%, averaging 39%.

In the higher DBH classes (more of 28 cm), it ranged from 47–60%, with an average of 54%. In the DBH classes up to 24 cm, crown width varied from 19 to 30% (on average 24% or 3.3 m), and for the DBH class more of 28 cm, the oscillation was 36–50% (average 44% or 7.5 m).

When conducting research, attention was drawn to the phenomenon of multi-vertex of Siberian pine trees, which clearly had a spread beyond the background indicators of natural stands. Immediately make a reservation that this applies to Object 1. Moreover, Siberian pines are clearly leading in this indicator at SP $1_{a,c}$ (frequency of 64 and 68%, respectively), i.e. plots that had previously entered the reproductive stage, with more rare (less dense) stands. In overly dense plots (SP $1_{b,d}$), where the tree crowns had thinner branches, the trunk was more clear of branches, with late and poor seed-bearing (39 and 34%). The average number of tree tops was two to three pieces (Table 3). It is noteworthy that multi-vertex trees were thicker, by about one DBH class (4 cm), which was observed in all plots, most likely because compensation is required to support a more developed crown. The height of the first fork (in many trees, there were

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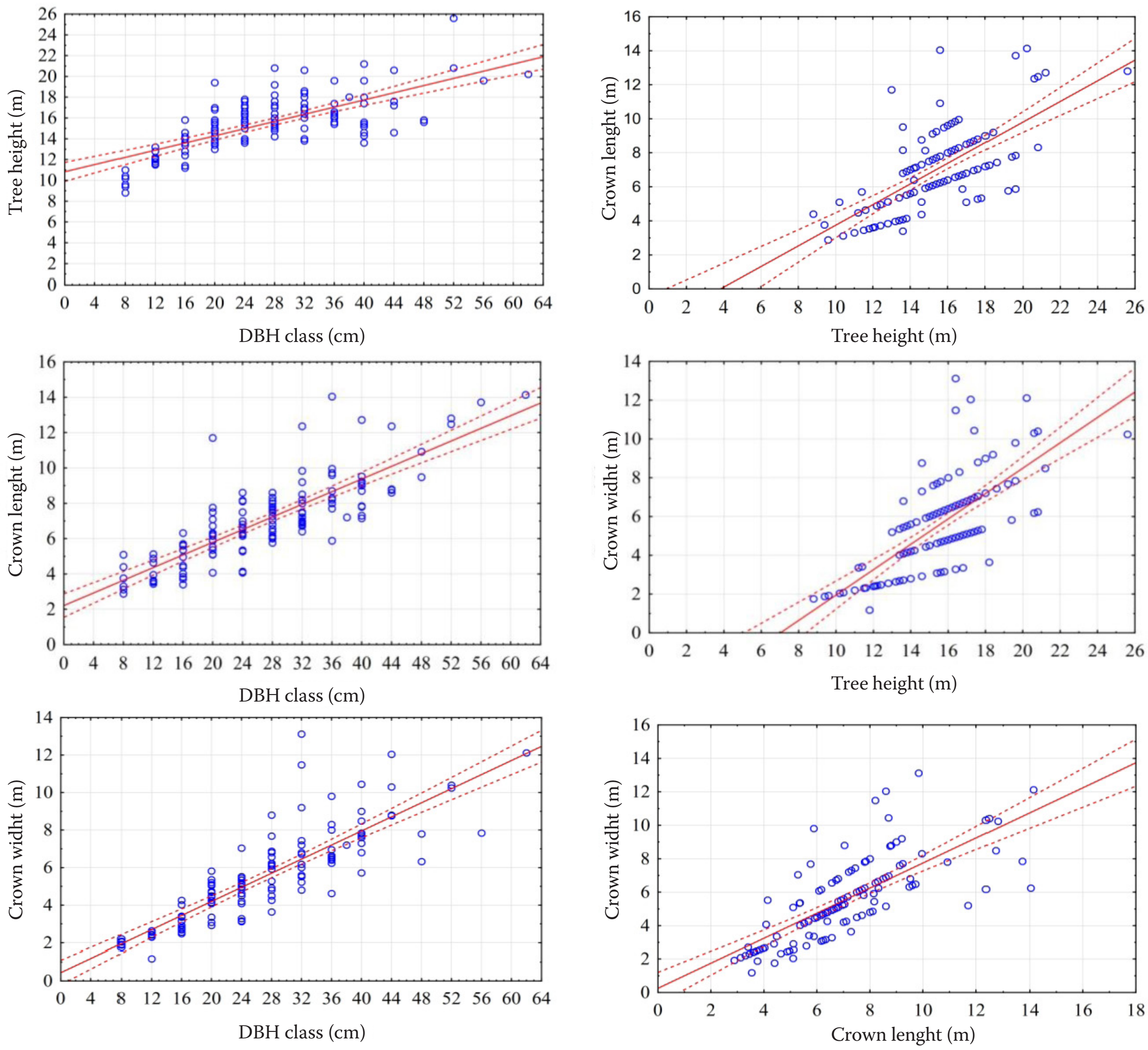

Fig. 3. Relationships between trunk and crown parameters of Siberian pine trees

Table 2. Tree parameters by DBH class

DBH class (cm)	Parameter		
	Tree height (m)	Crown length (m)	Crown width (m)
8	9.90 ± 0.32	3.76 ± 0.35	1.98 ± 0.06
12	12.15 ± 0.21	4.10 ± 0.24	2.28 ± 0.16
16	13.27 ± 0.38	4.79 ± 0.27	3.07 ± 0.17
20	15.28 ± 0.44	6.43 ± 0.45	4.45 ± 0.22
24	15.57 ± 0.37	6.48 ± 0.33	4.74 ± 0.26
28	16.43 ± 0.39	7.12 ± 0.19	5.89 ± 0.29
32	16.76 ± 0.46	7.93 ± 0.40	7.12 ± 0.62
36	16.58 ± 0.38	9.01 ± 0.67	7.00 ± 0.44
40	16.49 ± 0.78	8.84 ± 0.51	7.87 ± 0.40
44–62	18.76 ± 1.04	11.21 ± 0.68	9.46 ± 0.60

repeated cases of secondary top formation) varied in plots, but in most cases, it was 4–7 m.

Siberian pine seed production energy in the experimental plots

The highest SPE is characteristic for tree stands on SP 1_a and 1_c (1.21 ± 0.32 and 1.63 ± 0.37 cones·shoot^{-1}, Table 4). The stands meet the requirements of a PFSO. For the remaining SP (SP 1_b – 0.27 ± 0.16, SP 1_d – 0.88 ± 0.21, SP $2_{75\%}$– 0.81 ± 0.42 cones·shoot^{-1}), the SPE was significantly lower than for the recommended one.

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Table 3. Characteristics of multi-vertex trees

Characteristic	Plot			
	SP 1_a	SP 1_b	SP 1_c	SP 1_d
Average number of tree tops/limits (pcs)	2.6 ± 0.2/2–5	2.7 ± 0.2/2–6	3.0 ± 0.2/2–6	2.2 ± 0.1/2–3
Diameter of stand (cm)	32.6 ± 0.7	21.9 ± 0.8	34.3 ± 0.6	23.8 ± 0.4
Diameter of multi-vertex trees (cm)	33.6 ± 0.8	24.4 ± 1.1	35.4 ± 0.7	25.8 ± 0.6
Multi-vertex base height/limits (m)	7.1 ± 0.4/1.5–12	3.7 ± 0.3/0.5–8	4.8 ± 0.3/1.5–9	4.2 ± 0.3/1–8

The effects of crown and trunk parameters on seed production energy differed. In particular, the relationship between the radial growth of the stand and seed production energy has the following characteristic: at SP 1_c, the correlation coefficient was $r = -0.971$, i.e. the higher the seed production energy, the lower the radial growth of the trunk. At SP 1_a, the correlation had the same characteristic, but the relationship was weaker ($r = -0.561$). At SP 1_b and SP $2_{75\%}$, the characteristics were different ($r = 0.855$ and $r = 0.802$, respectively), i.e., these stands are still at their peak of growth and are just beginning to produce seeds. The stand at SP 1_d has already passed from the phase of intensive growth to the generative stage ($r = -0.345$). There was a negative relationship with stand density ($r = -0.759$), which we have already mentioned. More rare (less dense) stands are characterised by a higher seed production energy. Overly dense stands negatively affected the seed production of individual trees. For the remaining indicators, the relationship was positive: with age $-r = 0.894$, with tree height $-r = 0.590$, with tree diameter $-r = 0.826$, with tree volume $-r = 0.953$, with crown length $-r = 0.912$, with crown width $-r = 0.635$.

DISSCUSSION

The main effect of high-intensity thinning is a reduction of the total volume and an increase in the size of the remaining trees (for example, SP 1_a, 1_c compared to 1_b, 1_d). Similar results have been obtained by other researchers (Valinger et al. 2019). The start time of the response to the thinning is different. As a rule, the younger the tree, the faster it begins to increase its growth. In this regard, an interesting conclusion was made in the work of Bose et al. (2018), where the time of thinning needed to be adjusted to tree age, which is important for the efficiency of radiant energy use. Theoretically, younger trees and stands, as a rule, have a great-

Table 4. Characteristics of seed production energy (SPE) of Siberian pine in sampled stands

Plot	Model tree no.	DBH (cm)	Observation period (years)	SPE (cones·shoot^{-1})	The coefficient of variation of SPE (%)	Maximum SPE in high-yielding period (cones·shoot^{-1})
SP 1_c	1	32	13	1.65 ± 0.34	75	2.67 ± 0.36
	2	32	15	1.40 ± 0.42	116	3.00 ± 0.55
	3	32	16	0.60 ± 0.20	134	1.89 ± 0.59
SP 1_b	1	24	12	0.25 ± 0.15	206	1.00 ± 0.33
	2	20	8	0.29 ± 0.16	155	0.78 ± 0.22
	3	20	did not give seeds			
SP 1_a	1	32	11	1.26 ± 0.31	82	2.07 ± 0.40
	2	36	14	1.26 ± 0.29	85	1.92 ± 0.21
	3	32	12	2.36 ± 0.46	67	3.07 ± 0.35
SP 1_d	1	24	14	1.27 ± 0.36	107	3.44 ± 0.62
	2	24	12	0.83 ± 0.25	104	2.11 ± 0.29
	3	28	15	0.53 ± 0.16	117	1.08 ± 0.08
SP $2_{75\%}$	1	24	11	0.39 ± 0.15	130	–
	2	20	did not give seeds			
	3	28	9	1.24 ± 0.33	80	2.75 ± 0.25

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er potential to assimilate biomass after liberation from competition (Ryan et al. 1997), which was observed in SP 3_{Utal}. However, the implementation of this pattern is fair when age generations have comparable biometric dimensions. From a biological point of view, dominant trees with large crowns show a minimal (relative) response to thinning, which simply helps them maintain a fast growth rate, while less developed (oppressed) trees show a relatively greater response (Pukkala et al. 1998). In absolute terms, dominant trees increase their diameter to a greater extent than oppressed trees (Peltola et al. 2002).

Even low-intensity thinning (10–30%), which does not affect the average height and DBH, leads to an increase of the tree crown (Huang et al. 2016). As a result, the yield increases in proportion to the intensity of thinning (for example, SP 1_a and 1_c and 4).

Varying the height of the first fork, combined with multiple branching of the trunk, leads to the conclusion that there may be several reasons for this phenomenon. One of the earliest versions is that pests have an effect (Vasiliev 1938), while later, the low temperatures of winter and late spring (Pravdin 1963) were considered to play a role in this phenomenon. At the same time, studies have shown that the occurrence of multi-vertex trees in natural environments varies from 2 to 12% (Pravdin, Iroshnikov 1963). At our plots, the occurrence of Siberian pine trees with several vertexes was significantly higher. Alekseev (1979), who studied this phenomenon in Siberian pine forests near settlements of the Tomsk region, showed that in cultivated Siberian pine orchards (rare (low density) stands), damage occurs when collecting cones, as 3–8-year old axial shoots are frequently damaged (for example, SP 1_a and 1_c). In their place, powerful replacement shoots, generally three to five, develop from the downstream whorls, which form a multi-vertex Siberian pine tree. In taiga Siberian pine forests (over-dense stands), the apical buds or the 1-year sprouts often die, which, under conditions of high density, leads either to a quick replacement of the leader or to the formation of a narrow 2–3-vertex crown (SP 1_b and 1_d).

At the same time, our data confirm the conclusions made on the example of Siberian pine forests of the Tomsk region, where it has been shown that there is no periodicity in seed production of Siberian pine, but a change of seed periods to non-seed periods (Nekrasova 1961). This feature has also been noted for North American five-needle stone pines, in which good-yield years are highly variable in space and time (Barger, Ffolliott 1972).

For comparison, the average SPE of natural (background) Siberian pine forests in the middle taiga subzone of Western Siberia within the Tomsk region is 1.17 cones·shoot^{-1} (Nekrasova 1961). Those Siberian pine forests, SP 1_a and 1_c, produce higher yields of nuts than taiga Siberian pine forests, while seed production at other SPs is still lower.

However, in reality, given the stand density, the difference is considerably smaller, since the low yields of individual trees are compensated for by their large number per unit of area; thus, the difference in total seed productivity is smoothed out. In this regard, interesting data were obtained during the thinning of Siberian pine saplings with the aim of forming a PFSO in the Novosibirsk region (Kulakov 2004). Despite the different stand density, the same number of Siberian pines give seeds. In the first plot of 400 trees, 70% entered the generative phase, i.e. 280 trees·ha^{-1}, and in the second plot of 1,000 trees, 30%, i.e. 300 trees·ha^{-1}, entered this phase. It is evident that, when planning the density of Siberian pine orchards, one should rely on the projection of crowns (Alekseev, Demidenko 1990). In Russia, the prevailing direction for rare (low density) accommodation of seed orchards. It is noteworthy that while often losing sight of the main goal in the form of increased nut yields per unit area, it is necessary to take into account that the structure of Siberian pine crowns has a longline nature and that it is impractical to reduce crown closure to full lighting, since the cones grow in the upper female layer. As shown in previous studies (Alekseev 1984), over-dense Siberian pine orchards (250 trees·ha^{-1} in 60 to 70 years) are preferable to rare (low density) ones, since their total seed productivity is two times higher.

Prospects for increasing seed productivity in stone pines are available, and, as shown in the example of *Pinus pinea* L., it can be increased by rational thinning (Moreno-Fernandez et al. 2013). The results showed that thinning can increase the expected nut yield by more than 300% in dense and by 200% in rare (low density) stands (Pasalodos-Tato et al. 2016).

CONCLUSIONS

The generalisation of the experience of creating Siberian pine stands in the 1980s showed the pos-

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sibility of forming - stands, which produce seeds much earlier than natural forests. Since the beginning of the experimental work, about 35 years have passed, and all plots have entered the generative phase. However, only stands with a minimum density (395–435 trees·ha^{-1}) have a normal SPE (1.5 or more cones·shoot^{-1}). Over-dense stands (830 to 930 trees·ha^{-1}) are characterised by low SPE (two times or more below the threshold value). In all plots, there are Siberian pine trees with absent or with unacceptable SPE, which should be removed (DBH up to 28 cm). It has been established that SPE positively correlates with most tree parameters (age, height, diameter, volume, length and width of crown), and there is a negative relationship between radial growth and stand density.

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