Impact of four-eyed fir bark beetle on forest stands in Western Siberia, Russia

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Abstract. The four-eyed fir bark beetle Polygraphus proximus Blandf. from the Russian Far East has led to the decline of Siberian fir in significant areas across several Russian regions. Presently, the four-eyed fir bark beetle is a primary factor contributing to the degradation of fir forests and the occurrence of various changes in the flat part of Western Siberia. The study was conducted in stands with varying compositions, with a mandatory inclusion of a specific proportion of Siberian fir. Reference stands were located in Central Siberia, along the border of the forest-steppe (Krasnoyarsk forest-steppe) and taiga zones (mountain-taiga region of the Eastern Sayan). A comprehensive field study was conducted on research plots (a total of 10). The stands and outbreak areas presented here serve as a reference for the study area in terms of species composition, stand characteristics, and the degree of infestation of fir trees by the pest. The analysis yielded a scale that differentiated forest stands according to species composition and the extent of damage. The four-eyed fir bark beetle's infection and damage to stands were found to be influenced by species composition. The intensity of damage was found to vary among species, with fir forests experiencing the most significant damage, followed by Siberian pine forests, birch forests, Scots pine forests, and aspen forests. Consequently, from a forestry perspective, forests dominated by aspen and Scots pine exhibit the greatest resistance to the invasive impact of the four-eyed fir bark beetle in the Krasnoyarsk forest-steppe zone.

1 Introduction

Dendrophagous invasions pose a grave threat to forest ecosystems and the timber industry [1].

The alien species of bark beetle *Polygraphus proximus* Blandf., of Russian Far Eastern origin, has led to the death of Siberian fir trees within considerable areas of several Russian regions. The rapid propagation of the pest and its subsequent outbreaks give rise to the question of whether the most important functions of damaged forests, including carbon sequestration, can be preserved. The dynamics of forest stand viability have demonstrated a marked decline in the number of viable trees, accompanied by an increase in deadwood, litter,

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and soil composition. This shift has precipitated a transformation in the natural biological cycle of carbon within natural coniferous ecosystems [2].

In a collaborative effort by Krivets, Bisirova, Kerchev, and their associates, it was demonstrated that the four-eyed fir bark beetle has emerged as a predominant factor contributing to the degradation of fir forests and the occurrence of various alterations in the flat region of Western Siberia. The proliferation of this invasive species has been shown to induce substantial modifications in the composition and structure of the plant community, as well as in the xylophilic entomofauna [3].

In the studies of Debkov, the impact of the invasive bark beetle *Polygraphus proximus* Blandf. on Siberian fir *Abies sibirica* Ledeb is summarized. The findings indicate that 45 % of the area covered by fir forests has undergone a transition to low- and mid-density forests dominated by spruce and Siberian pine. Fir will restore its cenotic value during the first generation. In 27 % of the area, fir stands degrade to the state of sparse forests, where a transition to birch-aspen stands with partial participation of fir on 20–50 % of the area is predicted. In another 27 % of the area, dominance shifts to spruce, Siberian pine, and birch. However, the restoration of fir is predicted to occur in only 20–30 % of the area. In the remaining territory, deciduous species are expected to prevail [4].

According to the findings of Debkov [5], the height, diameter, and annual increment of firs that died or were severely weakened by attacks of the four-eyed fir bark beetle are significantly lower than those of healthy trees. In contrast to the distribution structure of living firs, the firs that died or were severely weakened due to the four-eyed fir bark beetle exhibited a significantly higher degree of grouping over short distances.

In the context of Krasnoyarsk Krai and Tomsk Oblast, the prevalence of ophiostomatoid fungi exhibited significant variations among the four-eyed fir bark beetle populations examined (76–100 %). The authors of the study explore the potential emergence of a novel complex of ophiostomatoid fungi associated with the four-eyed fir bark beetle in Siberia. This complex is hypothesized to result from the interaction of pest-introduced species from the Russian Far East with native Siberian fungi [6–8].

Remote sensing is a method for assessing the condition of forests. In the studies of Kerchev, Volkova, and Melnik [9], it was demonstrated that the geoinformatic approach to studying fir forests in areas affected by the four-eyed fir bark beetle outbreak facilitates the creation of a series of thematic maps that reflect large-scale spatial and temporal changes in ecosystems. This approach also enables the provision of a short-term forecast for the development of outbreaks.

Yuan Zhang, Anzhi Wang, Yage Liu, and colleagues obtained forest disturbance information based on multiple remote sensing datasets (Global Forest Change, MODIS, and ERA5-Land). The findings indicated that wind damage and insect infestation are the predominant factors contributing to forest degradation. Furthermore, an increase in temperature during wintering and a decrease in precipitation during active periods have been observed to enhance the risk of insect outbreaks [10].

2 Materials and methods

The study was conducted in forest stands of varying composition, with a mandatory inclusion of a specific proportion of fir. Reference stands were situated in Central Siberia, along the border of the forest-steppe (Krasnoyarsk forest-steppe) and the taiga zone (mountain-taiga region of the Eastern Sayan). Consequently, an evaluation of the growth and development of stands with highly diverse site conditions was undertaken.

A complex field study was conducted on research plots (RP), of which there were 10. Three strip plots were placed in each research plot, with an area of 500 (50 x 10) m^2 as the standard, and, in rare instances of high-density stand, 300 (30 x 10) m^2. Each strip plot was an independent object of study. The field study encompassed a comprehensive enumeration of trees, accompanied by their diameter measurement, and the health status of each tree was also documented, with the trees being categorized as living or dead. Additionally, the study investigated whether a tree was damaged by the four-eyed fir bark beetle or died due to its attack. Furthermore, for a subset of trees (20–50 trees) representing various species, diameter measurements were taken at a height of 1.3 m and the total height of the tree was recorded. Additionally, the following tree crown measurements were taken: the height of the beginning of the crown, the height of the maximum crown spread, and crown radii in four directions.

A total of 25 strip plots were subjected to examination. In addition, circular research plots were placed in research plots with 100 % tree mortality (RP-2 K-1) and in those where felling occurred after the outbreak of the four-eyed fir bark beetle (RP-5, K-2, K-3). These circular research plots were placed according to the State forest inventory methodology [11], including all the field study measurements (e.g., counting, assessment of regeneration, forest fuels, coarse woody debris).

The execution of all field studies was carried out with the utilization of standard measuring instruments commonly employed in forest inventory [12].

The predominant method of field studies was the strip method [12]. The selection of this method of accounting is substantiated by the fact that it enables the maximization of territory coverage, a strategy that is particularly advantageous when undertaking tasks in expansive geographical areas. A comprehensive overview of the methodological framework employed in both field and desk studies is available in numerous scientific and instructional resources [13, 14].

The methodology of the strip cruising is based on the principles of partial enumerative inventory. The trees were measured depending on their diameter at breast height (1.3 m). The width of the strip plots was set constant at 10 m, and the length of the strip plot was 30–50 m. The measurements data on individual strip plots were summed up and converted to 1 ha. The number of firs measured on each strip plot ranged from 120 to 1080 trees/ha, which was sufficient to obtain a characteristic of the forest stands.

In the course of the field studies, a total of 25 strip plots of various sizes were placed (the area of each individual strip plot ranged from 300 to 500 m^2) as well as three circular research plots of constant radius.

The assessment of forest stands was carried out according to standard methodological approaches presented in the classical works of Orlov [14], Anuchin [12], and Moiseev [13].

3 Results and discussion

A visual inventory is employed as a preliminary assessment of the stand characteristics. This method facilitates the establishment of a generalized perception of the original object, thereby enabling the capture of features that may not be identified during an instrumental inventory.

The following areas were included in the study: Divnogorsk, the Avtomobilist gardening partnership; the area near Verkhnyaya Biryusa village, situated 70 kilometers from Krasnoyarsk; Pamyati 13 Bortsov village, the road to a strip mine; and the Shumikhanskoye forest management unit, forest compartment 98, located 61 kilometers from Krasnoyarsk.

RP-1. *Tree layer:* pure or mixed dominated by Siberian fir, admixture of birch and aspen in the stand composition, age 75–80 years, average diameter 23–24 cm, average height 17–20 m, density 0.5–0.9, III bonitet class (quality class). *Shrub layer:* currants, rowan, meadowsweets, alder, willow. *Young trees:* dominated by Siberian fir with an admixture of Siberian pine, height 1.5 m, 3–4 thousand trees/ha, healthy. *Ground cover:* herb-rich (Figure 1).

RP-2. K-1. Complete degradation subsequent to the outbreak of the four-eyed fir bark beetle (Figure 2).

Fig. 1. Mixed stand dominated by Siberian fir (RP-1).

Fig. 2. Degraded Siberian fir-dominated stand (RP-2, K-1).

RP-2. *Tree layer:* mixed dominated by Siberian fir, admixture of Siberian pine, spruce, birch, aspen, age 70–80 years, average diameter 20–21 cm, average height 16–18 m, density 0.6–0.9, III–IV bonitet class (quality class). *Shrub layer:* rowan, meadowsweets, currants. *Young trees:* pure or mixed dominated by Siberian fir with an admixture of Siberian pine and birch, height 1.0–1.5 m, 3 thousand trees/ha, healthy. *Ground cover:* herb-rich.

RP-3. *Tree layer:* the first layer is dominated by Scots pine, admixture of Siberian fir, birch, Siberian pine, spruce, aspen, age of Scots pine 140–160 years, average diameter 32–40 cm, average height 25-31 m, density 0.9–1.0, I–II bonitet class (quality class). *Shrub layer:*

sparse, includes rowan, bird cherry, meadowsweets, rose. *Young trees:* dominated by Siberian fir with an admixture of Siberian pine and Scots pine, age 10 years, height 1.5 m, 0.5–4.0 thousand trees/ha, healthy. *Ground cover:* forest type – herb-rich Scots pine- and birch-dominated forest, ground cover vegetation include sedges, ferns, horsetails, wild garlic, vetches, feather mosses, stone bramble. *Features:* the development of the four-eyed fir bark beetle under the Scots pine and birch canopy in the Siberian fir layer.

RP-7. *Tree layer*: mixed dominated by birch and Siberian pine with an admixture of Scots pine, larch, Siberian fir, birch, spruce and aspen, birch age 85 years, spruce 120 years, Siberian fir 60 years, density 0.3–0.6, I–II bonitet class (quality class). *Shrub layer:* rowan, meadowsweets, honeysuckles, rose, bird cherry, red currant. *Young trees:* Siberian fir dominates with an admixture of Siberian pine and spruce, age 20 years, height 2.0–2.5 m, 8–20 thousand trees/ha, healthy. *Ground cover*: forest type – tall herbs-covered birch forest, sedges/herb-rich birch forest, sedges/herb-rich Siberian pine forest, ground cover vegetation include sedges, ferns, stone bramble, horsetails, feather mosses. *Features:* large-scale Siberian fir mortality along the stream due to the impact of the four-eyed fir bark beetle, uneven density, trees grow on northern and western slopes with a steepness of up to 10 °.

Table 1 provides a presentation of the general characteristics of forest stands damaged by the four-eyed fir bark beetle.

Table 1. Characteristics of the studied forest stands.

RP	Species composition, species	A, years	H av, m	d av, cm	ΣG, m^2/ha	P	Bonitet	Forest type	M, m^3/ha	Md, m^3/ha
RP-1 L-3	53F34B13Aind.S, SP	40			28.58	1.12	2	Fhr	214	114
	Fir		13.0	13.6						
	Birch		19.6	28.0						
RP-2 K-1	Complete degradation subsequent to the outbreak of the four-eyed fir bark beetle									
RP-2 L-5	60F26S8B6SP	70			22.25	0.78	3	Fhr	203	32
	Fir		15.4	18.1						
	Spruce		19.9	27.1						
RP-3 L-6	30P27F25A15B3SP	150			30.82	0.81	2	Phr	335	14
	Fir		13.1	9.5						
	Scots pine		30.0	24.4						
	Aspen		20.4	26.7						
RP-3 L-8	52B26F22Pind.SP	150			39.39	1.38	2	Bs/hr	360	27
	Fir		13.1	9.6						
	Birch		18.5	22.0						
	Scots pine		31.3	33.1						
RP-4 L-9	53A34B13F1SP	130			43.18	1.05	1	Ahr	463	61
	Fir		12.0	12.6						
	Aspen		30.7	33.4						
	Birch		28.4	30.4						
RP-7 L-16	50SP27B21S2F	60			19.03	0.39	2	SPs/hr	171	148
	Fir		11.5	5.1						
	Siberian pine		20.0	31.7						
	Birch		25.2	25.6						

Note: The species composition of a stand is indicative of the percentage contribution of a particular tree species; "ind." indicates that the following tree species occupies less than 2% of the stem volume in a given stand; A – aspen; B – Birch; F – fir; P – Scots pine; S – spruce; SP – Siberian pine. A – average age. Hav – average height. dav – average diameter. ∑G – basal area. P – density. Bonitet class indicates the quality class of a stand (1 – the most height-productive stands, 5 – the least-productive stands). M – growing stock. Md – stem volume of standing dead trees. Forest type: Fhr – herb-rich fir forest; Ahr – herb-rich aspen forest; Phr – herb-rich Scots pine forest; Bs/hr – sedges/herb-rich birch forest; SPs/hr – sedges/herb-rich Siberian pine forest.

The initial observation to be made pertains to the presence of a considerable number of mixed stands, with a preponderance of various species (Scots pine, Siberian pine, birch, aspen), in which Siberian fir trees grow. This phenomenon signifies the plasticity of the species, a characteristic that has been documented in the monograph by Falaleev [15]. The age of the forest stand is contingent on the dominant species and the time period during which the stand has existed. The age of the stands ranged from 40 to 150 years, and the stands exhibited pronounced age disparities, considering the young generation. The vertical structure of the stands was found to be insignificant, a phenomenon attributable to both the biodiversity of the stands and the stature of the trees. It is noteworthy that the dominant Scots pine, aspen, and birch trees in the stands have reached the age of overmaturity and are relinquishing their dominant positions to the fir, which in turn is being damaged by the four-eyed fir bark beetle. These processes have the potential to induce substantial alterations in the composition of forests, a consequence of invasive impact. The average height of the fir trees varied from 6.2 to 19.8 m; aspen from 16.9 to 30.7 m; birch from 17.9 to 29.6 m; spruce – 19.9 m; Scots pine 30.0–31.3 m; larch – 25.0–26.5 m and Siberian pine – 20.0 m. The average diameter corresponded to the following values: fir – 6.5–29.9 cm; aspen – 16.8–52.0 cm; birch – 19.8–33.4 cm; spruce – 27.1 cm; Scots pine – 24.4–60.0 cm; larch – 36.1–64.0 cm; Siberian pine – 31.7 cm.

The size indicators suggest that the fir develops under the canopy of other tree species. The height of the fir layer does not exceed 20 m, and trees are also thick, rarely exceeding 20 cm in diameter (maximum 29.9 cm).

The absolute and relative density of forest stands is contingent upon the composition, age, and degree of damage to the fir in the stand. It is noteworthy that, in addition to pure stands that have been completely destroyed by the pest (RP-2, K-1; RP-5), numerous stands exhibit overstocking, characterized by a density that exceeds the standard value (RP-1, L-3; RP-3, L-7,8; RP-7, L-15; RP-8, L-17,18). At this juncture, the damaged fir trees do not have a substantial impact on the state of the forest stands.

The quality of the site is also quite diverse, exhibiting variation depending on the dominant species and the height of the trees (I–III bonitet class). The forest types present in the area are primarily herb-rich and tall-herbs types, with occasional occurrences of stands of feather moss forest types.

The stem volume in the stands exhibits high variability, contingent on factors such as density, size, and degree of damage to the trees (variance from 128 to 639 m^3/ha). Correspondingly, the timber volume of standing dead trees is contingent on species composition, age, and the extent of invasive damage to the stand (variance from 9 to 301 m^3/ha).

The studies were conducted in forest stands that had been damaged by the four-eyed fir bark beetle. To assess the degree of invasive impact and ascertain the infestation status of forest stands, a series of computational analyses were conducted.

The composition of forest stands was determined in three ways: first, inventory composition (M) was determined through representation in total stem volume; second, biological composition (Nn) was determined by the number of trees; and third, biological composition before the impact of the pest (Np) was determined by the number of trees (Table 2).

It should be noted that in Scots pine-, aspen-, and birch-dominated stands, the species composition is determined by the total stem volume of old, few, and large trees. However, when the number of trees is considered, the same forest stands turn out to be dominated by Siberian fir. However, the presence of the four-eyed fir bark beetle has the potential to compromise the sustainability of the fir, thereby influencing the succession patterns within these stands.

Table 2. Species composition and total mortality in the stands damaged by the four-eyed fir bark beetle (fragment).

Research plot	Species composition			Mortality rate, %
	by total stem volume	by the number of trees	by the number of trees before the disturbance	
RP-1	53F34B 13A ind. S, SP	67F21A 10B1S1SP	75П16Ос 8Б1Е1К	53.0
L-3	The stand has been completely destroyed by the pest			
RP-2	60F26S 8B6SP	63F17B 12S7SP	75F11B 8S5SP	15.7
K-1	30P27F25A 15B3SP	69F12P8A 6B5SP	71F11P8A 6B4SP	4.2
RP-2	52B26F22P ind. SP	68F26B 5P2SP	77F18B 3P1SP	5.4
L-5	53A34B 12F1SP	48F28A 22B2SP	52F26A 20B2SP	3.1
RP-3	50SP27B21S 2F	37F22S22SP 19B	77F8S 8SP7B	76.8

The selected forest stands included stands with varying proportions of dead trees (total mortality rate) ranging from 0.0 to 100.0 %.

The sustainability of the fir trees was studied separately. The mortality rate (%), which was determined based on the number of trees, exhibited a range from 0.0 to 68.6 %. Similarly, the mortality rate, which was calculated based on the total stem volume, ranged from 0.0 to 99.3 %.

The proportion of fir trees infested by the pest is substantial, ranging from 0.0 to 72.2 % in terms of the number of trees and from 0.0 to 67.6 % in terms of the total stem volume.

In summary, it can be concluded that the studied stands can be regarded as a point of reference for the study area with regard to species composition, stand characteristics, and the degree of infestation of fir trees by the four-eyed fir bark beetle.

To evaluate the vulnerability of diverse forest communities to the infestation of the pest, the data were meticulously arranged, with considerations given to mortality rates and degree of damage by the pest. The outcome of this process yielded Table 3, which presents a comprehensive categorization of forest stands according to their species composition and damage degree.

Table 3. Differentiation of forest stands according to species composition and the extent of damage

Differentiation criterion	Degree of damage	Forest type determined by the dominant tree species
Deadwood (standing dead trees) volume	Minimal up to 3 %	Aspen forest with a small proportion of fir
	Medium up to 3.1–10.0 %	Scots pine- and birch-dominated forest
	High 10.1–50.0 %	Fir-dominated forest
	Severe more than 50.1 %	Forests of various species composition with a significant proportion of fir (B, SP, A)

4 Conclusion

A comprehensive evaluation of the infestation and its subsequent impact on forests reveals a hierarchy of vulnerability based on species composition, with fir forests ranking highest, followed by Siberian pine forests, birch forests, Scots pine forests, and aspen forests.

Consequently, from a forestry perspective, aspen- and Scots pine-dominated forests exhibit the greatest resistance to the invasive impact of the four-eyed fir bark beetle in the Krasnoyarsk forest-steppe zone.

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