The state of the dark coniferous forests in the foothills of the Eastern Sayan after a pest invasion

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Abstract. An assessment was conducted on the health of dark coniferous stands in the Biryusinskoe forestry. The study is of great significance in light of the environmental degradation caused by the invasive four-eyed fir bark beetle (*Polygraphus proximus* Blandford). The findings revealed that the fir-dominated stands are severely weakened or dying in the study area. The decline and dieback of fir stands are primarily caused by the invasive four-eyed fir bark beetle and other negative impacts. The text discusses the main factors contributing to this issue. The data obtained indicate that Alekseev's method of assessing forest health provides a more detailed and accurate description of the state of forests.

1 Introduction

Today, research on the state of forests is increasingly important, as forests are exposed to various biotic and abiotic factors.

Many regions of the world are experiencing forest declines and diebacks. That is also true for so-called dark coniferous forests (in the study area such forests are represented by stands dominated by Siberian fir/Siberian spruce/Siberian pine) [1]. The genus *Abies* (Mill.) is particularly susceptible to degradation and dieback. Fir forests are declining in Europe, Asia, North America and Japan [3-6].

Forest degradation has multiple underlying causes. According to research, the main drivers of dark coniferous forest decline are climate change, soil swamping, and the spread of parasitic fungi and insect pests [7].

A unique phenomenon in the Siberian taiga is occurring in some regions of Siberia, including Krasnoyarsk Krai [4]. This is the large-scale dieback of Siberian fir caused by the invasion of the four-eyed fir bark beetle (*Polygraphus proximus* Blandford). Currently, the pest has infested fir across most of its range in the southern taiga subzone. This is associated with the trees weakening due to water stress caused by rising temperatures and aridity [8].

It should be noted that the forest health decline is global and requires an integrated approach to solving the problem. Both human intervention and climate change are negatively

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impacting forest ecosystems. Therefore, studying the forests health becomes especially important for preserving biodiversity and maintaining environmental sustainability.

2 Materials and methods

The field studies were conducted in the Biryusinskoe forestry, located in the center of Krasnoyarsk Krai. The area of the forestry is 68.134 ha, 97.1% of which is covered by forest. According to the forest vegetation zoning developed for Krasnoyarsk Krai by the laboratory of the Sukachev Institute Forest & Timber Siberian Branch USSR Academy of Sciences, the study area belongs to the East Sayan mountain-taiga region of pine-Siberian pine-fir forests. The study area is dominated by fir forests, which occupy 35% of the forest area.

The research plots were placed in fir-dominated stands in forest compartment No. 38 in forest mapping units 2, 3, 10 and in forest compartment No. 24 in forest mapping units 40 and 42. Three circular research plots of constant radius 400 m² (R = 11.28 m) were placed in each mapping unit (Figure 1).

Fig. 1. Study locations.

The location of the research plots was chosen based on species composition and age structure. Tree cruising was carried out on each research plot (all measurements were recorded on a special field card). Each tree was assessed according to a set of visual characteristics using a 6-point health status scale. The first category includes healthy trees with no signs of weakening, the second category refers to weakened trees and the third category includes severely weakened plants. Trees in the first, second and third categories are considered viable. The fourth category includes trees that are dying, the fifth category refers to trees that have died in the current year (fresh deadwood) and the sixth category includes trees that have died in previous years (old deadwood) [9].

The original data were subjected to additional processing in order to reveal the characteristics of the forest stands. As a result, the following indicators were obtained: basal area ($\Sigma G_{1,3}$), volume of a tree trunk($V$), average diameter ($Dav$), average height ($Hav$),
density (P), growing stock (M) and deadwood stock (Md). The health of the forests was then assessed.

3 Results and discussion

The studied stands include the following tree species: Siberian fir (*Abies sibirica* Ledeb.), Scots pine (*Pinus sylvestris* L.), Siberian spruce (*Picea obovate* Ledeb.), Siberian pine (*Pinus sibirica* Du Tour), silver birch (*Betula pendula* Roth.). The main forest-forming species is the Siberian fir, which occupies from 6 to 9 units in the species composition in all studied stands (Table 1).

Table 1. Silvicultural and forest inventory of the studied forest stands.

<table>
<thead>
<tr>
<th>Forest compartments</th>
<th>Forest mapping unit</th>
<th>Area, ha</th>
<th>Composition</th>
<th>Age, years</th>
<th>Average height, m</th>
<th>Average diameter, cm</th>
<th>Bonitet class</th>
<th>Density</th>
<th>Forest type</th>
<th>Growing stock, m³/ha</th>
<th>Deadwood stock, m³/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>38 2 6.0 9F1S + P, ind B</td>
<td>140 21.4 18.4 4</td>
<td>0.38 Ffm</td>
<td>136 41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38 3 16.0 9F1P + B, ind S</td>
<td>130 21.5 18.2 4</td>
<td>0.44 Ffm</td>
<td>148 48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38 10 7.0 6F4S, ind P, SP</td>
<td>140 23.2 20.0 3</td>
<td>0.56 Ffm</td>
<td>246 65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 40 24.0 8F1S1SP, ind B</td>
<td>140 22.7 19.6 3</td>
<td>0.47 Ffm</td>
<td>192 64</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 42 25.0 7F3S ind SP, B</td>
<td>130 22.6 19.3 3</td>
<td>0.51 Ffm</td>
<td>205 52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Composition: '+' indicates that the following tree species occupies 2.5-5.0% in the total growing stock on the research plot, 'ind' indicates that the following tree species occupies 0.1-2.4% in the total growing stock on the research plot. Bonitet class describes forest productivity (1 is the highest-productivity class and 5 is the lowest-productivity class). Forest type: Ffm – feather moss-dominated fir forest, Ffn – tall herbs-dominated fir forest.

The age of fir varies from 130 to 140 years; Scots pine and Siberian pine are 190 years old. The diameter of the fir varies from 18.2 to 20.0 cm, and the average height from 21.4 to 23.2 m. The total growing stock varies from 136 to 246 m³/ha.

In the mapping units studied, the deadwood stock ranges from 41 to 65 m³/ha.

Two mapping units are covered by low-density stands, and three mapping units are covered by medium density forest stands.

Three of the mapping units have a fairly steep slope with different exposures ranging from 25 to 30°. Two mapping units are situated in flat areas.

The state of the forest stands was assessed using the weighted average forest health index and the forest health status (based on Alekseev's methodology) [10]. According to Alekseev's method, the L indicator is calculated using the following formula:

$$L = \frac{100 \times n_1 + 70 \times n_2 + 40 \times n_3 + 5 \times n_4}{N},$$  

(1)
where \( n_1, n_2, n_3, n_4 \) – number of trees without signs of weakening, weakened, severely weakened and dying trees respectively;

\( N \) – number of all trees in the research plot.

100, 70, 40, and 5 – coefficients expressing the vital status of healthy, damaged, severely damaged and dying trees, %.

The state of the forest stand was assessed using the L indicator, with gradations ranging from 'healthy' (100-80%), to 'weakened' (79-50%), 'severely weakened' (49-20%), and 'completely destroyed' (less than 19%).

Forest health status was assessed using the average health index of each species and then of all forest in the mapping unit [11].

The health index (Kav) of each tree species was calculated considering its share in the total growing stock of the forest stand:

\[
K_{av} = \frac{\sum P_i \times K_i}{100},
\]

where \( P_i \) – share of each health index (as a percentage) in the total growing stock of this tree species;

\( K_i \) – tree health index (\( K_i = 1 \) – without sighs of weakening, \( K_i = 2 \) - weakened, \( K_i = 3 \) – severely weakened, \( K_i = 4 \) - dying, \( K_i = 5 \) - dead).

The average forest health index (Kav.FS) was calculated based on the proportion of each tree species in the stand composition.

\[
K_{av,FS} = \frac{\sum P_i \times K_{av,i}}{10},
\]

where \( P_i \) - share of tree species in stand composition, in fractions of a unit;

\( Kav\ i \) – average health index of each tree species.

Based on the average forest health index, five degrees of forest degradation have been identified: 1st degree is characterized by the absence of signs of weakening (equivalent to 1.0-1.5); 2nd degree - weakened stands (1.6-2.5); 3rd degree - severely weakened stands (2.6-3.5); 4th degree - dying stands (3.6-4.5) and 5th degree - dead stands (more than 4.6).

Table 2 shows the results of the health assessment of the fir-dominated stands.

<table>
<thead>
<tr>
<th>Forest compartment / mapping unit</th>
<th>38/2</th>
<th>38/3</th>
<th>38/10</th>
<th>24/40</th>
<th>24/42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species composition</td>
<td>9F1S + P</td>
<td>9F1P + B</td>
<td>6F4S</td>
<td>8F1S1SP</td>
<td>7F3S</td>
</tr>
<tr>
<td>ind B</td>
<td>ind S</td>
<td>ind P, SP</td>
<td>ind B</td>
<td>ind SP, P, B</td>
<td></td>
</tr>
<tr>
<td>Average forest health index</td>
<td>3.6</td>
<td>3.6</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Forest health status</td>
<td>dying</td>
<td>dying</td>
<td>severely weakened</td>
<td>severely weakened</td>
<td>severely weakened</td>
</tr>
<tr>
<td>According to Alekseev</td>
<td>L, %</td>
<td>31.7</td>
<td>31.5</td>
<td>26</td>
<td>30.9</td>
</tr>
<tr>
<td>Forest health status</td>
<td>severely damaged</td>
<td>severely damaged (severely weakened)</td>
<td>severely damaged (severely weakened)</td>
<td>severely damaged (severely weakened)</td>
<td>severely damaged (severely weakened)</td>
</tr>
</tbody>
</table>

Table 2 shows that 60% of the fir stands are severely weakened. In such stands, trees are in decline (up to 50% of the crown is dead) and can be considered as potential deadwood [11]. Another 40% of the stands are dying (mapping units 2 and 3 of forest compartment No. 38) [11].
According to Alekseev, forest health in all mapping units was assessed as 'severely damaged (severely weakened)', indicating a high rate of tree mortality. The decline and dieback of coniferous forests can be attributed to a number of factors, including uneven precipitation, swamping, parasitic fungi and xylophagous insects. An important factor is the edaphic conditions formed under the influence of coniferous canopies, namely an increase in soil pH [7, 12]. However, the main reason for the degradation of fir forests in recent years has been the spread of the invasive four-eyed fir bark beetle. According to available data [13], tree mortality in fir stands during an outbreak of the pest ranges from 30 to 95%.

The forests studied are infested with the four-eyed fir bark beetle, which explains their severely weakened and dying condition. Alekseev's method, based on a detailed assessment of each tree, allows individual signs of disease and damage to be identified. It involves a more thorough examination of plant health, which can be particularly important in dark coniferous forests with a constant accumulation of deadwood. This method can provide a more accurate picture of the health of the forest and reveal damage to the stand.

On the other hand, the assessment based on the average forest health index may be less detailed but more applicable to large areas and to research where an average assessment is required without a detailed study of the condition of individual trees. It may be less suitable for assessing the negative impact of pest invasions in dark coniferous forests due to the lack of detail in assessing the condition of each tree.

Given the characteristics of dark coniferous forests, where deadwood is constantly accumulating, Alekseev's method is preferable because it provides a more detailed and in-depth assessment of disease and damage, making it possible to more accurately identify the negative impact of deadwood accumulation on the state of forest stands.

4 Conclusion

The assessment methods used to assess the state of dark coniferous forests revealed that over 60% of the fir stands examined were severely weakened, suggesting that most trees could be classified as deadwood. Additionally, 40% of the stands were identified as dying. According to Alekseev, the health status of stands in all mapping units was classified as 'severely damaged (severely weakened)', indicating a high tree mortality rate. Alekseev's method enables the identification of individual signs of diseases and damage in each tree. Therefore, it is preferred for assessing the condition of dark coniferous forests, where trees are constantly exposed to negative competitive and invasive effects. Alekseev's method provides a more detailed assessment of forest health, thus more accurately reflecting the actual situation.

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