The health of forest stands growing along tourist trails in the mountain taiga zone of southern Central Siberia

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Abstract. The research was conducted in forests situated within the Maly Borus peak tourist trail (Gornoe Forestry of the Shushensky Bor National Park). The objective of this study is to conduct a comprehensive evaluation of the current condition of forests that are subjected to a considerable degree of recreational use. The research methods employed include forest pathology examination, establishment of recreational digression of stands, quantifying damage to the surface roots, integral assessment of forest health, and correlation analysis of the data. The recreational disturbance of the stands along the trail has reached an advanced stage. The studied mixed stands are exhibiting signs of stress and are not distinct from surrounding stands (growing further from the trail). The tree species exhibiting signs of deterioration were as follows: Siberian spruce, Siberian fir (K_{av} = 1.5), Silver birch (K_{av} = 1.6), and Siberian pine (K_{av} = 2.1). The highest mortality rate is observed in Siberian pine (28%), including trees of dominant status. With regard to the proportion of trees that have recently died, the level of disruption to the forests within the trail is relatively low. No significant correlation has been identified between the health of all forest-forming species and root damage. The prevalence of diseases and damage (mainly in trunks) in all species exceeds 10%, with Siberian pine exhibiting the highest incidence at 78%. The most detrimental diseases (damage) and their combinations are: in Siberian pine (trunk wound + dry side + stem rot) and in Siberian fir (fir broom rust). While the condition of the forests within the tourist trail remains relatively stable, it is imperative to implement a systematic approach to forest pathology control and to prohibit the illicit extraction of Siberian pine nuts.

1 Introduction

Recreation and tourism are important components of ecosystem services provided by forest ecosystems [1, 2]. These services are of significant importance, as evidenced by the rising intensity of recreational use of forests in traditional recreation areas and the encroachment of such use into new forest areas, including undisturbed

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ecosystem+5444s in remote areas. Among the various forms of forest recreation is ecotourism, which is confined mainly to protected natural forest areas and attracts a considerable number of people [4-6]. In the south of Central Siberia in particular, mountain taiga forests of protected natural areas are experiencing an increase in tourist and recreational activities, with the growth of ecotourism being one of the key drivers of this development.

The recreational use of forests has both beneficial and detrimental effects on the environment. While it provides benefits to humans, such as relaxation and tourism, it can also lead to negative changes in forests. These changes can disrupt the functionality of all components of forest ecosystems. In forests, the most vulnerable layers are the lower ones: ground cover vegetation, shrub layer, and understory [8, 14-17]. As a result of increased recreational impact, forest health is deteriorated, the proportion of healthy trees is decreased, and the proportion of severely weakened and dying trees is increased [18-21]. The anthropogenic impact on forested areas is not evenly distributed. Areas with hiking trails, recreation areas, and parking areas experience the greatest loads. In such areas, forest health monitoring should be carried out for timely decision-making to increase their sustainability, optimize the arrangement of tourist and excursion areas, and preserve the natural environment [12, 22-24].

The objective of this study is to evaluate the current forest health status along one of the most popular tourist trails in the Gornoe Forestry of the Shushensky Bor National Park (southern Central Siberia). In accordance with the stated goal, the following tasks were completed: to determine the degree of recreational disturbance of stands on the tourist trail; to assess the forest health of the forest stand as a whole and of each tree species separately; to identify the main damage and diseases of trees, determine their symptoms; to assess the impact of anthropogenic damage to roots on the health of forest-forming tree species.

2 Materials and Methods

The objective of the study was to examine the impact of long-term recreational loads on forest stands within the Maly Borus peak tourist trail. The focus of the research was to assess the health of the forests along the tourist trail.

A field study was conducted in the third decade of July 2023. It included a cruising forest pathology examination and a detailed (instrumental) examination of the forest stand. The cruising involved a visual assessment of the general condition of the trees within and outside the path, as well as the characteristics of coarse woody debris accumulation. The degree of recreational disturbance (stage of digression) of trees within the trail was evaluated visually based on the relative area of ground cover vegetation trampled down to the parent material (Table 1), in accordance with Standard 56-100-95 [25].

Table 1. Classification of the stages of recreational digression of trees.

Stage	I	II	III	IV	V
Relative area of ground cover vegetation trampled down, %	Up to 1,0	1,1 – 5,0	5,1 – 10,0	10,1 – 25,0	More than 25,0

The detailed forest pathology examination was conducted on two sections of the trail, which were representative of the degree of disturbance to the phytocenosis (ground cover vegetation trampled down and tree roots exposure). Section 1 of the trail is situated downhill from the watershed border between forest compartments 5 and 8 to the turn-off leading to the "Waterfall." Section 2 begins at the indicated turn and descends towards the beginning of the trail. Consequently, the survey encompassed forest units 38, 33, and 32 within the confines of forest compartment 8. The stand characteristics, as delineated by the most recent forest inventory data, are presented in Table 2.

Table 2. Forest stand characteristics in the study area

Section	Forest unit within compartment 8*	Forest stand characteristics*	Forest stand composition (according to the cruising)
1	38	Forest stand composition: 30% - Siberian pine, 10% - Siberian spruce, 10% - Siberian fir, 50% - Silver birch. Ground cover dominated by tall-herbs and ferns. Average values for Siberian pine: age – 100 years, height – 20 m, diameter – 26 cm; bonitet class – 3. Stand density – 0,5. Growing stock – 240 m^3/ha. Understory: 80% - Siberian fir, 20% - Siberian pine. Average height - 2,0 m. 2000 young trees per ha. Healthy. Shrub layer is sparse and dominated by Spirea.	80 % - Siberian pine, 20 % - Siberian spruce, Up to 3 % - Silver birch.
	33	Forest stand composition: 40% - Siberian pine,20% - Scots pine, 10% - Siberian spruce, 10% - Siberian fir, 20% - Silver birch. Ground cover dominated by wood ferns and feather mosses. Average values for Siberian pine: age – 110 years, height – 21 m, diameter – 26 cm; bonitet class – 3. Stand density – 0,6. Growing stock – 270 m^3/ha. Shrub layer is sparse and dominated by Spirea.	
2	32	Forest stand composition: 60% - Silver birch, 10% - Aspen, 20% - Siberian fir, 10% - Siberian pine, 3-5% - Scots pine. Ground cover dominated by tall-herbs and ferns. Average values for Silver birch: age – 80 years, height – 23 m, diameter – 26 cm; bonitet class – 2. Stand density – 0,7. Growing stock – 200 m^3/ha. Understory: 80% - Siberian fir, 20% - Siberian pine. Average height - 3,0 m. 2000 young trees per ha. Healthy. Shrub layer is of mid-density and dominated by Spirea.	50 % - Silver birch, 20 % - Siberian pine, 20 % - Siberian fir, 10 % - Siberian spruce.

* – Data from the Forest Description of Gornoe Forestry of the Shushensky Bor National Park 01.01.2011

At the sample plots (sections of the trail), all the trees were measured, subdivided by species, diameter classes (by measuring the diameter at breast height), and health statuses. The health status of each tree was determined visually by assessing the condition of the crown, as well as other diagnostic signs [26]: 1 – no signs of weakening; 2 – weakened; 3 – severely weakened; 4 – dying; 5 – dead. Additionally, the presence of mechanical injuries to the trunks and branches was documented. In instances where a tree exhibited symptoms indicative of rot, necrosis, and canker, the data was recorded accordingly. The proportion (%) of bare and injured (with signs of deep damage) roots in the upper layer of the rhizosphere was also quantified for each tree.

The health of forest stands growing along the trail (in the sample sections) was evaluated using the following indicators obtained during the forest pathology examination: distribution of trees by health statuses (vitality spectrum); weighted average health status; mortality rate. The weighted average health status (index) for each tree species was calculated based on the basal area according to the formula:

$$K_{\text{av}} = (P_1 \times K_1 + P_2 \times K_2 + P_3 \times K_3 + P_4 \times K_4 + P_5 \times K_5)/100, \quad (1)$$

where P_i – proportion of trees in each health status (%); K_i – health status (1 – no signs of weakening, 2 – weakened, 3 – severely weakened, 4 – dying, 5 – dead). At $K_{av} \leq 1{,}5$ the tree species has no visible signs of weakening; $1{,}5 < K_{av} \leq 2{,}5$ – the tree species is weakened; $2{,}5 < K_{av} \leq 3{,}5$ – the tree species is severely weakened; $3{,}5 < K_{av} \leq 4{,}5$ – the tree species is dying; $K_{av} > 4{,}5$ – the tree species is dead [26]. The health status of the entire forest stand (mixed composition) on each section of the trail was established in accordance with the above gradation according to the value of the weighted average health index, which was calculated using the formula.:

$$K_{\text{av stand}} = \sum(D_{\text{i}} \times K_{\text{av i}})/10, \quad (2)$$

where D_i – the proportion of a tree species within a given stand composition, expressed as a unit fraction; $K_{av\ i}$ – average health status for each tree species [26].

The actual forest stand composition along the trail was determined based on the analysis of tree measurements and the calculation of the share of each species in the absolute density of the stand (the basal area). This is illustrated in Table 2.

The degree of violation of stand stability was determined based on an assessment of the amount of deadwood, which included dying trees (i.e., trees that are expected to die within a period of two years or less), dead trees, and blowdown. Stands are classified into three categories of disturbance severity: weak, moderate, and severe. The weak category is defined as a condition where up to 10% of trees are dying. The moderate category is characterized by a share of dying trees of 11-30% of trees, while the severe category is defined by a share of dying trees exceeding 30% [26].

The extent of tree disease prevalence and trunk damage in forest stands was quantified using the following formula:

$$P = n \times 100 / N, \quad (3)$$

where P – prevalence, %; n – number of damaged (infested) trees; N – total number of trees of the specific species within the designated study area.

The detrimental impact of diseases (or damage), including their combination, was evaluated by calculating the weighted average health index using formula 1 for the corresponding set of infested (or damaged) trees.

In analyzing the field data, we employed the use of a correlation coefficient, specifically the Pearson correlation coefficient (denoted as R), which serves to quantify the linear correlation between the characteristics of trees growing along the trail. The calculations were performed using the STATISTICA 10 software package.

3 Results and Discussion

The long-term impact of hiking recreation on the forest ecosystem has resulted in the disruption of phytocenoses within the designated tourist trail. This was reflected, first and foremost, in the ground cover vegetation, which, during the active passage of the tourist flow, was completely disrupted and replaced with the parent material. The visual assessment indicates that the degree of recreational disturbance of stands along the trail corresponds to stages IV-V of digression, as defined by the aforementioned scale. In the entirety of the forest units affected by recreational disturbance (forest biogeocenoses), the latest forest inventory indicates that trees have been affected at stages I-II.

The visual assessment, based on a complex of visible signs (including the state of the crown, the presence of injuries in trees, the mortality rate, etc.), demonstrated that the health of trees, which are considered relatively resistant to recreational loads [27], along the trail is not significantly different from that of adjacent stands that have not been subjected to intensive recreation. Based on the materials of the cruising forest pathology examination on two sections of the trail, quantitative indicators of forest health were calculated, including by tree species, as presented in Table 3. The general vital condition of forest stands along the trail was assessed as weakened (2 out of 5 health categories) based on the values of the integral indicator ($K_{av\ stand}$).

Table 3. Forest health indicators

Species	Vitality spectrum (distribution of trees by health statuses), %					Average tree diameter, cm		K_{av}	Stand composition	K_{av} stand
	1	2	3	4	5	total	dead			
Section 1										
P	32,0	43,5	17,8	0	6,7	36,5	32,3	2,1	80% - Siberian pine; 20% - Siberian spruce; Up to 3% - Silver birch.	2,00
S	46,8	35,0	12,0	0	6,2	24,0	28,1	1,8		
B	50,0	0	0	0	0	16,0	-	1,5		
Section 2										
B	47,2	50,1	8,3	0	0	26,5	-	1,6	50% - Silver birch; 20% - Siberian pine; 20% - Siberian fir; 10% - Siberian spruce.	1,63
P	60,5	11,4	3,0	6,8	18,3	26,6	23,1	2,1		
F	56,8	37,6	4,5	0	1,1	13,5	8,0	1,5		
S	97,5	0	0	0	2,5	25,3	8,0	1,1		

Note: P – Siberian pine *Pinus sibirica*, S- Siberian spruce *Picea obovata*, B – Silver birch *Betula pendula*, F – Siberian fir *Abies sibirica*

The health status of forest-forming species represented in forest stands exhibits considerable variation. The health status of Siberian pine is the most compromised of all the species under consideration. The K_{av} for the species in the study sections is 2.1, which corresponds to the "weakened" health category. This conclusion is also supported by the data on tree mortality, which includes the total number of medium and large trees in the fourth and fifth health categories. Moreover, the mean diameter of deadwood across the entire stand is nearly identical to the mean diameter of the Siberian pine (Table 3). The overwhelming prevalence of Siberian pine in the stand composition (80%) has led to a slight decline in the overall condition of the forest stand in the first section.

The Siberian fir is distinguished by a notably positive vitality structure, characterized by a prevalence of healthy trees (the combined proportion of trees classified as 1 and 2 categories of health status is 94.4%). Fir is located within the second layer beneath the birch/Siberian pine layer, which is presented in the second section of Table 3. The health status of birch and spruce is observed to be similar on average, as indicated by a K_{av} value of approximately 1.5–1.6, which suggests a slight weakening. However, a noteworthy distinction can be made between spruce and the other species with regards to tree mortality, whereby spruce demonstrates a mortality rate of 3–6% across both small and large specimens.

In general, the degree of disturbance to forest stands growing along the trail is minimal. The species most affected is the Siberian pine, with less than 10% of trees in the fourth health category (i.e., those that are dying). No dying or recently dead trees were identified among other tree species.

The impact of recreation on woody plants is evident in the damage caused to the upper layer of roots, which results from the chronic disruption of ground cover vegetation and upper soil horizon. The proportion of bare and damaged surface roots of trees in the trail projection varies considerably, from no signs of damage to 60% and even 90% (Table 4). The highest average rates of root damage were observed in trees of forest-forming species that are dominant in the surveyed sections. The species in question are Siberian pine and Silver birch. A significant direct relationship was established between trunk diameter and the degree of root exposure ($R = 0.578$, $p < 0.05$) and injury ($R = 0.570$, $p < 0.05$) for fir trees, indicating greater damage to surface roots in larger trees. Conversely, correlation analysis demonstrated a notable inverse correlation between the health index of fir trees and their diameter (Table 5), indicating that trees with larger diameters exhibit a higher vital status. For all analyzed forest-forming species, no significant relationship was identified between the condition of trees and indicators of damage to surface roots (Table 5).

Table 4. Indicators of damage to surface roots in trees growing along the trail

Species (number of trees)	Root exposure, %		Root damage, %	
	Average value	Min and max values	Average value	Min and max values
Pinus sibirica (*n* = 59)	35,86 ± 3,39	0 - 90	16,63 ± 2,00	0 - 60
Abies sibirica (*n* = 31)	20,97 ± 3,59	0 - 70	13,35 ± 2,34	0 - 50
Picea obovata (*n* = 26)	27,31 ± 4,00	0 - 80	9,08 ± 1,40	0 - 20
Betula pendula (*n* = 26)	35,42 ± 3,43	0 - 70	18,23 ± 2,24	0 - 40

Table 5. The correlation between the health index for forest-forming species and their size and root damage level.

Species (number of trees)	Tree characteristics		
	diameter at breast height (1.3 m)	share of exposed roots	Share of damaged roots
Pinus sibirica (*n* = 59)	- 0,201* (> 0,05)**	- 0,128 (> 0,05)	- 0,027 (> 0,05)
Abies sibirica (*n* = 31)	**- 0,586 (< 0,05)**	- 0,316 (> 0,05)	- 0,312 (> 0,05)
Picea obovata (*n* = 26)	- 0,231 (> 0,05)	- 0,160 (> 0,05)	- 0,213 (> 0,05)
Betula pendula (*n* = 26)	- 0,344 (> 0,05)	- 0,161 (> 0,05)	- 0,133 (> 0,05)

* – Pearson correlation coefficient; ** – significance level

The detailed examination revealed the presence of damage and diseases affecting trees, particularly in the trunk. The overall prevalence of these issues is notable, with the proportion of damaged (infested) trees for each species as follows (including cases of combined damage): Siberian pine - 78%, Siberian spruce - 50%, Siberian fir - 14% (5%), and Silver birch - 27% (2%) (Table 6). Therefore, Siberian pine trees are distinguished by the most unfavorable health status.

Table 6. Indicators of damage and disease on trees growing along the trail

<table>
<tr><th>Damage, disease
(and their combined manifestations)</th><th colspan="2">Prevalence
(P, %)</th><th>Health index
(Kav)</th></tr>
<tr><td colspan="4">Pinus sibirica (2,1)*</td></tr>
<tr><td>trunk wound (nuts collection consequence)</td><td colspan="2">9,1</td><td>1,5</td></tr>
<tr><td>dry side</td><td colspan="2">4,4</td><td>1,0</td></tr>
<tr><td>stem rot</td><td colspan="2">13,2</td><td>1,7</td></tr>
<tr><td>broken or dry top</td><td colspan="2">1,9</td><td>3,0</td></tr>
<tr><td>trunk wound + dry side</td><td colspan="2">14,3</td><td>1,9</td></tr>
<tr><td>dry side + stem rot</td><td colspan="2">13,2</td><td>2,3</td></tr>
<tr><td>trunk wound + dry side + stem rot</td><td colspan="2">22,1</td><td>2,4</td></tr>
<tr><td>total</td><td colspan="2">78,2</td><td></td></tr>
<tr><td colspan="4">Picea obovata (1,5)*</td></tr>
<tr><td>broken top</td><td colspan="2">2,6</td><td>2,0</td></tr>
<tr><td>dry side</td><td colspan="2">6,5</td><td>2,0</td></tr>
<tr><td>broken top + dry side</td><td colspan="2">5,2</td><td>5,0</td></tr>
<tr><td>total</td><td colspan="2">14,3</td><td></td></tr>
<tr><td colspan="4">Abies sibirica (1,5)*</td></tr>
<tr><td>dry side</td><td colspan="2">21,6</td><td>1,1</td></tr>
<tr><td>cankers on trunk</td><td>5,9</td><td rowspan="2">15,1</td><td>2,2</td></tr>
<tr><td>cankers on branches, «witches' brooms »</td><td>9,2</td><td>2,0</td></tr>
<tr><td>total</td><td colspan="2">36,7</td><td></td></tr>
<tr><td colspan="4">Betula pendula (1,6)*</td></tr>
<tr><td>dry side</td><td colspan="2">17,5</td><td>1,1</td></tr>
<tr><td>rotting base</td><td colspan="2">2,3</td><td>2,0</td></tr>
<tr><td>cankers</td><td colspan="2">4,6</td><td>1,0</td></tr>
<tr><td>dry top + stem rot</td><td colspan="2">2,3</td><td>3,0</td></tr>
<tr><td>total</td><td colspan="2">26,7</td><td></td></tr>
</table>

* – average health index for a tree species (for both sections of the trail)

The most prevalent ailments afflicting Siberian pine are trunk wounds (the result of nut collection with a sledgehammer), dry side, and stem rot, which were observed in approximately half of the trees (Table 6). The complex presence of these factors (occurring in different combinations in 50% of cases) has a significantly detrimental impact on the health of the trees. The high prevalence of stem rot in Siberian pine (pathogens have not been identified due to the absence of basidiomas) can be attributed to the trees' advanced age and the presence of numerous deep wounds in the trunks, which provide a conduit for fungal infections.

In a small proportion of Siberian pine, Siberian spruce, and Silver birch trees, damage to the trunk in the crown area is observed (prevalence of no more than 5%): broken top, dry top (Table 6). Concurrently, trees exhibiting such damage, at times in conjunction with additional defects (e.g., stem rot, dry side), are distinguished by the poorest health status (from severely weakened to dead). Minor dry sides, resulting from mechanical damage to trunks, are prevalent in numerous fir and birch trees (22% and 18%, respectively), yet do not manifest as visible weakening (K_{av} of damaged trees = 1.1).

Based on the presence of specific signs, namely cankers on trunks and branches, as well as clusters of shortened, underdeveloped shoots, a disease typical of fir was identified. This disease is known as fir broom rust and is caused by a pathogen belonging to the family of rust micromycetes, namely *Melampsorella caryophyllacearum* G. Schrot. The overall prevalence of 15% indicates the presence of an outbreak area, with the infested trees exhibiting a weakened status (K_{av} = 2.0-2.2) compared to the general health status of Siberian fir (K_{av} = 1.5) (Table 6).

4 Conclusion

The forest stands situated along the Maly Borus peak tourist trail are susceptible to the effects of prolonged recreational usage. This resulted in significant disruption to the forest stands, with the disturbance reaching extreme stages (IV and V) along the trail. The results of the forest pathology examination conducted in stands that had been disturbed by recreational activities revealed the following:

1. The mixed forest stands are weakened, and their visual appearance is indistinguishable from that of forest stands in areas not subjected to the same level of intense recreational activity (i.e., those situated further from the trail). In accordance with the average health status (K_{av}), the forest-forming species were situated in the following order of deterioration in health: Siberian spruce, Siberian fir (K_{av} = 1.5, indicating a healthy status), Silver birch (1.6, indicating a weakened status), and Siberian pine (2.1, indicating a weakened status). The highest tree mortality rate was observed in the Siberian pine, including trees of the first Kraft's Crown Classes (dominant status). Given the minimal presence of recently dead trees (found only in the Siberian pine, accounting for less than 10% of the total number of trees), it can be concluded that the degree of forest disturbance along the trail is relatively low.

2. The degree of exposure and injury to the surface roots in trees in the projection of the trail is estimated to be 90% and 60%, respectively. For fir trees, this figure rises markedly in line with the size of the tree in question. A significant correlation between the health category of trees of all forest-forming species and root damage has not been identified.

3. The prevalence of trees exhibiting signs of damage and disease (predominantly in the trunks) across all tree species exceeds 10%. In the case of Siberian pine, this figure stands at 78%, with instances of combined damage (trunk wound + dry side + stem rot) accounting for 50% of cases. The combined impact of complex damage (infestation) and recreational impact has a weakening effect on trees. The presence of fir broom rust (a typical affliction of this species) was identified in Siberian fir, which has the potential to weaken trees.

The results of the forest pathology examination indicate that the condition of the stands growing along the Maly Borus peak tourist trail is relatively stable, exhibiting only slight disturbances. It is recommended that systematic forest pathology monitoring be conducted in such stands in the future. To prevent an increase in disturbance and deterioration of the vital condition of the main forest-forming species, namely the Siberian pine, it is necessary to exclude the practice of illegal nut collection.

Acknowledgements

The research was carried out within the framework of the project "Methodological bases for assessment of forest pathology risks in southern Central Siberia" (№ FEFE-2024-0016) under the state order of the Ministry of Science and Higher Education of the Russian Federation for implementation by the Scientific Laboratory of Forest Health.

The authors express special gratitude to the Krasnoyarsk Regional Center for Collective Use of the Federal Research Center Krasnoyarsk Science Center of the Siberian Branch of the Russian Academy of Sciences for the equipment provided to ensure the implementation of the project "Methodological bases for assessment of forest pathology risks in southern Central Siberia” (No. FEFE-2024-0016).

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