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Incidence of Stem Rot in Forests Dominated by *Betula pendula* Roth in the Central Group of Regions of Krasnoyarsk Krai

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Abstract

Birch stands, dominated by *Betula pendula* Roth, are a common feature of boreal forests. Within the Krasnoyarsk (central) group of regions, they are concentrated in the taiga, subtaiga and forest steppe zones of actively managed forests, represented by stands of seed and shoot origin. The health and productivity of birch forests is often determined by the activity of wood-decay fungi, which leads to rot and decay in trees. The objective of the research is to evaluate the impact of stem rot on birch forests in the study area, with a focus on key ecological and silvicultural factors. The research methods employed included a reconnaissance survey of birch forests, a detailed forest pathology survey of forest stands on research plots (31 pcs.), comprehensive macroscopic diagnostics of stem rot, identification of xylotrophic fungi by basidiomes, integrated assessment of forest health, graph analytics and statistical data analysis. Stem rot has been identified in all birch forests in the study area. In shoot origin stands, the incidence rate has reached the stage of the disease center (i.e., more than 10% of trees are infected). The following wood-decay fungi have been detected on the trunks of living trees affected by rot: *Fomes fomentarius*, *Fomitopsis pinicola*, *Inonotus obliquus*, *Phellinus igniarius*, and *Trametes versicolor*. The infection typically infects trees via spores, finding entry through dying branches or mechanical and thermal wounds on trunks. In trees of shoot origin, stem rot is frequently transmitted via mycelium from stumps left after felling. This, in conjunction with diminished immunity, contributes to a substantially elevated incidence of stem rot in comparison to stands of seed origin. The research has not established a reliable correlation between the incidence of stem rot and forest stand characteristics due to the impact of human activity on birch forests (e.g., cutting, fires, tree injury). At the same time, no reliable connection has been established between the spread of stem rot and the stage of recreational disturbance. Trees of various sizes are affected by stem rot, usually proportional to their representation in the structure of the forest stand. The disease has a detrimental effect on the trees, which is clearly evident in the decline of forest health.

Keywords: boreal forests; birch forest; xylotrophic fungi; stem rot; forest stand origin; incidence of rot; tree health

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1. Introduction

Representatives of the genus *Betula* have a wide distribution in temperate and boreal forests [1–5]. At the start of 2024, birch and aspen forests made up 153.2 million hectares

(22.2%) of Russia's forest land, and this figure has been increasing [6]. In Krasnoyarsk Krai, located in Central Siberia, forests dominated by birch (primarily, *Betula pendula* Roth.) constitute 15.8% of the total forest cover of the region, ranking second only to larch forests [7]. In Central Siberia, a substantial proportion of birch stands are located in the subtaiga and forest steppe zones that are subject to active human management. Secondary stands of seed and shoot origin are more typical of these forests, while native birch forests with productive and species-rich herb layer vegetation (dominated by grasses and mesophilic herbs) are present in subtaiga forests [8]. The area of secondary birch stands is increasing as a result of active felling of coniferous forests. In addition, the resource value of birch forests is notable, with the timber and by-products of these plantations being a significant economic driver. Furthermore, these forests provide a range of essential ecosystem services.

The health and productivity of birch forests is largely determined by the presence of pests and pathogens [9–11]. In the context of pathogens, hemiparasites (facultative saprotrophs and facultative parasites) have the most significant impact on forest stands and forest ecosystems. They are responsible for initiating canker, necrosis and rot diseases in trees [12,13]. From an ecological standpoint, the development of stem rot in living trees due to wood-decay fungi (xylotrophic) is significant in the context of the ecosystem functions of wood-destroying organisms, particularly in birch forests [14–20]. Nevertheless, stem rot has been demonstrated to result in financial losses pertaining to commercial timber. Furthermore, trees with decayed trunks exhibit an increased vulnerability to windsnap. In summary, forest stands that are infected with stem rot are degrading, which results in a reduction in their capacity to provide goods and services [21–31]. There is evidence to suggest that *B. pendula* trees affected by stem rot exhibit reduced resistance to phyllophagous insects [32,33].

Despite the extensive body of literature and scientific knowledge pertaining to the subject of damage to birch forests caused by stem rot, this issue remains inadequately studied within the forests of Krasnoyarsk Krai. The extant literature provides limited insights into wood-decay fungi in birch forests, the health of such forests, and the incidence of rot in individual forest stands. In this regard, the objective of this study is to ascertain the ecological and silvicultural characteristics of the infestation of *B. pendula* stands by stem rot in Central Siberia (Krasnoyarsk Krai). The following working hypotheses have been postulated: the incidence of stem rot is elevated in trees of shoot origin; a direct correlation exists between the prevalence of rot and both age and forest recreation intensity; and stem rot exerts a detrimental effect on the health of birch forests. In accordance with the stated research aim and hypotheses, the research objectives comprised the following: the identification of the main pathogens causing stem rot in birch forests; the determination of the incidence rate of stem rot in stands considering their origin (seed, shoot); the analysis of the relationship between the prevalence of rot and both characteristics of forest stands and the level of recreational disturbance; the establishment of intracenotic features of tree damage by rot; and the assessment of the impact of stem rot on the health of birch stands.

2. Materials and Methods

2.1. Study Area

The research was conducted in herb-rich birch forests (mesophilic herbs and tall herbs groups of forest types) within six forest management units in the vicinity of the city of Krasnoyarsk (Figure 1). These forest management units are characterized by the greatest representation of birch forests in the region. The relative area of birch-dominated stands ranges from 17% (Mininskoe forest management unit) to 47% (Balakhtinskoe forest management unit) [34]. In accordance with the adopted forest zoning classification system,

the studied forest stands are categorized as part of the Central Siberian subtaiga-forest steppe region of the forest steppe zone and the Altai–Sayan mountain taiga region of the South Siberian mountain zone [7].

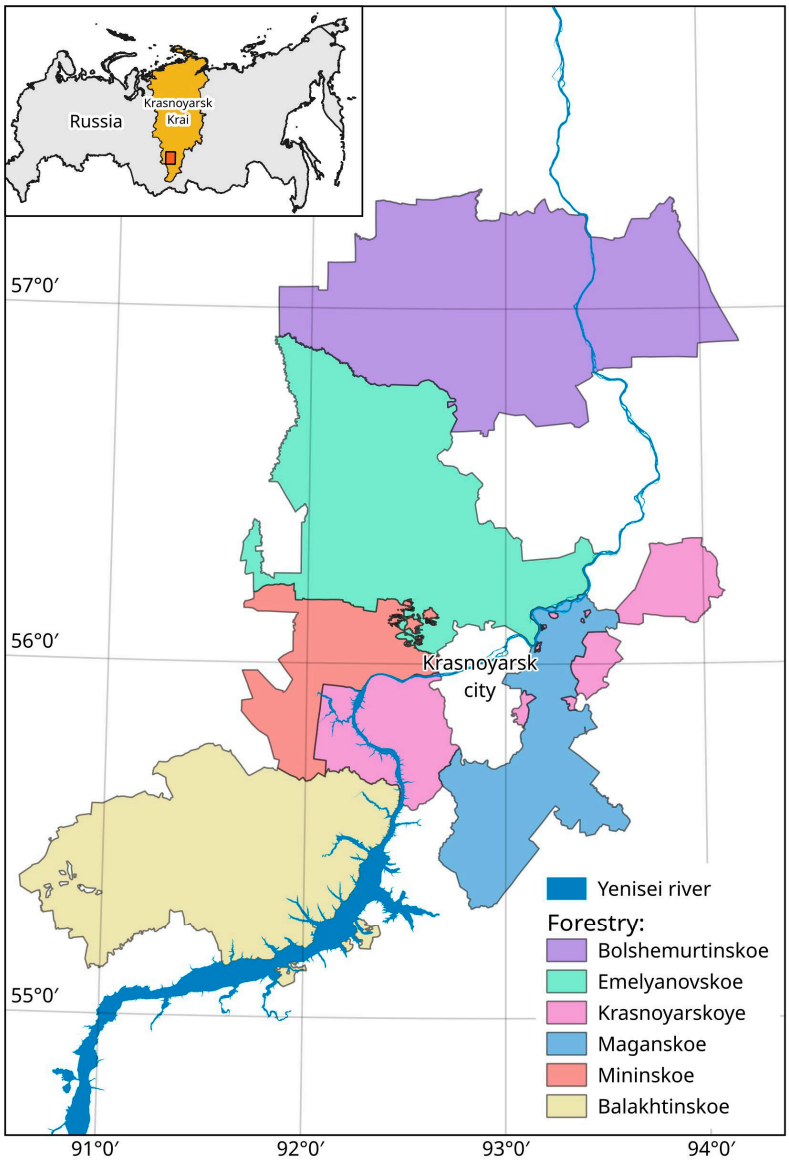

Figure 1. The forest management units where the research was conducted.

The birch forests that were the focus of the study were found to be characterized by varying degrees of anthropogenic disturbance. The primary factors contributing to the disturbance of these stands include recreational forestry, anthropogenic ground fires resulting from agricultural burning practices and the negligent handling of fire, and selective logging. The latter is indicative of a notable presence of stands of shoot origin, primarily in woodlands in forest steppe regions, which are colloquially referred to as 'island forests'.

2.2. Field Research Methods

The field studies encompassed reconnaissance and detailed surveying of birch forests. A reconnaissance survey was conducted on routes that were laid along the line of maximum length of forest areas (sections) that had been designated for the survey. In the course of the reconnaissance survey, a visual evaluation of the health status of birch stands was conducted. The species affiliation of fruiting bodies (basidiomas) of wood-decay fungi associated with birch wood was determined using reference literature [35,36]. The species

taxa of fungi have been presented in the work in accordance with the Index Fungorum database [37]. The substrate on which the fungi were found was also recorded. The following wood substrates were distinguished: L—living tree; S—snag, vertical fragment of windsnap; F—fallen trees of varying decay classes; and B—individual dry and fallen branches. During the reconnaissance survey stage, sites were selected for a detailed survey.

In the birch forests, the detailed survey of forest stands was conducted on 31 research plots (RP) in the following forest management units: Krasnoyarskoye—7, Mininskoe—10, Emelyanovskoe—5, Maganskoe—3, Bolshemurtinskoe—3, and Balakhtinskoe—3. The research plots encompassed a minimum of 100 birch trees. The stands selected for the study corresponded to the tasks being solved, as well as the diversity of forest biogeocenoses, which differed in origin, stand characteristics and intensity of recreation.

On the research plots, forest inventory was taken using visual and instrumental methods. Furthermore, the recreational disturbance was evaluated in accordance with industry standard OST 56100-95 [38] and the recommendations of Kazanskaya [39], which delineate five stages of forest digression. The identification of the stages was achieved through the ratio of the area of the surface that had been trampled down to the mineralized soil to the total area that had been surveyed: stage I—minor paths occupying up to 5% of the area, stage II—trampled areas occupy 5.1–10.0% of the area, stage III—10.1–15.0%, stage IV—15.1–25.0%, and stage V—more than 25%.

All *B. pendula* trees at each research plot were measured. They were categorized into four-cm diameter classes by measuring the diameter at a height of 1.3 m, and all trees were divided into the accepted health classes: 1—no signs of weakening; 2—weakened; 3—severely weakened; 4—dying; and 5—dead (including fresh and old deadwood, windthrow and windsnap). The health class of a tree was determined by a set of diagnostic crown features [40]. Trees infested with stem rot were identified by a set of macroscopic features: fruiting bodies of xylotrophic fungi; hollows; rotten branches; and dry sides, burnt areas, fire scars and frost cracks with signs of rot spreading from the wound.

2.3. Data Analysis

During the quantitative analysis of field research data, stem rot in living birch trees was regarded as a cumulative phenomenon, without differentiation into possible variants according to pathogens, entry point, or location in a tree.

The prevalence of stem rot (i.e., the damage to the forest stand) was determined on each research plot using the following formula, based on the detailed survey data [40]:

$$P = 100n/N, \quad (1)$$

where P—prevalence of stem rot, %; n—number of trees infected, pcs.; and N—total number of trees measured on a research plot, pcs.

The condition of the forest stands in general, along with its part that was affected by stem rot, was determined by calculating the average forest health index—K_{av} [40]:

$$K_{av} = (P_1 \times K_1 + P_2 \times K_2 + P_3 \times K_3 + P_4 \times K_4 + P_5 \times K_5)/100, \quad (2)$$

where P_i—proportion of stem volume of trees of each health class, %; K_i—health class (1—no signs of weakening; 2—weakened; 3—severely weakened; 4—dying; 5—dead). At $K_{av} \leq 1.5$ a forest stand on average does not show visible signs of weakening; $1.5 < K_{av} \leq 2.5$—weakened; $2.5 < K_{av} \leq 3.5$—severely weakened; $3.5 < K_{av} \leq 4.5$—dying; $K_{av} > 4.5$—dead.

The subsequent processing and analysis of the obtained data were carried out using statistical methods. The selection of criteria for comparative analysis and assessment

of the relationship was based on a preliminary test for normal distribution using the Kolmogorov–Smirnov test (d_{K-}). Furthermore, the disparities in the distribution of data in empirical samples from the normal distribution are not reliable at d_{K-} values corresponding to $p > 0.05$. The statistical calculations were executed using STATISTICA 10 software.

3. Results

As demonstrated in Table 1, the survey encompassed stands characterized by an absolute predominance of birch (80–90% of the total growing stock) within the taiga (subtaiga) and forest steppe zones. The study's examined sample is marked by heterogeneity with regard to the key forest stand characteristics. The stands are represented by both seed and shoot origin and by recreational disturbance (digression) from stage I to IV (Table 1).

Table 1. Characteristics of the forest stands studied.

RP	Predominant Origin of Trees	Stand Species Composition *	Mean Values			Quality Class	Relative Density	Recreational Disturbance Stage
			Age, Years	Height, m	Diameter, cm			
Taiga (subtaiga) forests								
1T	shoot	10B + A ind. P	55	17.0	17.7	3	0.8	II
2T	seed	10B ind. P, L	75	22.5	23.7	2	0.6	III
3T	seed	10B + P ind. A, L	60	21.0	21.3	2	0.7	I
4T	seed	8B2P + A	75	28.0	29.4	1	0.8	I
5T	seed	10B ind. A	84	21.0	24.2	3	0.7	I
6T	seed	9B1A + P	90	25.0	26.8	2	0.6	I
7T	seed	10B ind. P, A	86	24.0	31.9	2	0.8	I
8T	shoot	10B	90	22.5	32.8	3	0.5	IV
9T	seed	10B	85	27.5	30.8	1	0.7	I
10T	seed	10B ind. P	100	26.5	34.6	2	0.6	III
11T	shoot	10B ind. A	98	25.5	34.0	2	0.5	IV
12T	shoot	9B1P	96	28.5	40.4	1	0.6	III
13T	seed	9B1P ind. A, F	101	28.0	31.4	1	0.6	I
14T	seed	8B2P	91	25.0	32.4	2	0.7	I
15T	seed	8B2P + A	86	24.5	26.2	2	0.7	I
16T	shoot	6B4P	88	24.8	26.9	2	0.8	II
Forest steppe								
1L	shoot	10B + A	81	22.0	29.0	3	0.8	II
2L	shoot	10B	71	23.5	25.6	2	0.9	I
3L	shoot	10B	81	23.0	22.8	2	0.7	III
4L	seed	10B	55	20.0	19.0	2	0.8	I
5L	shoot	10B	60	17.0	18.5	3	0.6	III
6L	seed	10B + P	55	19.5	20.7	2	0.7	I
7L	shoot	10B + A, P	66	21.5	22.1	2	0.6	II
8L	shoot	9B1P	65	24.5	25.3	1	0.7	I
9L	shoot	9B1P + L, S	65	18.5	21.3	3	0.7	I
10L	shoot	9B1P ind. L, S	60	18.0	21.2	3	0.7	I
11L	shoot	9B1P ind. A	50	15.5	16.4	3	0.6	II
12L	shoot	10B	50	15.5	15.4	3	0.5	I
13L	shoot	10B + P	45	15.0	14.2	3	0.5	I
14L	shoot	10B	45	17.5	17.0	2	0.6	II
15L	shoot	10B ind. P	55	16.5	17.0	3	0.8	IV

* B—silver birch, A—aspen, P—Scots pine, L—Siberian larch, F—Siberian fir, S—Siberian spruce. '+' 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.

The wood-decay fungi that were identified through the examination of basidiomes and the wood substrates they have colonized are presented in Table 2.

Table 2. Wood-decay fungi on *B. pendula* woody substrates.

Fungi Species	Substrates *			
	L	**S**	**F**	**B**
Antrodiella semisupina (Berk. & M.A. Curtis) Ryvarden		+	+	
Armillaria mellea s.l.		+		
Daedaleopsis septentrionalis (P. Karst.) Niemelä		+	+	+
Fomes fomentarius (L.) Fr.	+	+	+	
Fomitopsis betulina (Bull.) B.K. Cui, M.L. Han & Y.C. Dai		+		+
Fomitopsis pinicola (Sw.) P. Karst.	+	+	+	
Ganoderma applanatum (Pers.) Pat.			+	
Inonotus obliquus (Fr.) Pilát	+			
Phellinus igniarius (L.) Quél.	+			
Trametes gibbosa (Pers.) Fr.		+	+	
Trametes versicolor (L.) Lloyd	+	+		
Trichaptum biforme (Fr.) Ryvarden		+		
Trichaptum fuscoviolaceum (Ehrenb.) Ryvarden		+	+	

* L—living tree; S—snag, vertical fragment of windsnap; F—fallen trees of varying decay classes; B—individual dry and fallen branches. The presence of a fungus is indicated by a '+'.

It has been established that the provenance of forest stands has an impact on their condition [41–43]. Consequently, the collected data were stratified into two samples. The first comprised research plots dominated by trees of seed origin, and the second comprised those of shoot origin (Table 3). The data in these samples is normally distributed, which allows us to use parametric criteria of statistical analysis in relation to them. Concurrently, analysis of both samples simultaneously reveals the aggregate sample to be non-normal.

Table 3. Prevalence of stem rot in birch-dominated stands.

Samples (Number of RP It Includes)	RP	Prevalence of Stem Rot—*P*, %	Normality Test
Forest stands of seed origin (n = 13)	2T	6.8	$d_{K\text{-}S}$ = 0.100 ($p > 0.05$)
	3T	5.4	
	4T	5.4	
	5T	8.2	
	6T	4.8	
	7T	9.1	
	9T	6.4	
	10T	2.0	
	13T	7.5	
	14T	2.5	
	15T	0.7	
	4L	3.6	
	6L	3.2	
Forest stands of shoot origin (n = 18)	1T	19.2	$d_{K\text{-}S}$ = 0.211 ($p > 0.05$)
	8T	7.0	
	11T	7.5	
	12T	11.2	
	16T	12.6	
	1L	6.5	
	2L	8.5	

Table 3. *Cont.*

Samples (Number of RP It Includes)	RP	Prevalence of Stem Rot—*P*, %	Normality Test
	3L	3.4	
	5L	8.0	
	7L	7.9	
	8L	24.6	
	9L	10.0	
	10L	6.8	
	11L	3.0	
	12L	11.2	
	13L	8.5	
	14L	14.4	
	15L	6.8	
Aggregate sample (n = 31)	$M \pm m$ *	7.83 ± 0.89	$d_{K\text{-}S}$ = 0.188 ($p < 0.05$)

* Arithmetic mean and standard error.

The results of the comparative analysis of the prevalence of stem rot in birch forests of seed and shoot origin are shown in Table 4. The analysis was performed using the *t*-test, assuming that the samples were normally distributed (see above).

Table 4. Comparative analysis of the prevalence of stem rot in birch forests of different origins.

Sample	Prevalence of Stem Rot, % ($M \pm m$) *	*t*-Test (at t_{05} = 2.1)
Birch forest of seed origin	5.05 ± 0.71	$t_{act.}$ (3.3) > t_{05}
Birch forest of shoot origin	9.84 ± 1.25	

* Arithmetic mean and standard error.

A paired correlation analysis was performed in order to ascertain the relationship between the prevalence of stem rot and forest stand characteristics (Table 5). The analysis of samples of forest stands of different origins was carried out using the Pearson coefficient. With regard to the data of the aggregate sample, which is non-normal (see above), the non-parametric Spearman coefficient was used.

The potential impact of recreational disturbance on the infestation of birch stands with stem rot was analyzed for all variants of data grouping (Table 6).

The diameter structure of the entire stand and its part affected by stem rot, along with a comparative analysis of the indicated samples in the disease centers (stands where stem rot infected over 10% of trees) are displayed in Figure 2 and Table 7.

In order to ascertain the impact of stem rot on the health of birch forests, it is recommended to employ the standardized scale of tree health [40]. This scale incorporates a comprehensive evaluation of tree morphology, with a particular emphasis on the crown. In this regard, a comparative assessment of the average health classes was carried out for all trees and those affected by stem rot for samples of seed and shoot origin (see Table 8). Preliminary analysis of the samples in question was performed to ascertain their normality. The comparative assessment was then undertaken using the *t*-test.

Table 5. Correlation matrix of characteristics of birch stands and the prevalence of stem rot (*P*).

Forest Stand Characteristics	Proportion of Birch	Mean Age	Mean Height	Mean Diameter	Quality Class	Relative Density
Seed origin (Pearson correlation coefficients)						
Proportion of birch	1					
Mean age	−0.329	1				
Mean height	−0.498	**0.756**	1			
Mean diameter	−0.329	**0.864**	**0.848**	1		
Quality class	0.306	−0.161	**−0.718**	−0.392	1	
Relative density	−0.078	−0.495	−0.217	−0.198	−0.030	1
P	0.409	0.090	0.047	0.064	−0.059	0.088
Shoot origin (Pearson correlation coefficients)						
Proportion of birch	1					
Mean age	−0.267	1				
Mean height	−0.307	**0.892**	1			
Mean diameter	−0.193	**0.933**	**0.912**	1		
Quality class	0.254	−0.446	**−0.780**	**−0.552**	1	
Relative density	−0.264	0.035	0.147	−0.020	−0.060	1
P	−0.196	−0.147	0.139	−0.007	−0.432	0.161
Aggregate sample (Spearman correlation coefficients)						
Proportion of birch	1					
Mean age	−0.307	1				
Mean height	**−0.400**	**0.874**	1			
Mean diameter	−0.269	**0.943**	**0.912**	1		
Quality class	0.298	**−0.461**	**−0.801**	**−0.548**	1	
Relative density	−0.121	−0.078	0.068	0.014	−0.092	1
P	0.097	−0.201	−0.188	−0.160	0.098	−0.030

Significant correlation coefficients are highlighted in bold ($p < 0.05$).

Table 6. Correlation between the prevalence of stem rot and the stage of recreational digression of forest stands.

Analyzed Sample	Correlation Coefficients	*p* Value
Seed origin	−0.098 *	>0.05
Shoot origin	−0.342 *	>0.05
Aggregate sample	0.117 **	>0.05

* Pearson, ** Spearman.

Table 7. Comparative analysis of the diameter structure of the entire birch stands and their part affected by stem rot (according to the data of the diagrams in Figure 2).

RP	Analysis of Empirical Series of Tree Distribution by Thickness Grades Using the λ Criterion (at $\lambda_{0.5} = 1.36$)	Mean Diameter, cm	
		All Birch Trees	Birch Trees Infected by Stem Rot
1T	$\lambda_{culc.} = 0.62 < \lambda_{05}$	17.7	19.5
12T	$\lambda_{culc} = 0.64 < \lambda_{05}$	40.4	41.0
16T	$\lambda_{culc.} = 0.73 < \lambda_{05}$	26.9	27.0
8L	$\lambda_{culc.} = 1.43 > \lambda_{05}$	25.3	23.1
12L	$\lambda_{culc.} = 0.51 < \lambda_{05}$	15.4	16.0
14L	$\lambda_{culc.} = 1.56 > \lambda_{05}$	17.0	17.3

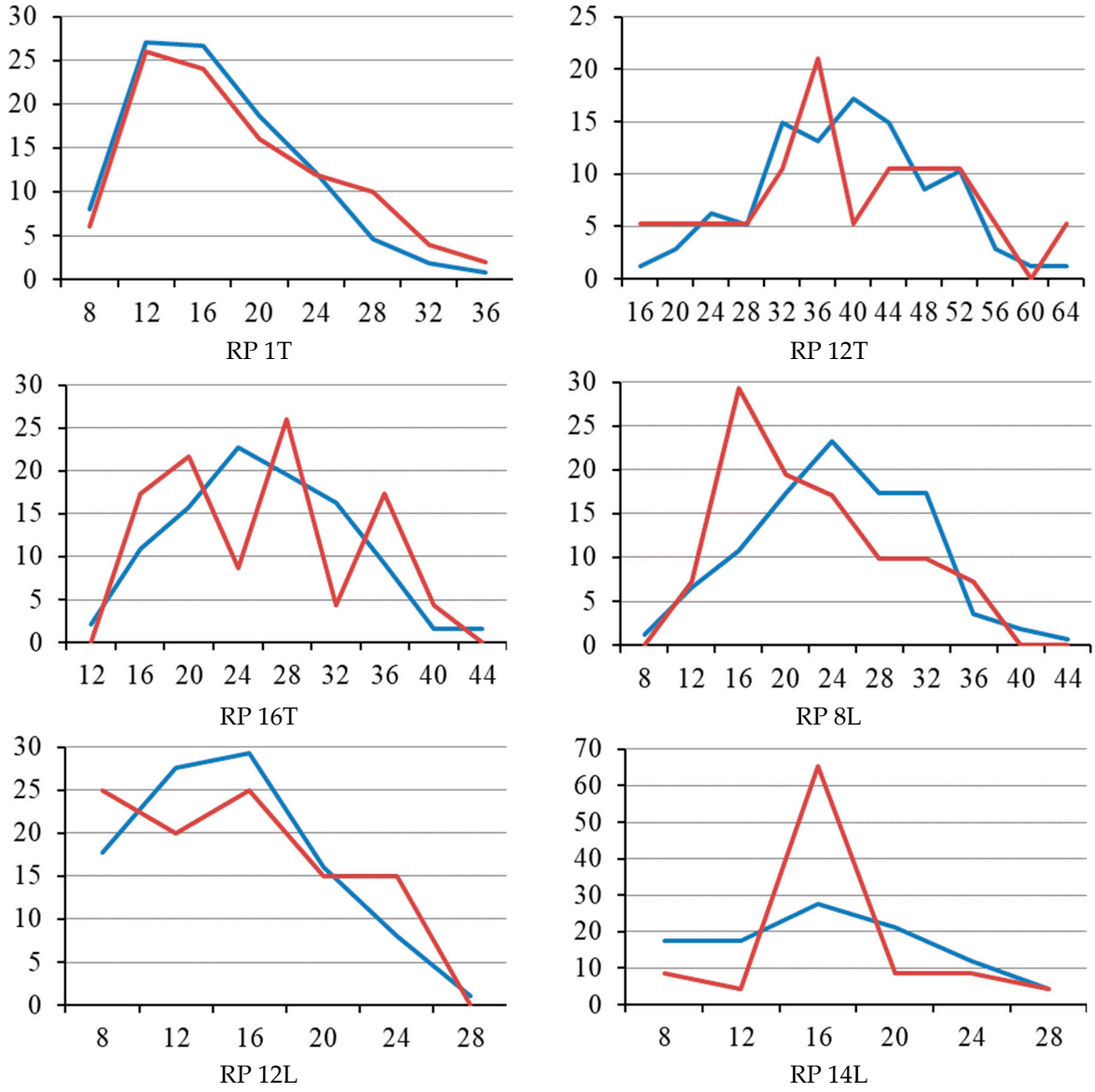

Figure 2. Distribution of all trees (blue) and those affected by stem rot (red) by diameter classes in the disease centers. The *x*-axis represents diameter classes (cm), the *y*-axis represents the relative number of trees (%).

Table 8. Impact of stem rot on the health of birch forests.

Forest Stand Origin	Analyzed Sample	Health Class ($M \pm m$) *	Normality Test ($d_{K\text{-}S}$ (p-Value))	t-Test (at t_{05} = 2.1)
Seed	Infected trees	1.94 ± 0.09	0.266 (>0.05)	$t_{act.}$ (3.3) > t_{05}
	All trees	1.58 ± 0.06	0.196 (>0.05)	
Shoot	Infected trees	1.96 ± 0.10	0.186 (>0.05)	$t_{act.}$ (3.4) > t_{05}
	All trees	1.58 ± 0.04	0.159 (>0.05)	

* Arithmetic mean and standard error.

4. Discussion

Given the documented diversity of the species composition of xylomycobiota in birch forests [14,44–47], it is evident that biotrophic species of wood-decay fungi that decompose wood in living trees are under-represented. During the course of the present

study, basidiomes of the following species were found in living trees: *Fomes fomentarius*, *Fomitopsis pinicola*, *Trametes versicolor*, *Phellinus igniarius*, and *Inonotus obliquus* (Table 2). The fruit bodies of the first three species were exclusively observed on dry sides, indicating that they initially infect trees through wounds.

Wood-decay fungi produce basidiospores that enter trees through dry branches and knot wounds (primarily *P. igniarius* and *I. obliquus*) or deep wounds on the trunks (dry sides, fire scars, frost cracks) and in trees of shoot origin—mainly through the mycelial inoculum from the parent stumps. In the context of living trees, the process of decay of wood fibers that runs perpendicular to the tree's grain predominantly occurs in the central part of the trunk. This is due to the fact that, in contrast to the sapwood, the heartwood exhibits a lower resistance to intravital biodegradation. However, stem rot of wound origin caused by the above-mentioned fungi (facultative parasites), especially in trees greatly weakened by fire or recreational activity, often affects the sapwood as well.

The phenomenon of stem rot has been identified in birch forests throughout the study area. The prevalence of stem rot in the surveyed stands was found to be below 8%, with a minimum of 0.7% recorded at RP 15T and a maximum of 24.6% at RP 8L (see Table 3). The variation in the prevalence rate of rot in the birch forests is attributable to the influence of a complex of factors (ecological, forestry and anthropogenic) on the "tree ↔ xylotrophic fungi" system.

A comparison of averaged data from stands of different origins, alongside a comparative assessment of sample means by the *t*-test, indicates a significantly higher incidence of stem rot in stands with a predominance of trees of shoot origin (Table 4). In such birch forests, stem rot can reach a stage where it is considered a disease center, with damage to the tree stand ranging from weak (10–20% of trees infected) to medium (21–30% of trees infected) (Table 3). This finding aligns with the observations reported by other researchers [26,32,48] and can be rationalized. Firstly, fungal infection has the potential to invade shoot-origin trees via multiple channels. Such an invasion may occur through wounds or via mycelium through the bole. The latter option is evidently predominant for trees of shoot origin and ensures clonal infection of trunks from the mother stump from a young age. Secondly, trees of shoot origin exhibit a diminished immune status [43], which prevents them from demonstrating adequate resistance to the penetration and propagation of pathogens that primarily affect stem biomass tissues. Such trees possess an ancient maternal root system, frequently exhibiting pronounced unilateral development, wide annual rings with loose xylem, and other characteristics [26]. It should be noted that the majority of shoot-origin birch forests are located in the forest steppe zone. This area has many years of experience in forest management, involving logging and subsequent vegetative renewal. Factors influencing this include adjoining agricultural lands, proximity to settlements and road infrastructure.

For all variants of data grouping, no significant relationship was found between the prevalence of stem rot and the recorded indicators, including the most expected one—with the age of *Betula pendula* stands (Table 5). It has been observed by numerous researchers that, as tree stands mature, there is an increase in the incidence of stem rot [49–53]. This phenomenon has been attributed to an age-related decline in the structural immune function of the xylem in trunks. Furthermore, there are a significant number of natural entry points for various pathogens. These include wound knots, which form when bottom branches die off. In the studied birch forests, this pattern is limited due to the significant representation of stands of shoot origin and successful primary invasion of xylotrophic fungi for reasons that are not related to the ontogenesis of trees and the age dynamics of stands. These reasons include mechanical and thermal injury to trunks. Consequently, the absence of a reliable

correlation between the incidence of birch forests with stem rot, and their characteristics, once again indicates anthropogenic disturbance of the studied forests.

Pursuant to the correlation analysis undertaken for all variants of the samples, it was determined that no significant relationship exists between the prevalence of stem rot and the stages of recreational digression (disturbance) (Table 6). Conversely, it is imperative to acknowledge the deleterious consequences of forest recreation, particularly in its unregulated form, on the health of forests and the prevalence of rot. This is further compounded by the exacerbation of mechanical injury to trees, instances of illegal logging, and anthropogenic forest fires. The impact of these factors on the spread of stem rot was previously discussed.

Trees of differing sizes (diameters) are susceptible to stem rot within *Betula pendula* dendrocenoses. A comparative analysis was performed using the λ criterion [54] of tree diameter distribution series, with data from research plots considered disease centers (stem rot prevalence rate is more than 10%). In most cases, the analysis did not reveal significant differences between the diameter structure of the entire stand and trees infected with stem rot (Figure 2, Table 7). The mean diameter of both the healthy trees and those infected with stem rot is found to be similar. In summary, stem rot has been observed to affect trees of various sizes. The severity of the affliction has been found to correlate with their proportion within the stand structure. However, instances of deviation from this pattern are documented, notably in the cases of RP 8L and 14L. These deviations can be attributed to the impact of chaos, which has been observed to inflict damage on trees of various sizes. The underlying mechanism is believed to be the frequent invasion of wood-decay fungi, which enter the tree through mechanical wounds that occur accidentally on the trunks. Examples of such wounds include frost cracks and directional notches.

When living trees are damaged, stem rot usually does not affect the physiologically active sapwood, which is responsible for transporting water. Therefore, stem rot does not directly contribute to the mortality of the tree. However, the propagation of stem rot in birch forests results in a detrimental alteration to their health, owing to the weakening of trees affected by the rot. The latter is reliably manifested in forest stands of both seed and shoot origin (Table 8). The development of stem rot in synergy with bacterial wetwood, a common occurrence in birch forests [55], particularly in conjunction with root rot (pathogen—*Armillaria mellea* s.l.), results in severe weakening and pathological tree mortality. Furthermore, when a tree is afflicted by rot, its wind and storm tolerance is reduced, thus contributing to the deterioration of the stand's condition and resulting in the accumulation of rotten windbreak.

5. Conclusions

In the birch forests of the Krasnoyarsk (central) group of regions, stem rot is ubiquitous as a result of the inevitable process of the intravital destruction of wood biomass accumulated in forest stands. The following species have been identified as pathogens causing stem rot: *Phellinus igniarius*, *Inonotus obliquus*, *Fomes fomentarius*, *Fomitopsis pinicola* and *Trametes versicolor*. The last three species are known to enter trees through wounds.

The prevalence of stem rot is significantly lower in birch forests dominated by trees of seed origin than in those dominated by trees of shoot origin, where the infestation can reach more than 20%. This phenomenon has been attributed to the compromised immune system of shoot origin trees, coupled with the potential for transmission of the infection from infected parent stumps, commencing from a juvenile stage.

In dendrocenoses, there is a tendency for trees of varying diameter to be affected by stem rot, contingent on their representation in the structure of the forest stand. It is important to note that deviations from this phenomenon may be observed in cases where

random portals of entry for pathogens manifest on the trunks. The development of rot in the trunks of trees has been shown to weaken the trees, with this weakness being most apparent at the cenotic level, regardless of the origin of the forest stand in question.

The findings of the present study have the potential to inform the adaptation of forestry practices in suburban birch forests that have been disturbed by selection cutting and recreation. Furthermore, these results may be applicable to commercial forests during the implementation of forest management activities. This is a particularly salient issue in the context of intensified forest management, which has resulted in an expansion of the area covered by birch forests.

It is recommended that subsequent investigation into this subject be directed towards the analysis of the impact that orographic and edaphic factors have on the incidence of stem rot in birch forests and the assessment of ecosystem service losses.

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References

1. Hultén, E.; Fries, M. *Atlas of North European Vascular Plants North of the Tropic of Cancer*; Koeltz Scientific Books: Königstein, Germany, 1986; ISBN 387-429-263-0.
2. Jonsell, B.; Karlsson, T. *Flora Nordica. Volume 1. Lycopodiaceae to Polygonaceae*; The Bergius Foundation the Royal Swedish Academy of Sciences: Stockholm, Sweden, 2000; ISBN 978-917-190-033-3.
3. Koropachinsky, I.Y.; Vstovskaya, T.N. *Woody Plants of Asian Russia*; SB RAS, Branch "Geo": Novosibirsk, Russia, 2002; ISBN 5-7692-0561-X.
4. Fischer, A.; Lindner, M.; Abs, C.; Lasch, P. Vegetation dynamics in central European forest ecosystems (near-natural as well as managed) after storm events. *Folia Geobot.* **2002**, *37*, 17–32. [CrossRef]
5. Hynynen, J.; Niemistö, P.; Viherä-Aarnio, A.; Brunner, A.; Hein, S.; Velling, P. Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in Northern Europe. *Forestry* **2010**, *83*, 103–119. [CrossRef]
6. *State Report: On the State and Protection of the Environment of the Russian Federation in 2023*; The Ministry of Natural Resources and Environment of the Russian Federation, Intellectual Analytics LLC., Federal State Budgetary Institution Scientific and Technical Progress Directorate, Foundation for Environmental Monitoring and International Technological Cooperation: Moscow, Russia, 2024; p. 707c. Available online: https://2023.ecology-gosdoklad.ru/ (accessed on 10 June 2025).
7. Forest Plan of Krasnoyarsk Krai, Approved by the Decree of the Governor of Krasnoyarsk Krai Dated 21.12.2018 No. 332-ug. Available online: http://mlx.krskstate.ru/lesplan?eyes=no (accessed on 10 June 2025).
8. Ilyina, I.S. Zonal patterns of vegetation cover of the West Siberian Plain. *Bull. All-Union. Geogr. Soc.* **1982**, *5*, 376–386.
9. Sinadsky, Y.V. *Birch: Its Pests and Diseases*; Nauka: Moscow, Russia, 1973.
10. Green, S. Fungi Associated with Shoots of Silver Birch (*Betula pendula*) in Scotland. *Mycol. Res.* **2004**, *108*, 1327–1336. [CrossRef]
11. Michalska, Z.; Myssura, M.; Walczak, U. Owady Minujące Gór Polski/Mining Insects of Polish Mountains. *Wiadomości Entomol.* **2010**, *29*, 73–82.
12. Minkevich, I.I. *Epiphytotiology of Fungal Diseases of Forest Species*; Forestry Academy: Leningrad, Russia, 1977.
13. Pavlov, I.N. Macromycetes of the boreal zone. *Conifers Boreal Area* **2009**, *26*, 7–8.
14. Arefiev, S.P. *Systematic Analysis of the Biota of Wood-Destroying Fungi*; Nauka: Novosibirsk, Russia, 2010; ISBN 978-5-02-032213-4.

15. Storozhenko, V.G. *Evolutionary Principles of Behavior of Wood-Destroying Fungi in Forest Biogeocenoses*; Grif and K: Tula, Russia, 2014; ISBN 978-5-8125-1931-5.
16. Halme, P.; Holec, J.; Heilmann-Clausen, J. The history and future of fungi as biodiversity surrogates in forests. *Fungal Ecol.* **2017**, *27*, 193–201. [CrossRef]
17. Niskanen, T.; Lücking, R.; Dahlberg, A.; Gaya, E.; Suz, L.M.; Mikryukov, V.; Liimatainen, K.; Druzhinina, I.; Westrip, J.R.; Mueller, G.M.; et al. Pushing the frontiers of biodiversity research: Unveiling the global diversity, distribution, and conservation of fungi. *Annu. Rev. Environ. Resour.* **2023**, *48*, 149–176. [CrossRef]
18. Mukhin, V.A.; Diyarova, D.K.; Zhuykova, E.V. The Specific and Total CO_2 Emission Activity of Wood-Decaying Fungi and Their Response to Increases in Temperature. *J. Fungi* **2024**, *10*, 448. [CrossRef]
19. Wei, Y.; Xue, J.; Shi, J.; Li, T.; Yuan, H. Comparative Transcriptome Analysis Explores the Mechanism of Angiosperm and Gymnosperm Deadwood Degradation by *Fomes fomentarius*. *J. Fungi* **2024**, *10*, 196. [CrossRef]
20. Gafforov, Y.; Yarasheva, M.; Wang, X.-W.; Rašeta, M.; Rakhimova, Y.; Kyzmetova, L.; Bavlankulova, K.; Rapior, S.; Chen, J.-J.; Langer, E.; et al. Annotated Checklist of Poroid Hymenochaetoid Fungi in Central Asia: Taxonomic Diversity, Ecological Roles, and Potential Distribution Patterns. *J. Fungi* **2025**, *11*, 37. [CrossRef] [PubMed]
21. Zhukov, A.M. *Fungal Diseases of the Upper Ob Forests*; Nauka, Siberian Branch: Novosibirsk, Russia, 1978.
22. Dobbertin, M. Tree growth as indicator of tree vitality and of tree reaction to environmental stress: A review. *Eur. J. For. Res.* **2005**, *124*, 319–333. [CrossRef]
23. Zalesov, S.V.; Koltunov, E.V. Root and stem rot of Scots pine (*Pinus silvestris* L.) and European birch (*Betula pendula* Roth.) in the Nizhne-Isetsky forest park in Yekaterinburg. *Agrar. Bull. Ural.* **2009**, *1*, 73–75.
24. Arhipova, N.; Gaitnieks, T.; Donis, J.; Stenlid, J.; Vasaitis, R. Butt rot incidence, causal fungi, and related yield loss in *Picea abies* stands of Latvia. *Can. J. For. Res.* **2011**, *41*, 2337–2345. [CrossRef]
25. Amosova, I.B.; Evdokimov, V.N. Patterns of distribution of stem rot of silver birch (*Betula pendula* Roth.) in the taiga forests of the Arkhangelsk region. In *Environmental Problems of the Arctic and Northern Territories*; Publishing House of NArFU: Arkhangelsk, Russia, 2012; Volume 15, pp. 54–57.
26. Balandaykin, M.E. Distribution of macromycetes *Inonotus obliquus* (Pers.) Pil. in birch stands of various origins. *KrasSAU Bull.* **2013**, *4*, 218–224.
27. Tatarintsev, A.I. Health of birch forests in the territory of the Krasnoyarsk group of districts. In *VII Readings in Memory of O.A. Kataev. Pests and Diseases of Woody Plants*; Selikhovkin, A.V., Musolin, D.L., Eds.; SPbGLTU: Saint Petersburg, Russia, 2013; pp. 92–93.
28. Kashin, D.A.; Fomina, O.A. Deciduous trees of the south of Tyumen Oblast: Main defects, economic activity and methods of increasing the yield of commercial timber from them. In *Current Issues in Science and Economy: New Challenges and Solutions, Proceedings of the LIII International Student Scientific and Practical Conference, Volgograd, Russian, 23–29 May 2019*; State Agrarian University of Northern Trans-Urals: Tyumen, Russia, 2019; pp. 596–601.
29. Roberts, M.; Gilligan, C.A.; Kleczkowski, A.; Hanley, N.; Whalley, A.E.; Healey, J.R. The effect of forest management options on forest resilience to pathogens. *Front. For. Glob. Change* **2020**, *3*, 7. [CrossRef]
30. Jiang, W.; Aishan, T.; Halik, Ü.; Wei, Z.; Wumaier, M. A Bibliometric and Visualized Analysis of Research Progress and Trends on Decay and Cavity Trees in Forest Ecosystem over 20 Years: An Application of the CiteSpace Software. *Forests* **2022**, *13*, 1437. [CrossRef]
31. Wei, Z.; Halik, Ü.; Aishan, T.; Abliz, A.; Welp, M. Spatial distribution patterns of trunk internal decay of Euphrates poplar riparian forest along the Tarim River, northwest China. *For. Ecol. Manag.* **2022**, *522*, 120434. [CrossRef]
32. Koltunov, E.V. Effect of stem rot on the composition and content of phenolic compounds in the leaves of silver birch (*Betula pendula* Roth.). *Chem. Plant Raw Mater.* **2019**, *3*, 169–176. [CrossRef]
33. Koltunov, E.V.; Yakovleva, M.I. Stem rot and its influence on the composition and content of phenolic compounds in the leaves of silver birch (*Betula pendula* Roth.) in the forests of the Trans-Urals under anthropogenic impact. *Mod. Probl. Sci. Educ.* **2015**, *5*, 647.
34. Forestry Regulations for Forest Management Units of Krasnoyarsk Krai for the Period 2019–2028. Available online: http://mlx.krskstate.ru/napravdeet/gos_les_reestr/les_reglam (accessed on 5 June 2025).
35. Lyubarsky, L.V.; Vasilyeva, L.N. *Wood-Decay Fungi of the Russian Far East*; Nauka: Novosibirsk, Russia, 1975.
36. Niemela, T. *Norrlinia 8: Polypores of Finland and Adjacent Russia Suomen Ja Laheisen Venajan Kiiavat*; University of Helsinki: Helsinki, Finland, 2001; pp. 1–120, ISBN 952-10-0107-0.
37. CABI. Index Fungorum. Available online: http://www.speciesfungorum.org (accessed on 5 June 2025).
38. *Industry Standard OST 56100-95*; Assessment Methods and Units of Measurement of Recreational Disturbance of Forest Ecosystems. The Federal Forestry Service of Russia: St. Petersburg, Russia, 1995. Available online: https://base.garant.ru/2157248/ (accessed on 5 June 2025).
39. Kazanskaya, N.S.; Lanina, V.V.; Marfenin, N.N. *Recreational Forests*; Forest Industry: Moscow, Russia, 1977.

40. Rules for Sanitary Safety in Forests Approved by Decree of the Government of the Russian Federation No. 2047 on 9 December 2020. Available online: https://base.garant.ru/75037636/ (accessed on 16 June 2025).
41. Atrokhin, V.G. *Forestry and Dendrology*; Forest Industry: Moscow, Russia, 1982.
42. Martynov, A.N.; Melnikov, E.S.; Kovyazin, V.F.; Anikin, A.S.; Minaev, V.N.; Belyaev, N.V. *Fundamentals of Forestry and Forest Inventory*; Lan: St. Petersburg, Russia, 2008.
43. Koltunov, E.V. Stem rot of silver birch (*Betula pendula* Roth.) in urban parks and suburban forests of Yekaterinburg and Sverdlovsk Oblast. *Mod. Probl. Sci. Educ.* **2016**, *6*, 493.
44. Mukhin, V.A. *Biota of Xylotrophic Basidiomycetes of the West Siberian Plain*; UIF "Nauka": Ekaterinburg, Russia, 1993.
45. Safonova, T.I. Trophic structure of mycobiota of birch forests of the Southern Urals. *Vestn. Orenbg. State Univ.* **2011**, *16*, 211–213.
46. Safonov, M.A.; Safonova, T.I. Wood-decay fungi living on the wood of *Betula pendula* in the Southern Urals (Orenburg region). *Vestn. Orenbg. State Univ.* **2012**, *6*, 66–71.
47. Ezhov, O.N. *Aphyllophoraceae Fungi of the Arkhangelsk Oblast*; Editorial and Publishing Department of the Ural Branch of the Russian Academy of Sciences: Ekaterinburg, Russia, 2013.
48. Balandaykin, M.E. Comparative analysis of birch stands with different morphological characteristics by the occurrence of macromycetes *Inonotus obliquus* (Pers.: Fr.) Pilat. *Nat. Sci.* **2014**, *1*, 7–16.
49. Yezhov, O.N.; Minkevich, I.I. Features of the spread of stem rot in pine. *Bull. High. Educ. Inst. Russ. For. J.* **1998**, *2–3*, 12–17.
50. Balandaykin, M.E. Determination of the frequency of occurrence of *Inonotus obliquus* (Pers.) Pil. by the age of the forest stand. *Sci. Notes Orel State Univ. Ser.* **2012**, *3*, 322–326.
51. Bogomolova, O.I. Some features of infection with stem rot of *Quercus robur* L. in the Orenburg Oblast. *Bullutin Orenbg. State Agrar. Univ.* **2013**, *4*, 224–226.
52. Safonov, M.A.; Ostapenko, A.V. Influence of environmental factors on the spread of stem rot in aspen trees. *Sci. Life* **2017**, *1*, 76–85.
53. Brydon-Williams, R.; Munck, I.A.; Asbjornsen, H. Incidence and ecology of the chaga fungus (*Inonotus obliquus*) in hardwood New England—Acadian forests. *Can. J. For. Res.* **2021**, *51*, 122–131. [CrossRef]
54. Falaleev, E.N.; Smolyanov, A.S. *Mathematical Statistics*; Publishing House of Krasnoyarsk State University: Krasnoyarsk, Russia, 1981.
55. Tatarintsev, A.I. Ecological-Coenotic Characteristics of the Bacterial Dropsy Infection Rate in Birch Forests in the Southern Part of Middle Siberia (Krasnoyarsk Group of Areas). *Contemp. Probl. Ecol.* **2014**, *7*, 221–227. [CrossRef]

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