Harmfulness of root rot in the stands planted on formerly arable land and clear-cuts after annosum-infected pine forests in Chernihiv Polissya physiographic region of Ukraine

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Abstract

The study was conducted in pure Scots pine (*Pinus sylvestris* L.) forests and mixed forests of Scots pine and silver birch (*Betula pendula* Roth.) within the Chernihiv Polissya physiographic region of Ukraine. The aim of the study was a comparative analysis of forest mensuration characteristics and health condition of pine and mixed pine-birch stands planted on formerly arable lands and cutover areas after pine stands infected by annosum root rot. It was found that in pine stands planted on formerly arable land, the average diameter of living trees in the root rot disease focus was 1–6% larger and the average diameter of dead trees was 11–23% larger than those outside the disease focus. Due to the pathological loss inside the disease foci, the pine stand density was much lower – by 14–38% and the growing stock volume was 16–35% less as compared to the outside areas. Mixed pine-birch stands (with a predominance of pine trees), established on the cutover areas after pine stands affected by root rot, had a 20% greater stock volume and the birch-pine stands (with birch predominance) in the clear-cuts had 18% greater stock volume than pure pine stands inside the root rot disease area. The pine trees were assessed as “weakened” in the mixed stands and as “severely weakened” in the pure pine stand inside the disease focus. The birch trees in mixed stands were characterized as “healthy”.

Key words: Scots pine; health condition; root rot; disease focus

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1. Introduction

About 1 million hectares of forest stands were established in Ukraine between the 1950s and 1970s on formerly arable land. Most of the stands were pure crops of pine (*Pinus sylvestris* L.). In such stands, the whole complex of biogeocoenotic relations typically has not formed yet. Therefore, the conditions of habitat for pine forests are rather specific and do not correspond to their ecological needs. The practice of afforestation of the non-forest land indicates the low resistance of such stands to pathological factors, in particular, to the root rot caused by *Heterobasidion annosum* s.l. (Ladeyshchikova et al. 1974; Sierota 2013).

In numerous studies, the root rot has been described as the most dangerous and harmful disease of root systems and butt part of coniferous plants. It causes the stock volume reduction in stands (Woodward et al. 1998; Gar-

belotto & Gonthier 2013; Lapitan et al. 2013; Vedmid et al. 2013; Musienko et al. 2018), predetermines their early degradation (Vollbrecht et al. 1994), provokes large-scale pest outbreaks (Lyamtsev 2015), and increases fire hazard and worsens the soil protection, water conservation and sanitary functions of a forest (Bendz-Hellgren et al. 1999). Also, root rot infected trees are non-resistant to wind damage (Woodward et al. 1998). According to Asiegbu et al. (2005), the economic losses associated with the *Heterobasidion* infection in Europe are estimated at 800 million euros per year.

In Ukraine, the area of coniferous forests affected by root rot is 13–16% of the total area of conifers in which pathological processes are detected (Utsky et al. 2010). In Polissya zone, the area of forest disease foci (90.9 thousand hectares) has increased by 30% up to 117.3 thousand hectares since 2007. Pine forests infected by root rot account for 72% (84.7 thousand hectares) of the area

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of stands with pathological processes detected (Chudak 2014).

H. annosum s.l. is widespread in the conifer forests of the Northern Hemisphere, especially in Europe, North and Central America, Russia, China and Japan (Bendz-Hellgren et al. 1999; Korhonen et al. 1998; Vasiliauskas et al. 2002; Dai et al. 2003; Asiegbu et al. 2005; Otrósina & Garbelotto 2010; Worrall et al. 2010; Wang 2012; Sierota 2013). Primary infection of trees is initiated by basidiospores and conidia of the fungus. Basidiospores are formed in the fruiting bodies, and conidia, throughout the growing season, on the mycelium in the loci where rotting is on the surface of infected stumps or roots (Negrutskiy 1986; Woodward et al. 1998; Garbelotto & Gonthier 2013). Basidiospores are formed when the average daily temperature exceeds 5°C. They infect freshly-cut surface of the stumps, from which then mycelium develops and infects adjacent trees. During winter felling, the probability of stump infestation decreases by 95% (Brandtberg et al. 1996).

The leading factors that cause the spread of root rot in pine forests on formerly arable land are the changes in physical (Ladeyshchikova et al. 1974), mechanical and biochemical properties of soil due to long-term agricultural use (Negrutskiy 1986; Vasiliauskas 1989; Artyukhovskiy 2000; Ladeyshchikova et al. 2001; Ustsky 2011; Sierota 2013; Lukyanets et al. 2019), as well as the specific nature of the growth and formation of pure dense pine stands planted in these conditions (Ladeyshchikova et al. 1974; Raspopina et al. 2013). Most often the fungus attacks pure pine stands of 11–40 years old growing in fresh infertile and fairly infertile pine site types (Volchenkova et al. 2012).

Biological methods of plant protection based on *Phlebiopsis gigantea* (Fr.) Mass. is known to be the most effective measure to prevent the spread of root rot (Rishbeth 1963). For example, the biological control agent Rotstop based on *Phlebiopsis gigantea* is widely used in European countries (Great Britain, Norway, Switzerland, Finland, Poland, Latvia, Belarus, etc.) in the form of a suspension or a dry product (Kenigvalde et al. 2011; Volchenkova & Zvyagintsev 2011; Sierota 2013; Kenigvalde et al. 2016). For the conditions of the eastern part of Ukraine, the biological product Penioflorin has been developed based on a spore suspension of the local *P. gigantea* strains (Demchenko & Sukhomlin 2000). However, due to economic difficulties, this agent is rarely used in Ukraine. Furthermore, since fruiting bodies of *H. annosum s.l.* are formed quite rarely in Ukrainian pine forests and only in years with sufficient precipitation, the spore infection of the pathogen plays a secondary role. Therefore, forestry interventions, mainly tending felling and sanitation felling, remain the primary means to control the disease. However, these measures are not particularly effective (Zvyagintsev et al. 2013).

Growing mixed and deciduous stands in abandoned agricultural land instead of pure pine ones is an effective

and future-oriented way to prevent the occurrence and spread of root rot. Such stands are more resistant to the disease. At the same time, they enable the formation of the natural composition of soil microbiota. The following tree species can be used for mixing with pine in fresh fairly infertile pine sites: *Betula pendula* Roth., *Quercus rubra* L., *Quercus robur* L., and *Alnus incana* (L.) Moench. Their proportion in these conditions must be at least 30 % (Alekseev et al. 1981; Negrutsky 1986; Bilous 2006). To reduce the infection level and to prevent the spread of root rot and also to form the natural composition of soil microbiota in formerly arable land, Peri et al. (1990), Ladeyshchikova et al. (2001), and Lygis et al. (2004) proposed to plant silver birch stands as a pine forecrop in fresh and moist fairly infertile pine sites. The most resistant are sparse (up to 2.5 thousand stems per ha) middle-aged mixed planted stands including shrubs that have rich species composition and grow in fresh fairly infertile sites in the northern part of Ukraine (Fedorov 1991). In Scots pine stands that grow on primary forest soils, the disease occurs relatively rarely and does not cause significant damage (Vasiliauskas 1989).

Despite the over 100-year history of the root rot research, the causes of increased Scots pine susceptibility to annosum root rot in formerly arable land have not been finally identified and effective practices to control the disease have not been developed. Therefore, the study of the root rot impact on the forest mensurational characteristics and health condition of Scots pine and silver birch stands within the Chernihiv Polissya physiographic region of Ukraine is extremely relevant as well as the development of practices that prevent and control the disease.

The aim of the study was the comparative analysis of forest mensurational characteristics and health condition of pure and mixed pine stands established in abandoned agricultural land and in the clear-cuts after pine stands infected by annosum root rot.

2. Materials and methods

The study was conducted in August–October, 2017. Scots pine and silver birch stands were assessed within the Gorodnyanske Forestry Enterprise located in the Chernihiv Polissya physiographic region of Ukraine (Fig. 1). The site of the study is typical for this region.

Chernihiv Polissya physiographic region is a low-lying undulating plain. The overall flatness of the territory is disrupted by the valleys of the Dnieper, Desna, and Snov rivers. The climate of the region is moderately continental. Annual rainfall is 500–610 mm. There are many lakes and swamps in the river valleys. The area of the swamps is 4.5% of the area of Chernihiv Polissya region. The widespread soils are sod-podzolic, bog, and gray forest ones. The forest cover of the region is the lowest compared to other Polissya regions and is about 18%.

Fig. 1. Location of the study site (Latitude 51°52'N–51°45'N; Longitude 31°15'E–31°30'E).

The largest forest areas are located between the rivers of Dnieper and Desna and Snov and Desna. Scots pine forests and mixed English oak and Scots pine forests predominate (Marinich et al. 1985).

To investigate forest mensurational characteristics and health condition of the annosum-infected Scots pine stands planted on formerly arable land, seven sample plots were laid out in the part of the stand containing infected and dead trees (disease foci, DF). Seven sample plots were established as a control (C) in a relatively healthy part (i. e. without signs of deterioration) of the same stand (the area outside the disease foci) (Table 1). Also, to compare to the stands planted on formerly arable land, two sample plots were laid out within the disease

foci and two sample plots outside the disease foci in the pine stands of the next generation replanted in clear-cuts after root rot infected stands. To compare the stand characteristics for annosum-infected pure pine stands with those for mixed ones planted in the clear-cuts after root rot infected stands, one sample plot was established in a mixed pine-birch stand and one sample plot in a mixed birch-pine stand (Table 2). These mixed stands were not infected by root rot.

The sample plots were established in the fresh fairly infertile pine sites. The size of the sample plot was determined, based on at least 200 trees of the main species on the plot. The trees were recorded by species, determining their diameters, assessing health condition and Kraft

Table 1. Forests mensurational characteristics of studied Scots pine stands established on formerly arable land.

Sample plot number	Age [years]	Part of the stand	Group of the trees	Stand density [stems ha ⁻¹]	Average diameter [cm]	Average height [m]	Total stand basal area [m ² ha ⁻¹]	Growing stock volume [m ³ ha ⁻¹]	Relative density of stocking	Health index I_c
3-DF	20	disease focus	living	1600	10.1	8.4	13.1	57	0.47	3.4
			dead	753	7.1	7.4	2.9	11	0.10	
3-C		control	living	2563	9.5	8.8	19.0	88	0.69	2.3
			dead	338	6.2	7.4	0.9	4	0.03	
4-DF	33	disease focus	living	982	18.2	17.8	25.8	214	0.66	2.3
			dead	182	16.4	17.1	3.8	30	0.10	
4-C		control	living	1148	18.1	18.3	30.3	259	0.76	1.5
			dead	52	13.8	16.2	0.7	6	0.02	
5-DF	47	disease focus	living	913	20.2	20.8	29.7	290	0.66	2.7
			dead	225	16.0	18.4	4.5	39	0.10	
5-C		control	living	1111	20.0	21.2	34.8	343	0.76	1.7
			dead	84	14.3	17.1	1.4	11	0.03	
6-DF	50	disease focus	living	775	21.4	20.9	27.6	265	0.61	3.2
			dead	290	16.8	19.5	6.3	58	0.14	
6-C		control	living	960	20.8	21.8	32.7	329	0.71	2.4
			dead	100	12.9	19.0	13.0	12	0.03	
7-DF	61	disease focus	living	422	29.7	26.6	29.0	353	0.61	2.6
			dead	113	22.3	24.2	4.4	51	0.09	
7-C		control	living	561	28.6	27.3	35.7	442	0.74	1.4
			dead	38	18.2	23.7	1.0	11	0.02	
8-DF	71	disease focus	living	530	27.7	23.8	32.0	346	0.67	2.3
			dead	125	24.5	23.3	5.9	63	0.13	
8-C		control	living	695	26.5	24.2	37.9	417	0.81	1.5
			dead	32	20.5	23.0	1.04	11	0.02	
9-DF	81	disease focus	living	541	28.4	26.4	33.9	407	0.72	3.2
			dead	273	19.2	22.5	7.9	83	0.16	
9-C		control	living	707	27.7	26.8	42.3	517	0.88	2.1
			dead	43	16.0	20.6	0.9	9	0.02	

Table 2. Forests mensurational characteristics of the stands established on clear-cuts after annosum-infected pine stands.

Sample plot number	Age [years]	Composition	Species	Group of the trees	Stand density [stems ha ⁻¹]	Average diameter [cm]	Average height [m]	Growing stock volume [m ³ ha ⁻¹]	Relative density of stocking	Health index Ic	
14–DF	29	90%Sp 10%Sb	Sp	living	1123	15.2	14.3	134	0.52	2.6	
				dead	165	11.9	13.0	12	0.05		
			Sb	living	207	10.1	13.5	10	0.06	1.1	
				dead	—	—	—	—	—		
14–C		90%Sp 10%Sb	Sp	living	1730	15.6	16.3	255	0.83	1.6	
				dead	67	10.1	14.1	3	0.01		
			Sb	living	244	12.9	18.1	28	0.12	1.0	
				dead	—	—	—	—	—		
11–DF	49	100%Sp	Sp	living	597	22.6	20.7	228	0.52	2.7	
dead				113	19.9	20.8	35	0.08			
11–C			100%Sp	Sp	living	940	22.0	20.5	334	0.80	1.7
					dead	95	14.3	17.8	13	0.03	
10	48	50%Sp 50%Sb	Sp	living	241	25.5	22.9	129	0.26	2.3	
				dead	30	12.9	17.0	3	0.01		
			Sb	living	567	18.9	20.2	155	0.55	1.4	
				dead	9	11.3	15.3	1	—		
12	49	80%Sb 20%Sp	Sb	living	990	17.1	21.9	231	0.74	1.5	
				dead	74	9.5	16.5	4	0.02		
			Sp	living	142	19.6	23.2	47	0.09	2.3	
				dead	20	15.2	20.7	3	0.01		

Notes: Sp – Scots pine; Sb – silver birch.

classes. The tree diameters were measured with a caliper at breast height (1.3 m above ground) within the accuracy of 0.1 cm. The average diameter of the trees was determined by dividing the total basal area of each species by the corresponding total number of stems. According to the calculated basal area of the average tree, the average diameters for all species were determined.

The tree heights were measured in field conditions using IU–1M hypsometer. The average height of the species predominating in the stand composition was determined graphically by the average diameter of the trees of this species. To develop the height curve, we measured the height of 25–30 trees, which were distributed by diameter classes in proportion to the total basal areas of trees in the sample plot. For other species, the height was measured for 10–15 trees close to a medium-sized tree.

The health condition of the stand was described by the health condition index I_c calculated by the formula [1] (Tarnopilska et al. 2018):

$$I_c = \frac{K_1 n_1 + K_2 n_2 + \dots + K_6 n_6}{N} \quad [1]$$

where: $K_1, \dots, K_6$ – the category of the health condition of the trees (from 1st to 6th); $n_1, \dots, n_6$ – the number of trees of the given health condition category; N – the total number of recorded trees in the sample plot.

We assessed the health condition of the trees using 6 categories, namely: the 1st – trees without signs of damage, the 2nd – weakened trees, the 3rd – severely weakened trees, the 4th – dying trees, the 5th – standing dead trees died over the present year, and the 6th – standing dead trees died over recent years (Table 3).

The root rot disease focus is an area occupied by a group of severely weakened and dying trees of 3rd and 4th categories of health condition, including gaps resulting from the sanitation felling of the trees damaged by annosum root rot (Fig. 2a). The area outside the disease foci (control) is a healthy part of the stand, not disturbed

by the pathogenic loss of trees (Fig. 2b). The disease-produced loss of forest consists of severely weakened and dying trees and fresh and old standing dead trees, i.e. the trees of the 3rd, 4th, 5th and 6th health condition categories (Sanitary Forests Regulations in Ukraine 2016). During the study, the type of dieback in the stands was defined as follows: focal dieback, when the foci of dying were formed; diffuse dieback, with individual trees damaged by root rot and stem pests; and mixed type of dieback, with the presence of focal and diffuse diebacks (Ladeyshchikova et al. 2001).

Detection of *H. annosum s.l.* was carried out using strains isolated from *Pinus sylvestris* by conidiospore germination. Trees visually damaged by root rot were used for sampling with cork borer from stump. Isolated strains grown on Hagem agar (Stenlid 1985) were determined to intersterility group by somatic incompatibility and PCR analysis (unpublished data) resulted in detection of *H. annosum s.s.*

The degree of differentiation of trees in stands was assessed according to the following Kraft's classification (Avery & Burkhart 2002; Tarnopilska et al. 2018): 1st class – predominant, exceptionally large trees; their crowns extend above the general level of the canopy; they

Fig. 2. Planted 71-year-old pine stand inside root rot disease focus, 8–DF (a) and outside the disease focus, 8–C (b).

Table 3. Scale applied in the assessment of health condition of Scots pine trees.

Category of health condition	Health condition index range	Canopy openness	Degree of needle development		Needle colour	Degree of stand damage
			%	Distribution of needles over shoots		
1 st – without signs of damage	1.00–1.50	dense canopy	90–100	no signs of deterioration	green	none
2 nd – weakened	1.51–2.50	open canopy	66–90	no signs of deterioration	green, light-green	weak
3 rd – severely weakened	2.51–3.50	much open canopy	33–66	concentrated	light-green	medium
4 th – dying	3.51–4.50	much open canopy	33	concentrated	yellowish or yellow-green	significant
5 th – standing dead trees died over the present year	4.51–6.00	—	0	no living needles	grey, yellow or reddish-brown	extreme
6 th – standing dead trees died over recent years	4.51–6.00	—	0	no living needles	—	extreme

have the largest, fullest crowns in the stand and thicker trunks; 2nd – dominant trees; their crowns make up the general level of the canopy; generally, they are shorter than the predominant trees and have straight trunks; 3rd – subdominant trees; they have the same height as the dominant trees but are relatively weakly developed and restricted often with other trees, there are some signs of suppression; 4th – suppressed trees, with crowns restricted on all sides or on two sides, or with one-sided development; their tops reach only the lower part of the canopy of the dominant trees; 5th class – the trees completely under the canopy of the dominant trees; dying and dead trees.

The site class of the stands (the productivity indicator depending on the soil fertility or site conditions) was determined using Orlov's site class scales developed on the basis of height, age, and origin of stands (Hrom 2007). Stand basal area (or a quantitative measure of the degree of crowding within the stand) was found as the sum of the basal area of all live trees in a stand per hectare ($\text{m}^2 \text{ha}^{-1}$). The relative density of stocking of a stand was calculated as the ratio of the stand basal area to the basal area of the 'normal' stand (Shvydenko et al. 1987). Growing stock volume was defined as the volume of all living trees per unit area ($\text{m}^3 \text{ha}^{-1}$), and the stand density as the number of living trees per unit area (stems ha^{-1}) (Hrom 2007).

Peculiarities of the stand structure are described by the curve of tree distribution in natural diameter classes. Natural diameter classes are the diameter classes of the trunks, expressed in decimal fractions of average stand diameter. The distribution of trees by the natural diameter classes is a generalized variation series describing the

variability of tree diameter within stands and the representation of certain diameter classes. In healthy stands with different composition, the distribution of trees by natural diameter classes was found to be approximately the same (Mashkovsky 2015). The skewness and kurtosis coefficients for the variational series (Hammer et al. 2001) were calculated to assess the impact of annosum root rot on the distribution of trees by natural diameter classes in the infected pine stands (Tables 4, 5).

3. Results

To specify the structure of the part of pine stands in the root rot foci, the natural diameter classes distribution within the disease foci was compared to that within the control plots. The analysis of the distribution of trees by natural diameter classes (Tables 6, 7) indicated that the distribution curves were close to normal in the vast majority of sample plots, both in the disease foci and in the control (Tables 4, 5). The skewness of the distributions was positive and significant in the sample plots 4–DF, 8–DF, and 6–C. This means that most trees have diameters smaller than the average diameter. The kurtosis of the tree distribution was negative and significant in all sample plots, except for 4–DF, 8–DF, 7–C, and 9–C.

In planted pine stands, the type of the dieback resulting from root rot damage was found to depend on the age of the stand. The distribution of the disease was diffuse in the young stands up to the age of 35 (3–DF and 4–DF sample plots) and mixed in the stands up to 50 years old (5–DF). In older stands, it became focal (6–DF, 7–DF, 8–DF, and 9–C).

Table 4. Results of statistical processing of the trees distribution by the natural diameter classes in the disease foci.

Statistical indicator	Sample plots							
	3–DF	4–DF	5–DF	6–DF	7–DF	8–DF	9–DF	11–DF
Kurtosis	–1.466	–0.061	–1.589	–1.017	–1.037	–0.368	–1.498	–1.288
Critical value of kurtosis ($st_{0.05}$)	0.863	0.890	0.873	0.863	0.873	0.873	0.873	0.873
Skewness	0.270	0.930	0.440	0.701	0.505	1.009	0.396	0.229
Critical value of skewness ($st_{0.05}$)	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711

Table 5. Results of statistical processing of the distribution of trees by the natural diameter classes in the control sample plots.

Statistical indicator	Sample plots							
	3–C	4–C	5–C	6–C	7–C	8–C	9–C	11–C
Kurtosis	–1.065	–1.798	–1.504	1.197	–0.862	–1.322	–0.584	–1.738
Critical value of kurtosis ($st_{0.05}$)	0.863	0.890	0.890	0.873	0.873	0.890	0.873	0.873
Skewness	0.356	0.502	0.428	1.597	0.697	0.406	0.397	–0.112
Critical value of skewness ($st_{0.05}$)	0.711	0.711	0.711	0.711	0.711	0.711	0.711	0.711

Table 6. Actual distribution of trees by the natural diameter classes in the disease foci (%).

Natural diameter classes	Sample plots							
	3-DF	4-DF	5-DF	6-DF	7-DF	8-DF	9-DF	11-DF
0.1	1.5	0	0	0	0	0	0	0
0.2	2.0	0	0	0.5	0	0	0	0
0.3	6.0	0	0	0	0.8	0	1.3	0
0.4	8.5	0	0.5	5.6	0.8	0	3.1	0.7
0.5	10.0	2.3	3.3	4.2	7.3	1.2	10	6.6
0.6	9.5	3.1	9.3	7.5	14.6	4.4	10	8.6
0.7	11.5	12.5	11.5	13.6	13.9	7.6	11.1	10.4
0.8	7.0	10.2	15.9	9.9	9.8	20.3	11.7	15.9
0.9	9.5	21.9	14.3	12.2	14.6	21.1	15.1	9.3
1.0	4.5	10.9	12.7	13.1	7.3	16.5	14.7	12.6
1.1	5.5	21.1	14.9	16.9	9.8	11.5	10.7	11.8
1.2	6.0	7.8	8.8	10.8	6.6	9.6	5.3	10.7
1.3	9.5	6.3	3.9	1.4	4.9	3.2	3.7	6.3
1.4	2.5	3.1	1.7	2.8	5.6	1.2	2.4	3.7
1.5	2.5	0.8	0.5	0.9	0.8	2	0.4	1.8
1.6	1.0	0	2.2	0	1.7	0.6	0	0.7
1.7	1.0	0	0.5	0	1.7	0.6	0.4	0.7
1.8	1.0	0	0	0.5	0	0	0	0
1.9	1.0	0	0	0	0	0	0	0
2.0	0.0	0	0	0	0	0	0	0

Table 7. Actual distribution of trees by natural diameter classes in the control plots (%).

Natural diameter classes	Sample plots							
	3-C	4-C	5-C	6-C	7-C	8-C	9-C	11-C
0.1	0.4	0	0	0	0	0	0	0
0.2	3.5	0	0	0	0	0	0	0
0.3	2.6	0	0	0.7	0	0	0	0
0.4	10.4	0	0	3.1	0.8	0	1.9	0.5
0.5	8.6	0.3	0.9	3.8	2.3	0	0	3.9
0.6	6.5	2.2	6.2	6.3	5.5	2.2	12.4	9.7
0.7	6.1	6.9	11.5	4.4	11.2	10.9	10.5	14
0.8	11.2	13.4	13.2	12	15.8	21	8.5	13.5
0.9	10.8	18.1	13.2	18.2	19	18.8	11.5	13.5
1.0	4.8	19.6	18.1	23.8	14.3	12.2	20.9	11.6
1.1	8.6	19.6	18.5	10.1	11.8	14.4	10.5	10.1
1.2	4.3	17	12.3	5	8	12.2	15.2	11.6
1.3	7.4	2.2	3.5	7.5	5.5	4.4	6.7	4.8
1.4	3.9	0.3	1.3	2.5	2.3	1.5	1.9	5.3
1.5	5.2	0.3	0	0.7	1.7	2.2	0	1.4
1.6	1.7	0	1.3	1.2	1.7	0	0	0
1.7	1.7	0	0	0.7	0	0	0	0
1.8	0.9	0	0	0	0	0	0	0
1.9	1.3	0	0	0	0	0	0	0
2.0	0	0	0	0	0	0	0	0

3.1. Pine stands planted on formerly arable land

For pine stands planted on abandoned agricultural land, a direct relationship was found between the age of the stand and the average diameter as well as between the age and average height of the trees, both dead and living. The average diameter of the living trees in the disease focus was 1–6% larger compared to the control (outside the disease focus) because of larger vital space contributing to the increase of radial increment of trees. However, this difference was not significant.

In root rot disease focus, there was dieback of thicker trees as compared to the control. Also, the difference between the average diameters of dead trees inside and outside the disease focus was significant and varied within 11–23% (Fig. 3). In the disease focus, the average height of living trees was 2–5% lower in comparison with the control. On the contrary, the height of the dead trees inside the root rot focus was up to 8% higher compared to that outside it as in the disease focus the trees with larger diameter were dying (Fig. 4).

In the root rot disease foci, due to the pathological mortality, the density of the pine stand was much smaller, by 14–38% and the growing stock volume was 16–35% lower as against pine stand outside the disease foci (Fig. 5). In the control areas, the growing stock of pine stand unevenly increased with age, and the number of trees decreased.

The negative impact of annosum root rot is evidenced by the increase in the stock of standing dead trees (Fig. 6). For example, the stock of dead trees in the controls was small and varied within 4–12 m³ ha⁻¹. In the disease foci, it increased from 11 m³ ha⁻¹ in 21-year-old stand to 83 m³ ha⁻¹ in 81-year-old one. In the 61-year-old pine stand, the stock of dead trees decreased slightly to 51 m³ ha⁻¹ due to the recent sanitation felling in it, which insignificantly influenced the general trend.

For pure Scots pine stands planted on formerly arable land the health condition index varied from 2.3 (weakened stand) to 3.4 (severely weakened stand) within the disease focus and from 1.4 (healthy stand) to 2.4 (weakened stand) in the control (Table 1).

3.2. Stands planted on clear-cuts after annosum-infected pine forests

All mensurational indicators for the parts of the stands within root rot disease foci showed significantly lower rates than those outside them, due to the negative effects of the disease. For example, in the mixed 29-year-old stand, the average diameter and height within the dis-

ease focus (14–DF) were below the control (14–C) by 3% and 12% respectively for Scots pine and by 22% and 25% for silver birch. The differences in the stand density inside and outside the disease focus were 35% for Scots pine and 15% for silver birch, in relative density of stocking they were 37% and 50% respectively; the growing stock differences were 47% and 64% for pine and birch respectively. Such differences were due to significant

Fig. 3. Average diameters of dead and living pine trees inside and outside annosum root rot disease foci depending on stand age.

Fig. 4. Average heights of dead and living pine trees inside and outside annosum root rot disease foci depending on stand age.

Fig. 5. The number of trees and growing stock volume of pine inside and outside root rot disease foci.

Fig. 6. Stock volume of dead standing trees inside and outside root rot disease foci.

annosum-induced mortality within the disease focus. In general, the part of the stand outside the disease focus had higher site class than the part inside it. The number of dead pine trees in root rot disease focus was 2.5 times larger than in the control, and their stock volume was 4 times greater. The degree of pine damage was medium inside the disease focus and weak outside it. Accordingly, within the disease focus, the pine part of the stand was assessed as “severely weakened” by the health condition ($I_c = 2.6$); in the control, it was “weakened” ($I_c = 1.6$). The birch part of the stand in the disease focus and in the control was assessed as “healthy” ($I_c = 1.0...1.1$).

The density of 49-year-old pine stand within the root rot disease focus (11–DF) was 36% lower than outside it (11–C) due to the disease-induced mortality. At the same time, the number of dead trees within the disease focus was 1.2 times larger. Lower stands density inside the center caused 3% excess in average diameter and 1% excess in average height. The stock volume of living trees was 32% lower in the disease focus as compared to the control. Instead, the stock of dead trees there was 2.7 times larger. The degree of the stand damage was medium inside the disease focus and weak outside it. Accordingly, the part of the stand inside the root rot disease focus was assessed as “severely weakened” ($I_c = 2.7$) and the control, as “weakened” ($I_c = 1.7$).

The mixed 48-year-old pine-birch stand (sample plot 10) had a growing stock volume of $284 \text{ m}^3 \text{ ha}^{-1}$. The proportion of Scots pine in the stock was 45% and the part of the silver birch amounted to 55%. The pine-birch stand had better health and higher productivity compared with those in the disease focus in pure pine stands of the same age (11–DF), planted on the clear-cut after annosum-infected stand (Table 2).

In mixed 49-year-old birch-pine stand (sample plot 12), the proportion of silver birch trees was 87% and Scots pine trees made 13%. Among the birch trees, the healthy ones prevailed (80%). The proportion of dead ones accounted for only 7% of the total number of trees in the stand. In the pine part of the stand, healthy trees

amounted to 48%, weakened and severely weakened ones were estimated at 15%. In this case, the proportion of dead pine trees was 12%. As for health condition, the birch part of the stand was “healthy” ($I_c = 1.5$) and the pine trees were assessed as “weakened” ($I_c = 2.3$).

Thus, the data (Table 2) suggested that in the mixed pine-birch and birch-pine stands, the birch trees had “healthy” condition ($I_c = 1.0...1.5$) while pine trees were assessed as “weakened” and “severely weakened” ($I_c = 1.6...2.6$).

4. Discussion

The results of the study showed that the impact of root rot on the health of the stands can be explained by a set of factors. The factors can include the intensity of pathological dieback; types, values, and timing of forest management actions; the type and the time of development of the dieback foci, etc. Over time, the disease progression leads to a decrease in total increment, the relative density of stocking and total stand volume. For example, the average height of living trees in the root rot disease foci was 2–5% less and the average diameter was 1–6% larger compared to the area outside the disease foci. The density of the part of pine stand within the disease foci was much less, by 14–38%, due to the annosum-induced mortality, and the growing stock volume was 16–35% lower than that outside the disease foci. The health condition index varied from 2.3 (“weakened stand”) to 3.4 (“severely weakened stand”) inside the foci of root rot disease and from 1.4 (“healthy stand”) to 2.4 (“weakened stand”) in the areas outside them.

The tree mortality in the uninfected part of the stand can be mainly attributed to the thinnest trees of the 4th–5th Kraft classes. In the disease focus, not only the trees of the 4th–5th Kraft classes but also the more developed trees of the 1st–3rd classes were dying, which are infected by annosum root rot exactly in the same way (Fig. 3). The height of the dead trees inside the root rot foci was 0–8%

higher compared to that outside them as in the disease foci the trees with larger diameter were dying. Regardless of the age of the stands, the average diameter and height of dead trees were much smaller than that of living ones. At the same time, in the disease foci, mortality was attributable to considerably thicker and slightly higher trees, in comparison with the control. The more intense opening within the infected part of the stand and, as a result, an increase in the growing space for the trees remaining in this part contributed to their greater growth in diameter and height (Fig. 4).

For the conditions of Ukrainian Eastern Polissya physiographic region, similar results were obtained by other authors (Raspopina et al. 2013). There was a decrease of 20–49% for the density and of 16–37% for the growing stock volume of the pine stand in root rot disease foci in comparison with the areas outside the foci due to the disease- and pest-induced mortality. The average height of planted Scots pine stands inside the disease foci was 3% lower, and the average diameter was 4% larger than those outside them. In the disease focus, the stand was assessed as “severely weakened” (I_c ranged from 2.6 to 3.4). Intact part of the stand was assessed as “weakened” (I_c was 1.7–2.4).

The investigation in Ukrainian Novgorod-Siverske Polissya (Lapitan et al. 2013) indicated the decrease in growing stock volume by an average of 24% and 33% in root rot disease foci in pre-mature and mature pine stands respectively. According to the data (Vedmid et al. 2013), the growing stock volume and the value of timber of pine stands in Eastern part of Ukrainian Polissya decreased by 1.5–2 times inside the annosum foci as compared to the outside part. In the Volyn Polissya region of Ukraine, the total standing volume and the value of timber of annosum-infected planted pine stands outside the disease foci were 42% larger than those inside them (Musienko et al. 2018).

The pure pine stands of the next generation, planted on the clear-cuts after annosum-infected pine forests (sample plots 11–DF and 11–C), were considerably exceeded by pure pine stands planted on formerly arable land (sample plots 5–DF and 5–C) in productivity and health. For example, in the disease foci, the growing stock volume in 5–DF was 21% higher than in 11–DF (Fig. 7). This is attributed to the increasing root rot infection level for the next generation of pure pine stands in already infected areas. The health condition for both test plots was not different during the survey ($I_c = 2.7$).

Mixed pine and birch (sample plot 10) and birch and pine (sample plot 12) stands of approximately equal age had 20% and 18% higher growing stock volumes respectively, as compared to the pure pine stand (11–DF) planted on clear-cut areas after annosum-infected pine stands. The pine health condition index in the mixed stands was 2.3 (“weakened stand”) and in the pure pine stand in the root rot disease focus it was 2.7 (“severely weakened stand”). The birch parts of the stands were healthy (I_c were 1.4 and 1.5).

In summary, the mixed stands planted on the clear-cuts after annosum-infected pine forests exceeded pure pine stands of the same age in growing stock volume. They were more annosum-resistant and had a much better health condition. Therefore, the addition and maintenance of broadleaved species, particularly silver birch, into the stand composition and the timely thinning of young stands can significantly increase the resistance of forests to annosum root rot and prevent the infection. Thus, establishing mixed stands on clear-cut areas after annosum-infected pine forests is justified from the forestry standpoint, due to their higher productivity and better health condition.

According to the study of Raspopina et al. (2013), the growing stock volume of root rot infected pine stands exceeded the growing stock of birch stands by 20%.

Fig. 7. Growing stock volume and health condition of the investigated pure and mixed stands.

However, the birch stands had a better health condition ($I_c = 1.6...2.1$) as compared with the infected pine stands ($I_c = 2.6...2.9$).

In the opinion of many researchers (Ladeyshchikova et al. 1974; Negrutskiy 1986; Vasilyauskas 1989; Peri et al. 1990; Raspopina et al. 2013), birch stands are more resistant to root rot damage. It is especially advisable to grow pure birch stands in fresh and moist fairly infertile sites on clear-cuts after annosum-infected pine stands, in order to prevent the disease spreading. In formerly arable lands in fresh fairly infertile pine site type, Alekseev et al. (1981) and Bilous (2006) suggested introducing at least 30% of silver birch into the composition of pine stand. This could accelerate the decomposition of forest litter and enrich the soil with nitrogen and ash mineral substances.

In the Chernihiv Polissya physiographic region of Ukraine, the growing stock volume of mixed pine and birch stands with 10–20% of silver birch was 10–35% higher than that of pure pine stands. Studies in north-eastern Poland showed that, in mixed pine stands, the growing stock was on average 41% larger as compared with pure ones (Bielak et al. 2014). In addition, mixed stands are more resistant to pests and pathogens; they contribute to the enrichment of biodiversity and the improvement of aesthetic and recreational values of forests (Felton et al. 2016).

Planting mixed pine and birch stands will enhance soil and water protection, sanitation, recreation and other beneficial properties of forests and improve the biodiversity of land disturbed by long-term agricultural use (Ladeyshchikova et al. 2001). Additionally, it will contribute to the formation of the natural composition of soil microbiota and will provide the opportunity to grow primary forests in the future.

5. Conclusions

The main threat to the pure pine stands planted on the clear-cut areas after annosum-infected pine forests is the danger of re-infestation of the stands. The mixed stands established under these conditions are more resistant to annosum root rot disease and have better health than pure pine ones. The clear-cut areas after annosum-infected pine stands should be reforested using mixed Scots pine and silver birch stands with 30–50% of Scots pine in the composition.

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