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THE IMPACT OF HETEROBASIDION ROOT ROT ON THE DENSITY, GROWING STOCK VOLUME, AND HEALTH CONDITION OF SCOTS PINE AND SILVER BIRCH STANDS IN VOLYN POLISSYA ZONE, UKRAINE

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Abstract

The study was carried out in Scots pine (*Pinus sylvestris* L.) forests in Gorodotske and Manevytske Forest Enterprises, which are situated in the Manevytsko-Volodymyretsky physiographic region of the Volyn Polissya zone in Ukraine. The aim of the study was to investigate the characteristics and health condition of Scots pine stands, infected by annosum root rot (*Heterobasidion annosum* (Fr.) Bref.), in the disease centres and in the part of the stands outside the centres (the control areas), as well as of silver birch (*Betula pendula* Roth) stands in Volyn Polissya. We have found that the density of planted 43–75-year-old stands of Scots pine, established on formerly arable lands, was 32–66 % lower in the centres of the root rot disease than in the control areas. The growing stock volume was 20–62 % lower, respectively. The health index of the stands varied from 1.7 (weakened trees) to 3.2 (severely weakened trees) in the disease centres and from 1.3 (healthy trees) to 1.6 (weakened trees) outside them. We revealed that birch stands established on formerly arable lands were more resistant to annosum root rot and had better health status compared to pine stands. A set of factors was found to cause the root rot of Scots pine stands on abandoned agricultural lands, some of which were growing overstocked pure stands and their untimely (late) thinning.

Key words: annosum root rot, health condition, *Heterobasidion annosum*, *Pinus sylvestris*, planted pine stands.

Introduction

Scots pine (*Pinus sylvestris* L.) is the main forest forming species in Polissya zone; it occupies about 60 % of the area covered with forest vegetation (Terentjev 2015). Pine stands in Polissya, especially pure pine plantations, established on abandoned agricultural lands in the middle of the 20th century, suffer great losses due to the root rot caused by the fungus *Heterobasidion annosum* (Fr.) Bref. (Negrutskiy 1986, Woodward et al. 1998).

The root rot reduces the productivity of forest stands, causes their early dieback, provokes massive pest outbreaks, increases fire hazard, worsens the soil-protective, water-conservation and sanitary functions of a forest. In addition, root rot affected trees are vulnerable to wind storms (Alekseev 1974, Vollbrecht et al. 1994, Brandtberg et al. 1996, Bendz-Hellgren et al. 1999, Volchenkova et al. 2012, Garbelotto and Gonthier 2013, Lapitan et al. 2013, Zvyagintsev and Volchenkova 2014, Lyamtsev 2015, Musienko et al. 2018).

The proportion of the area of conifers infected by root rot in Ukraine is 13–16 % of the total area of the coniferous stands in which pathological processes are detected (Ustsky et al. 2010). According to Chudak (2014), the basic infection level in the forests of Polissya in Ukraine is now provided by permanent foci of forest diseases. In recent years, there has been a negative dynamics: since 2007 the area of the foci of forest diseases has increased by 30 % from 90.9 to 117.3 thousand hectares. In the general structure of the stands, in which pathological processes are detected, 72 % of the area (84.7 thousand hectares) is occupied by pine forests infected by root rot. The largest centres of this disease are concentrated in Chernihiv (28.7 thousand hectares), Zhytomyr (14.2 thousand hectares), Kyiv (14.8 thousand hectares), Volyn (11.9 thousand hectares) and Rivne (11.1 thousand hectares) regions.

Annosum root rot occurs in all countries of Europe (Vasiliauskas et al. 2002, Wang 2012, Mead 2013, Sierota 2013), North America (Harrington et al. 1989, Woodward et al. 1998), Central America (Lewis 2002, Mead 2013), some regions of Australia (Mead 2013), Asia (Parmasto 1986, Dai et al. 2003) and Africa (Morocco) (Mead 2013).

The cause of the wide geographic and ecological range of root rot is a variety of ways of reproduction and infection (basidiospores, conidiospores or mycelium). Primary infections of trees occur via basidiospores and conidia of the fungus. Basidiospores are formed in the fruiting bodies, and conidia, throughout the growing season, on the mycelium where rotting is on the surface of infected stumps or roots (Negrutskiy 1986, Woodward et al. 1998).

The problem of emergence and spread of this disease in Ukraine arose in the middle of the 20th century since pine forest plantations have been established on considerable areas of abandoned agricultural lands, pastures, and wastelands, where soils had lost their forest properties. The association of root rot disease centres with planting on formerly arable lands has been indicated by a number of investigations (Ladeyshchikova et al. 1974, Sierota 1997, Kuznetsov 2005, Bilous 2009, Sierota 2013). The initiation and spread of this disease are attributed by most researchers to the presence of the upper arable layer of soil, the depth of which is limited to a densified layer often referred to as the ‘plow-pan’. The presence of such a layer prevents the roots to penetrate into the lower horizons of the soil that causes a decrease in the growth of the above-ground part of a tree and significantly weakens it (Ladeyshchikova et al. 1974, Negrutskiy 1986, Vasiliauskas 1989, Raspopina et al. 2013). Establishing plantations in areas after clear sanitary felling of the stands affected by annosum root rot increases the risk of the infection significantly (Negrutskiy 1986, Bilous 2009, Volchenkova et al. 2012).

A number of researchers (Vorontsov 1978, Artyukhovskiy 1998) assign an important role in spreading of the pathogen to stem pests, which are carriers of fungal spores, causing the infection. A high density (i.e. the number of living trees per hectare) of pure pine plantations, and therefore root contacts, leads to a decrease in their resistance to the root rot disease and group dying off (Vasiliauskas 1989, Volchenkova et al. 2012, Raspopina et al. 2013). Ladeyshchikova et al. (1974) and Raspopina et al. (2013), who conducted studies in Eastern Polissya region on sod-podzolic soils of formerly arable lands, showed that the initiation and spread of root rot were associated with the water-physical properties of the soils.

In order to increase the resistance of a stand against annosum root rot in formerly arable land, it was necessary to create mixed forest plantations involving deciduous species. The following species may be used to mix with Scots pine in fresh fairly infertile pine sites: silver birch (*Betula pendula* Roth), Red oak (*Quercus rubra* L.), English oak (*Quercus robur* L.), Grey alder (*Alnus incana* (L.) Moench). Their proportion must be at least 30 % in these conditions (Alekseev 1974, Negrutskiy 1986, Bilous 2009).

Biological methods of protecting plants from the root rot infection with the fungus *Phlebiopsis gigantea* (Fr.) Jülich have considerable advantages and in some conditions are the most effective tools for limiting the harmfulness of the disease. Rishbeth (1963) proved that *Phlebiopsis gigantea*, colonizing stumps, contributed to the inhibition of the pathogen in the roots, and suggested the use of this fungus for the biological control of *Heterobasidion annosum*. Rotstop biofungicide containing spores of *Phlebiopsis gigantea* fungus is widely used in Great Britain, Norway, Switzerland, Finland, Poland, Latvia, and Belarus (Sierota 2001, Kenigsvalde et al. 2011, Volchenkova and Zvygantsev 2011, Sierota 2013, Kenigsvalde et al. 2016, Kenigsvalde et al. 2017).

The antagonistic influence of local strains of this fungus on root rot and the possibility of its use for preventive purpose in the Left-Bank Forest-steppe of Ukraine were studied at the Donetsk National University. As a result of the research, a regulation was developed for the preparation of the biologic agent Penioflorin based on a spore suspension of selected *P. gigantea* strains, and an instruction for use was prepared (Demchenko and Sukhomlin 2000). However, this preparation (Boiko et al. 2001) has not been introduced in Ukraine, mainly for economic reasons.

It should be noted that in conditions of the forest-steppe in Ukraine, the fruiting bodies of *Heterobasidion annosum* in pine forests are formed very rarely in wet years. Therefore spore infection of the pathogen in such conditions plays a minor role, and the main way to control the disease is forest management, mainly sanitation felling, the effectiveness of which is insignificant. During the felling, all the dead trees in the disease centre and strips of unaffected stands on the perimeter of the centre are removed. Rather than protecting stands from the infection, this method of forest improvement also causes economic losses to the forestry industry, as high-quality green pine wood is progressively changed in deadwood in this case (Vasiliauskas 1989, Kuznetsov 2005, Zvyagintsev et al. 2013).

To reduce the annosum root rot infection level and to form a natural composition of soil microbiota, a number of investigators (Alekseev 1974, Peri et al. 1990, Ladeyshchikova et al. 2001, Lygis et al. 2004b) proposed to establish plantations of silver birch as a pine forecrop on former agricultural land in fresh and moist fairly infertile pine site types. However, a study by Lygis et al. (2004a) in Eastern Lithuania in 25-year-old *B. pendula* stands replanted in the *H. annosum* disease centres in *Pinus sylvestris* stands, which were clear-felled, indicated a low productivity

(45.0–76.1 $m^3 \cdot ha^{-1}$), high mortality rates, and comparatively low vigour of the trees due to a strong impact of root rot.

The influence of root rot on stands' features and health condition of Scots pine and silver birch in Volyn Polissya of Ukraine have not been sufficiently studied. Therefore, the identification of factors contributing to the root rot damage of pine stands and the study of their characteristics and health status, as well as the development of preventive and control measures for this disease, are extremely relevant.

The aim of the study was to analyse and compare forest mensurational characteristics and health condition of Scots pine stands infected by annosum root rot and healthy silver birch stands, which were growing on formerly arable lands, to investigate the possibility of replacing diseased pine stands with birch ones, which are more resistant to this fungus.

Material and Methods

An evaluation of stand characteristics was carried out in June and July 2017, using the methods of forest mensuration described by Neretin et al. (2006) and Hrom (2007). The study was performed in planted Scots pine forests on abandoned agricultural lands of two state forest enterprises: Gorodotske Forest Enterprise and Manevytske Forest Enterprise, which are located in Volyn Polissya zone of Ukraine (Fig. 1) and are representative for this

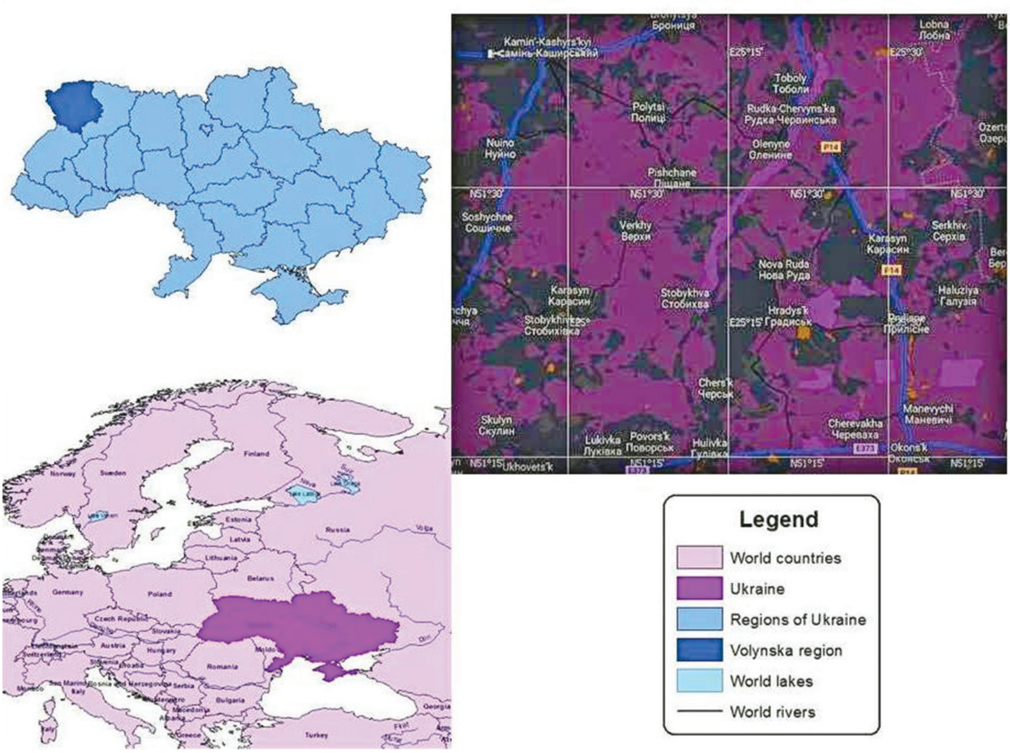

Fig. 1. Location of the study site.

zone. Scots pine is the main forest forming tree species in this area. It occupies near 68 % of the area covered with forest vegetation. The altitude of the sample plots was 179–210 m above sea level. The investigation covered the area of approximately 300 km^2.

To study the forest mensurational characteristics and health condition of Scots pine stands affected by annosum root rot, seven sample plots were established in the part of the stands, containing infected and dead trees (disease centres, DC). Seven sample plots were laid out as a control (C) in a relatively healthy part (i.e. without evidence of deterioration) of these stands (the area outside the disease centres) and two plots were established in 51-year-old and 62-year-old intact silver birch stands (Table 1). For birch and root rot infected pine stands, stand characteristics and health status were compared to assess whether infected pine stands should be replaced with birch ones. *B. pendula* stands were compared with planted Scots pine stands infected by root rot, which grow in the same forestry in the same forest site conditions and have the same age: sample plot 10 with 7-DC and sample plot 3 with 6-DC.

Table 1. Mensurational indices for pine plantations inside the root rot disease centres and in the control (outside the disease centres) and for birch plantations on abandoned agricultural lands.

Sample plot	Age, years	Part of the stand	Composition	Part 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	λ
5-DC	43	disease centre	10Sp	living	835	18.2	17.1	170.1	0.51	6.35
				dead	271	16	16.7	42.7	0.13	
			single Sb	living	89	10.1	12.0	4.4	0.03	
				dead	6	6.2	9.7	0.1	0	
5-C		control	10Sp	living	1244	17.1	17.5	238.2	0.68	
				dead	13	13.8	15.8	1.5	0	
			single Sb	living	100	10.7	13.5	5.9	0.03	
9-DC	47	disease centre	10Sp	living	456	27	22.1	261.6	0.55	6.79
				dead	17	20.8	20.6	5.3	0.01	
9-C		control	10Sp	living	665	25	21.9	326.9	0.71	
				dead	8	17	18.8	1.5	0	
2-DC	50	disease centre	10Sp	living	542	25.3	22.4	281.4	0.59	6.12
				dead	147	19.9	20.4	42.4	0.1	
2-C		control	10Sp	living	973	24	22.8	461.6	0.96	
				dead	53	14.3	18.2	6.9	0.02	
7-DC	51	disease centre	8Sp	living	538	22.1	20.9	190.4	0.44	5.28
				dead	338	22.1	20.7	133.1	0.3	
			2Sb	living	131	20.5	21.5	42.7	0.08	
				dead	6	26.5	23.1	3.5	0.01	
7-C		control	10Sp	living	1200	22.3	22.9	498.6	1.02	
				dead	30	12.9	19.6	3.4	0.01	
			Single Sb	living	90	19.2	22.3	27.3	0.06	

Sample plot	Age, years	Part of the stand	Composition	Part 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	λ
10	51	all stand	9Sb	living	724	20.2	22.0	234.5	0.76	–
				dead	21	15.6	19.6	3.5	0.01	
			1Sp	living	76	20.5	22.1	25.7	0.06	
8-DC	56	disease centre	10Sp	living	528	23	20.2	211.7	0.49	3.92
				dead	56	18.2	17.3	11.7	0.03	
8-C		control	10Sp	living	800	23	23.1	367.6	0.72	
				dead	14	14.3	19.1	2.1	0.01	
6-DC	61	disease centre	10Sp	living	458	27.7	24.6	306.8	0.58	5.37
				dead	132	25.3	24.1	72.1	0.14	
6-C		control	10Sp	living	799	27	26	541.3	0.97	
				dead	73	18.6	22.6	20.8	0.04	
3	62	all stand	10Sb	living	437	26.5	23.2	258.5	0.78	–
				dead	16	16.0	18.9	2.9	0.01	
4-DC	75	disease centre	10Sp	living	167	37.6	25.8	228.9	0.39	6.86
				dead	80	34.6	25	85.5	0.16	
4-C		control	10Sp	living	491	35	26.3	561.4	0.98	
				dead	5	22.6	22	2.1	0	

Note: Sp – Scots pine; Sb – Silver birch; single – single trees.

In fresh infertile pine site, four sample plots were laid out in Gorodotske Forest Enterprise: in 43-year-old mixed pine stand (sample plots 5-DC and 5-C) in Borove forestry and in 56-year-old pure pine stand (sample plots 8-DC and 8-C) in Lyshnivske forestry. The planting pine stand in 5-DC and 5-C was established on abandoned agricultural land using mixing pattern of 8 rows of Scots pine and 2 rows of silver birch. The pine stand in 8-DC and 8-C was linearly thinned in 2000 with continuous removal of trees in every 4th row. The thinning was carried out in winter without the use of biological or chemical preparations.

In the site type that is intermediate between fresh fairly infertile and fresh fairly fertile one, two sample plots, 9-DC and 9-C, were established in 47-year-old pure pine stand in Manevytske Forest Enterprise, Okonske forestry.

In fresh fairly infertile pine site, eight sample plots were laid out in pure pine stands in Gorodotske Forest Enterprise as follows: sample plots 2-DC and 2-C in 50-year-old stand (Gorodotske forestry), sample plots 7-DC and 7-C in 51-year-old stand and sample plots 6-DC and 6-C in 61-year-old pine stand (Novorudske forestry), and sample plots 4–DC and 4–C in 75-year-old pine stand (Borove forestry).

In almost all studied sample plots, stands were created with 2.0 × 0.5 m spacing of planting sites. The exceptions were 8-DC and 8-C where stands were planted using 1.5 × 0.5 m pattern. The soil was cultivated using PKL-70 plow. There were a few silver birch trees of natural origin in some of the plots (Table 1).

The studied sample plots were square shaped. The area of the sample plots ranged from 0.3 ha to 0.57 ha depending on the age of the stand (Table 2) and the number of the dominant trees was at least 200 stems on each plot. The tree diameter (DBH) was measured with a tree caliper at 1.3 m above ground level within the accuracy of 0.1 cm. The average diameter was calculated using the average basal area. The tree height was determined by hypsometer ИУ–1М for 35–45 trees in each sample plot under field conditions. The average height was estimated using a graph of height variance depending on the diameter of the specific stand that corresponds to the average DBH (Hrom 2007).

Table 2. Area of the sample plots and health condition of the investigated stands.

Sample plot number	Age, years	Composition	Area of the sample plot, ha	Health index I_c
5-DC	43	10Sp	0.32	2.6
		single Sb		1.9
5-C		10Sp	0.32	1.4
		single Sb		1.8
9-DC	47	10Sp	0.33	1.7
9-C		10Sp	0.31	1.4
2-DC	50	10Sp	0.34	2.6
2-C		10Sp	0.30	1.5
7-DC	51	8Sp	0.36	3.2
		2Sb		1.5
7-C		10Sp	0.32	1.4
		single Sb		1.2
10	51	9Sb	0.40	1.5
		1Sp		1.5
8-DC	56	10Sp	0.35	2.3
8-C		10Sp	0.32	1.4
6-DC	61	10Sp	0.43	2.3
6-C		10Sp	0.39	1.6
3	62	10Sb	0.45	1.5
4-DC	75	10Sp	0.57	2.9
4-C		10Sp	0.51	1.3

Note: Sp – Scots pine; Sb – Silver birch; single – single trees.

The site class of the stands is the indicator of their productivity depending on the soil fertility or site conditions. It was determined using the Orlov's site class scales developed on the basis of height, age and origin of stands (Hrom 2007). Stand basal area was found as the sum of the basal area of all live trees in a stand per hectare ($m^2 \cdot ha^{-1}$). 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 1987). Growing stock volume was defined as the volume of all living trees per unit area ($m^3 \cdot ha^{-1}$) , and the density of a stand as the number of living trees per unit area ($stems \cdot ha^{-1}$) (Hrom 2007).

The health condition of the trees was estimated 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 degree of stand damage was characterized by the health condition index I_c that was calculated as follows (Sanitary Forests Regulations in Ukraine 2016):

$$I_c = \frac{K_1 n_1 + K_2 n_2 + \ldots\ldots + K_6 n_6}{N}, \qquad (1)$$

where: K_1, …, K_6 – the category of the health condition of the trees; n_1, …, n_6 – the number of trees of the given health condition category; N – the total number of recorded trees in the sample plot.

Table 3. Scale used in determination of health status of Scots pine trees.

Category of health condition	Health condition index range	Canopy openness	Degree of needle development: %	Degree of needle development: Distribution of needles over shoots	Part of needles with chlorosis or necrosis	Needle colour
1st – without signs of damage	1.00–1.50	dense canopy	90–100	no signs of deterioration	0	green
2nd – weakened	1.51–2.50	open canopy	66–90	no signs of deterioration	up to 1/3	green, light-green
3rd – severely weakened	2.51–3.50	much open canopy	33–66	concentrated	1/3–2/3	light-green
4th – dying	3.51–4.50	much open canopy	33	concentrated	2/3	yellowish or yellow-green
5th – standing dead trees died over the present year	4.51–6.00	–	0	no living needles	1	grey, yellow or reddish-brown
6th – standing dead trees died over recent years	4.51–6.00	–	0	no living needles	1	–

The root rot disease centre 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 sanitary cutting of the trees affected by annosum root rot (Fig. 2a). The area outside the disease centres (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).

We identified the damage of pine stands, caused by annosum root rot, both visually (Ladeyshchikova et al. 2001) and by performing the experiment to stimulate the formation of fruiting bodies of annosum root rot (Negrutskiy 1986). The experiment was carried out both inside and outside a disease centre for trees of different categories of health condition. At a dis-

a ***b***

Fig. 2. Planted 61-year-old pine stands: *a* – in the root rot disease centre (6-DC); *b* – in the area outside the disease centre (6-C).

tance of 0.5 m from the tree, we dug pits up to 1 m long, 20–30 cm wide and 40 cm deep and cut the roots of the tree. The pits were covered with planks and moss. After three weeks fruiting bodies of the fungus have developed in cut roots. The fungus was identified by characteristic features, guided by the data of the special literature (Negrutskiy 1986). This provided the opportunity to observe that it was *Heterobasidion annosum* that caused the disease of the investigated pine stands. The formation of the fruiting bodies of annosum root rot did not occur in the areas outside the disease centres within affected pine forests and in birch stands. In the foci of root rot disease, fruiting bodies were not found in the roots of visually healthy trees (the 1st category of health condition) but they appeared en masse in the roots of the trees of the 3rd–5th health condition categories (Fig. 3).

During the study of stand characteristics, the non-parametric Kolmogorov-Smirnov goodness-of-fit test (λ) (Massey 1951) was used. For this purpose, two series of empirical distributions of tree diameters in paired sample plots (inside and outside root rot disease centres) in pine stands affected by annosum root rot were compared and their belonging to one general population was assessed according to the formula (2):

$$\lambda = d_{max}\sqrt{\frac{n_1 \cdot n_2}{n_1 + n_2}}, \quad (2)$$

where: d_{max} – the maximum difference between the values of the first and second series of cumulative frequencies; n_1, n_2 – the sums of all variants of the population.

a

b

Fig. 3. Fruiting bodies of *Heterobasidion annosum* in pine roots: *a* – a tree of the 3rd category of health condition; *b* – a tree of the 5th category of health condition.

In this case, for the calculation of d_{max} formula (3) was used:

$$d_{max} = \sqrt{\frac{p_1}{n_1}} - \sqrt{\frac{p_2}{n_2}}\ , \qquad (3)$$

where: $\sqrt{\frac{p_1}{n_1}}$ and $\sqrt{\frac{p_2}{n_2}}$ – the values of the first and the second series of cumulative frequencies; p_1 and p_2 – the frequencies (ratios of number of trees of a certain degree of thickness to the total number of trees in the sample plot).

The boundary value of the λ test, which depends on the confidence level, was calculated using the formula (4):

$$\lambda = \sqrt{\frac{1}{2} ln \frac{2}{P}}, \qquad (4)$$

where: P – the corresponding confidence level – 0.95; 0.99; 0.999.

The boundary values of the λ test were 1.36, 1.63 and 1.95 respectively.

All calculations were done using statistical software package MinitabTM (Minitab Inc., State College, USA) and PAST: Paleontological Statistics Software Package for Education and Data Analysis (Hammer et al. 2011).

Results

The analysis of λ value indicates that the compared populations of the trunk distribution by DBH categories, depending on the average diameter of the stands in the disease centres and in the controls, belong to different general populations and are described by different curves (λ = 3.92…6.86, λ > 1.95), that is, the probability of differences exceeds 99 % level (Table 1).

At the time of the study, in the 43-year-old pine stand (sample plots 5-DC and 5-C), only single birch trees remained at the stand due to the discrepancy between the site conditions and bioecological features of this species. As a result of a prolonged disease-producing loss of trees, the number of living trees per hectare in the pine stand was 33 % less and the average height was 2 % lower in the root rot disease centre (5-DC) as compared to those outside it (5-C). The average diameter, on the contrary, was greater by 6 % because the sparse stand and a large number of openings contribute to the increase of radial increment of trees (Table 1).

In the birch part of the stand in root rot disease centre, the number of living trees per hectare was 11 % less than in the control. The average diameter of the birch trees was 6 % less and the height was 11 % lower in the disease centre than outside the centre.

Due to the mortality and slow growth, growing stock of the stand was 29 % less in the disease centre than in the control. The total relative density of stocking in annosum root rot centre was significantly less than in the healthy part of the stand, 0.54 vs. 0.71 (Table 2). The health condition of the stand in the disease centre was severely weakened (the health condition index I_c was 2.6) due to a significant amount of dead standing trees (24.5 %) and the predominance of trees of the 2nd health category (35 %). Considering that the number of dead pine trees in the part of the stand outside the disease centre was only 1 % and the number and stock were dominated by trees of the 1st health category (70 %), the condition of the stand was assessed as healthy (I_c = 1.4). The birch stand was weakened both in the affected and in the healthy part of the stand (the health condition index was 1.9 and 1.8 respectively) because this forest site was unfavourable for silver birch growth (Table 2).

In the 47-year-old pure pine stand, the stand density in the root rot disease centre in 9-DC (456 stems ha^{-1}) was 32 % lower than in the control (9-C) (Table 1) resulting from the intensive mortality. Due to the less dense stand in the centre of the disease than outside the centre, the stock here was reduced by 20 %. The average diameter of the healthy part of the stand was 7 % less than that of the infected part but the average height was almost the same. Outside the disease centre, the share of healthy trees reached 72 % and the plantation was assessed as healthy (I_c = 1.4). In the centre of the disease, the share of trees of the 1st category of health condition accounted for 52 % and the stand was weakened (I_c = 1.7).

The results of the study indicated that in the disease centre of the 50-year-old stand (sample plot 2-DC), the stand density was 44 % less and the relative density of stocking was 0.37 less in comparison with the control (2-C) as a result of a prolonged disease-induced loss of trees and thinning. The growing stock volume was 39 % higher in the control than in the centre of the root rot disease. The average diameter of the tree stand was 5 % larger in the disease centre due to the low stand density. However, the average height here was somewhat lower – by 2 % – compared with the part of the stand outside the disease centre (Table 1). The proportion of dead trees (21 %) was four times greater in the centre than outside (5 %) because of the disease impact. In annosum root rot disease centre, the health condition of the stand was severely weakened (I_c = 2.6). This was due to the presence of a significant amount of standing dead trees, as well as to the pattern of trees distribution by categories of health condition. Thus, the proportion of trees of the 2nd category reached 39 %, and the share of trees of the 1st category accounted for only 32 %. The part of the stand outside the disease centre was assessed as healthy (I_c = 1.5); the trees of the 1st and 2nd categories of health condition dominated: 68 % and 26 % respectively.

The density of the pine part of the 51-year-old stand was 55 % less in the root rot disease centre (7-DC) than in the area outside the centre (7-C). The slow growth of pine stand in the centre of the disease was indicated by the average diameter and height that were 3 % and 9 % less, respectively, than those for the control. The growing stock volume of the pine stand was 62 % less in the centre of annosum root rot disease as compared with the stock outside it due to the disease-induced loss and slowing growth of the trees (Table 1). In contrast to the pine part of the stand, the density of the birch part in the disease centre was 31 % higher as compared with the control. The initial number of birch trees per hectare inside and outside the disease centre was the same. However, due to the high density of the stand outside the disease centre, birch was mostly removed during the thinning as less productive species compared to Scots pine (Table 1). In the root rot focus, the birch was not removed since the number of living healthy pine trees here was already insignificant. This suggests that birch trees are more resistant to annosum root rot affection than Scots pine ones. Due to the low stand density and relative density of stocking in the centre of the disease, the average diameter of the birch trees was 6 % higher and the average height was 4 % less. Outside the disease centre, the stand was highly dense, and its total relative density of stocking (1.08) was double than in the disease centre (0.52) (Table 1).

In the affected part of the stand, the proportion of dead standing trees was 38 % of the total number of trees in the sample plot. Accordingly, the health status of the stand inside the disease centre was severely weakened (I_c = 3.2), and the part of the stand in the control was healthy (I_c = 1.4). The birch trees in both parts of the plantation were assessed as healthy.

The spread of annosum root rot in 56-year-old Scots pine stand (sample plots 8-DC and 8-C) was scattering. In the disease centre, the natural seed reproduction of pine, oak (*Quercus robur* L.) and birch have been found, but it was poor.

Inside the disease centre (sample plot 8-DC), the density of the stand was 34 % less and the relative density of stocking was 0.23 below the control 8-C (Table 1) due to the disease-induced loss of trees and thinning. The growing stock volume was 42 % higher in the unaffected part of the stand than inside the disease centre. The average diameter of the stand in the root rot disease centre was almost identical to that in the control. However, outside the centre, the height of the stand was 13 % greater and the yield class was better (1st) than inside the disease centre (2nd).

The pine trees inside the disease centre belonged to the category of weakened ones (I_c = 2.3), unlike the part of the stand outside the centre, the health condition of which was much better: it was assessed as healthy (I_c = 1.4). The share of trees of the 1st health condition category was 68 % in the control and only 30 % in the centre of the disease.

The results of the studies on sample plots 6-DC and 6-C indicated that in the root rot disease centre (6-DC) the density of the 61-year-old planted stand and the growing stock volume were 43 % less, the average height was 5 % lower, and the relative density of stocking was 0.4 less as compared with the part of the stand outside the disease centre (6-C). Instead, the average diameter of the stand was

3 % larger in the disease centre due to the low relative density of stocking (Table 1). Pine stand was dense in the control and needed to be thinned.

The proportion of dead pine trees of the 5th and 6th health condition categories was 23 % in the disease centre and only 8 % outside of it. The stand was assessed as weakened, but in the control its condition was better (I_c = 1.6) as compared with the centre (I_c = 2.3).

In the centre of the annosum root rot disease, the density of living part of the 75-year-old plantation (sample plot 4-DC) was 167 stems ha^{-1}, which was 66 % less than outside the disease centre (sample plot 4-C) (Table 1). Accordingly, the relative density of stocking of the stand in the disease centre was also very low (0.39), in contrast to the fully-stocked stand in the control (0.98). The average diameter of the stand in the centre of the disease exceeded that of the healthy part of the stand by 7 % but the height of the stand outside the centres was slightly higher, by 2 %. In the control, the stock of the stand was 59 % larger than that in the root rot disease centre. In the part of the stand inside the disease centre, the share of trees of the 5th and 6th health condition categories reached one third of all trees in the sample plot (32 %), and therefore the condition of the stand was estimated as severely weakened (I_c = 2.9). In the control, the number of dead standing trees did not exceed 1 % and the condition of this part of the stand was healthy (I_c = 1.3).

The data of Table 1 show that the density of 51-year-old mixed birch stand of natural seed origin was 800 stems ha^{-1}, of which 724 stems (90 %) were silver birch trees and 76 stems (10 %) were Scots pine trees. The average diameter and average height of birch and pine trees were almost the same. The yield class of the mixed stand was I^a, the growing stock amounted to 360.2 m^3·ha^{-1} and the relative density of stocking was 0.82.

The mixed stand was estimated to be healthy. The average index of the health condition of birch and pine trees was 1.5, that is, at the border of the weakened one. The 1st category of the health condition included 62 % of birch trees and 59 % of pine trees; 34 % of birch trees and 32 % of pine trees were assigned to the 2nd one, and 1 % and 9 %, respectively, to the 3rd health category. The proportion of dead birch trees was insignificant (3 %).

The planted 62-year-old birch stand had the following mensurational characteristics: the density 437 stems·ha^{-1}, the average diameter 26.5 cm, the average height 23.2 m, the relative density of stocking 0.78, and growing stock volume 258.5 m^3·ha^{-1}. There were 68 % of healthy trees, 27 % of weakened ones, 2 % of very weakened and dying ones and 3 % of dead standing trees in its composition. The average diameter and height of the dead standing trees were considerably below those of the living trees: by 40 % and 19 % respectively. The stand was healthy (I_c = 1.5).

According to our study, the average height of pine stands on the sample plots inside the disease centres was typically 0–13 % less than outside the centres. The average diameter in the disease centres was 0–7 % over that in the control (Fig. 4) since larger feeding area and living space resulting from the stand thinning contribute an increasing diameter increment. This difference is insignificant and depends on a combination of some factors, such as the intensity of the mortality, the intensity and timing of thinning or sanitary felling, the stage and duration of development of the disease centre, etc.

In the disease centres, the pine stand

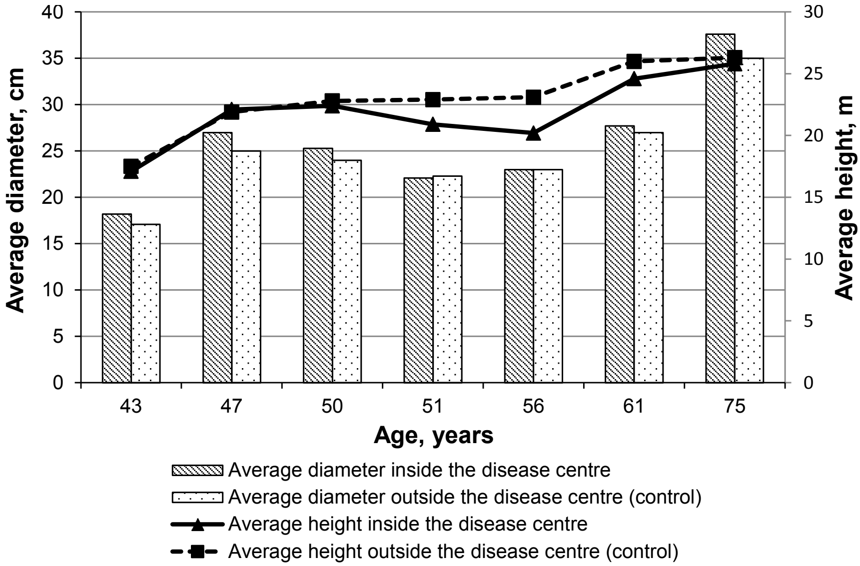

Fig. 4. The average diameter and the average height of pine stands of different age inside and outside root rot disease centres.

density and growing stock volume were significantly less, by 32–66 % and 20–62 % respectively, due to disease-induced loss (Fig. 5). The growing stock volume in the control areas gradually increased with aging (Fig. 5). The only exception was 56-year-old pine stand (sample plot 8-C), which grew in poorer forest site conditions (fresh infertile pine site type). The growing stock volume of the pine part of the stand inside the disease centre depended on the progression of the disease.

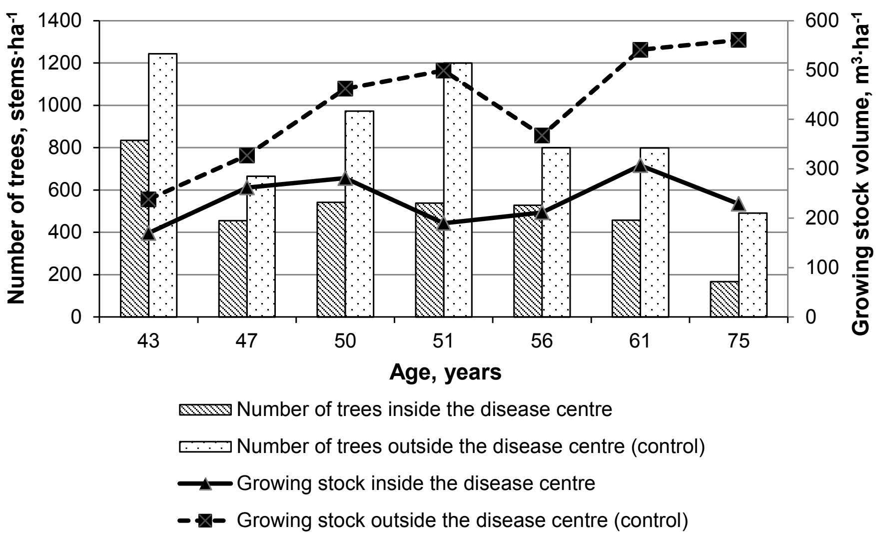

Fig. 5. The number of trees and growing stock volume of pine stands of different age inside and outside root rot disease centres.

In root rot disease centres, mortality was attributable to thicker (by 14–42 %) trees as compared to the control. In disease centres, the average diameter of living trees was 0–23 % larger than that of the dead ones. In the control areas (outside the centres), this difference increased up to 19–42 % (Fig. 6). Health condition index ranged from 1.7 (weakened trees) to 3.2 (severely weakened trees) for the part of the stands inside the disease centre and from 1.3 (healthy trees) to 1.6 (weakened trees) in control areas (Fig. 7). Birch stands established on formerly arable lands were healthy (I_c = 1.5).

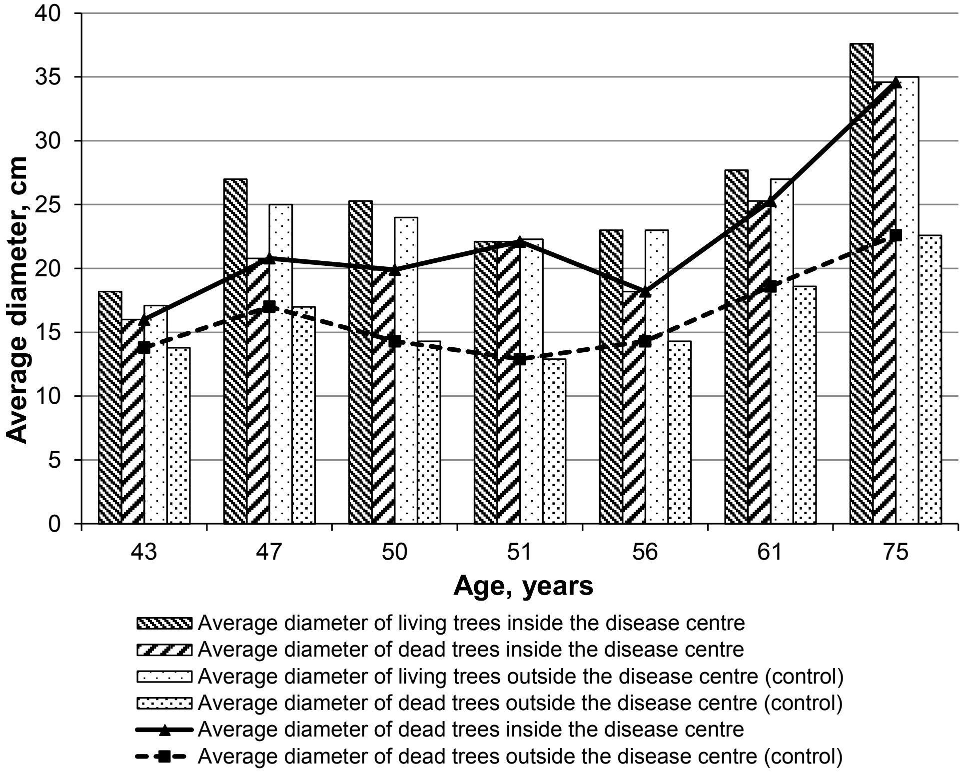

Fig. 6. The average diameter of dead and living trees inside and outside root rot disease centres for pine stands of different age.

Discussion

Our studies on stands' characteristics and health condition of Scots pine stands on formerly arable lands confirm the primary emergence of centres of annosum root rot disease in pure pine stands (or having a small percentage of silver birch trees) with high relative density of stocking (0.8–1.0). This is also consistent with the findings of other researchers who stated that dense pure pine stands without timely thinning create an environment conducive to spreading annosum root rot due to the increase in number of root contacts of closely-spaced trees (Ladeyshchikova et al. 1974, Vasiliauskas 1989, Volchenkova et al. 2012, Raspopina et al. 2013).

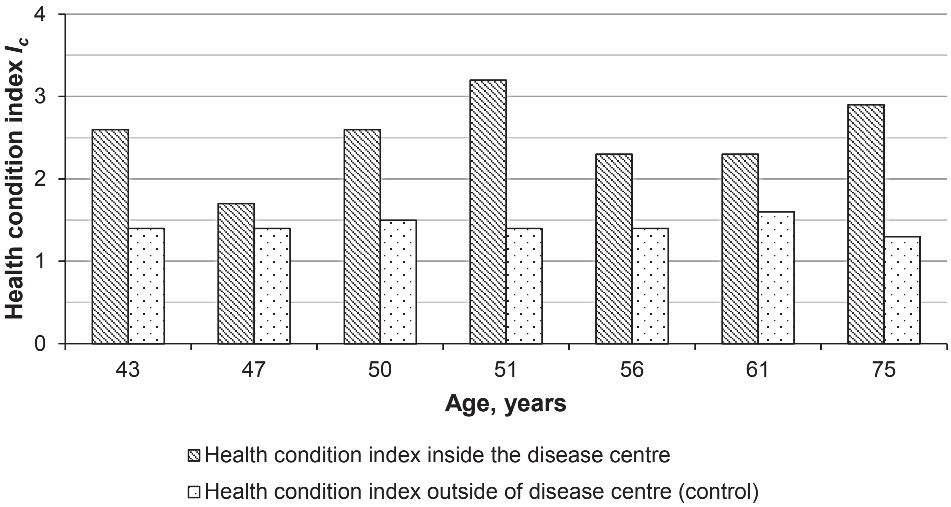

Fig. 7. The health condition index for pine stands of different age inside and outside root rot disease centres.

The given data (sample plots 3, 7-DC, 10) show that birch stands grown in fresh fairly infertile pine forest conditions were healthy (I_c = 1.5). The birch stand was weakened only in the sample plots 5-DC and 5-C (fresh infertile pine site type) because these forest-growing conditions are unfavourable for birch growth. Many workers (Ladeyshchikova et al. 1974, Lygis et al. 2004b, Negrutskiy 1986, Peri et al. 1990, Raspopina et al. 2013, Vasiliauskas 1989) also consider birch stands to be more resistant against annosum root rot. Establishing pure birch stands in the cut areas after stands affected by annosum root rot is especially advisable to prevent the disease. According to Alekseev (1974) and Bilous (2009), the share of birch in the composition of stands planted on former agricultural lands in fresh fairly infertile pine sites should be not less than 35 %, which will accelerate the decaying forest litter and enrich the soil with nitrogen and ash mineral substances. The growing mixed pine-birch stands will enhance soil-protective, water-conservation, sanitary, recreational and other beneficial properties of forests and improve the biodiversity of the lands disturbed by long-term agricultural use (Ladeyshchikova et al. 2001). In addition, it will contribute to the formation of the natural composition of the soil microbiota and will provide the opportunity to create more valuable pine forest stands in the future.

In conditions of Chernihiv Polissya, Ukraine, in planted mixed pine-birch stands with a 10–20 % of birch, the productivity of the stands was 10–35 % higher than that of pure pine plantations. The birch added intensified forest litter decomposition and promoted the accumulation of nutrients in the soil (Bilous 2009).

Similar results were obtained by Raspopina et al. (2013) in the research in the Ukrainian region of Eastern Polissya. According to their data, 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 centres in comparison with the areas outside the centres due to the disease- and pest-induced mortality. The average height of planted Scots pine stands inside the disease centres was slightly lower, and the average diameter was larger than those outside them. In the disease centre, the health condition of the stand was assessed as severely weakened (I_c = 2.6…3.4). Outside the root rot disease centre, the stand was weakened (I_c = 1.7…2.4).

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

At the age of 51, the growing stock volume of the pine stand affected by annosum root rot (233.1 $m^3 \cdot ha^{-1}$) (sample plot 7-DC) was 10 % lower than the stock of the birch stand (260.2 $m^3 \cdot ha^{-1}$) (sample plot 10). This was due to the slower growth of the pine stand resulting from its health deterioration to severely weakened (I_c = 3.2), in contrast to a healthy birch stand (I_c = 1.5). However, the growing stock volume of 61-year-old pine stand in the disease centre (sample plot 6-DC) was 16 % higher than that of the birch one of the same age (sample plot 3). This suggests that the health deterioration of the pine stand to weakened one (I_c = 2.3) did not significantly affect the growing stock. Therefore this pine stand is more productive than pure healthy birch stand at the sample plot 3 (I_c = 1.5).

According to the study of Raspopina et al. (2013), the growing stock volume of pine stands affected by annosum root rot exceeded the growing stock of birch stands by 20 %. Instead, the planted birch stands had better health condition (I_c = 1.6…2.1) as compared with the planted pine stands affected by root rot (I_c = 2.6…2.9). However, their health status was deteriorated considering that they were established in cut areas after planted pine stands affected by this fungus. In our case, the birch stands were created on former agricultural lands. In the above study (Raspopina et al. 2013), a set of factors was found to determine the root rot infection of pine stands, the main of which were growing overstocked pure plantations on abandoned agricultural lands and untimely thinning of the stands.

Conclusions

In the studied pine stands established on former agricultural lands, root rot disease centres emerged mainly in pure stands with high density of stocking (0.8–1.0). In the disease centres, the density of planted pine stands was significantly less, by 32–66 %, due to the disease-induced tree mortality, and the growing stock volume was 16−64 % lower than that outside the disease centres. The health condition index varied from 1.7 (weakened stand) to 3.2 (severely weakened stand) inside the centres of root rot disease and from 1.3 (healthy stand) to 1.8 (weakened stand) in the areas outside them. In root rot disease centres, the average height of pine stands was 0–13 % lower and the average diameter was 0–7 % over those values outside the centres. Mortality inside the disease centres was attributable to thicker, by 14–42 %, trees as compared to the part of the stand outside them.

Birch stands established on formerly arable lands were more resistant to annosum root rot and had better health status (I_c = 1.5) as compared to pine stands infected by root rot (I_c = 1.7…3.2). Increased resistance of stands against root rot can be achieved through addition and keeping of broadleaved species (35 %), particularly silver birch, into the stand composition and timely thinning of young stands. Mixed stands will contribute to soil-protective, water-conservation, sanitary, recreation and other beneficial properties of forests and improve the biodiversity of the land disturbed by long-term agricultural use.

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