Cent. Eur. For. J. 66 (2020) 3–11 sciendo DOI: 10.2478/forj-2019-0022

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Assessment of load and quality of logging residues from clear-felling areas in Järvselja: a case study from Southeast Estonia

Vahur Kurvits, Katri Ots*, Ahto Kangur, Henn Korjus, Peeter Muiste

Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Kreutzwaldi 5, 51014 Tartu, Estonia

Abstract

The properties of biomass-based fuel and combustion tests showed that logging residues are promising renewable energy sources. The data used in this study were collected from four clear-felling areas in Järvselja Training and Experimental Forest Centre, Southeast Estonia in 2013–2014. Logging was carried out by harvesters in Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* [L.] Karst.), silver birch (*Betula pendula* Roth.) and black alder (*Alnus glutinosa* L. Gaertn.) dominated stands with a small admixture of other tree species according to the cut-to-length method and logging residues were placed in heaps. The aim of this research is to assess different characteristics of logging residues (quantity, moisture content, energetic potential, ash content and amount) in clear-felling areas. The highest load of slash was measured on the birch dominated study site, where the dry weight of the logging residues was 29 t ha^{-1}. Only the branch fraction moisture content on the black alder dominated site (35.4%) was clearly different from respective values on other sites (21.6–25.4%). The highest calorific value of the residues was assessed with the residues from the birch dominated site, where in moist sample it was 365 GJ ha^{-1} and in dry matter 585 GJ ha^{-1}. The heating value of the fresh residues is highest in coniferous trees. The highest ash content in branch segments was registered for the black alder dominated site. Järvselja data indicate higher quality in conifer dominated sites, yet a higher load of logging residues in broadleaf dominated stands.

Key words: bioenergy; biomass of forest residues; energetic potential; moisture content; ash content

Editor: Bohdan Konôpka

1. Introduction

Public demand for ecosystem services is limiting a more extensive use of forests although wood consumption is increasing globally. Intensive forest management and deployment of underutilized resources (e.g. stumps and logging residues) on clear-felling sites are expected to ease the contradicting needs. The utilization of logging residues can improve also the economics of forest management as there are now available, efficient technologies for collecting residues from logging areas. At the same time, a market is slowly developing for logging residues, since geographically scattered local power plants have a higher demand for solid biofuels, including wood chips from logging residues. Substitution of fossil fuels by forest biomass as a CO_2-neutral energy source is a common policy target in many countries, including Northern Europe (Olsson et al. 1996; Stupak et al. 2007; Routa et al. 2012; Rytter et al. 2016).

Around two thirds of current renewable energy is produced mainly from solid biomass (90.8 Mtoe; mega tonne of oil equivalent is a unit of energy defined as the amount of energy released by burning one tonne of crude oil) followed by liquid (14.4 Mtoe) and gaseous (13.5 Mtoe) biomass sources (Sustainable and optimal... 2017). Switching to renewable energy sources has been quite successful in Estonia, e.g. the share of electricity generated from solid renewable sources in total electricity consumption has been increasing from 6% in 2009 to 18% in 2017 (Statistical Yearbook of... 2017). The share of energy produced from wood constituted 50% of electricity and 75% of heat energy production from renewable sources in 2016 (Statistical Yearbook of... 2017). However, logging residues from forest management operations should be considered and used more widely for energy production in Estonia (Muiste et al. 2004; Muiste & Kakko 2004; Uri et al. 2015). Analyses in the past and the potential for the future indicate that the availability of suitable wood for energy production in Estonia is several times higher than current consumption (Hepner et al. 2010).

There are different technologies available for efficient harvesting of forest biomass. The whole-tree harvesting technology can have short and long-term negative impacts on forest ecosystems (Mälkönen 1976; Egnell

---

**Corresponding author. Katri Ots, e-mail: katri.ots@emu.ee, phone: +372 53 435 107*

& Leijon 1997; Jacobson et al. 2000; Helmisaari et al. 2011; Wall 2012; Persson 2017). Intensive harvesting of forest biomass (utilization of whole-tree biomass, logging residues, stumps and roots, etc.) increases the mineralization of organic material and the removal of nutrients from the ecosystem compared to the traditional stem-wood harvesting (Møller 2000; Olsson et al. 2000; Palviainen 2005; Raulund-Rasmussen et al. 2008; Saarsalmi et al. 2010). If nutrient-rich parts of trees (needles, branches) are also harvested from the forest ecosystem, nutrient loss is considerably amplified. There is also a significant risk of changes in soil chemical properties (acidification, leaching out of nutrients, etc.) upon intensive harvesting of forest biomass in conifer stands (Staaf & Olsson 1991; Saarsalmi et al. 2010; de Jong et al. 2017). The exchangeable aluminium content increased and the calcium/aluminium ratio was significantly lower on the whole-tree harvesting sites than in the conventional harvesting area (Saarsalmi et al. 2010). The removal of macro- and microelements during intensive biomass harvesting should be compensated for on acid soils; the return of wood ash might prevent deficiency (Raulund-Rasmussen et al. 2008).

The aim of the current study is to assess different characteristics of logging residues (quantity, moisture content, energetic potential, ash content and amount) on clear-felling areas in Järvselja (Southeast Estonia).

2. Material and methods

The data used in this study was collected from four clear-felling areas in Järvselja Training and Experimental Forest Centre, Southeast Estonia (Table 1). Before clear-felling, the study sites were Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* [L.] Karst.), silver birch (*Betula pendula* Roth.) and black alder (*Alnus glutinosa* L. Gaertn.) dominated stands with a small admixture of other tree species (Table 2). Admixture species included Norway spruce, silver birch and small-leaved linden (*Tilia cordata* Mill.) on the sites. Logging was carried out on all study sites in 2013–2014 by harvesters according to the cut-to-length method and logging residues were placed in heaps. In the clear-felling areas all the trees were harvested, except the retention trees (up to 5% of stand volume). The heaps included treetops, branches and unconditional logs, and they covered 15–35% of the logging area on different sites. The maximum height of heaps was 0.6 m.

All study sites were measured and samples collected in the late autumn of 2014 as logging residues were left to dry during the summer at the sites. This method provides logging residues with low amounts of needles and leaves, as requested by the energy-converting industry (Nilsson et al. 2013). At each study site, all heaps were mapped and logging residue plots (LRP) were distributed evenly on the heaps. Five LRPs were established at sites A, C and D (on each site), and three LRPs at site B. The length of an LRP was 10 m and the width was the actual width of the heap. After the establishment of an LRP, the branches without foliage and billets were torn apart, separately piled and weighed. The samples of branches and billets were taken from each LRP for laboratory tests in November 2014 (birch, pine, spruce) and in April 2015 (alnus).

Laboratory tests were carried out at the laboratories of the Estonian University of Life Sciences where the moisture content, calorific value and ash content of the samples were determined according to standards (CEN/TS 14774 2004; CEN/TS 14775 2004; CEN/TS 14918 2005).

Table 1. Basic information on the study sites. Site types are according to Lõhmus (2004).

Study site	Area ha	Site type	Coordinates	Elevation [m a.s.l.]	Logging time
A	1.92	Myrtillus	58°15’38” N, 27°19’32” E	41	Feb 2014
B	0.30	Oxalis-Myrtillus	58°17’12” N, 27°17’52” E	34	Apr 2013
C	0.67	Aegopodium	58°18’12” N, 27°18’08” E	32	Dec 2013
D	3.42	Eutrophic fen	58°17’31” N, 27°21’04” E	33	Oct 2014

Table 2. Tree stand characteristics before clear-felling.

Study site	Tree species	A [years]	N [trees ha^{-1}]	H [m]	$D_{1.3}$ [cm]	G [m^2 ha^{-1}]	V [m^3 ha^{-1}]
A	Scots pine	120	531	25	25	26.0	296
	Norway spruce	120	4	26	26	0.2	3
	Norway spruce	40	303	7	5	0.7	3
	Silver birch	30	50	6	6	0.1	1
	All species		888			27.0	303
B	Norway spruce	75	252	27	33	21.6	277
	Scots pine	75	35	28	30	2.5	31
	All species		287			24.1	308
C	Silver birch	60	618	27	24	28.0	343
	Norway spruce	40	260	10	12	2.9	18
	Small-leaved linden	40	27	13	12	0.3	2
	All species		905			31.2	363
D	Black alder	70	461	23	23	19.2	197
	Silver birch	70	163	23	22	6.2	66
	Norway spruce	40	89	9	10	0.7	4
	All species		713			26.1	267

A – age, N – stem number, $D_{1.3}$ – diameter at breast height, H – height, G – basal area, V – stem volume.

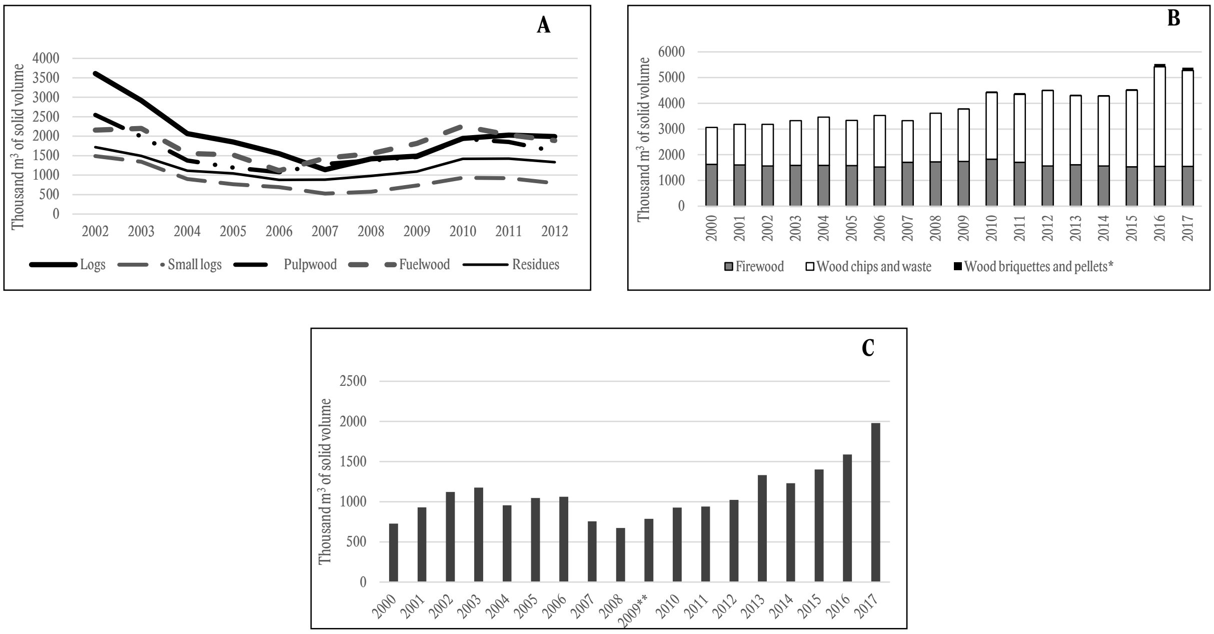


Fig. 1. Fellings by assortments (A), gross inland consumption (B) and export (C) of wood fuels in 2000–2017 in Estonia (Yearbook Forest 2013, 2014; Statistical Yearbook of... 2017).* 1,000 tons; ** accounting of assortments has changed since 2009.

Over the last five years, wood pellets have become an important fuel on the Estonian energy market (Fig. 1). In 2010–2015 the consuption of pellets has increased more than seven times. The increasing of regeneration fellings proportion during last years is promising for using residues (Fig. 1).

Statistical analysis was implemented using Statistica 10.0 software. Analysis of variance (ANOVA, Tukey's test and Tukey's Unequal N test) was used to test the equality of the means on the study sites.

3. Results

3.1. Quantity, moisture content, energetic potential and ash content of logging residues

The highest load of slash was measured at the birch dominated study site (C) in Järvselja Training and Experimental Forest Centre, where the dry weight of the logging residues was 29 t ha^{-1} (Table 3). Based on the load, the next site was Scots pine dominated site (A) where 25 t ha^{-1} (Table 3) of logging residues were measured. The spruce dominated site (B) and black alder dominated site (D) yielded with an almost comparable load, 12 t ha^{-1} and 16 t ha^{-1} of logging residues, respectively (Table 3). The weight consisted of an approximately double amount of residues from billets in comparison to branches in the case of pine and alder study sites; for birch an opposite result was observed (Fig. 2). The dry weight of birch branches differed statistically significantly ($p < 0.05$) in comparison to branches from the alder dominated site (Fig. 2).

Analyses indicate that the moisture content of residues on different sites with different dominating tree species is different (Table 3). The moisture content of alder site branches was statistically significantly higher ($p < 0.05$) in comparison to the moisture content of spruce and birch branches (Fig. 2). In general, no statistically significant difference was measured in the moisture content between the sites or between different fractions on the same site (Fig. 2). Only the branch fraction moisture content on the black alder dominated site (35.4%) was clearly different from respective values on other sites (21.6–25.4%), being 1.6 times higher (Fig. 2).

The calorific value of the residues was expressed as the calorific value of dry matter per kilogram and hectare and calorific value of moist samples (Table 3; Fig. 3). The highest value was assessed with the residues from the birch dominated site where in moist sample it was 365 GJ ha^{-1} and in dry matter 585 GJ ha^{-1} (Table 3). A relatively close result was obtained from the pine dominated site where the moist sample resulted in 332 GJ ha^{-1} and dry sample 497 GJ ha^{-1} (Table 3). The result from the spruce dominated site must be considered separately, since it included only branches and resulted with lowest calorific value, where in moist samples it was 164 GJ ha^{-1} and in dry sample 242 GJ ha^{-1} (Table 3). The heating value of coniferous species varied from 13.3 MJ kg^{-1} to 14.7 MJ kg^{-1} of fresh mass and heating value of broadleaf species varied from 11.0 MJ kg^{-1} to 13.8 MJ kg^{-1} of fresh mass (Fig. 3).

From the samples the ash content was obtained separately for branch and stem segments. The highest ash content in branch segments was registered for the black alder dominated site, where average ash content was 1.9%. This was followed by birch and spruce dominated

Table 3. Different characteristics of residues (mean ± standard deviation). Different letters indicate a statistically significant difference between parameters within tree species in the Tukey test $p < 0.05$.

Characteristic	Scots pine	Norway spruce*	Silver birch	Black alder
Fresh weight [tonnes]	31.8±19.8^{a}	4.7±2.2^{bc}	13.7±7.6^{a}	42.5±16.5^{a}
Dry weight [tonnes]	23.5±13.1^{a}	3.5±1.5^{bc}	9.6±5.6^{b}	27.0±10.0^{a}
Dry weight [t ha^{-1}]	24.5±10.3^{a}	11.7±5.0^{a}	28.6±9.1^{a}	15.8±4.2^{a}
Moisture content [%]	23.9±6.5^{a}	23.3±4.0^{a}	30.3±1.8^{a}	36.0±5.0^{bc}
Heating value [MJ kg^{-1}]				
Fresh residues	14.0±1.5^{a}	14.1±0.8^{a}	12.5±1.4^{a}	11.3±1.3^{a}
Dry residues	20.4±0.4^{a}	20.6±0.2^{a}	20.4±0.4^{a}	20.4±0.4^{a}
Energetic potential [GJ ha^{-1}]				
Fresh residues	332±142^{a}	164±63^{a}	365±113^{a}	179±56^{a}
Dry residues	497±208^{a}	242±106^{a}	585±185^{a}	321±86^{a}
Ash content [%]	0.48±0.25^{a}	1.43±0.37^{c}	1.0±0.50^{c}	1.35±0.69^{c}
Ash amount [t ha^{-1}]	0.10±0.04^{a}	0.17±0.07^{a}	0.32±0.12^{b}	0.19±0.06^{a}

*The data on Norway spruce contain only the characteristics of branches.

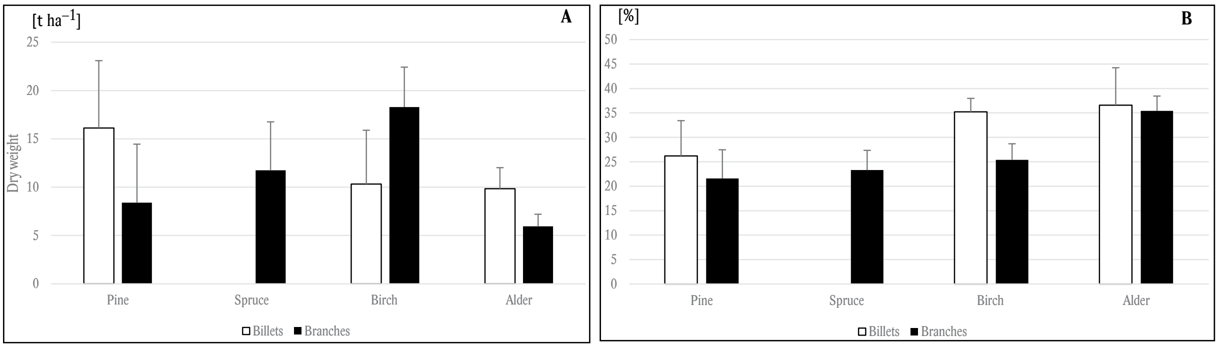


Fig. 2. The dry weight (t ha^{-1}) (A) and moisture content of residues (%) (B) (mean ± standard deviation).

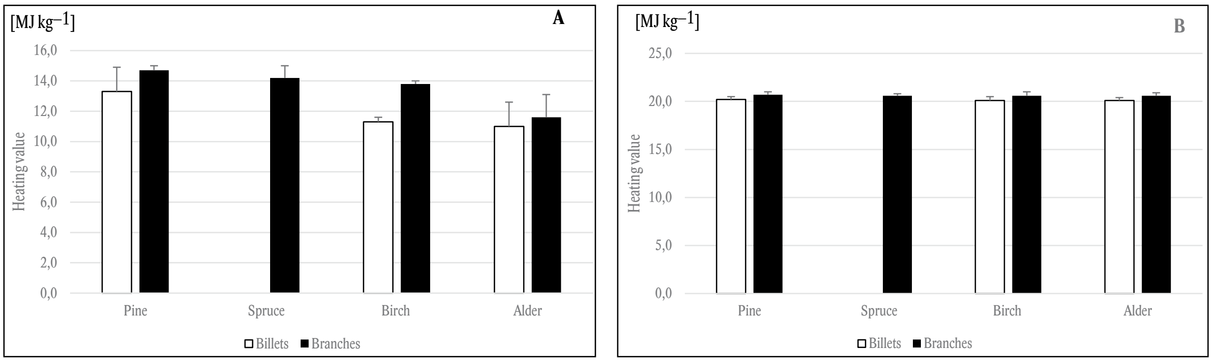


Fig. 3. The heating value of fresh (A) and dry residues (B) (MJ kg^{-1}) (mean ± standard deviation).

sites with 1.4%, where the branch ash content was statistically significantly ($p < 0.05$) higher than in the pine dominated site (0.7%) (Fig. 4). For the stem segments the highest ash content was also registered from the samples of the black alder dominated site (0.8%) and it was followed by birch (0.6%) and the pine dominated site 0.3% (Fig. 4). There were no stem residues left on the spruce dominated site. It appeared that not related to the species specific site difference the ash content in branch segments was statistically significantly ($p < 0.001$) higher (on average 2.5 times) than in stem segments (Fig. 4). In conclusion, the amount of ash in available logging residues was 0.1 tons per hectare on the pine dominated site, 0.2 tons per ha on spruce and black alder dominated sites and 0.3 tons per ha on the birch dominated site (Fig. 4).

4. Discussion

Living and dead branches, foliage, unmerchantable stemwood with bark, extracted stumps, small-diameter trees from early thinnings, also understory and broken pieces on the ground after harvesting merchantable wood are considered as primary forestry residues and have become a major source of bioenergy (Röser et al. 2008). The annual amount of felling residues reaches a total of 71 million m^3 in the Nordic and Baltic countries, with a potential of 44 million m^3 of residues (containing 6 million m^3 of stump wood) for energy production (Röser et al. 2008). Large differences exist in the amounts of residues of different species per hectare, depending mainly on the species- or mixture-specific shade tolerance, thickness of branches and bark, endurance of foli-

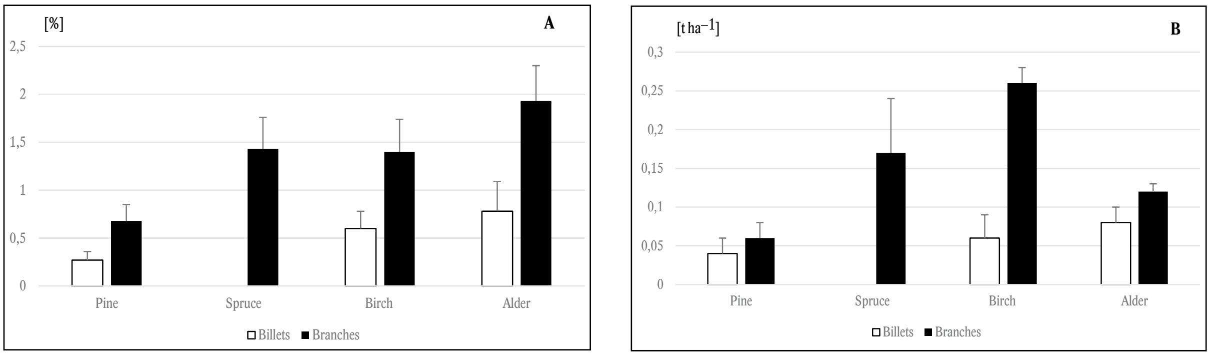


Fig. 4. The ash content of residues (%) (A) and the amount of ash (t ha^{-1}) (B) in the clear-cutting area (mean ± standard deviation).

age, durability of dead branches, the form and shape of the stem and the basic density of the different biomass components of a tree. Thinning of young pine stands was a long-time priority in Finland, because the territory of pine dominated forests was 80% of the total area of young forests (Vesisenaho & Nousainen 1997). During the last 20 years, the situation has changed in Finland – the total logging residue potential has risen from 8 million m^3 to 9.2 million m^3 – Norway spruce formed 5.6 million m^3 of the total potential, Scots pine 2.4 million m^3 and broadleaf species (mainly birches) 1.2 million m^3 (Räisänen & Athanassiadis 2013). Annual yield surveys of Estonian forests in 2002–2012 indicated that an average of 1.2 million m^3 of slash are generated every year, which amount to an average of 16.3% of logging residues of the total annual yield (Yearbook Forest 2014 2015). Average annual residues by tree species in 2008–2012 collected from different site types of Estonian forests are 33% spruce, 22% birch, 19% pine, 10% aspen, 7% grey alder, 6% black alder, and 3% other species.

In Estonia, 46% of heat energy is produced from biomass; it is possible to produce up to 2/3 of heat energy from local biomass (Statistical Yearbook of... 2017). The properties of biomass-based fuel and combustion tests showed that logging residues prove a promising renewable energy source, and their addition as surplus fuel to oil shale, the main local fuel in Estonia, could make the production of electricity from fossil oil shale more environmentally friendly and reduce the CO_2 emission from power plants (Kask et al. 2011). The use of low-quality wood for electricity production has reduced impacts on the environment: in 2011, the use of renewable biofuels decreased CO_2 emissions by 350,000–380,000 tonnes, and the amount of oil shale ash decreased by 180,000 tonnes (Eesti Energia 2012).

Potential quantities and the energetic value of the logging residues from fellings are high in Estonia, but logging residues from final fellings and first thinnings are still underutilized (Rosenvald 2001; Muiste et al. 2004). In 2000–2015, firewood fellings in Estonia amounted from 3 to 4.5 million solid cubic metres, of which the wood chips and waste proportion has changed from 47% to 66% (Yearbook Forest 2017 2018). Tree stumps removal is a novel potential source for renewable energy in Estonia (Uri et al. 2015). In 2013, only 33% of the total volume of potential residues was taken into use (Annual Report 2014). The sale of wood chips and residues collected from Estonian state forests has decreased from 330,000 m^3 in 2011 to 183,000 m^3 in 2016, forming 5–11% of the total volume of sold timber (Annual Report 2014, 2016; Yearbook Forest 2017, 2018). At the end of 2017, the demand for biomass for renewable energy production increased significantly (Yearbook Forest 2017, 2018). Wood pellets have become an important fuel type on the energy market in Estonia: in 2010–2015 the consumption of pellets increased more than seven times.

The volume of harvesting residues is very variable, depending mainly on the site type quality and species composition (Padari et al. 2010; Rytter et al. 2016). The technical biomass potential of forestry residues in Germany is between 37.9 and 61.8 million Mg (DM); energetic use ranges from 17.7 to 25.2 million Mg (DM) (Brosowski et al. 2016). Sweden demonstrated that increasing the use of harvesting residues by 2.5 times can be sustainable: the energy potential ranged from 40 PJ yr^{-1} (least intensive biomass harvest) to 155 PJ yr^{-1} (most intensive biomass harvest) (de Jong et al. 2017). Depending on the forest site type the oven dry weight of harvesting residues per m^3 of the stem varies from 22 m^3 ha^{-1} (raised bog site type) to 144 m^3 ha^{-1} (alder fen site type), the volume of stumps may be up to 130 m^3 ha^{-1}, and the share of harvesting residues of the volume of the stand varies from 4.4 to 28.8% (Padari et al. 2010; Uri et al. 2015).

Nurmi (1993) states that the quality and moisture content of fuelwood are much more important factors than the species from the users' point of view. Seasoned logging residues had the lowest dry matter loss, while the logging residues harvested and piled in autumn had the highest loss (Filbakk et al. 2011). The results of our study show that the dry weight of residues (billets and branches) was lower in the coniferous (pine and spruce) residues collected during spring than in the broadleaf species dominated stands (birch and alnus) where residues were collected in late autumn. Spruce dominated stands are considered the best sites for logging residue removal due to high yield – for instance Scots pine dominated stands produce ca half of the harvestable crown biomass of spruce dominated stands (Räisänen & Athanassiadis 2013; Yearbook Forest 2014, 2015). In our study the low quantity of spruce residues is due to the collecting of branches only.

The key question is how different handling and storage methods affect fuel properties (moisture content, dry matter losses, etc.) (Filbakk et al. 2011). The moisture content of logging residues is the most important quality factor affecting significantly the calorific value of woody biomass and transport costs (Pettersson & Nordfjell 2007). Weather and forest conditions have a greater impact on the moisture content of residues than the handling method (Nilsson et al. 2013), depending also on varying shapes of piles, differences in the material type and storage conditions, etc. (Pettersson & Nordfjell 2007; Kizha & Han 2017). Pettersson and Nordfjell (2007) reported that the moisture content fell to 18.2–20.7% for the covered and 18.8–24.9% for the uncovered material. The moisture content of tree tops and branches from broadleaf and coniferous forests may vary on a large scale from 25% to 60% (Garcia et al. 2015). Summertime, when the vapour pressure deficit of the ambient air is low, is usually the best season for open air drying of woody residues (Pettersson & Nordfjell 2007). Our study results show that the moisture content of coniferous (pine and spruce) residues collected during spring is lower (22–26%) than the moisture content of broadleaf species (birch and alnus) residues (25–37%) collected in late autumn. Thus, coniferous residues air-dried and achieved a moisture content equivalent to the moisture content of fire wood dried in the open air (approximately 20–25%) (Vares et al. 2005). The moisture content of pine and spruce branches is quite equal (22–23%) in our study area, but Hakkila (1989) observed a higher moisture content in fresh Scots pine branches (55%) than in Norway spruce branches (45%). The moisture content affected significantly dry matter loss (1–3% per month), with the highest dry matter loss being found in the samples with the least favourable drying conditions and in spruce bundles rather than in pine bundles (Filbakk et al. 2011).

Differences in the calorific value of logging residues depend on the chemical composition of different tree species and tree components (stem, branches, foliage, etc.) (Pettersson & Nordfjell 2007). Differences in the chemical composition are mainly due to the differences in cellulose and hemicelluloses in lignin, resin, terpenes and waxes that result in higher calorific values (Nurmi 1993). The net calorific value in the crown mass of young Norway spruce and Scots pine varies from 19.2 MJ kg^{-1} of dry mass for the foliage to 19.7 MJ kg^{-1} for the stem wood, respectively (Nurmi 1993). Corresponding values for Scots pine and Silver birch are 21.0 and 20.0 MJ kg^{-1} and 19.8 and 18.7 MJ kg^{-1}, respectively. The results of our study shows that the calorific value varied from 20.1 MJ kg^{-1} (billets) to 20.7 MJ kg^{-1} (branches) of dry mass. The heating value of the stem, branches and roots is highest in coniferous trees. The results of our study shows that the calorific value of coniferous species varied from 13.3 MJ kg^{-1} to 14.7 MJ kg^{-1} of fresh mass and calorific value of broadleaf species varied from 11.0 MJ kg^{-1} to 13.8 MJ kg^{-1} of fresh mass. The potential of residues from spruce dominated stands can reach 100 m^3 ha^{-1} equal to 1008 GJ ha^{-1}, and during forest harvesting the possible share of obtained residues suitable for use is 50–75% (Muiste et al. 2004). The potential energy content of harvested spruce stumps amounted to 290 MW h ha^{-1} (Uri et al. 2015). The average energy content of residues from final felling is 522 GJ ha^{-1} (maximum 831 GJ ha^{-1} in a birch and alder mixed stand) and from thinning 151 GJ ha^{-1} (maximum 259 GJ ha^{-1} in a pine stand) (Muiste et al. 2004). Results from our study area indicate that the energetic potential of fresh residues varies on a large scale: from 70 to 250 GJ ha^{-1} (fresh residues) and from 123 to 377 GJ ha^{-1} (dry residues).

Together with the rising interest towards the resource potential of harvest residues, there is a rising need to enhance the stand residues predictive capabilities of our forest biomass models (Eastaugh et al. 2013). Which general or site-specific equations are more accurate for estimating branch biomass, allometric studies could be give answer (Fortier et al. 2017). The young Norway spruce trees growing on soils with higher C/N ratio are more likely to have higher branches biomass (Dutcă et al. 2014). The strong environmental effect on the allometric relationship between diameter at breast height and compartment biomass have been observed (Forrester et al. 2017). Smaller diameeter at breast height trees had lower humidity content and lower proportion of branches (Fortier et al. 2017). Our results shows that from smaller average diameter at breast height stands with higher number of trees per hectare were collected higher amount of branches.

Investigations observed that the harvesting of residues will have positive and negative effects on the environment (soil and water quality, climate regulation, biodiversity, etc.) and ecosystem services (Jonsell 2008; de Jong et al. 2017; Ranius et al. 2018). Harvesting of Norway spruce stumps did not increase soil respiration intensity (Uri et al. 2015). CO_2 emissions decreased with an increasing rotation length: the highest annual biomass production was obtained with a rotation length of 40–60 years (Scots pine) and 80–100 years (Norway spruce) (Routa et al. 2012). Whole-tree clear cutting affected markedly the total amounts of carbon and nitrogen on the more fertile sites (Saarsalmi et al. 2010). Depending on harvesting intensity, the levels of macro- (N, P, K, Ca, Mg, S) and micronutrients (Mn, Zn, Cu) in forest soil and plants change, which either decreases or increases site productivity and biodiversity (Grønflaten et al. 2008; Jonsell 2008; Pyttel et al. 2015). Slash extraction has a stronger effect because the base cation contents, charge-balancing organic acid anions, are much higher in needles and branches compared with those in the stumps (de Jong et al. 2017). One way to compensate for nutrient loss is to return the ash from woody biomass burning to forest lands (Saarsalmi et al. 2005; Ingerslev et al. 2014; de Jong et al. 2017). Ash content of logging residues was in the range of 1.6–2.2% (mainly Norway spruce) and 1.0–1.2% for young trees (mainly downy birch) (Pettersson & Nordfjell 2007). Our research results show that the ash content of branches (0.7–1.9%) was more than 2 times higher than the ash content of billets (0.3–0.8%); the ash content of birch and alnus billets ranged from 0.6 to 0.8%. According to the residual biomass collected from our study areas the total amount of ash formed was 5.5 tonnes: 1, 0.1, 1.1 and 3.3 tonnes from pine, spruce, birch and alder sites, respectively. Based on the quantities of ash used in Scandinavia (2–3 tonnes per hectare in mineral soils or 4–5 tonnes per hectare in organic soils), ca 1–2 hectares of forests could be fertilized with ash from our study areas.

In the changed European security environment, concrete investments are required in the production of distributed renewable energy, because renewable energy solutions have proven their effectiveness while being the only sector of the energy industry with rapid innovations (Renewable Energy Yearbook 2016). Estonia has considerable renewable energy resources in the form of logging residues. This research only explored the use of logging residues as these are the main fuel for all heating power stations and combined heat and power plants heated with wood. In the middle of the 1990s, the transition of heating power stations to wood heating was started in Estonia with the support of the World Bank and other financial resources. Combined heat and power plants heated with wood have been built since 2009. All these additional facilities have increased the consumption of wood fuels. For the planned production of energy ca 4.6 million cubic metres of residues were needed (Hepner et al. 2010). Hence, the development of environmentally friendly and sustainable energy will require constantly increasing utilization of renewable energy sources in the future. However, the specific weight of logging residues is low and their distribution in a cutting area is widespread, and for this reason, collecting and processing them is labour-intensive and the used equipment are expensive (Vares et al. 2005). Logistics optimization is of great importance (selection of appropriate sites for chipping of residues, etc.) for assuring the economic feasibility of collecting logging residues. Taking into account the effects of implementing different technologies (intensive whole-tree harvesting, including stumps, thinning of only above-ground biomass, etc.) for collecting harvesting residues, which have been discussed in numerous studies, the future direction in Estonian conditions should be the cutting of above-ground biomass (stems and branches) exclusively. Compared to the production of forest chips, producing fuel from stumps requires using a completely different method, for example a special gripper attached to an excavator for uprooting, wood crushers instead of chippers for grinding stumps, and the obtained fuel, which has a high ash content, can only be burned in large CFB boilers. Neither economic nor ecological analyses support the practice of uprooting stumps; moreover, the latter lack a sufficient market in Estonia and there seem to be no current political or commercial interests in developing one. Although there is currently no interest in Estonia in such a fuel, the situation may change, because according to the framework convention on climate change which was adopted by several countries, carbon emissions have to be significantly reduced and alternatives to oil shale energy found.

5. Conclusions

The utilization of logging residues as fuel is a relatively affordable source of renewable energy. The quality (calorific potential and ash content) together with the moisture content of fuelwood are more important factors than the species from the users' point of view. Still the quality depends on the species-specific properties of the logging residues as well as on the species-specific chemical composition of the residues. Järvselja data indicate higher quality in conifer dominated sites, but a higher load of logging residues in broadleaf dominated stands. The moisture content of birch, pine and the spruce branch fraction was similar (21.6–25.4%); only on the black alder dominated site the moisture content (35.4%) was clearly different. The heating value of the billets and branches is highest in coniferous trees: the heating value of coniferous species varied from 13.3 MJ kg^{-1} to 14.7 MJ kg^{-1} of fresh mass and heating value of broadleaf species varied from 11.0 MJ kg^{-1} to 13.8 MJ kg^{-1} of fresh mass. It appeared that regardless of the species specifics and site differences, the ash content in branch segments was statistically significantly higher than in stem segments.

Acknowledgements

The fieldwork and laboratory analysis were supported by the grants from Järvselja Training and Experimental Forest Centre and the Estonian Environmental Investment Centre. This research was supported by institutional research funding IUT21-4 (B21004) of the Estonian Ministry of Education and Research and Rural Development Foundation of Estonia.

References

Brosowski, A., Thrän, D., Mantau, U., Mahro, B., Erdmann, G., Adler, P. et al., 2016: A review of biomass potential and current utilisation e Status quo for 93 biogenic wastes and residues in Germany. Biomass and Bioenergy, 95:257–272.

de Jong, J., Akselsson, C., Egnell, G., Löfgren, S., Olsson, B A., 2017: Realizing the energy potential of forest biomass in Sweden - How much is environmentally? Forest Ecology and Management, 383:3–16.

Dutkă, I., Negrutiu, F., Ioras, F., Maher, K., Blujdea, V.N.B., Ciuvăt, L.A., 2014: The influence of age, location and soil conditions on the allometry of young Norway spruce (*Picea abies* L. Karst.) trees. Notulae Botanicae Horti Agrobotanici, 42:579–582.

Eastaugh, C. S., Kangur, A., Korjus, H., Kiviste, A., Zlatonov, T., Velichkov, I. et al., 2013: Scaling issues and constraints in modelling of forest ecosystems: a review with special focus on user needs. Baltic Forestry, 19:316–330.

Egnell, G., Leijon, B., 1997: Effects of different levels of biomass removal in thinning on short-term production of *Pinus sylvestris* and *Picea abies* stands. Scandinavian Journal of Forest Research, 12:17–26.

Filbakk, T., Hoibo, O., Dibdiakova, J., Nurmi, J., 2011: Modelling moisture content and dry matter loss during storage of logging residues for energy. Scandinavian Journal of Forest Research, 26:267–277.

Forrester, D. I., Tachauer, I. H. H., Annighoefer, P., Barbeito, I., Pretzsch, H., Ruiz-Peinado, R. et al., 2017:. Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. Forest Ecology and Management, 396:160–175.

Fortier, J., Truax, B., Gagnon D., Lambert,F., 2017: Allometric equations for estimating compartment biomass and stem volume in mature hybrid poplars: general or site-specific? Forests, 8:1–23.

Garcia, D., Sangiorgio, S., Rosa, F., 2015: Estimating the potential biomasses energy source of forest and agricultural residues in the Cinque Terre Italian National Park. Energy Procedia, 82:674–680.

Grønflaten, L. K., Steinnes, E., Örlander, G., 2008: Effect of conventional and whole-tree clear-cutting on concentrations of some micronutrients in forest soil and plants. Forestry Studies, 48:5–16.

Hakkila, P., 1989: Utilization of residual forest biomass. Berlin, Heidelberg, New York, Springer.

Helmisaari, H. S., Hanssen, K H., Jacobson, S., Kukkola, M., Luiro, J., Saarsalmi, A. et al., 2011: Logging residue removal after thinning in Nordic boreal forests: Long-term impact on tree growth. Forest Ecology and Management, 261:1919–1927.

Hepner, H., Kaimre, P., Sirgmets, R., Teder, M., 2010: Macroeconomic analysis of the Estonian forest sector, Tartu.

Ingerslev, M., Hansen, M., Pedersen, L. B., Skov, S., 2014: Effects of wood chip ash fertilization on soil chemistry in a Norway spruce plantation on a nutrient-poor soil. Forest Ecology and Management, 334:10–17.

Jacobson, S., Kukkola, M., Mälkönen, E., Tveite, B., 2000: Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. Forest Ecology and Management, 129:41–51.

Jonsell, M., 2008: The effects of forest biomass harvesting on biodiversity. In: Röser, D., Asikainen, A., Raulund-Rasmussen, K., Stupak, I. (eds): Sustainabme use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic region. Dortrecht, Springer, p. 129–154.

Kask, Ü., Loosaar, J., Parve, T., Kask, L., Paist, A., Muiste, P. et al., 2011: Potential of biomass in Narva region regarding oil shale and biomass co-firing. Oil Shale, 28:181–192.

Kizha, A., Han, H.-S., 2017: Moisture Content in Forest Residues: an Insight on Sampling Methods and Procedures. Current Forestry Reports, 3:202–212.

Lõhmus, E., 2004: Estonian Forest Site types. Tartu, Eesti Loodusfoto, 80 p.

Møller, I. S., 2000: Calculation of biomass and nutrient removal for different harvesting intensities. New Zealand Journal of Forestry Science, 30:29–45.

Muiste, P., Kakko, T., 2004: Energywood harvesting in Estonia. Silva Carelica, 45:72–78.

Muiste, P., Kiivit, K., Niidumaa, M., 2004: The potential for using residues from thinning and final felling as fuel. Forestry Studies, 40:198–207.

Mälkönen, E., 1976: Effect of whole-tree harvesting on soil fertility. Silva Fennica, 10:157–164.

Nilsson, B., Blom, Å., Thörnquist, T., 2013: The influence of two diferent handling methods on the moisture content and composition of logging residues. Biomass and Bioenergy, 52:34–42.

Nurmi, J., 1993: Heating values of the above ground biomass of small-sized trees. Acta Forestalia Fennica, 236:1–30.

Olsson, B. A., Lundkvist, H., Staaf, H., 2000: Nutrient status in needles of Norway spruce and Scots pine following harvesting of logging residues. Plant and Soil, 223:163–175.

Olsson, B. A., Staaf, H., Lundkvist, H., Bengtsson, J., Rosén, K., 1996: Carbon and nitrogen in coniferous forest soil after clear-felling and harvests of different intensity. Forest Ecology and Management, 82:19–32.

Padari, A., Mitt, R., Pärn, L., Muiste, P., 2010: Dependence of volume (oven dry weight) of harvesting residues on forest site type. Forestry Studies, 52:30–39.

Palviainen, M., 2005: Logging residues and ground vegetation in nutrient dynamics of a clear-cut boreal forest. Joensuu, Faculty of Forestry of the University of Joensuu.

Persson, T., 2017: Stump harvesting for bioenergy - methods and environmental effects. Scandinavian Journal of Forest Research, 32:201–203.

Pettersson, M., Nordfjell, T., 2007: Fuel quality changes during seasonal storage of compacted logging residues and young trees. Biomass and Bioenergy, 31:782–792.

Pyttel, P. L., Köhn, M., Bauhus, J., 2015: Effects of different harvesting intensities on the macro nutrient pools in aged oak coppice forests. Forest Ecology and Management, 349:94–105.

Ranius, T., Hämäläinen, A., Egnell, G., Olsson, B., Eklöf, K., Stendahl, J. et al., 2018: The effects of logging residue extraction for energy on ecosystem services and biodiversity: A synthesis. Journal of Environmental Management, 209:409–425.

Raulund-Rasmussen, K., Stupak, I., Clarke, N., Callesen, I., Helmisaari, H-S., Karltun, E. et al., 2008: Effects of very intensive forest biomass harvesting on short and long term site productivity. In: Röser, D., Asikainen, A., Raulund-Rasmussen, K., Stupak, I. (eds.): Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic Region. Dortrecht, Springer, p. 29–78.

Rosenvald, A., 2001: Economical forest utilization. Tartu, Estonian Agricultural University Publishing Centre.

Routa, J., Kellomäki, S., Standman, H., 2012: Effects of forest management on total biomass production and CO_2 emissions from use of energy biomass of Norway spruce and Scots pine. BioEnergy Research, 5:733–747.

Räisänen, T., Athanassiadis, D., 2013: Potential and distribution of logging residues from final fellings in Finland. BioFuel Region.

Röser, D., Asikainen, A., Stupak, I., Pasanen, K., 2008: Forest energy resources and potentials. In: Röser, D., Asikainen, A., Raulund-Rasmussen, K., Stupak, I. (eds.): Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic region. Dordrecht, Springer, p. 928.

Rytter, L., Ingerslev, M., Kilpeläinen, A., Torssonen, P., Lazdina, D., Löf, M. et al., 2016: Increased forest biomass production in the Nordic and Baltic countries – a review on current and future opportunities. Silva Fennica, 50:1–33.

Saarsalmi, A., Derome, J., Levula, T., 2005: Effect of wood ash fertilisation on stand growth, soil, water and needle chemistry and berry yields of lingoberry (*Vaccinium vitis-idaea* L.) in a Scots pine stand in Finland. Forestry Studies, 42:13–33.

Saarsalmi, A., Tamminen, P., Kukkola, M., Hautajärvi, R., 2010: Whole-tree harvesting at clear-felling: Impact on soil chemistry, needle nutrient concentrations and growth of Scots pine. Scandinavian Journal of Forest Research, 25:148–156.

Staaf, H., Olsson, B. A., 1991: Acidity in four coniferous forest soils after different harvesting regimes of logging slash. Scandinavian Journal of Forest Research, 6:19–29.

Stupak, I., Asikainen, A., Jonsell, M., Karltun, E., Lunnan, A., Mizaraité, D. et al., 2007: Sustainable utilisation of forest biomass for energy – Possibilities and problems: Policy, legislation, certification and recommendations and guidelines in the Nordic, Baltic, and other European countries. Biomass & Bioenergy, 31:666–684.

Uri, V., Aosaar, J., Varik, M., Becker, H., Kukumägi, M., Ligi, K. et al., 2015: Biomass resource and environmental effects of Norway spruce (*Picea abies*) stump harvesting: An Estonian case study. Forest Ecology and Management, 335:207–215.

Vares, V., Kask, Ü., Muiste, P., Pihu, T., Soosaar, S. 2005: Handbook of Biofuel User. Tallinn University of Technology, 172 p.

Vesisenaho, T. J., Nousainen, I. K., 1997: Applying of whole tree skidding method to Scandinavian lumber harvesting conditions, p. 39–46.

Wall, A., 2012: Risk analysis of effects of whole-tree harvesting on site productivity. Forest Ecology and Management, 282:175–184.

Other sources

Annual Report, 2014: Tallinn, Estonian State Forest Management Centre.

Annual Report, 2016: Tallinn, Estonian State Forest Management Centre.

Renewable Energy Yearbook 2016, 2016: Tallinn, Estonian Renewable Energy Association.

CEN/TS 14774. 2004: Solid biofuels - Methods for the determination of moisture content - Oven dry method. Brussels: European Committee for Standardization.

CEN/TS 14775. 2004: Solid biofuels - Method for the determination of ash content. Brussels: European Committee for Standardization.

CEN/TS 14918. 2005: Solid biofuels - Method for the determination of calorific value. Brussels: European Committee for Standardization.

Eesti Energia, 2012: Eesti Energia. [Online] Available at: https://www.energia.ee/et/keskkond [Accessed 03 2016].

Statistical Yearbook of Estonia 2017, 2017: Tallinn, Statistics Estonia.

Sustainable and optimal use of biomass for energy in the EU beyond 2020, 2017: Annexes of the Final Report.

Yearbook Forest 2013, 2014: Tallinn, Estonian Environment Agency.

Yearbook Forest 2014, 2015: Tallinn, Estonian Environment Agency.

Yearbook Forest 2017, 2018: Tallinn, Estonian Environment Agency.

Cent. Eur. For. J. 66 (2020) 12–22 sciendo DOI: 10.2478/forj-2019-0027

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Variability of forwarder truckload parameters in the Pryazha forestry division of the Republic of Karelia (Russia): A computer experiment

Pavel Budnik[1]*, Ilya Shegelman[1], Vyacheslav Baklagin[2]

[1]*Petrozavodsk State University, 33, Lenin Str., Petrozavodsk, Republic of Karelia, Russia*
[2]*Northern Water Problems Institute of the Karelian Research Centre of the Russian Academy of Sciences, Aleksander Nevsky str., Petrozavodsk, Karelia, Russia*

Abstract

The goal of the present research is to analyze parameters of a bundle of logs for various models of forwarders in the Pryazha division of forestry of the Republic of Karelia. The investigated parameters were mass and volume of a bundle of logs, stacking factor of the bundle and the number of wood assortments in the bundle. The following models of forwarders have been investigated: John Deere 1210E, John Deere 1110E, Ponsse Elk, Ponsse Wisent, Amkodor 2661-01, Rottne F13D, Rottne F15D, Rottne F18D. We estimated the parameters of bundles formed from spruce sawlog 6.1 m long and bundles formed from spruce pulpwood 4 m long. Data on stem forms from harvester recorders have been collected to assess the parameters of a bundle of logs. Parameters of bundles have been determined based on computer experiment. The experiment consists of the following steps: random selection of the stem from the database; simulation of the cut-to-length process; simulation of log stacking process; calculation of parameters of a bundle of logs. We found that parameters of bundles vary to a quite substantial extent. Average variability of a bundle of logs formed of 6.1 m long spruce sawlog is 4.5 t, variability of the volume is 5.8 m^3, and variability of the number of wood assortments in a bundle is 49 pcs. For a bundle made up of 4 m long spruce pulpwood variability of mass is on average 2.8 t, that of volume – 2.09 m^3, that of the number of wood assortments – 57 pc. The presented results can inform transportation of wood on cutting areas, planning timber harvesting, as well as development new logging machines.

Key words: simulation study; computer experiment; mass of bundle; volume of bundle; number of logs in a bundle; load capacity

Editor: Tomáš Hlásny

1. Introduction

Cut-to-length wood harvesting method has been widely practiced in Europe (Proto et al. 2018a). In Nordic countries, harvesting is mainly performed with fully-mechanized cut-to-length wood harvesting system. (Tufts & Brinker 1993; Vossbrink & Horn 2004; Gerasimova & Sokolov 2014). Such a system includes harvester and forwarder (Talbot et al. 2003; Wang et al. 2005; Cambi et al. 2017; Proto et al. 2018b). Fully-mechanized cut-to-length harvesting system has also become increasingly used in the European North of Russia, in particular, in the Republic of Karelia (Gerasimov et al. 2012). When practicing cut-to-length wood harvesting, operations performed by forwarder are the most labour-consuming and expensive ones (Mousavi 2009). Therefore, it is a timely task to upgrade the design of such machines, increasing their reliability.

There is a great number of publications relating to the study of various aspects of forwarder operation (Proto et al. 2018a). The efficiency of forwarder depends on multiple factors, and the most important one is the distance of transportation. (Sever 1988; Ghaffarian et al. 2007). The productivity of forwarder relies heavily on the parameters of truck load (Nurminen et al. 2006; Proto et al. 2018b). Therefore, increased distance of transportation nfluences the parameters of a bundle of logs (weight, volume, number of wood assortments) on forwarder productivity grows. (Raymond 1989; Tiernan et al. 2004). However, research of bundle parameters has yet received little attention, what can decrease the accuracy and significance of the obtained results.

Productivity of forwarders depends on the number of wood assortments in a bundle, which defines the number of cycles of a loader during load and discharge (Tufts and

---

**Corresponding author. Pavel Budnik, e-mail: budnikpavel@yandex.ru, phone: +79535281068*

Brinker 1993; Tufts 1997; Manner et al. 2013). Minette et al. (2004) point that collection and discharge of logs consume most of the process cycle time of the forwarder operation. The negative impact of the forwarder on the soil is determined by the truck load parameters (Labelle & Jaeger 2019; Sirén et al. 2019). Many publications deal with ecological aspects, in particular, fuel consumption rate, energy efficiency and exhaust emission (Klvac et al. 2012; Lijewski et al. 2017). Fuel consumption rate and, consequently, exhaust emission depend on the parameters of a bundle of logs.

Research of the parameters of forwarder's bundle is important in order to assess terrain crossing capacity (Voinash & Vonash 2011) and to ensure machine design reliability (Golyakevich & Goronovskii 2017). Overloading of the machine negatively affects running gear parts and leads to their premature failure.

Therefore, the assessment of parameters of a bundle of logs to be transported is an important task related to various aspects of forwarder's operation. The solution of this problem will allow logging enterprises to increase the efficiency of logging management. In addition, for manufacturers of logging equipment, this will allow to choose the optimal combination of transmission parameters and components of the running gear parts for certain operating conditions.

The aim of this study was to analyze the parameters of a bundle of logs for various models of forwarders in the Pryazha division of forestry of the Republic of Karelia. In the study, analysis of the parameters of a bundle of logs was performed by using computer experiment. The objective was to assess the variability of mass and volume of a bundle of logs, stacking factor of the bundle and the number of wood assortments in the bundle. The additional objective was to establish the relationship between load area cross section of a forwarder and parameters of a bundle of logs. We have also compared load capacities of considered forwarders with simulated loaded bundle mass values to determine compliance of their load capacity with operating conditions.

2. Materials and methods

2.1. Study region

This research was conducted in the Pryazha division of forestry of the Republic of Karelia situated in the north of the European part of Russia (Fig. 1). The republic borders with Finland in the west and by the White Sea in the north-east. Pryazha division of forestry is located in the southern part of the Republic of Karelia between Lake Ladoga and Lake Onega. Total estimated timber volume in the Republic of Karelia is 980 mln. m^3 including Pryazha division of forestry where timber volume is 58 mln. m^3. In the Republic of Karelia, the volume of mature and old growth forests, where harvesting operations are mainly performed, is 289 mln. m^3. The volume of mature and old growth forests is 10 mln. m^3 in the Pryazha division of forestry. Felling volume in Karelia is 8.2 mln m^3 with 11.5 mln m^3 of annual allowable cut. In the Pryazha division of forestry the forestry is characterized by the largest extent of annual allowable cut – 82% of max allowed cut. Actual felling volume is 665 thous m^3. The road network for logging of the Pryazha division of forestry is one of the most developed in the Republic of Karelia. In the Pryazha division of forestry average volume of stem is 0.198 m^3 and average timber volume is 132 m^3 ha^{-1}. Forest taxation data of the areas from which the material has been accumulated, are typical for southern part of Karelia.

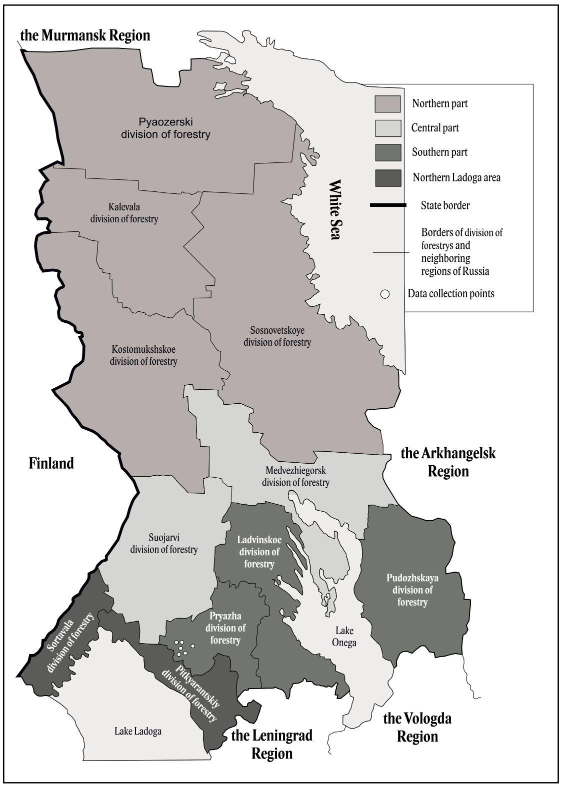


Fig. 1. Map of the Republic of Karelia and the location of sites, where data from forest forwarders were collected.

2.2. Material

In order to assess the parameters of a bundle of logs, data on stem forms have been collected. The data have been collected in the Western part of Pryazha division of forestry where logging is most intensive (Fig. 1). Records downloaded from harvester computers have been the source data in this study. These files contained the data about the processed stems in the cutting areas located in the study region. The data included tree species, stem length (length tree without tip), stem volume, diameter values every 10 cm of stem length. We have collected the data about 53 911 stems. Based on the data, a database was formed. The results of statistical processing of the data contained in the database are shown in Fig 2.

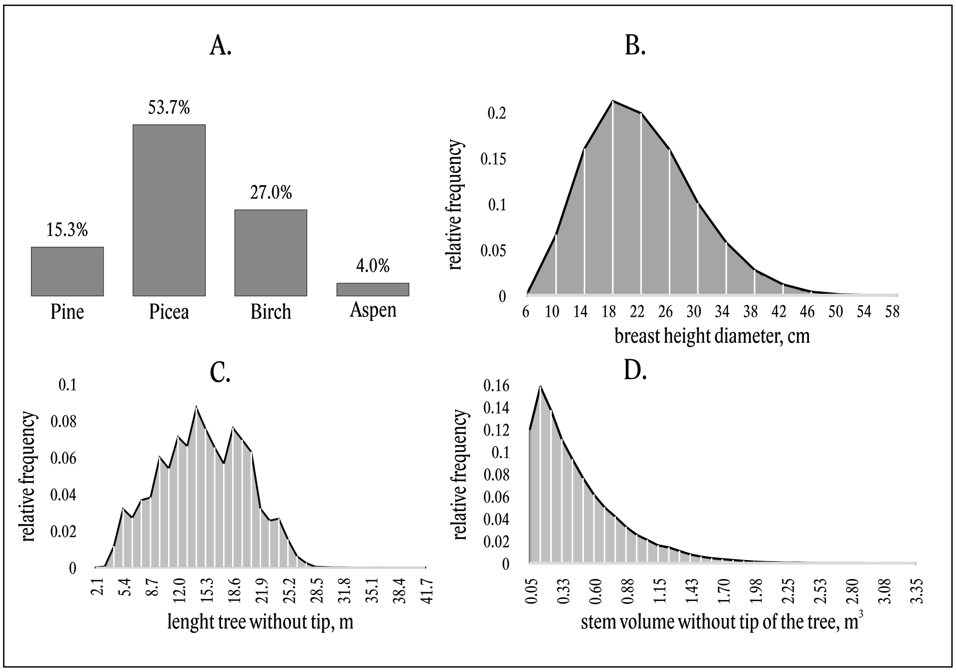


Fig. 2. Statistical characteristics of the collected data. A is distribution of stems by species, B is distribution of stems by breast height diameter, C is distribution of stems by height, D is distribution of stems by volume.

2.3. Investigated machines

We investigate a broad range of machine type which enable robust inferences and are relevant for the Republic of Karelia. Table 1 gives the technical characteristics of the evaluated machines.

Table 1. Specifications of the evaluated models of forwarders.

Name of model	Load capacity [t]	Load area cross section [m^2]
John Deere 1210E	13	4.0
John Deere 1110E	12	4.0
Ponsse Elk	13	4.5
Ponsse Wisent	12	4.5
Amkodor 2661-01	12	4.4
Rottne F13D	14	4.7
Rottne F15D	15	4.8
Rottne F18D	18	4.8

2.4. Methods

2.4.1 Study outline

We estimated the parameters of bundles formed from spruce sawlog 6.1 m long (No 1) and bundles formed from spruce pulpwood 4 m long (No 2). Evaluation of variability of parameters of forwarder's bundle of logs requires a great number of measurements (hundreds of measurements per one characteristic). For this reason, we used a computer experiment based on the here developed simulation model.

The simulation model is implemented in form of a program (MS Windows application) using the syntax of C# language. The process of forming a bundle consisting of the given type of logs has been simulated by means of this model. The following input data have been used for the computer experiment: stem forms properties, parameters of wood assortments to be loaded (species, length, diameter limits in upper and lower cuts); load platform characteristics; loading mode, distance from the protective guard of load area to the nearest woodbunk. The computer experiment has been carried out 10 000 times for every combination of the input data.

The experiment consists of the following steps:

1. random selection of the stem from the database;
2. simulation of the simulation of cut-to-length process of the selected stem;
3. simulation of log stacking process;
4. calculation of parameters of a bundle of logs.

Stages 1–3 have been repeated until a bundle was fully loaded, i.e. the forwarder load area was loaded to the height of wodbunks stands.

At the stage 2, the cut-to-length process was simulated, consisting of determining parts of the selected stem satisfying the parameters of the assortment (log No 1 or log No 2). Assortment parameters were length, limits in lower cut, limits in upper cut. We used different algorithms to simulate of cut-to-length process for log No 1 and log No 2. The algorithm for log No 2 did not allow it to be obtained from butt-log portion. This is due to it is usually not allowed to saw pulpwood from butt-log portion.

The received log (part of the selected stem) has been represented as a number of perfect frustums of cone with 10 or less cm height for the cones situated on the edges of the log. The number of cones and the diameters of their bases have been the characteristics of the log. The log volume with bark (Q_{log}, mass (M_{log}), diameter in lower (d_{lower})

and in upper (d_{upper}) cut have been calculated on stage 2. Table 2 defines parameters used during calculation of Q_{log} and M_{log}, and Table 3 – mathematical expressions.

Table 2. Designation of values used during calculation of Q_{log} and M_{log}.

Symbol	Explanation
n	number of frustums of cone accounted for log
$d_{1,i}$	diameter of lower base of the *i*-th frustum of cone, for *i* = 1, *n*
$d_{2,i}$	diameter of upper base of the *i*-th frustum of cone, for *i* = 1, *n*
h_i	height of the *i*-th frustum of cone (h_i = 10 cm, except for limit cones in log for which value h_i is defined by interpolation)
Q_{bark}	volume of bark in log
Q_{wood}	log underbark volume
l_1	distance from butt of the selected stem to lower base of the first frustum of cone in log
l_2	distance from butt of the selected stem to upper base of the last frustum of cone in log
L	distance from butt of the selected stem
$\rho(L)$	average density of fresh spruce wood at *L* distance
ρ_b	average density of fresh spruce wood bark
k	double thickness of bark
d_k	diameter over bark
a and *b*	coefficients of linear equation for calculation of k
W	moisture content of wood
A, *B*, *C* and *D*	coefficients of equation for calculation of $\rho(L)$ value

Table 3. Expressions used for calculation of Q_{log} and M_{log}.

Equation	Equation number
$Q_{log} = \sum_{i=1}^{n} \frac{\pi h_i(d_{1,i}^2 + d_{1,i}d_{2,i} + d_{2,i}^2)}{12}$	[1]
$Q_{bark} = Q_{log} - \sum_{i=1}^{n} \frac{\pi h_i\left((d_{1,i} - k)^2 + (d_{1,i} - k))(d_{2,i} - k) + (d_{2,i} - k)^2\right)}{12}$	[2]
$Q_{wood} = Q_{log} - Q_{bark}$	[3]
$M_{log} = Q_{wood} \cdot \frac{\int_{l_1}^{l_2} \rho(L)dL}{l_2 - l_1} + \rho_b \cdot Q_{bark}$	[4]
$k = a + bd_k$	[5]
$\rho(L) = 1.0262 \,.\, (1 + 0.01W) \,.\, (AL^3 + BL^2 + CL + D)$	[6]

In order to calculate value under expression [5] the following coefficient values were found suitable for the study area $a = 0.206$ and $b = 0.0356$. Expression [5] and values of coefficients *a, b* have been taken from state standard GOST 32594-2013 "Roundtimber. Methods of measurements". This standard considers main regulations of European standard EN 1309-2:2006 "Round and sawn timber – Method of measurement of dimensions – Part 2: Round timber – Requirements for measurement and volume calculation rules".

Expression [6] comes from the studies of Poluboyarinov (1976), Bogdanov et al. (1981) and Borovikov et al. (1989). Coefficients A, B, C and D for freshly-felled spruce at average moisture content of 91% were 0.000105, −0.005, −0.35, 380. Density of bark was set to 1239 kg m^{-3} (Tsyvin 1973).

During stage 4 mass (*M*) and volume (*Q*) of fully loaded bundle, number of logs in a fully loaded bundle (*N*), stacking factor of a fully loaded bundle (K_q) have been determined. Values *M* and *Q* have calculated as a sum of values Q_{log} and M_{log} of all the logs contained in the formed bundle. Value K_q has been determined according to the expression:

$$K_q = \frac{Q}{S_k . L} \quad [7]$$

where S_k – load area cross section, L – length of wood assortment.

Forwarder's bundles of logs have been formed from one type of wood assortment. In order to assess the possibility of collecting a bundle of assortments we have introduced a coefficient K_p:

$$K_p = N / N_{stem} \quad [8]$$

where N_{stem} is number of generated stems accounted for a bundle of assortments.

2.4.2 Simulation of log stacking process

Forwarder load area is a half-frame on which a protective guard and woodbunks are installed (Fig. 3). The volume of logs transported in the load area is defined by the height of the woodbunks stands. Configurations of load area woodbunks of the considered models are shown in Fig. 4.

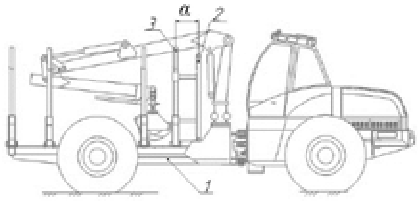


Fig. 3. Forwarder scheme: 1 – half-frame, 2 – protective guard, 3 – woodbunk stand.

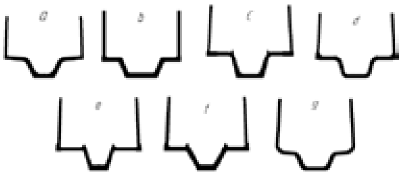


Fig. 4. Shapes of forwarder woodbunks: a – John Deere 1210E and 1110E, b – Amkodor 2661-01, c – Rottne F18D, d – Ponsse Elk, e – Rottne F13D, f – Rottne F15D, g – Ponsse Wisent.

Simulation of the process of log stacking into the load area (stage 3) was realized on a 2-dimensional space (Fig. 5). Technically, a woodbunk is represented as an assembly of components characterizing its outer shape as it is shown in Fig. 6. The following elements have been used to describe a woodbunk shape: "wall" (vertical segment); "floor" (horizontal segment); "plane" (inclined segment); "point" (point of joining the elements). Each element has assigned coordinates in a Cartesian coordinate system. Elements were selected so as to best fit the size and shape of the woodbunk.

Fig. 5. Graphic display of log stacking process simulation.

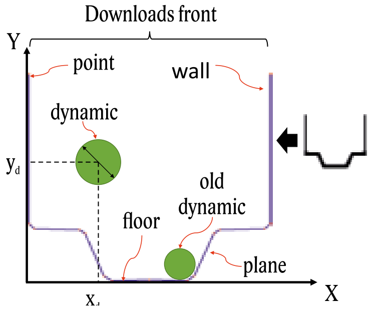


Fig. 6. Woodbunk scheme used in the simulation of log stacking process.

The logs (parts of the selected stems) were represented by their cross sections. The parameters of logs were obtained in stage 2 (simulation of cut-to-length process). We used the cross section of the log at distance α from the log edge (Fig. 3). Value has been defined as a distance from the protective guard to the nearest woodbunk for the respective forwarder model. The value of α was laid either from lower end of the log, or from the top. We alternated the log edge. However, for logs obtained from one stem, the edge did not alternate.

Log has been represented by a "dynamic" element and marked by the center coordinates (x_d, x_d), diameter (d_d) and circumference defined as $(x - x_d)^2 + (y - y_d)^2 = d^2_d/4$. Characteristic d_d has been defined by the cross section diameter of log situated at the given distance from its edge (α).

Simulation of log stacking process has involved log cross section ("dynamic" element) move within the woodbunk representation layout. Loading has been simulated piece by piece. We used the algorithm which ensured balanced load of the woodbunk layout. Simulation has been carried out with step $\Delta y = 1$ mm. To describe the interaction of elements, we used the equations obtained on the basis of analytical geometry and laws of theoretical mechanics. These equations characterized three types of interaction of an "dynamic" element with system elements (elements describing woodbunk shape and "old dynamic" elements): collision condition, separation condition, equilibrium condition.

The collision condition was to check for availability of common points between "dynamic" element and other elements. On each simulation step the collision conditions have been checked in the following consequence: "floor", "point", "plane", "old dynamic". If the collision condition was fulfilled, then the "dynamic" element moved along the element it encountered with step Δy. Otherwise, the element "dynamic" moved along the y–axis.

The separation condition was to check for the loss of common points between the "dynamic" element and the other element. If the separation condition was satisfied, but the interaction condition not, then the "dynamic" element moved along the *y* axis. The equilibrium condition was test of the possibility of movement of the "dynamic" element in its interaction with more than one system element. Here we considered constraining forces on the "dynamic" element and used laws of theoretical mechanics.

2.4.2 Data analysis

The result of the computer experiment were values of mass (*M*) and volume (*Q*) of a fully loaded bundle of logs, stacking factor of the fully loaded bundle (K_q) and the number of wood assortments in the fully loaded bundle (*N*) for investigated forwarders. Computer experiment data were statistically processed. We estimated mean observation, minimum value, maximum value and sample range. Frequency distribution curves and cumulative distribution functions (*F*(*M*)) for each value have been constructed. Values *M* which with probability 0.9 and 0.99 will not be exceeded (value *M* at *F*(*M*) = 0.9 and 0.99) were determined based on the cumulative distribution functions. Additionally, we determined arithmetic mean values of *M*, *Q*, *N* between all the forwarders for 4, 4.2, 4.5, 4.7, 4.8 m^2 load area cross sections.

Variability of *M*, *Q*, *N*, K_q values was estimated by analysis of mean observations, sample ranges and frequency distribution curves. To determine compliance of load capacity the considered forwarder models with operating conditions, comparison of mean observation, maximum value, minimum value of mass, mass at *F*(*M*) = 0.9 and 0.99 with load capacity was carried out. To establish the relationship between load area cross section of a forwarder and parameters of a bundle of logs, we achieved analytical models using the arithmetic mean values of *M*, *Q*, *N*. The analytical models are based on classical least squares.

3. Results

3.1. Variability of fully loaded bundle characteristics

Table 4 contains mean, minimum and maximum values of a fully loaded bundle of logs (*M*) derived from simulated data. Sample range is 4.0 – 5.7 t for the bundles made of logs of type No 1; 4.5 t on average for all the considered models. For the bundles formed from the logs of type No 2, sample range is 1.4 – 1.8 t (1.6 t on average). Average value of mass of a bundle formed from the logs of type No 1 is 1.5 times greater than that of a bundle made of the logs of type No. 2. Depending on the model of forwarder, the variability of mass of a bundle formed from logs of type No 1 has been 2.3 – 3.4 times (on average 2.8 times) larger than the variability of mass of a bundle formed from the logs of type No 2.

Table 5 contains mean, minimum and maximum values of a fully loaded bundle of logs (*Q*) derived from simulated data. For the bundle of logs formed from the logs of type No 1 samples range has been within 5.2 – 7.4 m^3 (5.85 m^3 on average, in respect to all the considered models). For the bundles formed from logs of type No 2, samples range has been within the interval of 1.9 – 2.3 m^3 (2.09 m^3 on average). For all the studied forwarder models the average volume value of a bundle formed from logs of type No 1 is 1.5 times higher than the average volume value of a bundle formed from logs of type No 2. The variability of volume of bundle formed from logs of type No 1 has been larger than the variability of volume of bundle formed from wood assortments of type No 2, for all the considered forwarder models – by 2.3 – 3.4 times (by 2.8 times on average).

Table 6 provides the mean observations, the minimum values, the maximum values of the wood assortments number of a fully loaded bundle (*N*) derived from simulated data. For bundles of logs formed from logs of type No 1 sample range has been within 46 – 51 pcs (49 pcs on average for all the studied models). For bundles made up of wood logs of type No 2, sample range has been within the interval 52 – 62 pcs (57 pcs on average). Average assortments number of a bundle formed from logs of type No 2 is 2.1 times higher than average assortments number of a bundle made up of logs of type No 1 for all the models of forwarders. Variability of assortments number in a bundle formed from logs of type No 2 has been 1.0 – 1.3 times greater (1.8 times on average), of the variability in a bundle formed from logs of type No 1 for all the studied models of forwarder.

The mean observations, the minimum values, the maximum values of stacking factor of the fully loaded bundle (K_q), obtained on the basis of simulation, are presented in Table 7. For bundles of logs made up logs of type No 1 the sample range has been within 0.20 – 0.25 (0.21 on average for all the considered models). For bundles formed from logs of type No 2, sample range has been within 0.10 – 0.12 pcs (0.11 on average). In the mean, the difference in value between bundles formed from logs

Table 4. Variability of fully loaded bundle mass.

Forwarder models	Load area cross section [m^2]	Load capacity [ton]	*M* for No 2 [ton]			*M* for No 1 [ton]		
			min	mean	max	min	mean	max
John Deere 1210E/1110E	4	13/12	9.36	10.13	10.86	13.00	15.09	17.13
Amkodor 2661-01	4.4	12	10.22	11.07	11.89	14.21	16.48	18.76
Ponsse Elk	4.5	13	10.42	11.21	11.96	14.20	16.69	18.68
Ponsse Wisent	4.5	12	10.42	11.32	12.18	14.97	16.86	19.08
ROTTNE F13D	4.7	14	10.95	11.71	12.46	15.01	17.43	19.41
ROTTNE F15D	4.8	15	10.97	11.90	12.66	14.71	17.75	20.38
ROTTNE F18D	4.8	18	11.10	11.92	12.73	15.54	17.73	19.61

Table 5. Variability of fully loaded bundle volume.

Forwarder models	Load area cross section [m^2]	*Q* for No 2			*Q* for No 1		
		[m^3]					
		min	mean	max	min	mean	max
John Deere 1210E/1110E	4	12.15	13.15	14.10	16.91	19.63	22.28
Amkodor 2661-01	4,4	13.26	14.37	15.43	18.49	21.44	24.41
Ponsse Elk	4,5	13.53	14.56	15.53	18.48	21.71	24.29
Ponsse Wisent	4,5	13.54	14.69	15.80	19.47	21.93	24.86
ROTTNE F13D	4,7	14.21	15.20	16.17	19.50	22.67	25.27
ROTTNE F15D	4,8	14.26	15.45	16.42	19.14	23.08	26.52
ROTTNE F18D	4,8	14.41	15.47	16.52	20.22	23.06	25.51

Table 6. Variability of wood assortments number of a fully loaded bundle.

Forwarder models	Load area cross section [m^2]	*N* for No 2 [pcs]			*Q* for No 1 [pcs]		
		min	mean	max	min	mean	max
John Deere 1210E/1110E	4	138	163	192	52	78	98
Amkodor 2661-01	4,4	155	178	207	60	85	106
Ponsse Elk	4,5	154	180	214	62	86	112
Ponsse Wisent	4,5	156	182	209	59	87	109
ROTTNE F13D	4,7	161	189	223	64	90	112
ROTTNE F15D	4,8	162	192	221	65	91	114
ROTTNE F18D	4,8	159	192	220	62	91	113

Table 7. Variability of stacking factor of the fully loaded bundle.

Forwarder models	Load area cross section [m^2]	K_q for No 2 [pcs]			K_q for No 1 [pcs]		
		min	mean	max	min	mean	max
John Deere 1210E/1110E	4	0.737	0.797	0.855	0.675	0.784	0.890
Amkodor 2661-01	4.4	0.742	0.804	0.863	0.681	0.790	0.899
Ponsse Elk	4.5	0.738	0.794	0.847	0.664	0.780	0.873
Ponsse Wisent	4.5	0.732	0.794	0.854	0.693	0.781	0.885
ROTTNE F13D	4.7	0.743	0.795	0.846	0.672	0.781	0.871
ROTTNE F15D	4.8	0.735	0.796	0.846	0.649	0.783	0.900
ROTTNE F18D	4.8	0.737	0.791	0.845	0.681	0.777	0.859

of type No 1 and bundles made up logs of type No 2 is minor and equal to 0.014. Variability of value for bundles formed from logs of type No 1 has been on average 2 times greater than in bundles formed from logs of type No 2 for all the considered models of forwarders.

Coefficient K_p value for a bundle formed from type No 1 logs has been varied between 0.27 – 0.91 (0.46 on average). For a bundle made up of No 2 type logs, K_p coefficient has averagely been 0.98 varied between 0.66 – 1.44.

We showed here that with forwarder load area cross section of 4 m^2 mass of a fully loaded bundle of logs formed from 6.1 m long spruce sawlog is on average 15.09 t, volume – 19.63 m^3, number of wood assortments in a bundle – 78 pcs. With forwarder load area cross section of 4.8 m^2 mass of a bundle is on average 17.74 t, volume – 23.07 m^3, number of wood assortments in a bundle– 91 pcs. With forwarder load area cross section of 4 m^2 mass of a bundle formed from 4 m long spruce pulpwood is on average 10.13 t, volume – 13.15 m^3, number of wood assortments in a bundle – 163 pcs. When increasing forwarder load area cross section up to 4.8 m^2 mass of a bundle is on average 11.91 t, volume – 15.46 m^3, number of wood assortments in a bundle– 192 pcs.

In the mean mass of a bundle formed from 6.1 m long spruce sawlog and its volume is 1.5 times greater than the respective parameters of a bundle formed from 4 m long spruce pulpwood. Number of wood assortments in a fully loaded bundle made up of 4 m spruce pulpwood is on average 2.1 times greater than number of assortments in a bundle from 6.1 m long spruce sawlog.

Average variability of a bundle of logs formed from 6.1 m long spruce sawlog is 4.5 t, that of volume 5.8 m^3, and that of the number of wood assortments in a bundle 49 pcs. For a bundle made up of 4 m long spruce pulpwood variability of mass is on average 2.8 t, that of volume – 2.09 m^3, that of the number of wood assortments – 57 pc. On a practical level such significant variability of the truck load parameters is supposed to cause fluctuation of the machine's productivity. Besides, it indicates the irregularity of loads the machine experiences during operation.

The results illustrates that stacking factor depends almost not at all on load area cross section. In addition to it, in the mean difference between the values of stacking factor for a bundle made of 6.1 m long spruce sawlog and for a bundle formed from 4 m long spruce pulpwood is minor and equal to 0.014. Averagely stacking factor for a bundle made up of 6.1 m long spruce sawlog is 0.782, and for 4 m long spruce pulpwood – 0.796.

Fig. 7 shows frequency distribution curves of masses of bundles for the investigated forwarder models obtained on the basis of simulation. The frequency distribution curves are roughly symmetrical and unimodal. Increase of load area cross section has resulted in shifting the variation curve to the right (Fig 7A, 7C). Shape of the frequency distribution curves of different forwarder models with similar values of load space cross section has been differed (Fig. 7B, 7D). Frequency distribution curves for Q and N values have been similar to the frequency distribution curves for M value.

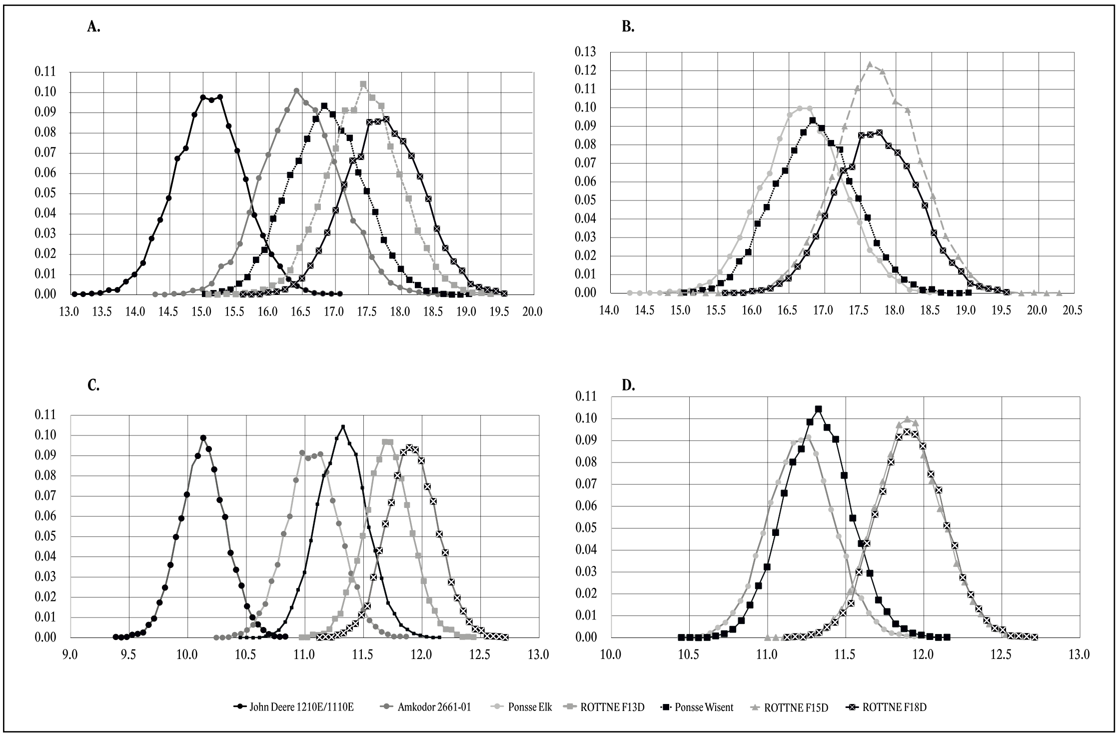


Fig. 7. Frequency distribution curves of *M* value for the considered models of forwarders, where A, B are bundles formed from logs of type No 1, C, D are bundles formed from logs of type No 2. X–axis is mass of fully loaded bundle. Y–axis is relative frequency.

3.2. Comparison of load capacity forwarders with simulated fully loaded bundle mass values

Fig. 8 presents the results of comparison of load capacity values of the investigated forwarder models with minimum, maximum values of the simulated samples for *M* value. Values of mass of bundles of logs with *F*(*M*) = 0.9 and *F*(*M*) = 0.99 are shown as well. For the bundles formed from the logs of type No 1, load capacity values have been less than minimum value of the samples, except for models Rottne F15D, Rottne F18D (Fig. 7A). For the bundles formed from the logs of type No 2 load capacity values have exceeded maximum values of the samples for all the considered forwarder models. (Fig. 7B).

3.3. Influence of load area cross section on average fully loaded bundle parameters

Dependences of mean volume of a bundle of logs, mean mass of a bundle and average number in a bundle from forwarder load area cross section have been of linear type (Fig. 9). We showed here that the parameters (*M*, *Q*, *N*) of fully loaded bundle formed from 6.1 m long spruce saw-log change greater than the parameters of fully loaded bundle formed from 4 m long spruce pulpwood with the same change of load area cross section.

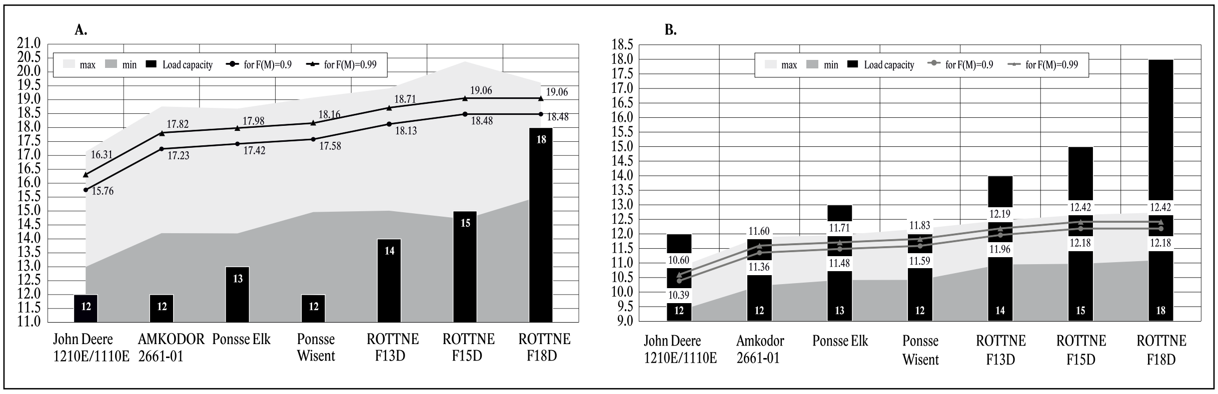


Fig. 8. Comparison of forwarder load capacity with maximum value of simulated fully loaded bundle mass, minimum value, simulated mass at *F*(*M*) = 0.9 and 0.99 (*F*(*M*) – cumulative distribution functions): A – bundles formed from the logs of type No 1, B – bundles formed from the logs of type No 2.

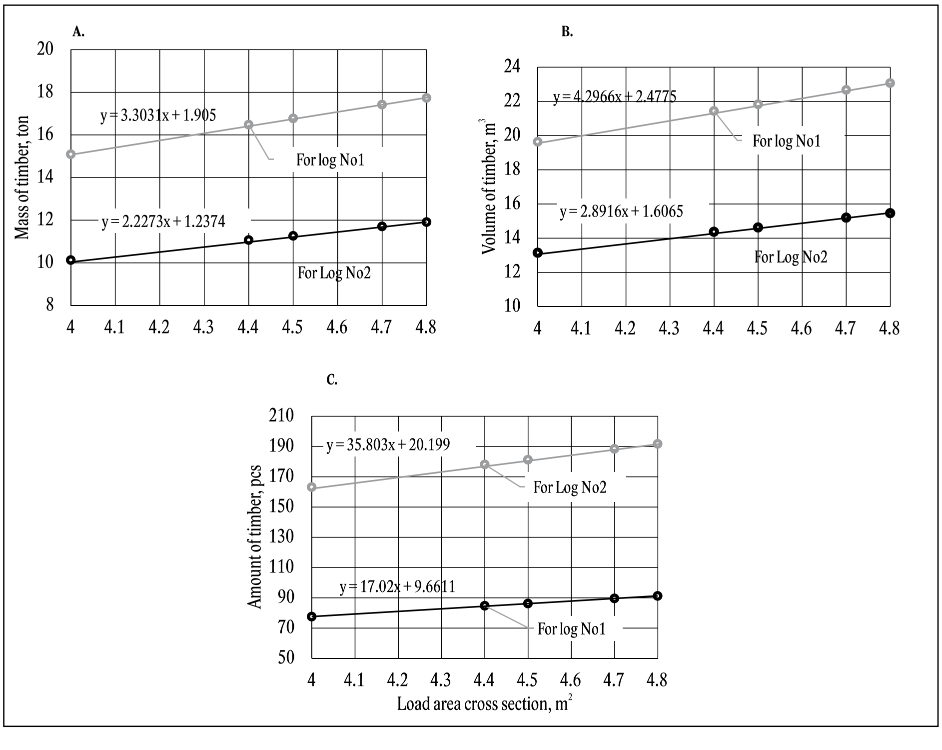


Fig. 9. Dependence of average parameters of a bundle of logs from load area cross section: A – for *M* value, B – for *Q* value, C – for *N* value.

4. Discussion

4.1. Agreement between simulated and observed load capacity values

Comparison of forwarder load capacities and results of the computer experiment showed that all the studied models of forwarders have sufficient load capacity to transport a bundle formed from 4 m long spruce pulpwood. However, forwarders Amkodor 2661-01 and Ponsse Wisent showed poorer performance in this regard.

The limitation of this study is that all the calculations have been carried out for spruce wood. The density of spruce is less than that of pine, birch or aspen; and the density of fresh wood during the wettest season can increase (Poluboyarin 1976). Therefore, mass of a bundle, when transporting wood assortments of other species, can exceed the values obtained during the computer experiment.

All the considered forwarder models have insufficient load capacity to transport a fully loaded bundle formed from 6.1 m long spruce sawlog. Even minimum value of mass of a bundle under the received samples is higher than the load capacity of most of the studied models. Such bundles are always transported due to safety margin of a construction. The results indicate considerable variability of parameters of a fully loaded bundle of logs in the investigated dataset, as well as of insufficient load capacity of the studied forwarder models during transportation of a fully loaded bundle made up of 6 m long logs.

4.2. Effect of forwarder woodbunk shape on bundle characteristics

The obtained results have not allowed drawing a firm conclusion about the influence of load area woodbunks shape on the parameters of a bundle of logs. On the one hand, the results indicate that load area woodbunks shape does little for the average characteristics. On the other hand, differences in shapes of frequency distribution curves for forwarder models with similar load area cross sections point to the fact that woodbunks shape can have certain influence. This indicates that for certain forest stems there is a shape of woodbunks that allows decreasing to some extent the irregularity of parameters of a fully loaded bundle of logs.

4.3. Modeling uncertainty

The received evidences about variability of bundle parameters agree quite well with results of the researches conducted in other regions of Europe (Danilović et al. 2014; Pandur et al. 2015; Proto et al. 2018a, 2018b). The results do not contradict the studies earlier performed in the Republic of Karelia. For instance, Katarov et al. (2012) investigated the influence of Ponsse Elk forwarder on soil in Medvezhiegorsk division of forestry were conducted. The authors recorded the average mass of truck load of 13 t. Our studies have shown that on average mass of a fully loaded bundles formed from 4 m long logs is 11.2 t, and those formed from 6.1 m long – 16.7 t. In general, average parameters of a fully loaded bundle according to the results of our researches are comparable to the values recorded by the researches done in other regions (Slamka & Radocha 2010; Manner et al. 2013; Danilović et al. 2014; Pandur et al. 2015; Petaja et al. 2018; Proto et al. 2018a, 2018b).

The proposed simulation model has some disadvantages. First, simulation of logs loading were conducted in a 2–D space. Therefore, curvature of logs, various flaws, knots, as well as physics of interaction of logs along the overall length, influencing final position of log in load area, are not considered. This may leads to the overestimation of the calculated parameters of a bundle of logs.

Second, the model does not consider forces of inertia and gravity, which provoke additional compaction of logs in forwarder load area and the increase of bundle's stacking factor.

Stem forms in the research have been based on the harvesters' recorders data. Therefore, the third reason of the calculation uncertainties is related to measurements errors of harvesters' recorders. For example, the requirements in Finland stipulate that the measurement error shall be within ± 4% (Nieuwenhuis & Dooley 2006). However, with proper calibration the present day harvesters' measurement systems can ensure accuracy within ± 2% (Gingras 1995). The researches conducted in Ireland indicate that measurement accuracy is mainly within ± 5%, however, cases when the accuracy was beyond ± 7% have been registered (Nieuwenhuis & Dooley 2006). In Russia regulatory documents allow measurement deviations and errors when determining round timber volumes within ± 5%.

Additional errors in defining parameters of fully loaded bundles based on harvester recorders are related to the specific character of diameter measurement. When measuring the diameter, if its value is greater than the value measured at the previous moment of time, then the value of the previous measurement is to be recorded. It allows neutralizing bumps on the stem and swells in places where knots grow, when defining the volume of log. However, these elements influence stacking factor of a bundle when putting logs into the load area.

The fourth reason of errors in calculations is associated with the determination of density of wood and log bark. The wood density varies not only depending on a tree height, but also on its diameter (Poluboyarinov 1976). Our researches have not taken into account wood density variation depending on diameter. An average value on a respective tree height has been used. Besides, density depends on moisture content of wood that can vary greatly depending not only on the period of time, but also on the place, where a tree grows in forest stand. We have used average moisture content of fresh wood as a reference in our studies. We have not taken into account variation of bark density as per stem length. An average value has been used.

The fifth reason is caused by the limitedness of the used the database that is unable to totally describe the whole variety of stem shapes of the trees on the territory under consideration.

4.4. Territorial applicability of results

Purpose of the research has been to assess the parameters of a bundle of wood assortments for Pryazha division of forestry of the Republic of Karelia. The results mostly describe the conditions of southern part of the Republic of Karelia (Fig. 1). For northern part of Karelia it can be expected that the obtained values for the parameters of bundles of logs would be in some way greater than those actually observed. It can be explained by the fact that the trees in the stands of northern part are smaller in size than in Pryazha division of forestry. The trees in the stands of Northern Ladoga area are bigger in size than in Pryazha division of forestry. This suggests that the parameters of bundles of logs received during from the computer experiment would, probably, be less than the actual ones for the conditions of Northern Ladoga area.

5. Conclusion

The research has presented the results of the evaluation of parameters of fully loaded bundles of logs from Pryazha division of forestry of the Republic of Karelia. This study was based on computer experiment and considerable amount of empirical data on tree stems. The results can be used by forwarder operators, producers of logging machines, harvest planners.

The study has shown substantial variability in the investigated parameters of bundles. The longer the assortments, which form a bundle, the greater the variability of parameters. Load capacity of the all investigated forwarder models, when transporting bundles formed from logs with length above 6 m, is insufficient. We recommend forwarder operators loading the load area by 3/4 at the most, when making up a bundle of 6 m long assortments. It will reduce the risk of load capacity excess.

For designers of logging machines, we recommend ensuring load capacity of at least 16 t with load area cross section of 4 m^2, and with the area of 4.8 m^2 – 19 t. Intermediate values can be found by interpolation. These values of load capacity do not consider the margin, which is usually 20–30%.

Acknowledgments

The researches have been performed within the frameworks of implementing grant of the President of the Russian Federation No. MK-5321.2018.8.

References

Bogdanov, E. I., Kozlov, B. A., Peych, N. N., 1981: Spravočnik po suške drevesiny. Moscow, Forest industry, 192 p.

Borovikov, A., M., Ugolev, B., N., 1989: Spravočnik po drevesine. Moscow, Forest industry, 296 p.

Cambi, M., Grigolato, S., Neri, F., Picchio, R., Marchi, E., 2017: Effects of forwarder operation on soil physical characteristics: a case study in the Italian Alps. Croatian Journal of Forest Engineering, 37:233–239.

Danilović, M., Stojnić, D., Karić, S., Sučević, M., 2014: Transport of Technical Roundwood by Forwarder and Tractor Assembly from Poplar Plantations. Nova mehanizacija šumarstva, 35:11–22.

Gerasimov, Y., Senkin, V., Väätäinen, K., 2012: Productivity of single-grip harvesters in clear-cutting operations in the northern European part of Russia. European Journal Forest Research, 131:647–654.

Gerasimova, Y., Sokolov, A., 2014: Ergonomic evaluation and comparison of wood harvesting systems in Northwest Russia. Applied Ergonomics, 45: 318–338.

Ghaffarian, M. R., Stampfer, K., Sessions, J., 2007: Forwarding productivity in Southern Austria. Croatian Journal of Forest Engineering, 28:169–175.

Gingras, J-F., 1995: Recent Developments in Chip Cleaning and Cut-To-Length Harvesting Technologies in Finland. Forest Engineering Research Institute of Canada (FERIC) Eastern Division, Internal Report: IR-1995-06-01.

Golyakevich, S. A., Goronovskii, A. R., 2017: Evaluation of Loading Dynamics and Fatigue Life for a Forwarder Half-Frame Articulation. Journal of Machinery Manufacture and Reliability, 46:52–62.

Klvac, R., Fischer, R., Skoupy, A., 2012: Energy use of and emissions from the operation phase of a medium distance cableway system. Croatian Journal of Forest Engineering, 33:79–88.

Labelle, E. R., Jaeger, D., 2019: Effects of Steel Flexible Tracks on Forwarder Peak Load Distribution: Results from a Prototype Load Test Platform. Croatian Journal of Forest Engineering, 40:1–23.

Lijewski, P., Merkisz, J., Fuć, P., Ziółkowski, A., Rymaniak, L., Kusiak, W., 2017: Fuel consumption and exhaust emissions in the process of mechanized timber extraction and transport. European Journal of Forest Research, 136:153–160.

Manner, J., Nordfjell, T., Lindroos, O., 2013: Effects of the number of assortments and log concentration on time consumption for forwarding. Silva Fennica, 47:1–19.

Minette, L. J., Moreira, F. M. T., De Souza, A. P., Machado, C. C., Silva, K. R., 2004: Análise técnica e econômica do forwarder em três subsistemas de colheita de florestas de eucalipto. Rev Árvore, 28:91–97.

Mousavi., S. R., 2009: Comparison of productivity, cost and environmental impacts of two harvesting methods in Northern Iran: short-log versus long-log. Ph.D. Thesis. University of Joensuu, Finland.

Nieuwenhuis, M., Dooley, T., 2006: The Effect of Calibration on the Accuracy of Harvester Measurements. International Journal of Forest Engineering, 17: 25–33.

Nurminen, T., Korpunen, H., Uusitalo, J., 2006: Time consumption analysis of the mechanized cut-to-length harvesting system. Silva Fennica, 40:335–363.

Pandur, Z., Horvat, D., Šušnjar, M., Zoric, M., Kneževic, M., 2015: Load space utilization of a Valmet 860.4 forwarder. Proceedings of the 48th FORMEC Symposium 2015 Oct 4 – 8, 2015, Linz, Austria, p. 271–275.

Petaja, G., Kaleja, S., Zimelis, A., Lazdins, A., 2018: Comparison of productivity of standard and accumulating forwarder grapple in thinning. Engineering for rural development, p. 1366–1371.

Poluboyarin, O., N., 1976: Plotnosť drevesiny. Moscow, Forest industry, 160 p.

Proto, A. R., Macrì, G., Visser, R., Visser, R., Harrill, H., Russo, D. et al., 2018a: A Case Study on the Productivity of Forwarder Extraction in Small-Scale Southern Italian Forests. Small-Scale Forestry, 17:71–87.

Proto, A. R., Macrì, G., Visser, R., Visser, R., Harrill, H., Russo, D. et al., 2018b: Factors affecting forwarder productivity. European Journal Forest Research, 137:143–151.

Raymond, K. A., 1989: Mechanised shortwood thinning with forwarder extraction (Project Report 42). New Zealand Logging Industry Research Association, p. 1–17.

Sever, S., 1988: Proizvodnost i perfomanse forvardera u radovima privlacenja drva. Mehanizacija Sumarstva, 18:59–87.

Sirén, M., Salmivaara, A., Ala-Ilomäki, J., Launiainen, S., Lindeman, H., Uusitalo, J. et al., 2019: Predicting forwarder rut formation on fine-grained mineral soils. Scandinavian Journal of Forest Research, 34:145–154.

Slamka, M., Radocha, M., 2010: Results of harvesters and forwarders operations in slovakian forests. Lesnícky časopis - Forestry Journal, 56:1–15.

Talbot, B., Nordfjell, T., Suadicani, K., 2003: Assessing the Utility of Two Integrated Harvester-Forwarder Machine Concepts Through Stand-Level Simulation. International Journal of Forest Engineering, 14:31–43.

Tiernan, D., Zeleke, G., Owende, P. M. O., Kanali, C. L., Lyons, J. et al., 2004: Effect of working conditions on forwarder productivity in cut-to-length timber harvesting on sensitive forest sites in Ireland. Biosystems Engineering, 87:167–177.

Tsyvin, M. M., 1973: Ispoľzovanije drevesnoj kory. Moscow, Forest industry, 96 p.

Tufts, R. A, Brinker, R. W., 1993: Productivity of a Scandinavian system while second thinning pine plantations. Forest Products Journal, 43:24–32.

Tufts, R. A., 1997: Productivity and cost of the Ponsse 15–series, cut–to–length harvesting system in southern pine plantations. Forest Products Journal, 47:39–46.

Voinash, A. S., Vonash, S. A., 2011: Issledovanije vlijanija rejsovoj nagruzki na prochodimosť guseničnogo sortimentovoza. Forest Journal, 5:47–53.

Vossbrink, J., Horn, R., 2004: Modern forestry vehicles and their impact on soil physical properties. European Journal Forest Research, 123:259–267.

Wang, J., LeDoux, C. B., Yaoxiang, L., 2005: Simulating cut-to-length harvesting operations in Appalachian hardwoods. International Journal of Forest Engineering, 16:11–27.

Cent. Eur. For. J. 66 (2020) 23–36 sciendo DOI: 10.2478/forj-2019-0026

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Effect of climate and air pollution on radial growth of mixed forests: *Abies alba* Mill. vs. *Picea abies* (L.) Karst.

Petr Mikulenka[1], Anna Prokůpková[2], Zdeněk Vacek[2]*, Stanislav Vacek[2], Daniel Bulušek[2], Jaroslav Simon[1], Václav Šimůnek[2], Vojtěch Hájek[2]

[1] *Mendel University Brno, Faculty of Forestry and Wood Technology, Zemědělská 1/1665, CZ – 613 00 Brno, Czech Republic*

[2] *Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, CZ – 165 21 Prague 6 - Suchdol, Czech Republic*

Abstract

Norway spruce (*Picea abies* [L.] Karst.) and silver fir (*Abies alba* Mill.) are main tree species of Central Europe that are currently highly vulnerable in times of global climate change. The research deals with the effect of climate and air pollution on radial growth of silver fir and Norway spruce in mixed age-varied (56 – 146 years) forests in the Jeseníky Protected Landscape Area, the Czech Republic. The objectives were to evaluate biodiversity, structure and production, specifically interaction of radial growth of fir and spruce to air pollution (SO_2, NO_X, tropospheric ozone) and climatic factors (precipitation, air temperature). Concentration of SO_2 and NO_X had negative effect on radial growth of fir, while radial growth of spruce was more negatively influenced by tropospheric ozone. Fir showed higher variability in radial growth and was more sensitive to climatic factors compared to spruce. On the other hand, fir was relatively adaptable tree species that regenerated very well when the pressure of stress factors subsided (air pollution load, Caucasian bark beetle, frost damage). Low temperature was a limiting factor of radial growth in the study mountainous area, especially for fir. Fir was significantly sensitive to late frost, respectively, spruce to winter desiccation and spring droughts with synergism of air pollution load. Generally, older forest stands were more negatively influenced by air pollution load and climatic extremes compared to young trees.

Key words: silver fir; Norway spruce; tree-ring dating; stand structure; biodiversity; Central Europe

---

Editor: Bohdan Konôpka

---

1. Introduction

Silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* [L.] Karst.) are the most productive of native European coniferous tree species (Korpeľ et al. 1982). Silver fir is a tree species currently growing in Central and Southern Europe (Korpeľ et al. 1982). Its range is relatively small, rather local, more or less coinciding with the distribution of mountain massifs and zones. Fir is predominantly a mountain species that, in the northern part of its area, descends to the hills or, marginally, lowlands (Hejný & Slavík 1997). In warm climate areas it moves to higher altitudes (Musil & Hamerník 2007). It is a species of oceanic climate with mild winters and with demands for sufficient moisture during the year (Bernadzki 2008). Silver fir suffers from strong winter frosts. Long-lasting low temperatures result in the formation of false heart (Úradníček et al. 2001). In the Czech Republic, fir concentrates in lower mountain areas. Its optimum is on gleyed and waterlogged soils at 500–900 m a.s.l. (Hejný & Slavík 1997). Particular attention has been paid to the importance of fir in silviculture and to the consequences of its decreasing numbers in Europe since the 16th century (Cramer 1984; Larsen 1986). In the course of the last century, the reduction in numbers continued in many places (Gömöry et al. 2004) and today, both natural and anthropogenic stresses often contribute to the mortality of fir individuals (Bošeľa et al. 2014). In spite of that, fir and fir-mixed forests make up an important part of the central and south-eastern European landscape (EEA 2006; Bošeľa et al. 2018). On the other hand, Norway spruce has a continuous distribution in Northern Europe and islet in the mountains of Central and Southern Europe (Auders & Spicer 2012; Farjon & Filer 2013). In the Czech Republic, spruce occurs in the Hercynian-Carpathian region, where it grows in almost all the mountains at 700–1350 m a.s.l. (Úradníček et al. 2009). Spruce grows predominantly on poor soils of podzol and cambisol (Binkley & Fisher 2013), where, how-

---

*Corresponding author. Zdeněk Vacek, e-mail: vacek@fld.czu.cz ever, nitrogen deposition has increased forest growth in recent decades (Viet et al. 2013; Meunier et al., 2016). Spruce is very sensitive to air pollution (especially SO_2) and droughts (Godek et al. 2015; Vacek et al. 2017, 2019). Significant disturbances in spruce stands are also caused by windstorms and bark beetle outbreaks (Čada et al. 2013; Vacek et al. 2015), especially in the context of the advancing global climate change (Hanewinkel et al. 2013).

Global climate change puts pressure on forest ecosystems (Bonan 2008; Usbeck et al. 2010; Čater & Diaci 2017), with tree growth most affected by rising temperatures and drought (Frank et al. 2015; Hartmann et al. 2015). In general, these factors make trees more vulnerable to forest insects and pathogens (Choat et al. 2012; Anderegg et al. 2013). Consequently, a number of studies supply evidence that climatic factors also significantly affect the growth of silver fir (Gentilesca & Todaro 2008; Koprowski 2013). In many areas, withering of firs is directly ascribed to climate change (Hanewinkel et al. 2013; Boettger et al. 2014; Konôpková et al. 2018). Accordingly, some authors suggest that fir can achieve greater productivity in mixed stands (Toïgo et al. 2015) and also that fir growth sensitivity to summer droughts is lower in mixed stands (Metz et al. 2016; Vitali et al. 2017).

In relation to climate variability, changes in the radial growth of trees and in the sequence of phenological features and their ecological species amplitude occur, whereas these changes are affecting the dynamics of the communities (Rita et al. 2014). Climate change, however, also indirectly contributes to more frequent dry seasons that are consistent with a potential 4–27% reduction in precipitation in Europe (Ripullone et al. 2009), primarily in summer (Gao & Giorgi 2008). In particular, warm summers and repeated drought significantly affect the health of fir and spruce (Büntgen et al. 2014; Gazol et al. 2015; Konôpková et al. 2018). The largest decline in fir growth has been recorded in the southern part of its area (Battipaglia et al. 2009; Cailleret & Davi 2010). Hand in hand with the anticipated increase in climatic extremes (Coumou & Rahmstorf 2012; Kogan et al. 2013) species diversity of forest ecosystems is expected to alter in many places (McDowell & Allen 2015). This is in line with the fact that climate warming leads to shifts in species areas in response to a change in their climate optimum, with major impacts at the margins of the species areas (Davis et al. 2005; Lenoir et al. 2009; Hernández et al. 2019). From this point of view, fir is supposed to be one of the species that will replace spruce in many places because fir is more resistant to drought than spruce (Vitali et al. 2018).

Changing climate conditions will, in the future, call for emphasis on responsible, close-to-nature management based on detailed knowledge of species-specific growth responses, climate change-induced stimuli (Bolte et al. 2009; Elliott et al. 2015). Growth responses should then be investigated through annual ring increments of individuals, as annual tree-rings provide detailed retrospective information on tree growth under previous conditions of ecosystem environments (Altman et al. 2017; Sohar et al. 2017) and reliably reflect the link between growth, climatic and extreme climatic phenomena (Gazol et al. 2016; Bhuyan et al. 2017). The specific environmental conditions are usually reflected in the annual rings' width (Koprowski 2013). Some factors, such as frost or summer drought, may have an immediate effect on the ring width, while other factors such as winter drying may affect the rings with delay because growth tissues are relatively calm during winter months (Putalová et al. 2019). The effect of different environmental factors therefore causes different annual ring widths and structures that systematically alter the tree's growth dynamics (Fritts 1976; Cukor et al. 2019a, b).

In addition to climate, air pollution also has a significant impact on radial growth (Elling et al. 2009; Diaci 2011; Boettger et al. 2014; Bošeľa et al. 2014), as fir was considered one of the species most sensitive to air pollution (Wentzel 1980; Ulrich 1981). A strong air pollutant load, in particular, decreases the ring width significantly (Sander & Eckstein 2001; Wilczyński 2006). However, other environmental stimuli, especially insect pests, fungal pathogens etc., also influence the variability of the ring width (Schweingruber 1996). A decline of the fir during the period of air pollution ecological disasters was often associated with the damage of fir stands caused by the Caucasian fir gall aphid (*Dreyfusia nordmannianae*) and the balsam woolly aphid (*Dreyfusia piceae*) – (Mrkva 1994). Pathogenic infections also contributed to the deterioration of fir health (Brill et al. 1981; Blaschke 1982). These environmental stimuli usually manifest and pass too quickly to be a reliable indicator of forest ecosystem degradation (Godek et al. 2015). However, temporal weather anomalies within growth trends can be separated, as they are similar in all stands of the same species in the area, whether air-polluted or not; it is similar in the case of biotic pests (Ferretti et al. 2002; Sensuła et al. 2015). In recent years, increased regeneration and recovery of fir growth trend has been observed in a number of places where pollution has been reduced (Elling et al. 2009; Hauck et al. 2012).

This paper evaluates the effect of climate and air pollution on the radial growth of fir and spruce mixed age-varied forest stands cultivated by close-to-nature methods in the Jeseníky Mts. The objectives were 1) to determine structure, biodiversity and production parameters of fir-spruce mixed forest stands, 2) to compare the dynamics of radial growth of fir and spruce and their differences, 3) to describe the effect of air pollution load (SO_2, NO_X, tropospheric ozone), climatic factors (temperature, precipitation) and pathogenic infections on growth of both the study tree species and 4) to estimate the relationship between climate, air pollution and radial growth of fir and spruce.

2. Material and methods

2.1. Study area

The area of interest is located in the Jeseníky Protected Landscape Area, in the east part of the Czech Republic. The study site belongs to the gene reserve of GZ 160-3 Hofwald silver fir and is located at the foothills of the Hrubý Jeseník mountain range on 136.4 ha at an altitude of 625–725 m a.s.l. The area serves for protection and reproduction of gene diversity of an important population of silver fir. The silver fir stands are richly structured, belonging to special-purpose forests and managed in the selection and shelterwood system. The annual temperature of the locality is 6.4 °C, and the annual precipitation varies around 705 mm. The vegetation period lasts 130 days. The geological base consists mainly of phyllites, partially quartzites and sediments. Mesotrophic cambisols are the predominant soil type, with sporadic pseudogleys and gleys.

Tree species composition include 40% silver fir and 20% Norway spruce. European beech (*Fagus sylvatica* L.), sycamore maple (*Acer pseudoplatanus* L.), European white birch (*Betula pendula* Roth.) and European larch (*Larix decidua* Mill.) are admixed, with black alder (*Alnus glutinosa* [L.] Gaertn.) on soils affected by water. The communities belong to the association *Luzulo-Abietetum albae* Oberdorfer 1957. Localization of permanent research plots (PRP) is shown in Fig. 1 and a summary of the PRP basic data is given in Table 1.

2.2. Data collection

Field-Map technology (IFER-Monitoring and Mapping Solutions Ltd.) was used to determine the structure of the tree layer of mixed forest stands on five PRP of 50 × 50 m (0.25 ha) in 2018. The positions of all trees with diameter at breast height (DBH) ≥ 7 cm were localized. The height of the live crown base and the crown diameter were also measured in the tree layer, at least in 4 directions perpendicular to each other. Diameters of the tree layer were measured by a Mantax Blue metal calliper (Haglöf, Sweden) with an accuracy of 1 mm and heights were measured using a Vertex laser hypsometer (Haglöf, Sweden) with an accuracy of 0.1 m.

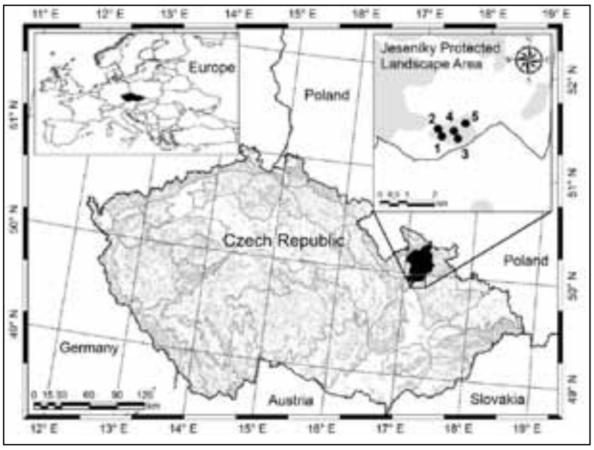


Fig. 1. Localization of mixed stands of silver fir and Norway spruce on permanent research plots Janovice 1–5 in the Jeseníky Protected Landscape Area; grey colour indicates forest cover.

Data for radial growth analysis was obtained by taking cores at a height of 1.3 m by a Pressler borer (Mora, Sweden) from 20 live dominant and co-dominant fir and spruce trees. The core samples were randomly (RNG function in Excel) taken from trees in upslope/downslope direction in spring 2019. Annual ring widths were measured with an accuracy of 0.01 mm by an Olympus binocular microscope on the LINTAB measuring table and recorded with TsapWin software (Rinntech).

2.3. Data analysis

The basic structure, diversity and production characteristics of the tree layer were evaluated by the SIBYLA 5.1. forest growth simulator (Fabrika & Ďurský 2005). The stand volume was calculated according to Petráš & Pajtík (1991). The relative stand density index (SDI; Reineke 1933), the crown closure (CC; Crookston & Stage 1999) and the crown projection area (CPA) were observed for each plot. The maximum SDI value was derived from the model of the yield tables (Halaj et al.

Table 1. Overview of the basic site and stand characteristics of the permanent research plots in 2018 according to Forest Management Plan.

PRP	GPS	Altitude [m]	Exposition	Slope [°]	Forest site type	Geology	Soils	Tree species, proportion [%]	Age [y]	Stand volume [m^3 ha^{-1}]
1	49°56.638'N 17°13.515'E	695	SE	7	5K	phyllite	cambisol	AA 20, PA 50, LD 25, FS 5	146	639
2	49°56.632'N 17°13.408'E	710	E	3	5K	quartzite	cambisol	AA 15, PA 60, LD 24, FS 1	139	605
3	49°56.573'N 17°13.817'E	660	SE	3	5O	sediment	gleysol	AA 45, PA 50, AG 5	56	387
4	49°56.604'N 17°13.785'E	670	SE	3	5O	sediment	gleysol	AA 30, PA 65, AG 5	60	398
5	49°56.701'N 17°13.930'E	675	SE	4	5K	sediment	cambisol	AA 40, PA 60	85	501

Notes: forest site type: 5O – *Fageto-Abietum variohumidum mesotrophicum*, 5K – *Abieto-Fagetum acidophilum*; tree species: AA – silver fir (*Abies alba* Mill.) PA – Norway spruce (*Picea abies* [L.] Karst.), LD – European larch (*Larix decidua* Mill.) FS – European beech (*Fagus sylvatica* L.), AG – black alder (*Alnus glutinosa* [L.] Gaertn.).

1987). Periodic annual increment (PAI) was derived for a period of 5 years. Diversity was evaluated by species richness (Margalef 1958), species heterogeneity (Shannon 1948), species evenness (Pielou 1975), Arten-profile index (Pretzsch 2006), diameter and height differentiation (Füldner 1995), crown differentiation and total stand diversity (Jaehne & Dohrenbusch 1997; Table 2).

In order to date the core samples (16–20 analysed samples per tree species on each PRP) and eliminate the errors associated with an occurrence of missing tree-rings, each incremental series was cross-dated using the PAST4 statistical tests (Knibbe 2007) and subsequently subjected to visual inspection according to Yamaguchi (1991). If a missing ring was found, a ring of 0.01 mm width was inserted in its place. A 100-year spline in PRP 1 and 2, 50-year spline in PRP 3 and 4, and 70-year spline in PRP 5 were used to eliminate the age trend. Detrending was made in R, in the Dplr package. The main dendrochronological character indices were calculated, as described by methodology according to Bunn & Mikko (2018), focusing on characterising each plot and tree species separately. The expressed population signal (EPS) was calculated for detrended data sets that indicates the reliability of a chronology as a fraction of the join variance of a theoretically infinite tree population, signal to noise ratio (SNR) that evaluates the signal strength of the chronology and R-bar inter-series correlation (Fritts 1976).

The analysis of negative pointer years characterizing extreme low radial growth was done according to Schweingruber (1996). For each tree the pointer year was tested as an extremely narrow tree-ring that does not reach 40% of the increment average from the four preceding years. The occurrence of the negative year was proved if such a strong reduction in increment occurred at least in 20% of trees on the PRP.

Data from air pollution monitoring stations and meteorological stations were used to derive air pollutant and climatic factors. An analysis of air pollution situation by SO_2, NO_X and the tropospheric ozone mean and maximum concentrations in the growing season was performed using available data from the Košetice station (1993–2017; 532 m a.s.l.; GPS 49.5735N 15.0803E). Tropospheric ozone concentration for forest was characterized by exposure index AOT40F (Werner & Spranger 1996). Climatic factors (air temperature and precipitation) conditions were evaluated on the basis of data from the Světlá Hora meteorological station covering the years (1970–2018; 628 m a.s.l.; GPS 50.9448N, 17.2295E). The development of air temperature and precipitation conditions was studied on the basis of a mean annual air temperature, air temperature in (non-) growing season, air temperature in individual months, annual sum of precipitation, sum of precipitation in (non-) growing season and sum of precipitation in individual months.

The standardized (detrended) tree-ring index series from the PRP were correlated by the Pearson correlation coefficient with the climate data (precipitation, air temperatures) and air pollution data (SO_2, NO_X and tropospheric ozone concentrations) in the Statistica 12 (StatSoft, Tulsa). The DendroClim software (Biondi & Waikul 2004) was used to model radial growth depending on climate monthly characteristics. Unconstrained principal component analysis (PCA) in Canoco 5 (Šmilauer & Lepš 2014) was used to analyse relationships between growth of fir and spruce on the PRPs, climatic factors and air pollution data in 1993–2017. Data were log-transformed, centred and standardized before the analysis.

3. Results

3.1. Structure and biodiversity of the stands

The number of live trees ranged between 336 – 816 trees ha^{-1} with the stand density index of 0.62 – 0.88 in 2018 (Table 3). The mean basal area was in range of 43.4 – 53.3 m^2 ha^{-1}. The stand volume ranged from 486 m^3 ha^{-1} (PRP 3) to 594 m^3 ha^{-1} (PRP 5). Fir had the largest stand volume (74.2 and 54.6%) on two PRP (3 and 4), and spruce (65.9, 60.2 and 68.0%) on three PRP (1, 2 and 5). European larch occurred only on two PRP and its share was marginal (2.2 and 4.3%). The periodic annual increment was 7.7–10.8 m^3 ha^{-1} y^{-1} and the mean annual increment varied between 8.1–9.9 m^3 ha^{-1} y^{-1}.

In terms of species diversity, species richness was low (*D* 0.157–0.298), species heterogeneity ranged from low to medium (*H´* 0.256–0.354) and species evenness shows moderate to very high species diversity (*E* 0.588–0.968; Table 4). The vertical structure was relatively variable (*A* 0.428–0.675), ranging from moderately diversified (PRP 1, 2, 4, 5), consisting of two storeys, up to a substantially diversified spatial structure (PRP 3) which consists of 3 storeys. Füldner's index of height (TM_h 0.132–0.532) and diameter (TM_d 0.252–0.580) differentiation points to stands with mostly low (PRP 1, 3, 4, 5) to medium (PRP 2) structural differentiation. In terms of total stand

Table 2. Overview of indices describing the stand diversity and their common interpretation.

Criterion	Quantifiers	Label	Reference	Evaluation
Species diversity	Richness	D (Mai)	Margalef (1958)	minimum D = 0, higher D = higher values
	Heterogeneity	H´ (Si)	Shannon (1948)	minimum H´ = 0, higher H´ = higher values
	Evenness	E (Pii)	Pielou (1975)	range 0–1; minimum E = 0, maximum E = 1
Vertical diversity	Arten-profile index	A (Pri)	Pretzsch (2006)	range 0–1; balanced vertical structure A < 0.3; selection forest A > 0.9
Structure differentiation	Diameter dif.	TM_d (Fi)	Füldner (1995)	range 0–1; low TM < 0.3; very high differentiation TM > 0.7
	Height dif.	TM_h (Fi)		
	Crown dif.	K (J&Di)	Jaehne & Dohrenbusch (1997)	low K < 1; very high differentiation K > 3
Complex diversity	Stand diversity	B (J&Di)	Jaehne & Dohrenbusch (1997)	monotonous structure B < 4; uneven structure B = 6–8; very diverse structure B > 9

Table 3. Structural and production characteristics on permanent research plots 1–5 in 2018.

PRP	Age [y]	dbh [cm]	h [m]	v [m^3]	N [trees ha^{-1}]	BA [m^2 ha^{-1}]	V [m^3 ha^{-1}]	PAI [m^3 ha^{-1} y^{-1}]	MAI	CC [%]	CPA [ha]	SDI
						Abies alba						
1	146	22.0	11.78	0.465	352	13.1	164	2.6	2.73	44.8	0.59	0.25
2	139	38.8	23.74	1.563	144	16.6	225	3.5	3.75	32.4	0.39	0.26
3	56	32.4	23.75	0.902	400	33.0	361	7.5	6.02	70.1	1.21	0.54
4	60	27.4	21.20	0.599	480	28.3	288	7.1	4.80	78.9	1.55	0.49
5	85	41.3	29.41	1.692	112	15.0	189	3.7	3.15	50.2	0.70	0.22
						Picea abies						
1	146	43.6	30.20	1.901	192	28.5	365	4.1	6.08	49.3	0.68	0.38
2	139	42.5	27.62	1.768	192	26.8	340	4.2	5.67	48.8	0.67	0.37
3	56	30.3	23.24	0.710	176	12.7	125	1.9	2.08	39.7	0.51	0.20
4	60	30.8	23.22	0.711	320	23.8	228	3.3	3.80	65.6	1.07	0.37
5	85	38.5	27.14	1.330	304	35.2	404	4.1	6.73	75.8	1.42	0.50
						All tree layer						
1	146	30.5	17.96	0.911	608	43.9	554	6.8	9.23	77.4	1.49	0.68
2	139	40.7	25.96	1.680	336	43.4	565	7.7	9.42	65.4	1.06	0.62
3	56	31.8	23.59	0.843	576	45.6	486	9.4	8.10	82.0	1.71	0.73
4	60	28.9	22.08	0.646	816	53.3	527	10.8	8.78	93.2	2.69	0.88
5	85	39.3	27.75	1.428	416	50.2	594	7.6	9.90	88.0	2.12	0.72

Notes: Age – mean stand age, dbh – mean quadratic diameter at breast height, h – mean height, v – mean tree volume, N – number of trees per hectare, BA – basal area, V – stand volume, PAI – periodic annual increment, MAI – mean annual increment, CC – canopy closure, CPA – crown projection area, SDI – stand density index.

Table 4. Biodiversity of tree layer on permanent research plots 1–5 in 2018.

PRP	D (Mai)	H′ (Si)	E (Pii)	A (Pri)	TM$_d$ (Fi)	TM$_h$ (Fi)	K (J&Di)	B (J&Di)
1	0.157	0.354	0.588	0.531	0.300	0.256	1.983	7.320
2	0.298	0.289	0.960	0.488	0.580	0.532	1.720	5.630
3	0.166	0.256	0.850	0.675	0.291	0.176	0.805	3.917
4	0.172	0.342	0.717	0.551	0.300	0.183	0.938	5.236
5	0.161	0.265	0.880	0.428	0.252	0.132	0.784	3.506

Notes: D – species richness index, H′ – species heterogeneity index (entropy), E – species evenness index, A – Arten-profile index, TM$_d$ – diameter differentiation index, TM$_h$ – height differentiation index, K – crown differentiation index, B – total diversity index.

diversity, PRP 3 and 5 show monotonous structure (*B* 3.506–3.917), PRP 2 and 4 even structure (*B* 5.236–5.630) and PRP 1 shows uneven structure (B = 7.630). The crown differentiation ranges from fairly low (PRP 3–5) to moderate (PRP 1 and 2). Generally high biodiversity was on older (139–146 y) mature forest stands on PRP 1–2 compared to younger stands (56–85 y) on PRP 3–5.

3.2. Tree-ring characteristics

Characteristics of dendrochronology analysis are numerically described in Table 5 that shows basic indicators. Average tree-ring width was the lowest on PRP 1 in spruce (1.63 mm ± 0.69 SD) and on PRP 2 in fir (1.63 mm ± 0.98 SD) on the oldest PRP, while the highest increment was on PRP 3 in spruce (3.84 mm ± 1.39 SD). Generally, the higher radial growth was in spruce compared to fir (except PRP 1). Expression population signal value shows a high number in PRP 4 (0.944 and 0.903), but EPS was significant (significant EPS level is 0.850) in both tree species on all PRP except fir on PRP 2 (0.849). SNR value shows that best chronology (without noise) was in fir on PRP 3 and 4 (16.938 and 11.353). The highest SNR noise was described in fir on the oldest PRP 1 and 2 (3.078 and 5.260). First-order autocorrelation shows values ranging from 0.654 to 0.844 and R-bar from 0.241 to 0.504.

3.3. Dynamics of radial growth of fir and spruce

Significant negative years with low radial increment were observed in older stands on PRP 1, 2 and 5 and in one case on PRP 3 (Table 6). Significant decrease in radial growth was observed especially in fir (3–5 significant years) compared to spruce (1–3 significant years). On

Table 5. Characteristics of the tree-ring chronologies of fir and spruce on permanent research plots 1–5.

PRP	Species	No. of trees	SD	Mean [mm]	ar1	R-bar	EPS	SNR
1	SP	18	0.69	1.63	0.762	0.311	0.879	7.265
	AA	17	0.97	1.69	0.835	0.267	0.859	5.260
2	SP	18	0.89	1.75	0.784	0.329	0.889	8.001
	AA	16	0.98	1.63	0.844	0.241	0.849	3.078
3	SP	20	1.39	3.84	0.723	0.288	0.854	5.830
	AA	20	1.29	3.60	0.654	0.405	0.919	11.353
4	SP	19	1.38	3.32	0.773	0.354	0.903	9.302
	AA	20	1.17	2.89	0.731	0.504	0.944	16.938
5	SP	17	1.23	2.93	0.752	0.380	0.894	8.449
	AA	20	1.31	2.65	0.814	0.367	0.899	8.895

Notes: No. of trees – number of analyzed samples, SD – standard deviation, ar1 – first-order autocorrelation, R-bar – inter-series correlation, EPS – expression population signal, SNR – signal-to-noise ratio.

PRP 1, 2 and 5, the radial dynamics of fir showed decrease caused by the Caucasian fir gall aphid in synergism with air pollution in 1970–1982 (Fig. 2). Significant negative years with low radial increment of fir in 1929, 1933, 1956, 1962 and 1996 were caused by cold years, when the assimilation apparatus was damaged by late frosts. In 1996, the mean coldest temperature from January to March was measured (−5.3 °C in 1996, mean −1.5 °C).

Table 6. Significant negative pointer years characterizing extreme low radial growth of fir and spruce on permanent research plots 1–5.

Negative pointer years	Silver fir	Norway spruce
PRP 1	1929, 1956, 1962, 1996	1948, 1993
PRP 2	1929, 1933, 1956, 1972, 1996	1980, 1993, 2004
PRP 3	—	1965
PRP 4	—	—
PRP 5	1962, 1979, 1996	—

In spruce, significant negative year 1993 was characterized by the synergism of the highest max. SO_2 concentration (140 µg m^{-3}, mean 38 µg m^{-3}) in the observed period and a lack of precipitation (28 mm, mean 52 mm) on the beginning of growing season (March–May). More significant winter desiccation also occurred in the early spring of 1948 and in 1992–1995. Reduced increment in spruce in 2004 was caused by low precipitation in the growing season. In the study period, several increases in radial growth were observed due to favourable climatic conditions, but also because of silviculture intervention, especially in younger forest stands. For example, on PRP 4 due to strong competition, thinning of 34 m^3 ha^{-1} was carried out in 2006 and the radial increment subsequently increased (Fig. 2).

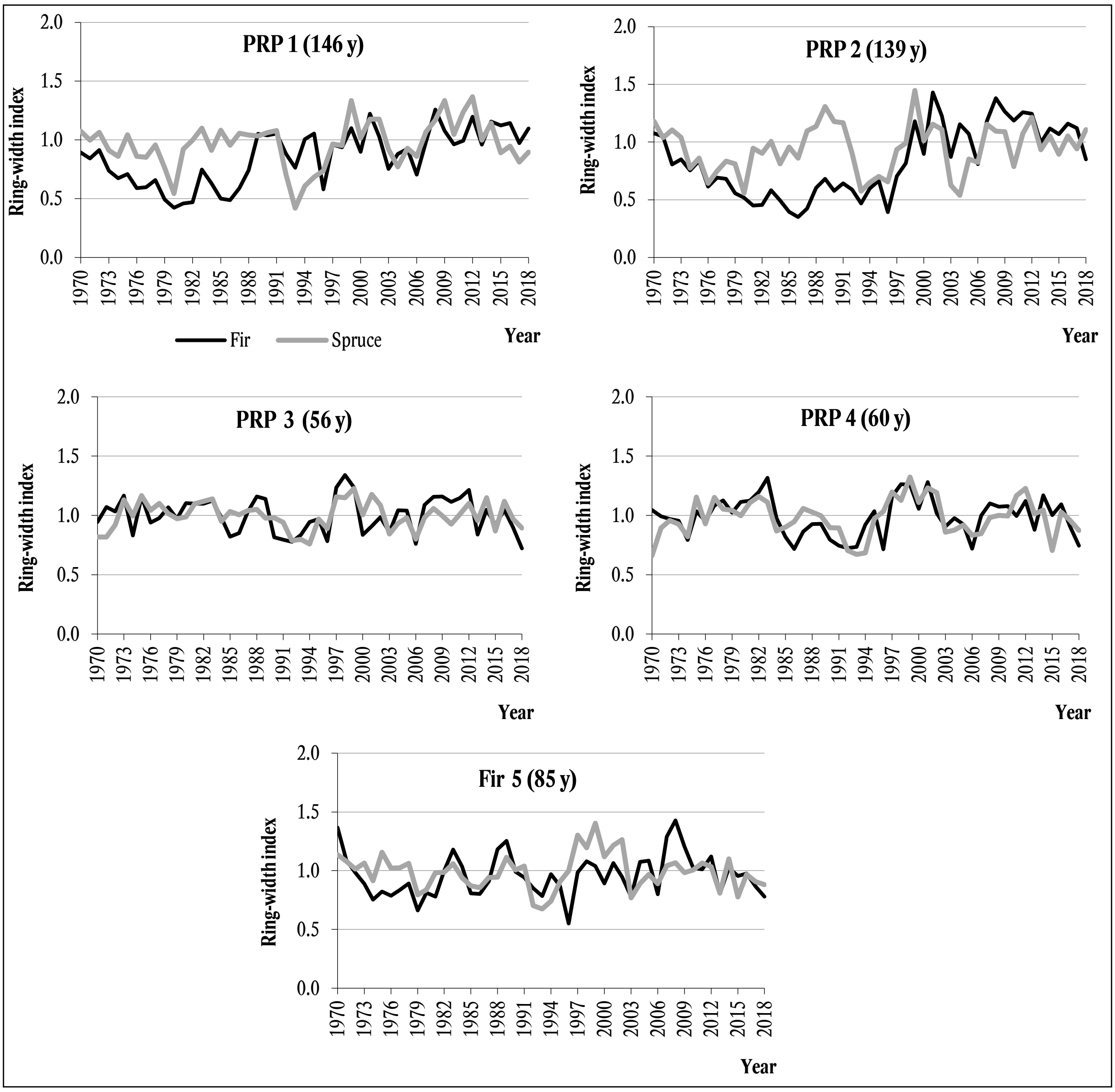


Fig. 2. Standardized mean chronology of silver fir (black line) and Norway spruce (gray line) in 1970–2018 expressed by the tree-ring index on permanent research plots 1–5 (the number of samples in 1970 – PRP 3: spruce 50% and fir 75%; PRP 4: spruce 58% and fir 75%; PRP 1, 2 and 5 100% of spruce and fir; in 1978 100% of samples on PRP 1–5).

Generally, the higher variability in radial growth was observed in fir (± 0.20 SD) in 1970– 2018, while the standardized mean site chronology of spruce was relatively more balanced (± 0.16 SD) with partial fluctuations (Fig. 2). Since 1993 the comparable situation in growth variability (± 0.18 SD) has been observed in both tree species. The variability of radial growth was increasing with age of trees, while the highest fluctuation was on PRP 1 and 2 (136–146 y; ± 0.23 SD) and the lowest on PRP 3 and 4 (56–60 y; ± 0.14 SD).

3.4. Effect of climatic factors on radial growth of fir and spruce

Climatic analyses in relation to radial growth showed several significant ($\alpha = 0.05\%$; $r = -0.34$–0.36) months in 1970–2018 (Fig. 3). Radial growth of fir was more sensitive to monthly temperature and precipitation compared to spruce. To be precise, on the oldest PRP 1, fir was the most sensitive to climatic factors (8 significant months) from all variants (PRP and tree species). The air temperature had significant effect on radial growth of fir

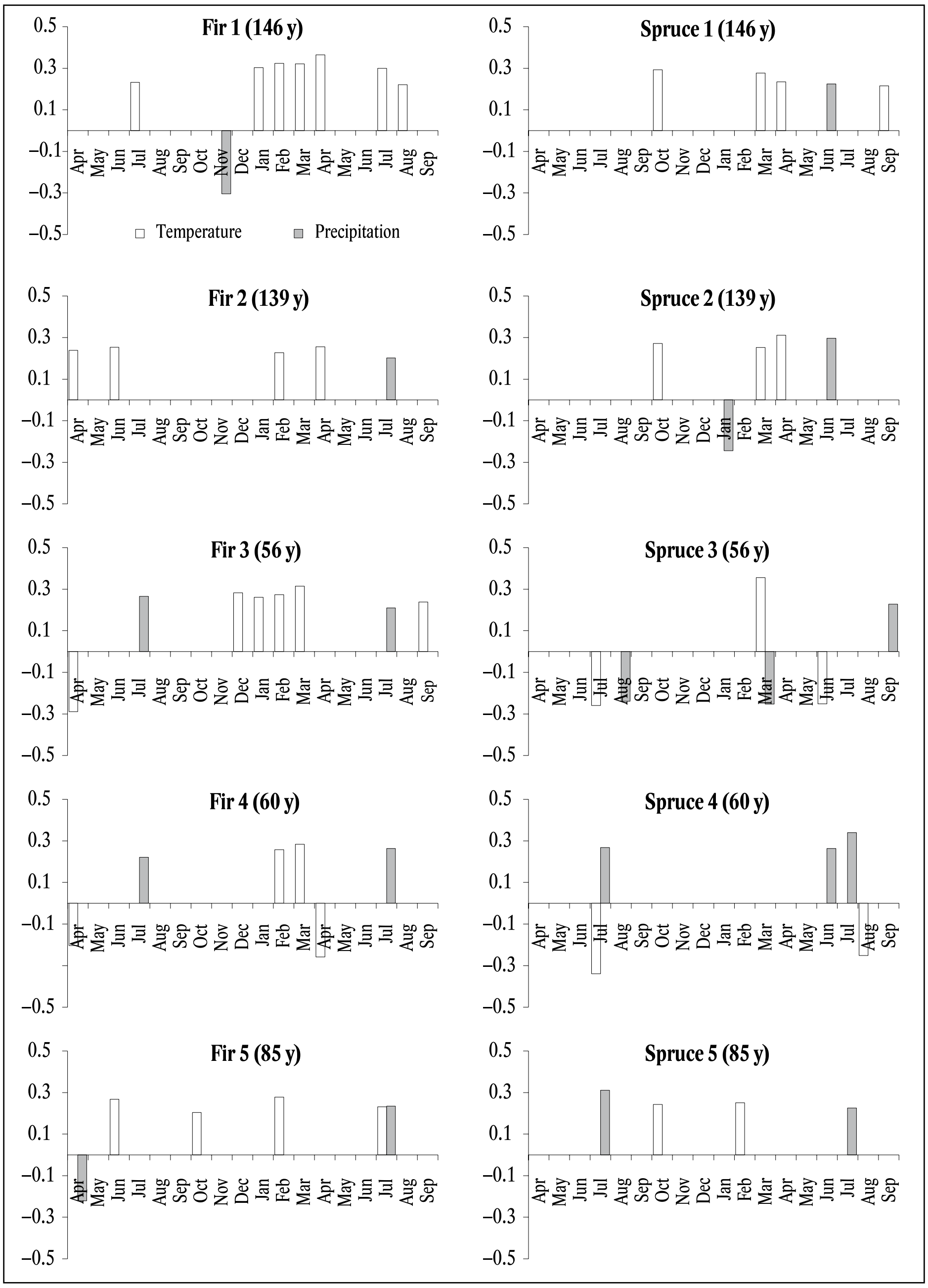


Fig. 3. Correlation coefficients of the standardized tree-ring index chronology of silver fir (left) and Norway spruce (right) with the monthly air temperature (white colour) and precipitation (grey colour) from April to December of the preceding years (capitals) and from January to September of the current year (lower case) on permanent research plots 1–5 in 1970–2018. Only correlation coefficients of statistically significant values are presented ($\alpha = 0.05\%$).

compared to low impact of precipitation. The effect of air temperature was prevailingly positive on all PRP, while in spruce on PRP 3 and 4 the effect of temperature was negative. July (in precipitation) together with February, March and April (in air temperature) were the most significant months in relation to climate-sensitive on radial growth of fir.

In spruce, climate sensitivity of diameter increment was similar on all PRP (4–6 significant months) compared to high variability in fir (5–8 significant months). In younger forest stands, the effect of precipitation was prevailing or equable, while radial growth of spruce in older stands was more affected by air temperature. Diameter increment of spruce was positively correlated especially with the precipitation in June and with air temperature in October of the previous year and March of the current year (Fig. 3).

3.5. Interactions between radial growth, air pollution and climate

Maximum and mean SO_2 concentrations had significant negative effect on fir and spruce radial growth in the oldest stands on PRP 1 and 2 and in fir on PRP 5 ($p < 0.05$–0.001; Table 7). The highest effect of SO_2 concentration was observed in fir ($p < 0.01$) compared to spruce ($p < 0.05$). NO_X concentrations were in significant negative correlation with fir radial growth on PRP 1, 2 and 4 ($p < 0.05$–0.01), while no significant effect was observed in spruce. The mean AOT40F had a similarly negative effect on fir and spruce radial growth, especially on PRP 1 and 2. Conversely, maximum value of exposure index was in significant negatively correlation with spruce growth an all PRP ($p < 0.05$–0.01), while in fir it was observed only on two PRP. Generally, SO_2 and NO_X concentrations had higher effect on fir radial growth, while spruce diameter increment was more influenced by tropospheric ozone. The effect of air temperature on fir and spruce radial growth was significant. The highest effect on radial growth ($p < 0.001$) was exerted by mean annual air temperature of the current year, especially in fir. On the other hand, precipitation did not have any significant effect on the fir radial growth stands ($p > 0.05$) compared to two (on PRP 4 and 5) significant correlations ($p < 0.05$) with a sum of precipitation in the growing season of the current year.

The results of PCA are represented in an ordination diagram in Fig. 4. The first ordination axis explains 43.3% of data variability, the first two axes together explain 59.4% and the first four axes 75.2%. The x-axis illustrates the mean radial growth of fir stands along with ozone exposure index (AOT40F) and the second y-axis represents the sum of precipitation in the current year and in the growing season. SO_2 and NO_X concentrations (mean annual and maximum) were negatively correlated with radial growth of fir and spruce PRP 1 and 2, while ozone exposure index had prevailing negative effect on radial growth of spruce and silver fir on PRP 1 and 2. In relation to air pollution, SO_2 concentrations contribute greatly to the explained variability by the first principal component. On the other hand, precipitation, in terms of climatic factors, contributes less to the explained variability compared to air temperature, especially low effect of precipitation in the non-growing season was observed. Overall, the effect of air temperature on diameter increment was more significant in fir compared to spruce. Conversely, precipitation had higher effect on radial growth in spruce, both especially in the growing season in younger forest stands.

4. Discussion

On the European scale, increased forest ecosystem increment has been apparent since the 1970s, having been often attributed to rising air temperatures in combination with increased nitrogen deposition and increasing atmospheric CO_2 (De Vries et al. 2006; Bontemps et al. 2011). In the Czech Republic, however, the increment of stands has also been significantly limited by a number of negative factors during this period (Putalová et al. 2019;

Table 7. Correlation matrix describing interactions between radial growth of fir and spruce (on permanent research plots 1–5 and summary), precipitation and air temperature (1970–2018) and concentrations of SO_2, NO_X and AOT40F (1993–2017). Significant correlations are designated by * ($p < 0.05$) and ** ($p < 0.01$).

RWI	SO_2 mean	SO_2 max	NO_X mean	NO_X max	AOT40F mean	AOT40F max	Temp ActAnn	Temp ActVeg	Prec ActAnn	Prec ActVeg
Fir1	−0.49*	_−0.51**_	_−0.52**_	−0.33	_−0.58**_	−0.35	_0.61**_	0.43*	−0.18	−0.01
Fir2	_−0.87**_	_−0.83**_	−0.26	_−0.51**_	_−0.57**_	_−0.58**_	0.42*	0.26	−0.14	−0.03
Fir3	−0.17	−0.20	0.02	−0.19	−0.22	−0.32	0.02	−0.05	0.06	0.13
Fir4	−0.35	−0.39	−0.22	−0.41*	−0.39	−0.39	0.14	−0.04	0.16	0.22
Fir5	−0.47*	−0.50*	−0.20	−0.20	−0.42*	−0.31	0.34*	0.17	0.01	0.12
FirΦ	_−0.62**_	_−0.63**_	−0.28	−0.41	−0.50*	−0.47*	_0.45**_	0.25	−0.07	0.09
Spruce1	_−0.65**_	_−0.60**_	−0.03	−0.37	_−0.56**_	_−0.65**_	0.23	0.21	−0.05	0.08
Spruce2	_−0.54**_	−0.48*	−0.20	−0.18	_−0.51**_	−0.47*	_0.40**_	0.35*	−0.07	0.06
Spruce3	−0.31	−0.29	−0.15	−0.22	−0.45*	_−0.56**_	0.04	−0.12	0.15	0.23
Spruce4	−0.21	−0.17	−0.04	−0.26	−0.34	_−0.56**_	−0.06	−0.09	0.17	0.29*
Spruce5	−0.17	−0.14	−0.07	−0.24	−0.26	_−0.51**_	0.07	−0.08	0.18	0.34*
SpruceΦ	−0.45*	−0.40*	−0.09	−0.28	−0.48*	_−0.61**_	0.19	0.10	0.07	0.22

Notes: SO_2 (NO_X)mean – mean annual SO_2 (NO_X) concentration, SO_2 (NO_X)max – maximum SO_2 (NO_X) concentrations, mean (max) AOT40F – ozone exposure index, TempActAnn – mean annual air temperature of the current year, TempActVeg – mean air temperature in the growing season of the current year, PrecActAnn – annual sum of precipitation of current year, PrecActVeg – sum of precipitation in the growing season of the current year.

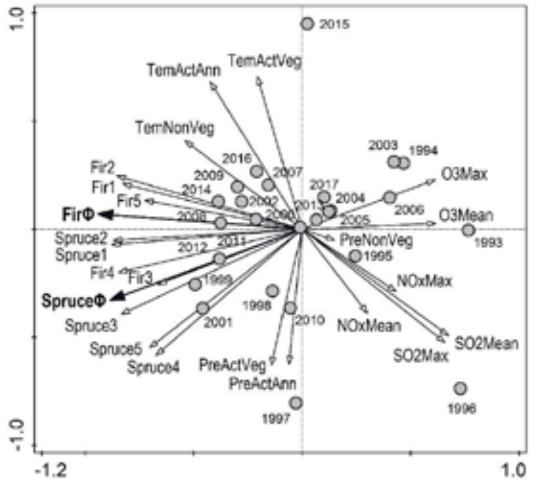


Fig. 4. Ordination diagram of PCA showing relationships between climate data (Tem – mean air temperature, Pre – sum of precipitation, Act – current year, Veg – growing season, NonVeg – non-growing season), ozone exposure index AOT40F and SO_2 and NO_X concentrations (mean – mean annual concentration, max – maximum concentration) and tree-ring width for fir and spruce on permanent research plots 1–5 and on average (Φ); codes ● indicate years 1993–2017.

Vacek et al. 2019). Our results clearly confirm this effect of various negative factors, both biotic and abiotic, on the radial increment of fir and spruce on the studied plots. Climatic factors showed considerable variability over the studied period: the increment at the beginning of the period was influenced by cold or frost damage, while at the end of the period, the effect of higher air temperatures and lower precipitation totals was more prominent, which is, essentially, in line with the climate change. Other climate change research led to similar results (Hanewinkel et al. 2013; Konôpková et al. 2018). Specifically, fir was affected not only by the climate but also by the Caucasian fir gall aphid and air pollution in our conditions. This confirms greater variability in radial growth in fir on the study PRP compared to spruce. Although after year 1993, the fir showed significant increase and stabilization in radial growth. Overall, fir proved to be significantly more sensitive to NO_X and SO_2 concentrations in comparison to spruce, especially in older forest stands. On the other hand, spruce was more sensitive to the ozone exposure index. Generally, older stands were more sensitive to the air pollution load, climatic factors and changes in comparison to younger forest, in which radial growth is more influenced by tree competition and silvicultural intervention.

The mixing of tree species in forest stands also plays an important role (Vacek et al. 2019). Vitali et al. (2017) reported lower growth sensitivity to summer droughts in mixed stands. Mina et al. (2018), in turn, documented that the increment of spruce and fir trees is higher when growing together in a mixed stand rather than in monocultures. Similar results are also reported by Toïgo et al. (2015). Forrester et al. (2013) then give reasons for better increment in mixed stands compared to monocultures by more efficient use of underground resources rather than the above-ground. Also, in the case of mixed stands, a better litter ratio and the mineral nutrient cycle in general may be a positive factor (Block 1997; Augusto et al. 2002). In the case of mixing fir and spruce, the positive effects are justified by their ability to create different root systems (Forrester & Albrecht 2014). It can thus be assumed that the variability of increment on the PRP studied in this work was reduced due to mixing. This statement can also be supported by results from monoculture stands where the variability of increment is more diverse (Putalová et al. 2019). On the other hand, the positive effect of mixing on increment strongly depends on climatic and habitat conditions (Huber et al. 2014). However, the effect of climate change may not be negative in alpine areas or at high altitudes (Bolte et al. 2010; Di Filippo et al. 2012).

Climate change effects also depend on tree species (Rötzer et al. 2017a; Vacek et al. 2018). Pretzsch et al. (2013) documented that spruce, unlike beech, reacts to drought by a more pronounced decrease in increment. However, when comparing the increment of spruce and fir, our results do not confirm such development unambiguously. On the other hand, it is necessary to admit that a number of various factors affected the studied areas and, thus, it is hard to single out and quantify solely the influence of drought on the increment. Accordingly, the effect of the air temperature and precipitation in the individual months on the increment of individual tree species is also highly differentiated. However, it is clear from the results that climate data have a significant effect on the increment, which corresponds to the results of correlation analyses of numerous other works, e.g. Dittmar et al. (2003), Friedrichs et al. (2009) or Härdtle et al. (2013). On the basis of long-term research, Vitali et al. (2018) confirm positive correlation of lower-altitudes increment with summer precipitation and negative correlation with summer air temperatures, both for spruce and for fir; this study, though, does not bring significant higher-altitude correlation neither for spruce nor for fir. In the study area (660–710 m a.s.l.) air temperature had prevailingly positive significant effect on radial growth, especially in the first quarter of the year and more in fir compared to spruce.

Relatively significant differentiation of our results can be explained both by the microhabitat conditions and the different type of root systems. Trees may also manifest different incremental responses in the context of a species-specific form of water management strategy, where isohydric species such as spruce close their stomata in dry seasons to maintain a consistent minimum water leaf potential to prevent high water losses and water balance disruption in the plant (del Río et al. 2014). However, this reaction may result in reduced photosynthetic activity and overall reduction in increment (Klein 2014; Roman et al. 2015). Also, different drought adaptation strategies vary from species to species, and can generate better maintenance of osmoregulatory and hydrological functions (O'Brien et al. 2014). Moreover, the mixing of deciduous and indeciduous tree species can lead to better growth by diversifying sources from the environment, which can ultimately lead to stress reduction (Pretzsch et al. 2014). In our case, for example, spruce and fir trees can benefit from greater amounts of light and water through larch crown leakage in spring and winter, when larches do not have needles. Rötzer et al. (2017b) describe an illustrative example of such profitable relationship between spruce and beech. Last but not least, a different type of root system also contributes to increased resource efficiency in stands (Dănescu et al. 2016). Higher spring air temperatures are also favoured by the fir as they reduce late frosts to which fir is sensitive (Lebourgeois et al. 2010) and accelerate the onset of cambial activity (Gričar & Čufar 2008; Swidrak et al. 2014). Similarly, in our study, high air temperature in February and March significantly positively influenced radial growth of fir. Moreover, June and July (the period when a great part of radial increment is produced) were confirmed as significant months in the Jeseníky Mts., such as in other mountain spruce forests (Král et al. 2015; Králíček et al. 2017). Mild winter conditions may also improve the increment (Harrington et al. 2010). Conversely, correlation between the increment of fir and precipitation at medium and higher altitudes is generally not as significant as the air temperature (Rolland et al. 1999; Carrer et al. 2010). On the study PRP, low air temperature was a significant limiting factor of radial growth of firs compared to low correlation with precipitation. Significantly higher effect of precipitation on diameter increment was observed in spruce because of higher altitude optimum for its growth.

5. Conclusion

The study of radial growth in mixed age-varied fir-spruce forest stands in the Jeseníky Mts. Protected Landscape Area documents higher growth variability and sensitivity to climatic factors and air pollution (SO_2 and NO_X concentrations) in fir compared to spruce. A significant reduction in the radial increment of fir in the late 1970s and early 1980s was induced by air pollution in synergism with Caucasian fir gall aphid infestation, late frosts and winter desiccation. Impact of numerous negative factors is clearly seen on the increment in not only fir, but also in spruce. In spruce, it is primarily the impact of air pollution (especially max. tropospheric ozone concentrations) and drought. On the other hand, fir is a very flexible tree species that regenerates well when the stress factors impact subsides (air pollution, climatic extremes, pathogens). It is therefore a perspective stabilizing tree species, which, even in the face of global climate change, plays an important role in forest ecosystems. What matters is its ability to be an important soil improving tree species and a productive part of various mixed forest stand with sun-tolerant, semi shadow- and shadow-tolerant tree species. A support of fir in suitable habitats is further enhanced by the large-scale decline of spruce, not only in the Czech Republic but also in all Central Europe.

Acknowledgments

This study was supported by the Ministry of Agriculture of the Czech Republic (NAZV No. QK11910292) and by the Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences (IGA No. A02/19). We are grateful to two anonymous reviewers and editor-in-chief for their constructive comments and valuable suggestions that helped improve the manuscript.

References

Altman, J., Fibich, P., Santruckova, H., Dolezal, J., Stepanek, P., Kopacek, J. et al., 2017: Environmental factors exert strong control over the climate-growth relationships of *Picea abies* in Central Europe. Science of the Total Environment, 609:506–516.

Anderegg, W. R., Kane, J. M., Anderegg, L. D., 2013: Consequences of widespread tree mortality triggered by drought and temperature stress. Nature Climate Change, 3:30–36.

Auders, A. G., Spicer, D. P., 2012: Royal Horticultural Society Encyclopedia of Conifers: A Comprehensive Guide to Cultivars and Species. Royal Horticultural Society, 1507 p.

Augusto, L., Ranger, J., Binkley, D., Rothe, A., 2002: Impact of several common tree species of European temperate forests on soil fertility. Annal of Forest Sciences, 59:233–253.

Battipaglia, G., M. Saurer, P. Cherubini, Siegwolf R. T. W., Cotrufo M. F., 2009: Tree rings indicate differentdrought resistance of a native (*Abies alba* Mil.) and a non-native (*Picea abies* [L.] Karst.) species cooccurring at a drysite in Southern Italy. Forest Ecology and Management, 257:820–828.

Bernadzki, E., 2008: Jodła pospolita – ekologia, zagrożenia, hodowla. PWRiL, Warszawa, p. 7–9.

Bhuyan, U., Zang, C., Menzel, A., 2017: Different responses of multispecies tree ring growth to various drought indices across Europe. Dendrochronologia, 44:1–8.

Binkley D., Fisher, R. F., 2013: Ecology and Management of Forest Soils. 4th Edn. Chichester: Wiley-Blackwell, 347 p.

Biondi, F., Waikul, K., 2004: Dendroclim 2002: AC++ program for statistical calibration of climate signals in tree ring chronologie. Computers & Geosciences, 30:303–311.

Blaschke, H., 1982: Schadbild und Ätiologie des Tannensterbens: III. Das Vorkommen einer Phytophthora-Fäule an Feinwurzeln der Weißtanne (*Abies alba* Mill.). European Journal of Forest Pathology, 12:232–238.

Block, J., 1997: Disposition rheinland-pfälzischer Waldbodensubstrate gegenüber Versauerung. In: Ministerium für Umwelt und Forsten Rheinland-Pfalz: Waldschäden. Boden- und Wasserversauerung durch Luftschadstoffe in Rheinland-Pfalz, Mainz, p. 16–27.

Boettger, T., Haupt, M., Friedrich, M., Waterhouse, J. S., 2014: Reduced climate sensitivity of carbon, oxygen and hydrogen stable isotope ratios in tree-ring celulose of silver fir (*Abies alba* Mill.) influenced by background SO_2 in Franconia (Germany, Central Europe). Environmental Pollution, 185:281–294.

Bolte, A., Ammer, C., Löf, M., Madsen, P., Nabuurs, G.-J., Schall, P. et al., 2009: Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. Scandinavian Journal of Forest Research, 24:473–482.

Bolte, A., Hilbrig, L., Grundmann, B., Kampf, F., Brunet, J., Roloff, A., 2010: Climatechange impacts on stand structure and competitive interactions in a southern-Swedish spruce-beech forest. European Journal of Forest Research, 129:261–276.

Bonan, G. B., 2008: Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science, 320:1444–1449.

Bontemps, J. D., Hervé, J. C., Leban, J. M., Dhôte, J. F., 2011: Nitrogen footprint in a long-term observation of forest growth over the twentieth century. Trees – Structural and Function, 25:237–251.

Bošeľa, M., Petráš, R., Sitková, Z., Priwitzer, T., Pajtík, J., Hlavatá, H. et al., 2014: Possible causes of the recent rapid increase in the radial increment of silver fir in the Western Carpathians. Environmental Pollution, 184:211–221.

Bošeľa, M., Lukac, M., Castagneri, D., Sedmák, R., Biber, P., Carrer, M. et al., 2018: Contrasting effects of environmental change on the radial growth of co-occurring beech and fir trees across Europe. Science of the Total Environment, 615:1460-1469.

Brill, H., Bock, E., Bauch, J., 1981: Über die Bedeutung von Mikroorganismen im Holz von *Abies alba* Mill. für das Tannensterben. Forstwissenschaftliches Centralblatt, 100:195–206.

Büntgen, U., Tegel, W., Kaplan, J. O., Schaub, M., Hagedorn, F., Bürgi, M. et al., 2014: Placing unprecedented recent fir growth in a European-wide and Holocene-long context. Frontiers in Ecology and the Environment, 12:100–106.

Bunn, A., Mikko, K., 2018: Chronology Building in dplR. CRAN - R Project, 13 p.

Cailleret, M., Davi, H., 2010: Effects of climate on diameter growth of co-occurring *Fagus sylvatica* and *Abies alba* along an altitudinal gradient. Trees, 25:265–276.

Carrer, M., Motta, R., Nola, P., 2010: Significant mean and extreme climate sensitivity of Norway spruce and silver fir at mid-elevation mesic sites in the Alps. PLoS One, 7: e50755.

Coumou, D., Rahmstorf, S., 2012: A decade of weather extremes. Nature Climate Change, 2:491–496.

Cramer, H. H., 1984: On the Predisposition to Disorders of Middle European Forests. In: Pantzenschutz-Nachrichten Bayer, 37, p. 97–207.

Cukor, J., Vacek, Z., Linda, R., Vacek, S., Marada, P., Šimůnek, V. et al., 2019a: Effects of bark stripping on timber production and structure of Norway spruce forests in relation to climatic factors. Forests, 10:320.

Cukor, J., Vacek, Z., Linda, R., Sharma, R. P., Vacek, S., 2019b: Afforested farmland vs. forestland: Effects of bark stripping by *Cervus elaphus* and climate on production potential and structure of *Picea abies* forests. PloS one, 14:e0221082.

Crookston, N. L., Stage, A. R., 1999: Percent canopy cover and stand structure statistics from the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-24. Ogden, UT. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 11 p.

Čada, V., Svoboda, M., Janda, P., 2013: Dendrochronological reconstruction of the disturbance history and past development of the mountain Norway spruce in the Bohemian Forest, central Europe. Forest Ecology and Management, 295:59–68.

Čater, M., Diaci, J., 2017: Divergent response of European beech, silver fir and Norway spruce advance regeneration to increased light levels following natural disturbance. Forest Ecology and Management, 399:206–212.

Dănescu, A., Albrecht, A. T., Bauhus, J., 2016: Structural diversity promotes productivity of mixed, uneven-aged forests in southwestern Germany. Oecologia, 182:319–333.

Davis, M. B., Shaw, R. G., Etterson, J. R., 2005: Evolutionary responses to a changing climate. Ecology, 86:1704–1714.

De Vries, W., Reinds, G. J., Gundersen, P., Sterba, H., 2006: The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Global Change Biology, 12:1151–1173.

del Río, M., Schütze, G., Pretzsch, H., 2014: Temporal variation of competition and facilitation in mixed species forests in Central Europe. Plant Biology, 16:166–176.

Di Filippo, A., Biondi, F., Maugeri, M., Schirone, B., Piovesan, G., 2012: Bioclimate andgrowth history affect beech lifespan in the Italian Alps and Apennines. Global Change Biology, 18:960–972.

Diaci, J., 2011: Silver fir decline in mixed old-growth forests in Slovenia: an interaction of air pollution, changing forest matrix and climate. In: Moldoveanu, A. (ed.): Air Pollution – New Developments. InTech, p. 263–274.

Dittmar, C., Zech, W., Elling, W., 2003: Growth variations of common beech (*Fagus sylvatica* L.) under different climatic and environmental conditions in Europe – a dendroecological study. Forest Ecology and Management, 173:63–78.

EEA, 2006: European forest types: categories and types for sustainable forest management reporting and policy. EEA Technical Report No 9/2006 (Copenhagen), 114 p.

Elling, W., Dittmar, C., Pfaffelmoser, K., Rötzer, T., 2009: Dendroecological assessment of the complex causes of decline and recovery of the growth of silver fir (*Abies alba* Mill.) in Southern Germany. Forest Ecology and Management, 257:1175–1187.

Elliott, K. J., Miniat, C. F., Pederson, N., Laseter, S. H., 2015: Forest tree growth response to hydroclimate variability in the southern Appalachians. Global Change Biology, 21:4627–4641.

Fabrika, M., Ďurský, J., 2005: Stromové rastové simulátory. Zvolen, EFRA, 112 p.

Farjon, A., Filer, D., 2013: An Atlas of the World's Conifers: An Analysis of their Distribution, Biogeography, Diversity and Conservation Status, Brill, 524 p.

Ferretti, M., Innes, J. L., Jalkanen, R., Saurer, M., Schäffer, J., Spiecker, H. et al., 2002: Airpollution and environmental chemistry – what role fortree-ring studies? Dendrochronologia, 20:159–174.

Forrester, D. I., Kohnle, U., Albrecht, A. T., Bauhus, J., 2013: Complementarity in mixed-species stands of *Abies alba* and *Picea abies* varies with climate, site quality and stand density. Forest Ecology and Management, 304:233–242.

Forrester, D. I., Albrecht, A. T., 2014: Light absorption and light-use efficiency in mixtures of *Abies alba* and *Picea abies* along a productivity gradient. Forest Ecology and Management, 328:94–102.

Frank, D., Reichstein, M., Bahn, M., Thonicke, K., Frank, D., Mahecha, M. D. et al., 2015: Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts. Global Change Biology, 21:2861–2880.

Friedrichs, D. A., Trouet, V., Büntgen, U., Frank, D. C., Esper, J., Neuwirth, B. et al., 2009: Species-specific climate sensitivity of tree growth in Central-West Germany. Trees, 23:729–739.

Fritts, H. C., 1976: Tree Ring and Climate. Academic Press, New York, 576 p.

Füldner, K., 1995: Strukturbeschreibung in Mischbeständen. Forstarchiv, 66:235–606.

Gao, X., Giorgi, F., 2008: Increased aridity in the Mediterranean region under green-house gas forcing estimated from high resolution regional climate projections. Global Planetary Change, 62:195–209.

Gazol, A., Camarero, J. J., Gutierrez, E., Popa, I., Andreu-Hayles, L., Motta, R. et al., 2015: Distinct effects of climate warming on populations of silver fir (*Abies alba*) across Europe. Journal of Biogeography, 42:1150–1162.

Gazol, A., Camarero, J. J., Anderegg, W. R. L., Vicente-Serrano, S. M., 2016: Impacts ofdroughts on the growth resilience of Northern Hemisphere forests. Global Ecology and Biogeography, 26:166–176.

Gentilesca, T., Todaro, L., 2008: Crescita radiale e risposte climatiche dell'abete bianco (*Abies alba* Mill.) in Basilicata. Forest@-Journal of Silviculture and Forest Ecology, 5:47–56.

Godek, M., Sobik, M., Błaś, M., Polkowska, Ž., Owczarek, P., Bokwa, A., 2015: Tree rings as an indicatorof atmospheric pollutant deposition to subalpinespruce forests in the Sudetes (Southern Poland). Atmospheric Research, 151:259–268.

Gömöry, D., Longauer, R., Liepelt, S., Ballian, D., Brus, R., Kraigher, H. et al., 2004: Variation patterns of mitochondrial DNA of *Abies alba* Mill. in suture zones of postglacial migration in Europe. Acta Societatis Botanicorum Poloniae, 73:203–206.

Gričar, J., Čufar, K., 2008: Seasonal dynamics of phloem and xylem formation in silver fir and Norway spruce as affected by drought. Russian Journal of Plant Physiologist, 55:538–543.

Halaj, J. et al., 1987: Rastové tabuľky hlavných drevín ČSSR. Bratislava, Príroda, 361 p.

Hanewinkel, M., Cullmann, D. A., Schelhaas, M.-J., Nabuurs, G.-J., Zimmermann, N. E., 2013: Climate change may cause severe loss in the economic value of European forest land. Nature Climate Change, 3:203–207.

Härdtle, W., Niemeyer, T., Assmann, T., Baiboks, S., Fichtner, A., Friedrich, U. et al., 2013: Long-term trends in tree-ring width and isotope signatures (δ^{13} C, δ^{15} N) of *Fagus sylvatica* L. on soils with contrasting water supply. Ecosystems, 16:1413–1428.

Harrington, C. A., Gould, P. J., St. Clair, J. B., 2010: Modeling the effects of winter environment on dormancy release of Douglas-fir. Forest Ecology and Management, 259:798–808.

Hartmann, H., Adams, H. D., Anderegg, W. R., Jansen, S., Zeppel, M. J., 2015: Research frontiers in drought-induced tree mortality: crossing scales and disciplines. New Phytologist, 205:965–969.

Hauck, M., Zimmermann, J., Jacob, M., Dulamsuren, C., Bade, C., Ahrends, B. et al., 2012: Rapid recovery of stem increment in Norway spruce at reduced SO_2 levels in the Harz Mountains, Germany. Environmental Pollution, 164:132–141.

Hejný, S., Slavík, B. (eds.), 1997: Květena České republiky. 1. díl, Praha, Academia, 557 p.

Hernández, L., Camarero, J. J., Gil-Peregrín, E., Sánchez, M. Á. S., Cañellas, I., Montes, F., 2019: Biotic factors and increasing aridity shape the altitudinal shifts of marginal Pyrenean silver fir populations in Europe. Forest Ecology and Management, 432:558-567.

Huber, M. O., Sterba, H., Bernhard, L., 2014: Site conditions and definition of compositional proportion modify mixture effects in *Picea abies–Abies alba* stands. Canadian Journal of Forest Research, 44:1281–1291.

Choat, B., Jansen, S., Brodribb, T. J., Cochard, H., Delzon, S., Bhaskar, R. et al., 2012: Global convergence in the vulnerability of forests to drought. Nature, 491:752–755.

Jaehne, S. C., Dohrenbusch, A., 1997: Ein Verfahren zur Beurteilung der Bestandesdiversität. Forstwissenschaftliches Centralblatt, 116:333–345.

Klein, T., 2014: The variability of stomatal sensitivity to leaf water potential across tree species indicates a continuum between isohydric and anisohydric behaviours. Functional Ecology, 28: 1313–1320.

Knibbe, B., 2007: PAST4: personal analysis system for treering research, Version 4.2. SCIEM, Vienna.

Kogan, F., Adamenko, T., Guo, W., 2013: Global and regional drought dynamics in the climate warming era. Remote Sensing Letters, 4:364–372.

Konôpková, A., Kurjak, D., Kmeť, J., Klumpp, R., Longauer, R., Ditmarová, L. et al., 2018: Differences in photochemistry and response to heat stress between silver fir (*Abies alba* Mill.) provenances. Trees – Structure and Function, 32:73-86.

Koprowski, M., 2013: Spatial distribution of introduced Norway spruce growth in lowland Poland: The influence ofchanging climate and extreme weather events. QuaternaryInternational, 283:139–146.

Korpeľ, S., Paule, L., Laffers, A., 1982: Genetics and breeding of the silver fir (*Abies alba* Mill.). Annal Forestry, 9:151–184.

Král, J., Vacek, S., Vacek, Z., Putalová, T., Bulušek, D., Štefančík, I., 2015: Structure, development and health status of spruce forests affected by air pollution in the western Krkonoše Mts. in 1979–2014. Lesnícký časopis – Forestry Journal, 61:175–187.

Králíček, I., Vacek, Z., Vacek, S., Remeš, J., Bulušek, D., Král, J. et al., 2017: Dynamics and structure of mountain autochthonous spruce-beech forests: impact of hilltop phenomenon, air pollutants and climate. Dendrobiology, 77:119–137.

Larsen, J. B., 1986: Das Tannensterben: eine neue Hypothese zur Klärung des Hintergrundes dieser rätselhaften Kompexkrankheit der Weisstanne (*Abies alba* Mill.). Forstwissenschaftliches Centralblatt, 105:381–396.

Lebourgeois, F., Rathgeber, C. B. K., Ulrich, E., 2010: Sensitivity of French temperate coniferous forests to climate variability and extreme events (*Abies alba, Picea abies* and *Pinus sylvestris*). Journal of Growing Science, 21:364–376.

Lenoir, et al., 2009: Differences between tree species seedling and adult altitudinal distribution in mountain forests during the recent warm period (1986-2006). Ecography, 32:765–777.

Margalef, R., 1958: Information theory in ecology. General Systematics, 3:36–71.

McDowell, N. G., Allen, C. D., 2015: Darcy's law predicts widespread forest mortality under climate warming. Nature Climate Change, 5:669–672.

Metz, J., Annighöfer, P., Schall, P., Zimmermann, J., Kahl, T., Schulze, E.D. et al., 2016: Site-adapted admixed tree species reduce drought susceptibility of mature European beech. Global Change Biology, 22:903–920.

Meunier, C. L., Gundale, M. J., Sanchez, I. S., Liess, A., 2016: Impact of nitrogen deposition on forest and lake food webs in nitrogen-limited environments. Global Change Biology, 22:164–179.

Mina, M., del Río, M., Huber, M. O., Thürig, E., Rohner, B., 2018: The symmetry of competitive interactions in mixed Norway spruce, silver fir and European beech forests. Journal of Growing Science, 29:775–787.

Mrkva, R., 1994: Korovnice kavkazska (*Dreyfusianordmannianae* Eckstein), obrana proti ní a její podíl na ústupu jedle. Lesnictvi – Forestry, 40:361–370.

Musil, I., Hamerník, J., 2007: Jehličnaté dřeviny. Přehled nahosemenných i výtrusných dřevin, Lesnická dendrologie 1, Praha, Academia, 352 p.

O'Brien, M. J., Leuzinger, S., Philipson, C. D., Tay, J., Hector, A., 2014: Drought survival of tropical tree seedlings enhanced by non-structural carbohydrate levels. Nature Climate Change, 4:710.

Petráš, R., Pajtík, J., 1991: Sústava česko-slovenských objemových tabuliek drevín. Lesnícky časopis, 37:49–56.

Pielou, E. C., 1975: Ecological diversity. New York: Wiley, USA, 165 p.

Pretzsch, H., 2006: Wissen nutzbar machen für das Management von Waldökosystemen. Allgemeine Forstzeitschrift/Der Wald, 61:1158–1159.

Pretzsch, H., Schütze, G., Uhl, E., 2013: Resistance of European tree species to drought stress in mixed versus pure forests: evidence of stress release by interspecific facilitation. Plant Biology,15:483–495.

Pretzsch, H., Rötzer, T., Matyssek, R., Grams, T. E. E., Häberle, K. H., Pritsch, K. et al., 2014: Mixed Norway spruce (*Picea abies* [L.] Karst.) and European beech *Fagus sylvatica* [L.] stands under drought: from reaction pattern to mechanism. Trees, 28:1305–1321.

Putalová, T., Vacek, Z., Vacek, S., Štefančík, I., Bulušek, D., Král, J., 2019: Tree-ring widths as an indicator of air pollution stress and climate conditions in different Norway spruce forest stands in the Krkonoše Mts. Central European Forestry Journal, 65:21–33.

Reineke, L. H., 1933: Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research, 46:627–638.

Ripullone, F., Borghetti, M., Raddi, S., Vicinelli, E., Baraldi, R., Guerrieri et al., 2009: Physiological and structural changes in response toaltered precipitation regimes in a Mediterranean macchia ecosystem. Trees, 23:823–834.

Rita, A., Gentilesca, T., Ripullone, F., Todaro, L., Borghetti, M., 2014: Differential climate–growth relationships in *Abies alba* Mill. and *Fagus sylvatica* L. in Mediterranean mountain forests. Dendrochronologia, 32:220–229.

Rolland, C., Michalet, R., Desplanque, C., Petetin, A., Aimé, S., 1999: Ecological requirements of *Abies alba* in the French alps derived from dendro-ecological analysis. Journal of Growing Science, 10:297–306.

Roman, D. T., Novick, K. A., Brzostek, E. R., Dragoni, D., Rahman, F., Phillips, R. P., 2015: The role of isohydric and anisohydric species in determining ecosystem-scale response to severe drought. Oecologia, 179:641.

Rötzer, T., Biber, P., Moser, A., Schäfer, C., Pretzsch, H., 2017a: Stem and root diameter growth of European beech and Norway spruce under extreme drought. Forest Ecology and Management, 406:184–195.

Rötzer, T., Häberle, K. H., Kallenbach, C., Matyssek, R., Pretzsch, H., 2017b: Tree species and size drive water consumption of beech/spruce forests (*Fagus sylvatica/Picea abies*) – a simulation study highlighting growth under water limitation. Plant Soil, 418:337–356.

Sander, C., Eckstein, D., 2001: Foliation of spruce in the Giant Mts. and its coherence with growth and climate over the last 100 years. Annals of Forest Science, 58:155–164.

Sensuła, B., Wilczyński, S., Opała, M., 2015: Tree Growth and Climate Relationship: Dynamics of Scots Pine (*Pinus sylvestris* L.) Growing in the Near-Source Region of the Combined Heat and Power Plant During the Development of the Pro-Ecological Strategy in Poland. Water, Air, & Soil Pollution, 226:220.

Shannon, C. E., 1948: A mathematical theory of communications. Bell System Technical Journal, 27:379–423.

Schweingruber, F. H., 1996: Tree Rings and Environment Dendroecology. Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, 609 p.

Sohar, K., Altman, J., Lehečková, E., Doležal, J., 2017: Growth–climate relationships of Himalayan conifers along elevational and latitudinal gradients. International Journal of Climatology, 37:2593–2605.

Swidrak, I., Gruber, A., Oberhuber, W., 2014: Xylem and phloem phenology in co-occurring conifers exposed to drought. Trees, 28:1161–1171.

Šmilauer, P., Lepš, J., 2014: Multivariate analysis of ecological data using CANOCO 5. Cambridge university press, 361 p.

Toïgo, M., Vallet, P., Perot, T., Bontemps, J.-D., Piedallu, C., Courbaud, B., 2015: Overyielding in mixed forests decreases with site productivity. Journal of Ecology, 103:502–512.

Ulrich, B., 1981: Eine ökosystemare Hypothese über die Ursachen des Tannensterbens (*Abies alba* Mill.). Forstwissenschaftliches Centralblatt, 100:228–236.

Úradníček, L., Maděra, P., Kolibáčová, S., Koblížek, J., Šefl, J., 2001: Dřeviny České republiky. Písek, Matice lesnická, 333 p.

Úradníček, L., Madera, P., Tichá, S., Koblížek, J., 2009: Dřeviny České Republiky. Lesnická práce, Kostelec nad Černými lesy, 367 p.

Usbeck, T., Wohlgemuth, T., Dobbertin, M., Pfister, C., Bürgi, A., Rebetez, M., 2010: Increasing storm damage to forests in Switzerland from 1858 to 2007. Agricultural and Forest Meteorology, 150:47–55.

Vacek, S., Hůnová, I., Vacek, Z., Hejcmanová, P., Podrázský, V., Král, J. et al., 2015: Effects of air pollution and climatic factors on Norway spruce forests in the Orlické hory Mts. (Czech Republic), 1979–2014. European Journal of Forest Research, 134:1127–1142.

Vacek, S., Černý, T., Vacek, Z., Podrázský, V., Mikeska, M., Králíček, I., 2017: Long-term changes in vegetation and site conditions in beech and spruce forests of lower mountain ranges of Central Europe. Forest Ecology and Management, 398:75–90.

Vacek, S., Vacek, Z., Kalousková, I., Cukor, J., Bílek, L., Moser, W.K. et al., 2018. Sycamore maple (*Acer pseudoplatanus* L.) stands on former agricultural land in the Sudetes-evaluation of ecological value and production potential. Dendrobiology, 79:61–76.

Vacek, S., Vacek, Z., Ulbrichová, I., Remeš, J., Podrázský, V., Vach, M. et al., 2019: The Effects of Fertilization on the Health Status, Nutrition and Growth of Norway Spruce Forests with Yellowing Symptoms. Scandinavian Journal of Forest Research, 34:1–49.

Vacek, Z., Vacek, S., Slanař, J., Bílek, L., Bulušek, D., Štefančík, I. et al., 2019: Adaption of Norway spruce and European beech forests under climate change: from resistance to close-to-nature silviculture. Central European Forestry Journal, 65:129–144.

Viet, H. D., Kwak, J. H., Lee, K. S., Lim, S. S., Matsushima, M., Chang, S. X. et al., 2013: Foliar chemistry and tree ring δ 13 C of *Pinus densiflora* in relation to tree growth along a soil pH gradient. Plant and Soil, 363:101–112.

Vitali, V., Büntgen, U., Bauhus, J., 2017: Silver fir and Douglas fir are more tolerant to extréme droughts than Norway spruce in south-western Germany. Global change biology, 23:5108–5119.

Vitali, V., Büntgen, U., Bauhus, J., 2018: Seasonality matters – The effects of past and projected seasonal climate change on the growth of native and exotic conifer species in Central Europe. Dendrochronologia, 48:1–9.

Wentzel, K. F., 1980: Weissitanne = immissionsempfindlichste einheimische Baumart. Allgemeine Forstzeitschrift, 35:373–374.

Werner, B., Spranger, T. (ed.), 1996: Manual on Methodologies and Criteria for Mapping Critical Levels/Loads and Geographical Areas where they are Exceeded, UN ECE CLRTAP. Berlin, UBA, 204 p.

Wilczyński, S., 2006: The variation of tree–ring widths of Scots pine (*Pinus sylvestris* L.) affected by air pollution. European Journal of Forest Research, 125:213–219.

Yamaguchi, D. K., 1991: A simple method for crossdating increment cores from living trees. Canadian Journal Forest Research, 21:414–416.

Cent. Eur. For. J. 66 (2020) 37–48 sciendo DOI: 10.2478/forj-2019-0025

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

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

Viktor Tkach[1], Oksana Tarnopilska[1, 2], Oleksiy Kobets[1], Volodymyr Luk'yanets[1], Maksym Rumiantsev[1], Iryna Obolonyk[1] *, Sergiy Musienko[2]

[1]*Ukrainian Research Institute of Forestry and Forest Melioration named after G. M. Vysotsky, 86, Pushkinska Street, Kharkiv, 61024, Ukraine*

[2]*O. M. Beketov National University of Urban Economy in Kharkiv, 17, Marshal Bazhanov Street, Kharkiv, 61002, Ukraine*

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

---

Editor: Andrej Kunca

---

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; Garbelotto & 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 (Ustsky 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

---

**Corresponding author. Iryna Obolonyk, e-mail: obolonik@uriffm.org.ua, phone: +38 050 300 88 64* 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; Otrosina & 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 (Kenigsvalde et al. 2011; Volchenkova & Zvyagintsev 2011; Sierota 2013; Kenigsvalde 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):

$$I_c = \frac{K_1 n_1 + K_2 n_2 + \cdots .... + K_6 n_6}{N} \qquad [1]$$

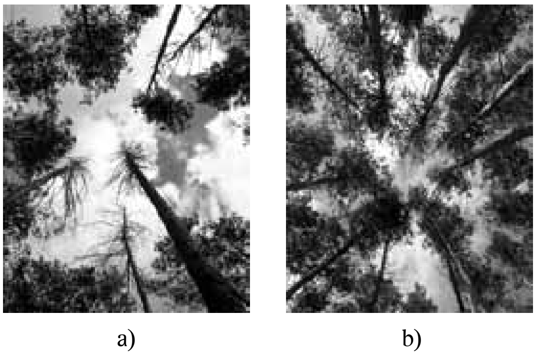
where: $K_1, ..., K_6$ – the category of the health condition of the trees (from 1st to 6th); $n_1, ..., n_6$ – the number of trees of the given health condition category; N – the total number of recorded trees in the sample plot.

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



a) b)

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		
1st – without signs of damage	1.00–1.50	dense canopy	90–100	no signs of deterioration	green	none
2nd – weakened	1.51–2.50	open canopy	66–90	no signs of deterioration	green, light-green	weak
3rd – severely weakened	2.51–3.50	much open canopy	33–66	concentrated	light-green	medium
4th – dying	3.51–4.50	much open canopy	33	concentrated	yellowish or yellow-green	significant
5th – standing dead trees died over the present year	4.51–6.00	—	0	no living needles	grey, yellow or reddish-brown	extreme
6th – 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 (m^2 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 (m^3 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 distrubution 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 m^3 ha^{-1}. In the disease foci, it increased from 11 m^3 ha^{-1} in 21-year-old stand to 83 m^3 ha^{-1} in 81-year-old one. In the 61-year-old pine stand, the stock of dead trees decreased slightly to 51 m^3 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 disease 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

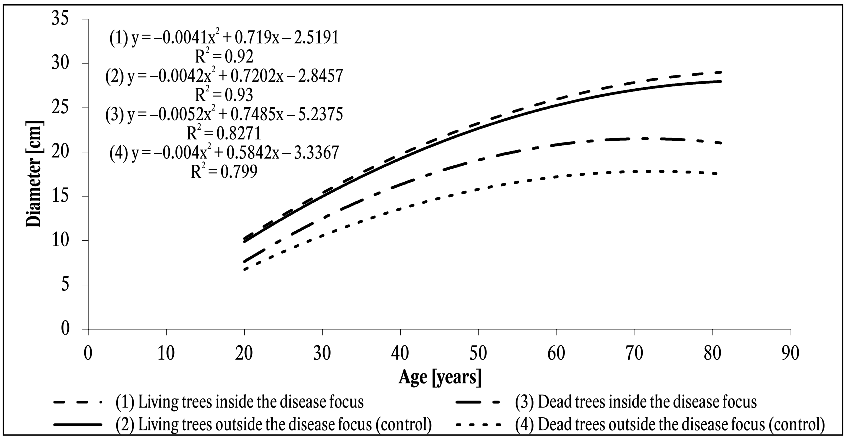


Fig. 3. Average diameters of dead and living pine trees inside and outside annosum root rot disease foci depending on stand age.

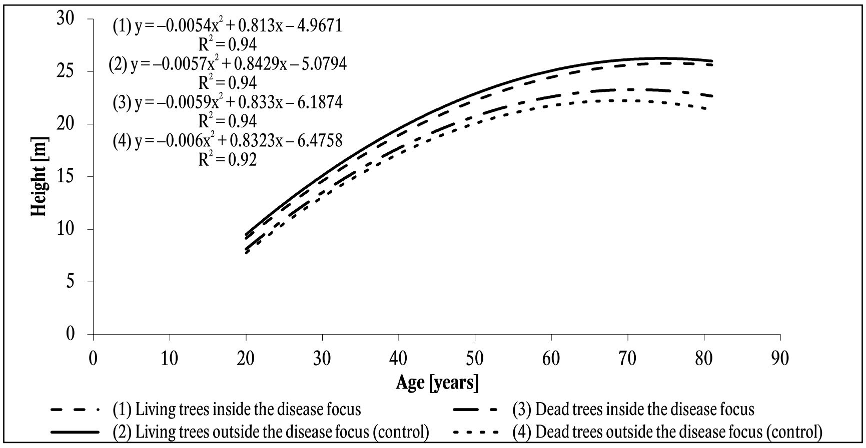


Fig. 4. Average heights of dead and living pine trees inside and outside annosum root rot disease foci depending on stand age.

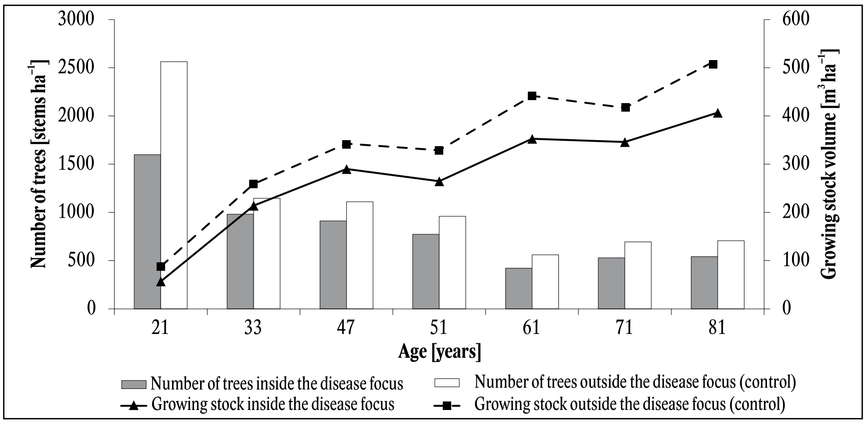


Fig. 5. The number of trees and growing stock volume of pine inside and outside root rot disease foci.

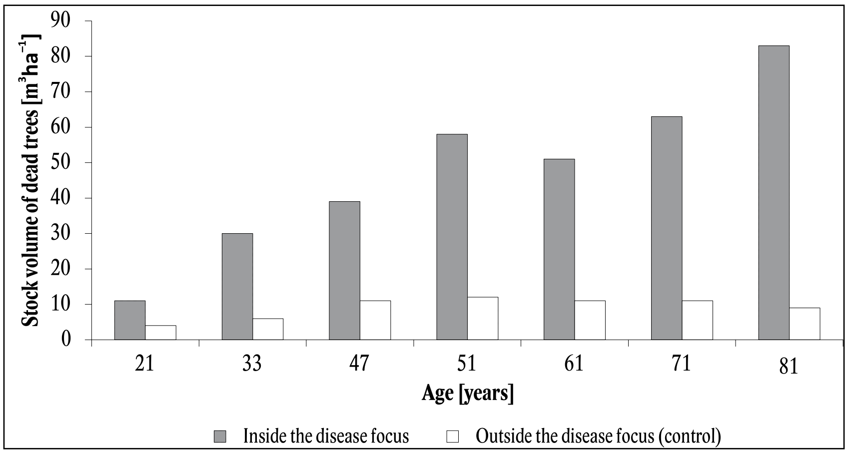


Fig. 6. Stock volume of dead standing trees inside and outside root rot disease foci.

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 m^3 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%.

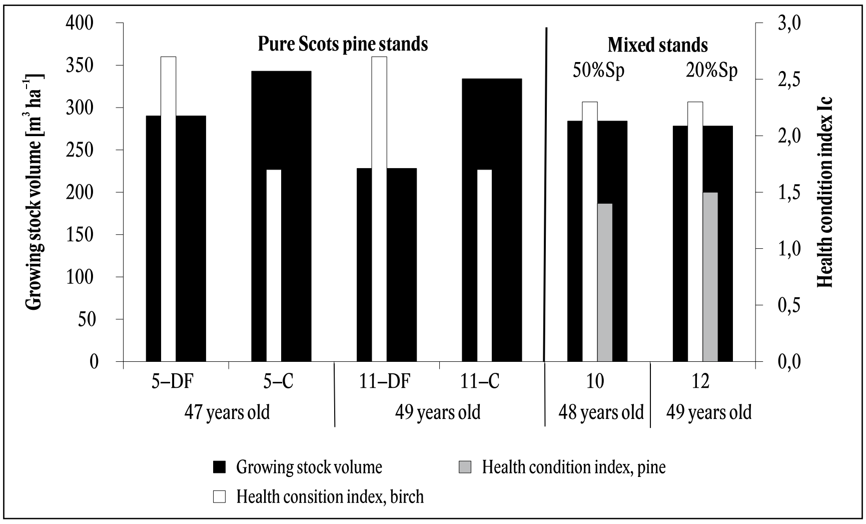


Fig. 7. Growing stock volume and health condition of the investigated pure and mixed stands.

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 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.

References

Alekseev, I. A., Vaskov, S. P., Pokshaeva, N. N., 1981: Creation of resilient pine plantations. In: Protection of conifer stands from root rot: Proceedings of Scientific Conference of Belarus and Baltic Republics, Minsk, 9–10 September, 1981, Minsk, p. 6–7.

Artyukhovskiy, A. K., 2000: Growing of pine in formerly arable land. The Bulletin of Central Black Earth Regional Department of Forest Sciences of Academy of Natural Sciences, Voronezh State Academy of Forestry and Technologies, 3:174–176.

Asiegbu, F. O., Adomas, A., Stenlid, J., 2005: Conifer root and butt rot caused by *Heterobasidion annosum* (Fr.) Bref. s. l. Molecular Plant Pathology, 6:395–409.

Avery, T. E., Burkhart, H. E., 2002: Forest Measurements. N.Y., McGraw-Hill Pub., 456 p.

Bendz-Hellgren, M., Brandtberg, P.-O., Johansson, M., Swedjemark, G., Stenlid, J., 1999: Growth rate of *Heterobasidion annosum* in *Picea abies* established on forest land and arable land. Scandinavian Journal of Forest Research, 14:402–407.

Bielak, K., Dudzińska, M., Pretzsch, H., 2014: Mixed stands of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* [L.] Karst) can be more productive than monocultures. Evidence from over 100 years of observation of long-term experiments. Forest Systems, 23:573–589.

Bilous, M. M., 2006: Establishing forest stands on land ubsuitable for agriculture. In: Proceedings of Scientific Conference for Academics, Researchers and Postgraduates, 11–12 April, 2006, Kyiv, p. 66–67.

Brandtberg, P.-O., Johansson, M., Seeger, P., 1996: Effects of season and urea treatment on infection of stumps of *Picea abies* by *Heterobasidion annosum* in stands on former arable land. Scandinavian Journal of Forest Research, 11:261–268.

Chudak, V. V., 2014: Information about condition of forests in Polissya and Podillya zones of Ukraine. Available at: http://dklg.kmu.gov.ua/forest/control/uk/publish/article;jsessionid=0496D5C46F8CDF9F264E0C1FC35FC96B.app2?art_id=118307&cat_id=81209.

Dai, Y.-C., Vainio, E. J., Hantula, J., Niemelä, T., Korhonen, K., 2003: Investigations on *Heterobasidion annosum* s.lat. in central and eastern Asia with the aid of mating tests and DNA fingerprinting. Forest Pathology, 33:269–286.

Demchenko, S. I., Sukhomlin, M. N., 2000: Investigation of the antagonistic activity of *Peniophora gigantea* (Fr.) Mass. for use in biological control of root rot. The Bulletin of Nikitskiy Botanical Garden, 76:52–54.

Fedorov, N. I., 1991: Ecological basis for the protection of pine stands from root rots. In: Protection of forest ecosystems and rational use of forest resources: 2nd All-Union Scientific Conference. Part 1. Moscow, MFTI, p. 147–148.

Felton, A., Nilsson, U., Sonesson, J., Felton, A. M., Roberge, J. M., Ranius, T. et al., 2016: Replacing monocultures with mixed-species stands: Ecosystem service implications of two production forest alternatives in Sweden. Ambio, 45:124–139.

Garbelotto, M., Gonthier, P., 2013: Biology, epidemiology, and control of *Heterobasidion* species worldwide. Annual Review of Phytopathology, 51:39–5.

Hammer, O., Harper, D. A. T., Ryan, P. D., 2001: PAST: paleontological statistics software package for education and data analysis. Palaeontologia Electronica, 4:1–9.

Hrom, M. M., 2007: Forest inventory. Lviv, RVV NLTU, 416 p.

Kenigsvalde, K., Donis, J., Korhonen, K., Gaitnieks, T., 2011: Biological control of *Heterobasidion* root rot of coniferous stumps by *Phlebiopsis gigantea* – literature review. Mežzinātne, 23:25–40.

Kenigsvalde, K., Brauners, I., Korhonen, K., Zaļuma, A., Mihailova, A., Gaitnieks, T., 2016: Evaluation of the biological control agent Rotstop in controlling the infection of spruce and pine stumps by *Heterobasidion* in Latvia. Scandinavian Journal of Forest Research, 31:254–261.

Korhonen, K., Capretti, P., Karjalainen, R., Stenlid, J., 1998: Distribution of *Heterobasidion annosum* intersterility groups in Europe. In: Woodward, S., Stenlid, J., Karjalainen, R., Hüttermann, A. (eds.): *Heterobasidion annosum*: Biology, Ecology, Impact and Control. Wallingford, CAB International, p. 93–104.

Ladeyshchikova, E. I., Pobegaylo, A. I., Belyy, G. D., Alekseev, I. A., Chernykh, A. G., Pasternak, P. S. et al., 1974: About the predisposing causes to the disease for pine forests on formerly arable lands. In: Ladeyshchikova, E. I., Pobegaylo,A. I., Pasternak, P. S., Ladnykh, L. F. (eds.): Root Rot. Kharkiv, Prapor, p. 22–31.

Ladeyshchikova, O. I., Ustsky, I. M., Chernykh, O. H., Mokrytsky, V. O., Bersneva, L. O. (eds.), 2001: Guideline to protect pine plantations against root rot. Kharkiv, URIFFM, 28 p.

Lapitan, O. V., Zhemchuzhin, V. Y., Melnik, T. I., 2013: Components of damage from the root fungus in ripening and mature pine stands of Novgorod-Siverskiy Polyssya. The SNAU Vestnik, 11:14–19.

Lukyanets, V., Lisnyak, A., Tarnopilska, O., Musienko, S., Garbuz, A., Kraynukov, A., 2019: Physical and chemical properties of soils in potential approaches of Volynic Polisse, violated by root rot. Folia Geographica, 61:98–119.

Lyamtsev, N. I., 2015: Findings of root rot studies in the Buzuluksky pine forest. In: Storozhenko, V. G., Zviagintsev, V. B. (eds.): Problems of Forest Phytopathology and Micology: Materials of the IX International conference, 19–24 October, 2015, Minsk-Moscow-Petrozavodsk, Minsk, BSTU, p. 118–121.

Lygis, V., Vasiliauskas, R., Stenlid, J., Vasiliauskas, A., 2004: Silvicultural and pathological evaluation of Scots pine afforestations mixed with deciduous trees to reduce the infections by *Heterobasidion annosum* s.s. Forest Ecology and Management, 201:275–285.

Marinich, A. M., Pashchenko, V. M., Shishchenko, P. G., 1985: The nature of the Ukrainian SSR. Landscapes and physiographic mapping. Kyiv, Naukova Dumka, 224 p.

Mashkovsky, V. P., 2015: Commoditization of the rated cutting by assortment tables with tree row distribution according to natural diameter classes. Problems of Forest Science and Forestry: collection of scientific works of Institute of Wood of NAS of Belarus, 75:340–348.

Musienko, S., Luk'yanets, V., Tarnopylska, O., Kobets, O., Babenko, V., 2018: Merchantability and assortment structure of pine stands affected by root rot in the Volyn Polissya region, Ukraine. Central European Forestry Journal, 64:96–103.

Negrutskiy, S. F., 1986: Annosum root rot. Moscow, Agroptomizdat,196 p.

Otrosina, W. J., Garbelotto, M., 2010: *Heterobasidion occidentale* sp. nov. and *Heterobasidion irregulare* nom. nov.: a disposition of North American *Heterobasidion* biological species. Fungal Biology, 114:16–25.

Peri, T., Korhonen, K., Sairanen, A., 1990: Occurrence of *Heterobasidion annosum* in pure and mixed spruce stands in Southern Finland. Scandinavian Journal of Forest Research, 5:113–125.

Raspopina, S. P., Tarnopilska, O. M., Lukjanets, V. A., Kobets, O. V., 2013: Standing forest and characteristics of soils in focuses of dispersion a pine fungus (*Heterobasidion annosum* (Fr) Bref.) on abandoned agricultural lands of East Polissya. Scientific Bulletin of UNFU, 23.13:64–73.

Rishbeth, J., 1963: Stump protection against Fomes annosus. III. Inoculation with *Peniophora gigantea*. Annals of Applied Biology, 52:63–77.

Sanitary Forests Regulations in Ukraine, 2016: Approved by Cabinet of Ministers of Ukraine, Kyiv, 20 p. Available at: http://zakon5.rada.gov.ua/laws/show/555-95-%D0%BF.

Shvydenko, A. Z., Strochinsky, A. A., Savich, Yu. N., Kashpor, S. N. (eds.), 1987: Regulatory reference materials for forest inventory of Ukraine and Moldova. Kyiv, Urozhay, 559 p.

Sierota, Z., 2013: *Heterobasidion* root rot in forests on former agricultural lands in Poland: Scale of threat and prevention. Academic Journal, 8:2298–2305.

Stenlid, J., 1985: Population structure of *Heterobasidion annosum* as determined by somatic incompatibility, sexual incompatibility, and isozyme patterns. Canadian Journal of Botany, 63:2268–2273.

Tarnopilska, O., Musienko, S., Lyalin, O., Tkach, L., Babenko, V., 2018: The effect of alternative thinning regimes on growth and stability of Scots pine plantations in southern forest-steppe in Ukraine. Forestry Ideas, 24:51–72.

Ustsky, I. M., 2011: Soil features of annosum-infected pine stands within Novgorod-Siverskiy Polissya. Lisovyy zhurnal, 2:48–52.

Ustsky, I. M., Taran, T. V., Belous V. P., 2010: Comprehensive assessment of the distribution of forest-pathological processes (differentiated by administrative regions of Ukraine) and the forecast for the distribution of pathological processes in Ukrainian forests by 2015. Kharkiv, URIFFM, 53 p.

Vasiliauskas, A., 1989: Root fungus and the resistance of coniferous forests' ecosystems. Vilnius, Mokslas Publishers, 175 p.

Vasiliauskas, R., Juska, E., Vasiliauskas, A., Stenlid, J., 2002: Community of *Aphyllophorales* and root rot in stumps of *Picea abies* on clear-felled forest sites in Lithuania. Scandinavian Journal of Forest Research, 17:398–407.

Vedmid, M. M., Tarnopilska, O. M., Kobets, O. V., Zuev, E. S., Lozitsky, V. G., 2013: State, productivity and assortment structure of first generation pine and birch stands cultivated on abandoned agricultural lands of East Polissya. Forestry and Forest Melioration, 122:12–23.

Volchenkova, G. A., Zvyagintsev, V. B., 2011: The development of biological methods to limit the harmfulness of annosum root rot. Collection of scientific papers of the Forest Institute of the National Academy of Sciences of Belarus, 71:445–455.

Volchenkova, G. A. Zvyagintsev, V. B., Krivitskaya, Z. I., Zhdanovich, S. A., 2012: Distribution of centers of infection by *Heterobasidion annosum* (Fr.) Bref. in the pine stands of Vitebsk, Minsk and Mogilev regions. Proceedings of BSTU, 1:225–228.

Vollbrecht, G., Gemmel, P., Elfving, B., 1994: Forest management with the purpose of reducing windthrow and infection by *Heterobasidion annosum* in *Picea abies* – preliminary results from a field experiment. In: Vollbrecht, G.: Effects of silvicultural practices on the incidence of root and butt rot in Norway spruce with special emphasis on *Heterobasidion annosum*. Doctoral thesis, Swedish University of Agricultural Sciences, Alnarp, Sweden.

Wang, L. Y., 2012: Impact of *Heterobasidion* spp. root rot in conifer trees and assessment of stump treatment. With emphasis on *Picea abies*, *Pinus sylvestris* and *Larix* × *eurolepis*. Doctoral Thesis (Summary). Swedish University of Agricultural Sciences, Alnarp, Acta Universitatis agriculturae Sueciae (1652–6880): 97, 66 p.

Woodward, S., Stenlid, J., Karjalainen, R., Hutterman, A. (eds.), 1998: *Heterobasidion annosum*: Biology, Ecology, Impact and Control. Wallingford, CAB International, 589 p.

Worrall, J. J., Harrington, T. C., Blodgett, J. T., Conklin, D. A., Fairweather, M. L., 2010: *Heterobasidion annosum* and *H. parviporum* in the southern Rocky Mountains and adjoining States. Plant Disease, 94:115–118.

Zvyagintsev, V. B., Volchenkova, G. A., Zhdanovich, S. A., 2013: Silvicultural and forest protection activities in pine stands affected by *Heterobasidion annosum* (Fr.) Bref. Proceedings of BSTU, 1:223–226.

Cent. Eur. For. J. 66 (2020) 49–59 sciendo DOI: 10.2478/forj-2020-0001

CENTRAL EUROPEAN
Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Beetles and nematodes associated with wither Scots pines

Olena Andreieva[1]*, Oleksandr Korma[2], Olena Zhytova[1], Ivan Martynchuk[1],
Anatoliy Vyshnevskyi[1]

[1]*Zhytomyr National Agroecological University, Stary Bulv., 7, Zhytomyr, 10008, Ukraine*
[2] *Chernigiv National University of Technology, Shevchenko str., 95, Chernigiv, 14035, Ukraine*

Abstract
This study focused on the occurrence of xylophagous beetles and nematodes in the different parts of *Pinus sylvestris* L. trees of different health condition in the pure stands in Zhytomyr region (Central Polissya). Stem fragments with thin, thick and transitional bark, branches and twigs were examined in each of 12 model trees. Xylophagous beetles were identified by adults or by galleries. Nematodes were isolated from wood samples in the laboratory using the Baermann method and identified by morphometric characteristics. Among 10 species of xylophagous beetles, *Ips acuminatus* (frequency 16.7%; dominance 17.9%) and *I. sexdentatus* (frequency 11.1%, dominance 54.6%) dominated, which prefer the fragments with thin and thick bark respectively. No xylophagous beetle was found in the healthy and slightly weakened trees. Among 15 nematode species, 40% were saproxylic, 33.3% entomophilic, 13.3% phytophagous, and by 6.7% predators and species associated with fungi. An entomophilic nematodes *Cryptaphelenchus macrogaster* f. *acuminati* was common in all parts of stem and branches (frequency of occurrence 25–33.3%). An entomophilic nematodes *Parasitorhabditis acuminati* and a predator *Fuchsia buetschlii acuminati* had the highest frequency of occurrence (41.7%) under the thin bark and in the branches. The frequency of these species in colonized with xylophagous insects stem fragments with thin bark was significantly higher than in respective not colonized fragments.

Key words: *Ips acuminatus*; *Ips sexdentatus*; entomophilic nematodes; phytophagous nematodes; predator; *Bursaphelenchus*; saproxylic nematode

---

Editor: Jaroslav Holuša

---

1. Introduction

Health condition of pine stands worsens in last decades promoted by climate change and anthropogenic activity, which increases the vulnerability of trees to different injurious organisms, including xylophagous insects, pathogenic fungi, bacteria, nematodes, etc. (Wood 1982; Sauvard 2007; Pernek et al. 2012; Siitonen 2014; Andreieva et al. 2018; Meshkova et al. 2018).

Xylophagous insects, mainly bark beetles from subfamily Scolytinae (family Curculionidae), longhorn beetles (Cerambycidae), and jewel beetles (Buprestidae) are the most evident and the most studied agents of tree decline (Wood, 1982; Sauvard 2007). They develop, at least the part of their life cycle, inside xylem or phloem tissues of a tree (Lieutier et al. 2016). The xylophagous insects, which inhabit living trees and bring to their mortality at high population density, cause physiological harm, which increases due to their maturation feeding in living trees and pathogen vectoring (Lieutier et al. 2016; Meshkova 2017).

Another type of harm is technical because it brings to losses of timber quality and can be caused by insects inhabiting living, felled, wind-broken or windthrown trees. Its severity depends on larval galleries and pupal chambers width and depth, their distribution in stem parts with thick, transitional or thin bark. Each species of xylophagous insects is evaluated by a certain score of physiological and technical harm, as well as by general harm considering physiological, technical harm and number of generations per year. It was proved that the same insect species can be non-harmful, low, moderately or extremely harmful depending on region, population density and other conditions (Meshkova 2017).

The presence of pathogenic or parasitic organisms can play an important role in the harmful consequences of tree colonization by xylophagous insects. Along with profound researches of blue-stain and wood-decaying fungi vectoring by bark beetles (Linnakoski et al. 2012; Davydenko et al. 2014, 2017), considerable attention is paid to nematodes (d'Errico et al. 2015; Holuša et al.

---

*Corresponding author. Olena Andreieva, e-mail: andreeva-lena15@ukr.net, phone: +38-096-351-51-30

2017; Korma & Sigaryova 2017), especially after spread of pine wilt disease caused by pinewood nematode or pine wilt nematode' (PWN) *Bursaphelenchus xylophilus* (Steiner & Buhrer 1934) Nickle 1970 (Nematoda: Aphelenchoididae) (Mota et al. 1999). This nematode inhabits in the resin canal systems of infected pines, spreading across the stem, branches, and roots (Mamiya 1983). This nematode is spread by beetles of the genus *Monochamus* (Coleoptera, Cerambycidae) through maturation feeding on the bark, particularly *Monochamus galloprovincialis* (Olivier 1795) (Coleoptera Cerambycidae), which usually inhabit weakened trees (Meshkova 2017; Dayi & Akbulut 2018).

Some researchers suspect other nematode species dangerous to pine trees, especially *B. mucronatus* (Kulinich & Ryss 2006; Kozlovsky 2016; Ryss et al. 2018). At the same time research of the nematode spread in the forest zone of Ukraine (Polissya) revealed *Bursaphelenchus* species only in drying-up trees. No nematode was found in the trees, weakened by wood-decaying fungi, as well as from the trees, which were not colonized by bark beetles (Davydenko et al. 2015). If nematode species suspected to be harmful are revealed only in the drying up trees, they cannot be the cause of its weakening.

Nematodes associated with trees are subdivided into different ecological groups. Some of them are phytophagous nematodes and are vectored by insects (Dayi & Akbulut 2018). Another group includes the entomophilic nematodes of xylophagous insect-pests of living or recently felled trees (Grucmanová & Holuša 2013; Holuša et al. 2017; Takov et al. 2019) and can be the ground for the production of biological means of tree protection on the base of entomophilic nematodes. Other nematodes are associated with insects, whose larvae develop in decaying wood, with predatory insects living in the galleries of xylophagous insects or living in tree sap or on bark surface (Blinova 1982), can be predators, nematodes associated with fungi and saproxylic species (Korma & Sigaryova 2017). Unlike xylophagous beetles, both phytophagous nematodes and entomophilic nematodes are less studied in forest stands of Ukraine (Korma & Sigaryova 2017) than in agrocenoses (Pylypenko & Kalatur 2015). Therefore, the control measures against the first group and the use of the second group to control insect pests are poorly developed. However, due to the urgency of pine forest decline, it was important to reveal, if nematodes inhabiting trees can be harmful to a tree or for bark beetles. Therefore, the research of the spread of nematodes associated with trees of different ecological groups together with xylophagous beetles can be also the ground for elaboration on the measures of forest protection from phytophagous nematodes.

Contrary to most other pine species, Scots pine possesses in its youth stage a light-brown smooth bark on the full stem length. With increasing tree age on the lower part of stem the bark gradually becomes thick, scaly dark grey-brown, with deep cracks; flakes of bark form irregularly shaped plates. The bark remains thin, flaky and orange on the upper stem and branches. Such differentiation goes on during all lifespan of pine. Bark shape and thickness depends on race and provenance as well as influenced by forest sites (Schultze-Dewitz & Koch 2008).

Host selection by xylophagous beetles is based on visual and olfactory signals from host trees (Wood 1982), as well as host physical properties like bark thickness (Paine et al. 1981; Amezaga & Rodrıguez 1998; Borkowski & Skrzecz 2016). Different bark beetles colonize stem parts depending on bark thickness, which correlates with phloem humidity and quality as feed resource as well as provides certain defense in winter (Saarenmaa 1983). Therefore, a study of stem insects and other organisms' distribution along the stem provides indirect confirmation of the associations on pine trees.

The aim of this study was to reveal the spread features of xylophagous beetles and nematodes associated with trees in the different parts of Scots pine trees of different health condition.

2. Material and methods

The research was carried out in the pure Scots pine (*Pinus sylvestris* L.) forests of 70 and 100 years old in Stanyshivske and Levkivske forestries of the State Zhytomyr Forest Enterprise (Zhytomyr region, so-called Central Polissya of Ukraine).

The long-term climate characteristics of the region are following: the length of the growing season is 205 days; annual air temperature is +6.8 °C, minimum –38 °C; annual rainfall is 552 mm, among which 60% of precipitation falls during the growing season. The average freezing depth of soil is 56 cm, maximum 120 cm. In average permanent snow cover is set on December 15 and melts on March 5th. Prevailing types of soils are fresh and humid soddy podzolic loams and sandy loams (Buzun et al. 2018).

Prevailing types of forest site conditions in the region are fresh relatively poor forest site conditions and humid relatively poor forest site conditions – so-called 'fresh soubor' and 'humid soubor' according to Ukrainian forest typology (Migunova 1993).

In two forests, four foci of Scots pine forest decline were chosen as sample plots (Table 1). Three trees of different health condition were felled on May 29, 2018, in each sample plot. Trees of the 1st (healthy), 3rd (severely weakened), and 4th (drying up) category of health condition were felled in SP 1 and SP 2. Trees of the 2nd (weakened), 3rd (severely weakened), and 5th (recently died) category of health condition were felled in SP 3. Trees of the 1st (healthy) and 2nd (weakened) category of health condition were felled in SP 4. Total of 12 trees felled.

Category of tree health condition was evaluated on a range of visual characteristics (crown density and color,

Table 1. Characteristics of sample plots.

Sample plots (SP)	Locality	Plot; subcompartment	Latitude, Longitude	Forest site conditions*	Age [years]	Height [m]	DBH [cm]
SP 1	Stanyshivske	33; 8.6	50° 23’ N 28° 85’ E	humid	70	24	26
SP 2	Stanyshivske	33; 43.4	50° 23’ N 28° 85’ E	fresh	70	24	26
SP 3	Levkivske	30: 15	50° 22’ N 28° 71’ E	fresh	70	24	28
SP 4	Levkivske	28; 1	50° 21’ N 28° 72’ E	humid	100	22	32

*Fresh or humid relatively poor forest site conditions (Migunova 1993).

the presence and proportion of dead branches in the crown, etc.) according to “Sanitary rules in the forests of Ukraine” (Anonymous 1995).

Parts of a stem with thin, thick and transitional bark, as well as branches and twigs were examined in each model tree. In our model trees, the height from the soil of stem part with thick bark was 5 – 9 m, with thin bark 2.5 – 12 m, and with transitional bark 9 – 17.5 m. The width of thick bark was 20 – 30 mm, of transitional bark 5 – 15 mm, and of thin bark 2 – 4 mm.

For each felled tree in the central part of the region with a thick, transitional, and thin bark, a fragment 1 m long was selected for examination. The diameter of fragments with thick bark was 26 – 32 cm, with transition bark 16 – 24 cm, with thin bark 8 – 14 cm. The length of examined fragments of branches and twigs was 0.5 m, and their diameter was 2 – 4 cm and 5 – 8 cm, respectively.

From each of 12 trees, 5 fragments were taken: from parts of a stem with thin, thick and transitional bark, from a branch and a twig, in total 60 fragments.

In these fragments, xylophagous beetles were identified directly by adults or by characteristic galleries, and wood samples were taken from each fragment for nematodes isolation.

Wood samples for nematodes isolation were taken as saw cuts with a saw to a depth of 2 – 5 cm in two places at a distance of 10 cm from each other and then chipping off with a chisel and a hammer. The obtained sample was split with an ax and then was crushed with pruners into fragments 1–2 cm in size. The twig and branch samples were sawed and then crushed.

Nematodes were isolated from wood samples in the laboratory using the Baermann method (Southey 1970). The crushed wood sample was placed in a funnel with a diameter of 12 – 15 cm and a tilt angle of 50°. A rubber tube of the appropriate diameter was put on the narrow end of the funnel, and a vial was inserted into the free end of the tube. In the middle of the funnel brass or synthetic sieve was placed with a hole size of 0.1 mm. The crushed sample was put onto the sieve and added water so that the water level was 1 – 2 cm higher.

Active nematodes in water come out of wood and, due to a greater specific gravity than water, are lowered to the bottom of the test tube. After 24 hours, the test tube was disconnected from the hose. The contents of the test tube were heated in a water bath at a temperature of 50 – 60 °C for 2 – 4 minutes and then fixed with a solution of TAF (7 ml of 40% formalin, 2 ml of triethanolamine, 91 ml of distilled water) or 4 – 6% solution of formalin.

Nematodes were identified by morphometric characteristics (Korma & Sigaryova 2017). Their distribution in different parts of a tree was evaluated as the proportion of respective samples with the presence of certain species. The population density of each nematode species was evaluated as an individuals’ number per sample.

The frequency of occurrence of nematode species was evaluated as the proportion of samples with the presence of particular species from all 60 examined samples.

As no beetles and their galleries except *Ips acuminatus* (Gyllenhal 1827) galleries were found in twigs and branches, and only this species was found in the fragments with thin bark, we calculated the frequency of beetles as the proportion of tree fragments with the presence of particular species in 36 fragments from 12 trees (12 stem fragments with thin, 12 stem fragments with transitional bark and 12 stem fragments with thick bark).

Dominance of each beetle species was calculated as the proportion of stem fragments with the presence of this species of the total number of populated fragments.

The dominance of each nematode species was calculated as the proportion of tree fragments with the presence of this species of the total number of populated fragments.

Normality tests, summary statistics, one-way analysis of variance (ANOVA), Tukey HSD test with a significance level of $p < 0.05$ and Welch F test were performed. Microsoft Excel software and statistical software package PAST: Paleontological Statistics Software Package for Education and Data Analysis (Hammer et al. 2001) were used.

3. Results

3.1. Xylophagous beetles

Not a single stem fragment populated by any xylophagous beetle was detected in the sample areas SP 3 and SP 4. The significance of the frequency of xylophagous beetles in SP 1 and SP 2 was not proved (Welch F test: F = 0.0829; df = 13.4, p = 0.7778). In total, 10 species of xylophagous beetles were identified (Table 2, Fig. 1).

Table 2. Frequency (%) (±SE) of xylophagous beetles in different parts of Scots pine trees.

Species	Parts of stem		
	thin bark	transitional bark	thick bark
	(N=12)		
	Cerambycidae		
Acanthocinus griseus (Fabricius, 1792)	0.0	8.3±7.98	0.0
Acanthocinus aedilis (Linnaeus, 1758)	0.0	0.0	8.3±7.98
Arhopalus rusticus (Linnaeus, 1758)	0.0	0.0	16.7±10.76
	Curculionidae: Scolytinae		
Ips acuminatus (Gyllenhal, 1827)	25.0±12.50	25.0±12.50	0.0
I. sexdentatus (Boerner, 1767)	0.0	8.3±7.98	25.0±12.50
Tomicus piniperda (Linnaeus, 1758)	0.0	16.7±10.76	0.0
T. minor (Hartig, 1834)	0.0	16.7±10.76	0.0
Orthotomicus proximus (Eichhoff, 1867)	0.0	0.0	16.7±10.76
Trypodendron lineatum (Olivier, 1795)	0.0	0.0	8.3±7.98
Crypturgus pusillus (Gyllenhal, 1813)	0.0	8.3±7.98	0.0
All species	25.0±12.50	83.3±10.76	75.0±12.50

N – number of stem fragments.

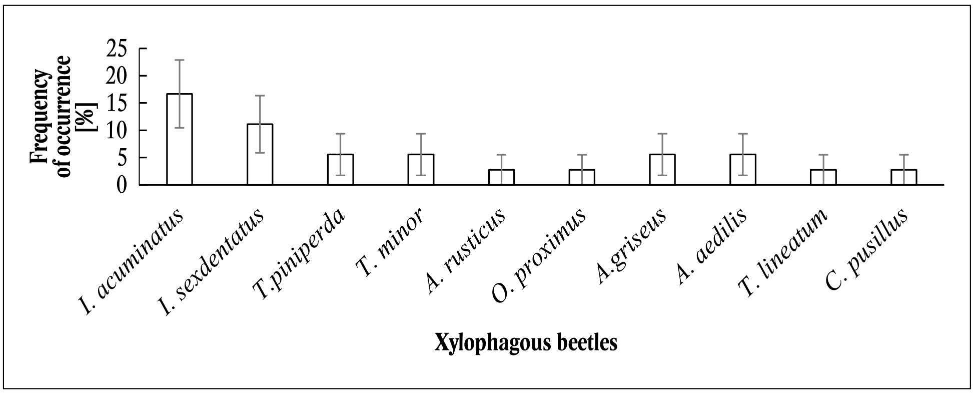


Fig. 1. Frequency of occurrence of xylophagous beetles in analyzed Scots pine trees (±SE) (the species are arranged in decreasing order of frequency of occurrence; N = 36; stem fragments with different bark).

The highest frequency was found in *I. acuminatus* (16.7% of stem fragments) and *I. sexdentatus* (11.1% of stem fragments) (Fig. 1).

The frequency of occurrence of *T. piniperda, T. minor, O. proximus,* and *A. rusticus* was 5.6%. The rest 4 species were found only in 2.8% of stem fragments (see Fig. 1).

Each xylophagous beetle species was confined to a specific part of the tree (see Table 2). Only *I. acuminatus* was found in the fragments with thin bark (frequency 25%). However, it has the same frequency in the fragments with transitional bark (25%). *I. sexdentatus* occurred in 25% of fragments with thick bark and in 8.3% fragments with transitional bark. The both *Tomicus* spp., *A. griseus,* and *C. pusillus* were found only under transitional bark. Longhorn beetles *A. aedilis*, *A. rusticus*, and bark beetles *O. proximus* and *T. lineatum* were found only under thick bark (see Table 2).

Significant differences were absent in the frequency of occurrence of *Ips sexdentatus* in the stem parts with thick and transitional bark (Welch F test: F = 1.158; df = 18.69; p = 0.2956). The frequency of occurrence of xylophagous beetles in the total samples from fresh relatively poor and humid relatively poor forest site conditions was 72.2 and 55.6% respectively, however, the difference was not statistically significant (Welch F test: F = 1.663E–06; df = 17.92; p = 0.999). The frequency of most common species *I. acuminatus* and *I. sexdentatus* was 1.3 and 3 times higher in the fresh relatively poor than in the humid relatively poor forest site conditions (Fig. 2), however, the difference was not statistically significant (Welch F test: F = 0.7727; df = 31.65; p = 0.386 for *I. acuminatus*; F = 0; df = 34; p = 1 for *I. sexdentatus*). Species *A. aedilis*, *T. lineatum*, and *C. pusillus* were found only in the stem fragments from fresh relatively poor forest site conditions. The longhorn beetles *A. rusticus* and *A. griseus* were found only in the fragments from humid relatively poor forest site conditions.

No xylophagous beetle was found in analyzed stem fragments from the trees of the 1st and 2nd categories of health condition. In the dead trees, only sporadic longhorn beetles *A. rusticus* and *A. aedilis* were presented (one beetle of each species). There was no significant difference (Welch F test: F = 1.415E–06; df = 17.35, p = 0.9991) in the frequency of occurrence of xylophagous beetles in the trees of the 3rd category (severely weakened trees) and of the 4th category (drying up trees according to health condition score) (Fig. 3).

By the proportion in the total number of tree fragments, *I. sexdentatus* dominated (54.6% from all beetles) (Table 3). The proportion of *I. acuminatus*, *T. piniperda*, and *T. minor* was 3.1, 4.7 and 6.7 times less in the total number of samples, than of *I. sexdentatus*. Obvious domination of *I. acuminatus* in the samples with thin bark and

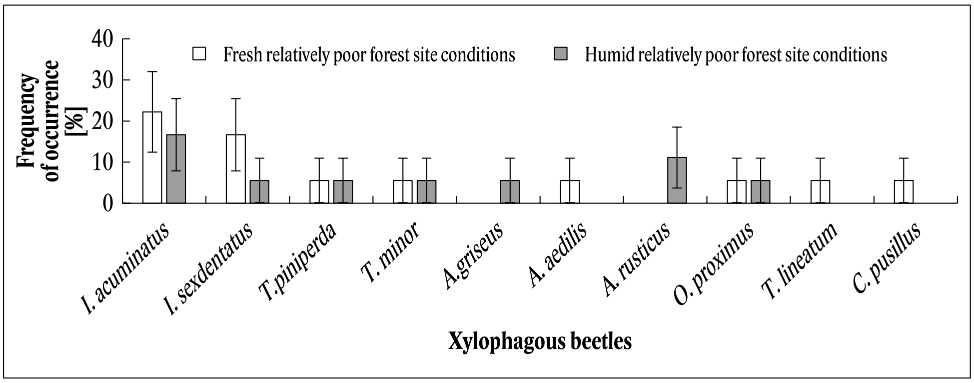


Fig. 2. Frequency of occurrence of xylophagous beetle species in analyzed Scots pine trees in different forest site conditions (±SE) (the species are arranged in decreasing order of frequency of occurrence).

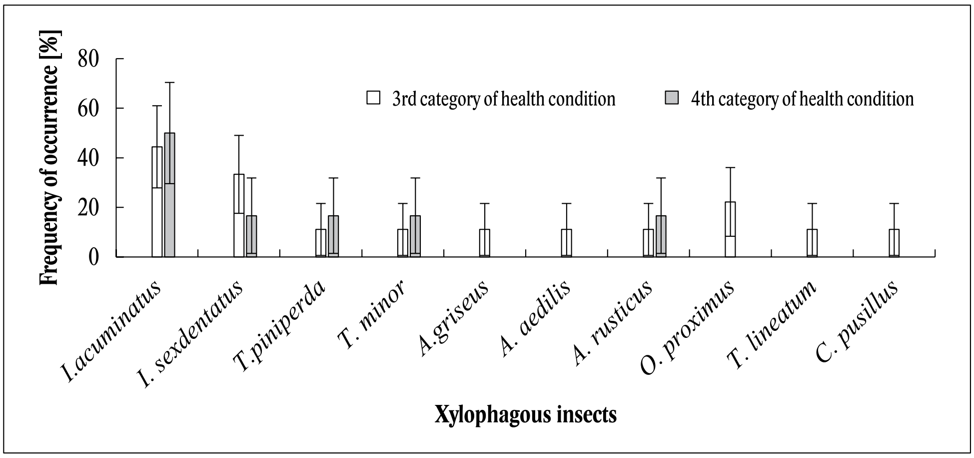


Fig. 3. Frequency of occurrence of xylophagous beetle species in analyzed Scots pine trees of different health condition (±SE) (3rd category – severely weakened trees; 4th category – drying up trees according to health condition score [Anonymous 1995]; the trees of the 1st and 2nd categories of health condition were not inhabited by xylophagous beetles).

Table 3. Proportion of xylophagous beetles in different stem fragments of Scots pine (±SE).

Species	Total (N=36)*	Parts of stem thin bark	transitional bark	thick bark
			(N=12)	
I. acuminatus	17.9±3.83b**	100.0	27.9±4.48b	0.0
I. sexdentatus	54.6±4.98bc	0.0	1.6±1.27a	90.6±2.92b
T. piniperda	11.7±3.22b	0.0	37.7±4.85b	0.0
T. minor	8.2±2.74b	0.0	26.2±4.40b	0.0
A. griseus	0.5±0.71a	0.0	1.6±1.27a	0.0
A. aedilis	0.5±0.71a	0.0	0.0	0.9±0.92a
A. rusticus	1.0±1.00a	0.0	0.0	1.7±1.30a
O. proximus	3.6±1.86ab	0.0	0.0	6.0±2.37a
T. lineatum	0.5±0.71a	0.0	0.0	0.9±0.92a
C. pusillus	1.5±1.23a	0.0	4.9±2.16ab	0.0
Berger-Parker index	0.5	1.0	0.4	0.9

Note: * N – number of stem fragments; ** Values followed by the same letter are not significant within column at the 95% confidence level.

I. sexdentatus in the stem fragments with thick bark is supported by the Berger-Parker index (see Table 3).

3.2. Nematodes

Nematodes associated with trees (15 species) were revealed in 56.7% of samples (Table 4).

The most of nematodes were saproxylic (6 species, or 40%) and entomophilic (5 species, or 33.3%). Phytophagous nematodes were in the third place (2 species, or 13.3%). Predators and species associated with fungi were represented by one species each (by 6.7%). The frequency of nematode species in the samples from Scots pine trees from four sample plots didn't differ statistically (Welch F test: F = 1.686; df = 30.11; p = 0.1911). The frequency of certain nematode species in the samples from Scots pine trees was from 1.7 to 36.7% (Fig. 4).

Entomophilic nematodes had the highest frequency of occurrence and the highest species proportion (see Table 4, Fig. 4).

Table 4. Nematodes and their belonging to trophic groups in total sample from Scots pine trees.

Family	Species	Trophic group
Bunonematidae	*Bunonema poligraphi* (Fuchs, 1930) Sachs, 1949	saproxylic
Rhabditidae	*Parasitorhabditis acuminati* (Fuchs, 1915) Sobolev et Paramonov, 1954 (syn. *Rhabditis obtusa acuminati* Fuchs, 1915; *Parasitorhabditis obtusa acuminati* (Fuchs, 1915) Fuchs, 1937)	entomophilic
Diplogasteroididae	*Diplogasteroides sexdentati* Vosylyte, 1979	saproxylic
Diplogasteroididae	*Rhabdontolaimus carinthiacus* Fuchs, 1931	saproxylic
Diplogasteridae	*Tridontus longicaudata* Khera, 1965	saproxylic
Diplogasteridae	*Fuchsia buetschlii acuminati* Ruhm, 1956	predator
Cephalobidae	*Anguilluloides procera* Weingartner, 1954 (syn. *Alloionema procerum* Weingartner, 1954)	saproxylic
Cephalobidae	*Cephalobus persegnis* Bastian, 1865	saproxylic
Contortylenchidae	*Contortylenchus acuminati* Ruhm, 1956	entomophilic
Tylenchidae	*Ditylenchus striatus* Fuchs, 1938 (syn. *Anguillonema striata* Fuchs 1938)	associated with fungi
Aphelenchoididae	*Laimaphelenchus penardi* (Steiner, 1914) Filipjev et Sch.-Stekhoven, 1941	entomophilic
Ektaphelenchidae	*Cryptaphelenchus macrogaster f. acuminati* Ruhm, 1956	entomophilic
Parasitaphelenchidae	*Parasitaphelenchus acuminati* Ruhm, 1956	entomophilic
Parasitaphelenchidae	*Bursaphelenchus sexdentati* Ruhm, 1960	phytophagous
Parasitaphelenchidae	*Bursaphelenchus eggersi* Ruhm, 1956	phytophagous

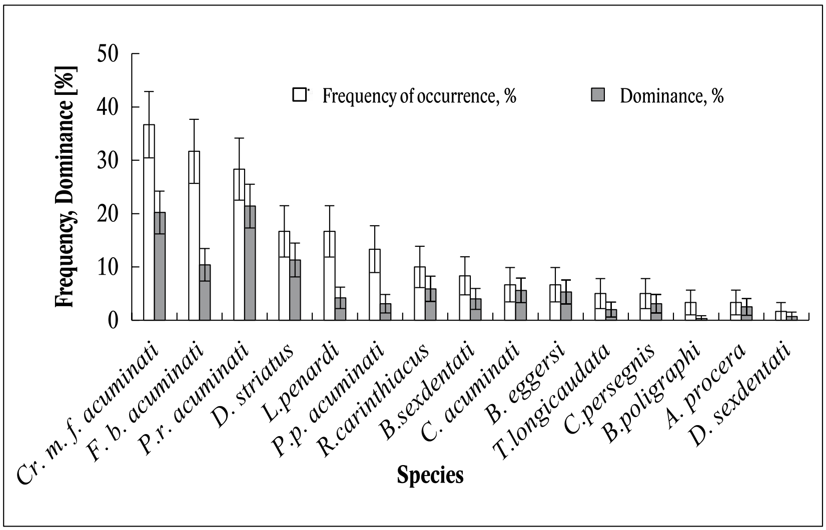


Fig. 4. Frequency of occurrence and abundance of nematode species in Scots pine trees (±SE)
(*Cr. m. f. acuminati – Cryptaphelenchus macrogaster f. acuminati; F. b. acuminati – Fuchsia buetschlii acuminati; P.r. acuminati – Parasitorhabditis acuminati; D. striatus – Ditylenchus striatus; L. penardi – Laimaphelenchus penardi; P.p.acuminati – Parasitaphelenchus acuminati; R. carinthiacus – Rhabdontolaimus carinthiacus; B. sexdentati – Bursaphelenchus sexdentati; C. acuminati – Contortylenchus acuminati; B. eggersi – Bursaphelenchus eggersi; T. longicaudata – Tridontus longicaudata; C. persegnis – Cephalobus persegnis; B. poligraphi – Bunonema poligraphi; A. procera – Anguilluloides procera; D. sexdentati – Diplogasteroides sexdentati.*

Nematodes were found in twigs, branches, and stem parts with thin, transitional and thick bark (Fig. 5). Significant differences were not proved both in species number (Welch F test: F = 0.1197; df = 27.44; p = 0.9743) and their abundance (Welch F test: F = 0.07535; df = 27.46; p = 0.9891).

The frequency of two nematodes was the highest in all parts of a tree (Table 5). Entomophilic nematode *Cryptaphelenchus macrogaster* f. *acuminati* had the minimal frequency of occurrence 25% under the thick bark and maximal frequency of occurrence under the thin bark and in branches. Its frequency of occurrence under transitional bark and in the twigs was 33.3%, which is the highest for these parts of a tree. The second species with high occurrence in all parts of a tree was predator *Fuchsia buetschlii acuminati* with the frequency of occurrence 41.7% under the thin bark and in the branches and the frequency of occurrence 25% in other parts of a tree. An entomophilic nematode *Parasitorhabditis acuminati* had a high frequency of occurrence (41.7%) under the thin bark and in the branches, frequency of occurrence 25% in twigs and under transitional bark and only 8.3% under the thick bark.

In general, the frequency of occurrence of entomophilic nematodes was the highest among trophic groups. In average it was 25% under the thin bark, 23.3 and 20% in branches and twigs, 18.3% under transitional bark and 15% under the thick bark. Nematodes *Bursaphelenchus sexdentati* and *Bursaphelenchus eggersi* are considered as phytophagous nematodes like other members of this genus. Their average frequency of occurrence was rather low in all parts of a tree (4.2 – 8.4%), except stem part with thick bark (15% on average). The frequency of occurrence of saproxyllic nematodes was 4.2 – 6.9% in twigs, branches and under thin bark, and only 2.8% under thick bark.

The number of nematode species was significantly higher in the trees of the 3rd category of health condition

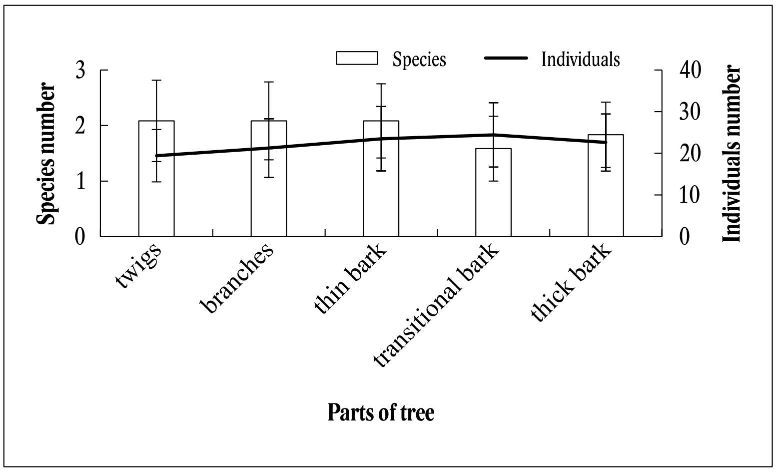


Fig. 5. Frequency of occurrence and abundance of all nematode species in certain fragments of Scots pine trees (±SE) (12 samples of each fragment: twigs, branches, thin bark, transitional bark, and thick bark, 60 samples in total).

Table 5. Frequency of nematodes in parts of Scots pine trees (±SE).

Nematode species	Parts of tree				
	twig	branch	thin bark	transitional bark	thick bark
Bunonema poligraphi	8.3± 7.96a	0	8.3± 7.96a	0	0
Parasitorhabditis acuminati	25.0± 12.50b	41.7± 14.23b	41.7± 14.23b	25.0± 12.50b	8.3± 7.96a
Diplogasteroides sexdentati	8.3± 7.96a	0	0	0	0
Rhabdontolaimus carinthiacus	8.3± 7.96a	16.7± 10.77ab	8.3± 7.96a	8.3± 7.96a	8.3± 7.96a
Tridontus longicaudata	8.3± 7.96a	0	16.7± 10.77ab	0	0
Cephalobus persegnis	8.3± 7.96a	8.3± 7.96a	8.3± 7.96a	0	0
Anguilluloides procera	0	0	0	8.3± 7.96a	8.3± 7.96a
Fuchsia buetschlii acuminati	25.0± 12.50b	41.7± 14.23b	41.7± 14.23b	25.0± 12.50b	25.0± 12.50b
Ditylenchus striatus	25.0± 12.50b	16.7± 10.77ab	16.7± 10.77ab	8.3± 7.96a	16.7± 10.77ab
Contortylenchus acuminati	0	8.3± 7.96a	0	8.3± 7.96a	16.7± 10.77ab
Laimaphelenchus penardi	25.0± 12.50b	8.3± 7.96a	16.7± 10.77ab	16.7± 10.77ab	16.7± 10.77ab
Cryptaphelenchus macrogaster f. acuminati	33.3± 13.60b	41.7± 14.23b	50.0± 14.43b	33.3± 13.60b	25.0± 12.50b
Parasitaphelenchus acuminati	16.7± 10.77ab	16.7± 10.77ab	16.7± 10.77ab	8.3± 7.96a	8.3± 7.96a
Bursaphelenchus sexdentati	8.3± 7.96a	8.3± 7.96a	8.3± 7.96a	0	16.7± 10.77ab
Bursaphelenchus eggersi	8.3± 7.96a	0	0	16.7± 10.77ab	8.3± 7.96a

Note: Values followed by the same letter are not significant within column at the 95% confidence level.

than in the trees of the 2nd category (Welch F test: F = 11.16; df = 24.99; p = 0.002627). Nematodes number gradually decreased from the trees of the 3rd to the 5th category of health condition (Fig. 6).

At the same time, nematode abundance (number of nematode individuals) continued to increase from the 2nd to the 4th category of health condition and decreased in the dead trees (of the 5th category of health condition). The differences between nematode abundance in the trees of the 2nd and the 3rd categories (Welch F test: F = 14.91; df = 25.5; p = 0.000688) as well as in the trees of the 3rd and the 5th categories (Welch F test: F = 6.343; df = 12.13; p= 0.0268) are significant.

Only four nematode species were found in the trees of the 2nd category of health condition (Table 6). The frequency of occurrence of *Fuchsia buetschlii acuminati* and *Cryptaphelenchus macrogaster* f. *acuminati* was the highest in all living trees, however, these species were absent in dead trees.

The highest frequency of occurrence of nematodes of all trophic groups was found in the trees of the 3rd category of health condition. Phytophagous nematodes and

Table 6. Frequency of occurrence of different nematode species in Scots pine trees of different health condition (±SE).

Species	Health condition category			
	2nd	3rd	4th	5th
Bunonema poligraphi	0	0	1.67±4.05a	1.67±6.41a
Parasitorhabditis acuminati	0	16.7±9.63a	5.01±6.90a	0
Diplogasteroides sexdentati	0	0	1.67±4.05a	0
Rhabdontolaimus carinthiacus	0	1.67±3.31a	0	3.34±8.98a
Tridontus longicaudata	0	0	3.34±5.68a	1.67±6.41a
Cephalobus persegnis	0	3.34±4.64a	1.67±4.05a	0
Anguilluloides procera	0	3.34±4.64a	0	0
Fuchsia buetschlii acuminati	5.01±8.25a	13.36±8.78a	3.34±5.68a	0
Ditylenchus striatus	1.67±4.84a	8.35±7.14a	5.01±6.90a	0
Contortylenchus acuminati	0	1.67±3.31a	3.34±5.68a	1.67±6.41a
Laimaphelenchus penardi	3.34±6.79a	3.34±4.64a	1.67±4.05a	3.34±8.98a
Cryptaphelenchus macrogaster f. acuminati	5.01±8.25a	16.7±9.63a	5.01±6.90a	0
Parasitaphelenchus acuminati	0	8.35±7.14a	5.01±6.90a	0
Bursaphelenchus sexdentati	0	1.67±3.31a	3.34±5.68a	1.67±6.41a
Bursaphelenchus eggersi	0	5.01±5.63a	1.67±4.05a	0

Note: Values followed by the same letter are not significant within column at the 95 % confidence level.

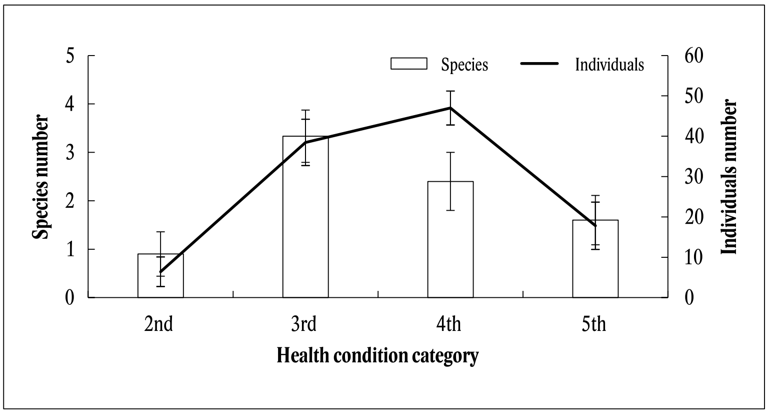


Fig. 6. Frequency of occurrence and abundance of nematode species in Scots pine trees of different health condition (±SE).

saproxylic species were absent in the trees of the 2nd category of health condition, whereas predators and associated with fungi species were absent in the dead trees (see Table 4).

The most common entomophilic nematode – *Parasitorhabditis acuminati* was absent in the stem fragments with thick and transitional bark which were not colonized with xylophagous insects (Table 7). The frequency of *Parasitorhabditis acuminati* in colonized stem fragments with thin bark was significantly higher than in respective not colonized fragments.

The frequency of another high spread entomophilic nematode – *Cryptaphelenchus macrogaster f. acuminati* didn't differ significantly in colonized and not colonized stem samples. The predator nematode – *Fuchsia buetschlii acuminati* was found in both colonized and not colonized stem samples, however, its frequency was significantly higher in colonized stem fragments with thin bark (see Table 7).

4. Discussion

Ten species of xylophagous beetles were revealed in the sample trees (see Table 2), and their distribution for the most part of Europe (Davydenko et al. 2015; Lieutier

Table 7. Frequency of occurrence of most common nematode species in Scots pine trees inhabited with xylophagous insects (±SE).

Species	Stem fragment		Welch F test		
	colonized with xylophagous insects	not colonized with xylophagous insects	F	df	p
	Stem fragments with thick bark				
Parasitorhabditis acuminati	33.3±19.24	0.0	—	—	—
Fuchsia buetschlii acuminati	50.0±20.41	16.7±15.23	1.429	9.245	0.2618
Cryptaphelenchus macrogaster f. acuminati	33.3±19.24	33.3±19.24	0	10	1
	Stem fragments with transitional bark				
Parasitorhabditis acuminati	33.3±19.24	0.0	—	—	—
Fuchsia buetschlii acuminati	33.3±19.24	16.7±15.23	0.3846	9.494	0.5497
Cryptaphelenchus macrogaster f. acuminati	33.3±19.24	16.7±15.23	0.3846	9.494	0.5497
	Stem fragments with thin bark				
Parasitorhabditis acuminati	66.7±19.24	16.7±15.23	3.462	9.494	0.094
Fuchsia buetschlii acuminati	66.7±19.24	16.7±15.23	3.462	9.494	0.094
Cryptaphelenchus macrogaster f. acuminati	66.7±19.24	33.3±19.24	1.25	10	0.2897

et al. 2016; Korma & Sigaryova 2017; Andreieva et al. 2018). Dominance of *I. acuminatus* and *I. sexdentatus* is characteristic for bark beetles' outbreaks of last years (Siitonen 2014; Meshkova et al. 2018), because they have advantages like multivoltinous species (Leutier et al. 2016; Meshkova 2017).

An absence of *Monochamus galloprovincialis* (Olivier 1795), which is responsible for vectoring of phytophagous nematodes (d'Errico et al. 2015; Mamiya 1983; Ryss et al. 2018), in our sample trees can be explained by sampling more early (end of May) than the swarming of this longhorn beetle in the region (Meshkova et al. 2017).

Not a single stem fragment was populated by xylophagous beetles in the sample areas SP3 and SP4. It may be explained by the fact that the trees of the 1st, 2nd and 5th category of health condition (healthy, slightly weakened and dead) dominated in the sample from these plots. Usually, the trees of the 1st and 2nd categories of health condition are not attractive for xylophagous insects, and the dead trees are usually abandoned by these insects or were not colonized in the case of quick drying up (Meshkova 2017).

Confinement of each bark beetle species to the stem parts with particular bark thickness is connected with insect adaptation to certain humidity and temperature level (Sauvard 2007; Borkowski & Skrzecz 2016; Lieutier et al. 2016). For example, *I. acuminatus* and *T. minor* prefer the upper part of the stem with thin bark, and *I. sexdentatus* and *T. piniperda* prefer the lower part of the stem with thin bark. Recent years *I. acuminatus* and *I. sexdentatus* had the highest frequency of occurrence and proportion (see Table 2, 3), which is a result of its outbreak in studied regions (Siitonen 2014; Lieutier et al. 2016; Meshkova et al. 2018). Due to multivoltinism, the above-mentioned species replaced *T. piniperda* and *T. minor* both in the forest and in the stem level (Meshkova 2017).

Usually, at high density, the bark beetles concentrate not only in the preferable part of the tree but also in the other parts of the tree (Amezaga & Rodrigues 1998; Meshkova 2017). In our research, *I. acuminatus* dominates in the stem fragments with thin bark (Berger-Parker index=1), and *I. sexdentatus* dominates in the stem fragments with thick bark (Berger-Parker index = 0.9). The both species together with other xylophagous insects present in the stem part with transitional bark, where the Berger-Parker index is 0.4 (see Table 3).

Forest site conditions did not affect significantly the frequency of occurrence of xylophagous beetles (see Fig. 2), because at high population density they inhabit all susceptible trees (Wood 1982; Sauvard 2007). Both fresh and humid forest site conditions are favorable for Scots pine growth in Ukraine (Migunova 1993), although in the case of drought the fresh forest site conditions can be more attractive for xylophagous insects (Meshkova et al. 2018).

Fifteen nematode species were found in analyzed tree fragments, no new species for the fauna of Ukraine and Europe were detected for the first time in this study.

Some species from genera *Contortylenchus, Parasitylenchus, Parasitorhabditis, Parasitaphelenchus*, and *Cryptaphelenchus* are mentioned as entomophilic (parasitic) nematodes of bark beetles in Europe (Nedelchev et al. 2008).

However, the distribution of nematodes by ecological trophic grouping is somewhat conditional (Korma & Sigaryova 2017). The larval stages of parasitic nematodes may be obligatory or optional parasites of insects, with a free-living stage under the bark of an affected tree. At the same time, they can be associated with fungi or be saprobionts. Conversely, phytophagous nematodes with a pronounced pathological effect on larval stages may partially parasitize on the surfaces of insect-vectors or in the abdominal cavity. Some *Bursaphelenchus* species only in certain environmental conditions deal as phytophagous nematodes. They penetrate into plant tissues and destroy the epithelium of the resin ducts and can kill the tree (Mamiya 1987; Zhao et al. 2009).

Two identified species of the genus *Bursaphelenchus* are considered as phytophagous nematodes (Kulinich & Ryss 2006). However, they were identified only in the trees of the 2nd category of health condition (see Table 5), which makes one doubt that all members of the genus *Bursaphelenchus* are phytophagous nematodes.

In our study, five identified nematodes have species name "*acuminati*" and two nematodes have species name "*sexdentati*", which respects their association with the most abundant xylophagous beetles – *I. acuminatus* and *I. sexdentatus* and is agree with other authors (Blinova 1982; Grucmanová & Holuša 2013; Yaman et al. 2016; Slonim et al. 2018). The most abundant entomophilic nematodes *Cryptaphelenchus macrogaster* f. *acuminati* and *Parasitorhabditis acuminati*, as well as a predator *Fuchsia buetschlii acuminati* are associated with Ips acuminatus. Usually, the high frequency of occurrence and abundance of any entomophagous or entomopathogenic organism is characteristic of the decline phase of the bark beetle outbreak (Sauvard 2007). As we know, that an outbreak of *I. acuminatus* in the region started over 5 years ago (Davydenko et al. 2015; Meshkova et al. 2018), we can assume that in the investigated forest the outbreak of this bark beetle has also the trend to collapse.

The preferences of bark beetles to the parts of pine stem and forest health condition are rather well-known (Amezaga & Rodrigues 1998; Sauvard 2007) and are supported in this study. However, within-tree distribution of nematodes is studied only for pinewood nematode (PWN), *Bursaphelenchus xylophilus*, a serious invasive and destructive species, is listed as a quarantine pest in the legislation of more than 40 countries (Zhao et al., 2009).

The highest frequency of occurrence of nematodes in the trees of the 3rd category of health condition and abundance in the trees of the 4th category of health condition (see Fig. 6) is explained by domination of entomophilic nematodes (see Table 4), which follow their hosts (Holuša et al. 2017). However, the phytophagous nematodes also follow bark beetles, which facilitate their penetration into the tree (Grucmanova & Holuša 2013; Korma & Sigaryova 2017).

Usually, xylophagous beetles do not attack healthy trees, however, they can weaken them during maturation feeding and then attack successfully (Lieutier et al. 2016; Meshkova 2017). If the beetles colonize the weakened trees (of the 2nd category of health condition) in April, then to the end of May (the time of our assessment) these trees had the 3rd or the 4th category of health condition. Entomophilic nematodes could penetrate the tree simultaneously with bark beetles.

In our study, nematodes were found in all parts of the stem, branches, and twigs (see Fig. 5). The frequency of *Parasitorhabditis acuminati* and *Fuchsia buetschlii acuminati* in stem fragments with thin bark colonized with xylophagous insects was significantly higher than in respective not colonized fragments (see Table 6). However, even these nematodes were sometimes found in the samples without xylophagous insects.

5. Conclusion

Among 10 species of xylophagous beetles, *Ips acuminatus* and *I. sexdentatus* dominated. Only *I. acuminatus* was found in the stem fragments with thin bark and much less in the fragments with transitional bark. *I. sexdentatus* occurred in the fragments with thick bark and much less with transitional bark. The both *Tomicus* spp., *A. griseus,* and *C. pusillus* were found only under transitional bark. Longhorn beetles *A. aedilis*, *A. rusticus*, and bark beetles *O. proximus* and *T. lineatum* were found only under the thick bark. No xylophagous insect was found in analyzed samples from the trees of the 1st and 2nd category of health condition.

Among 15 nematode species 40% were saproxylic, 33.3% entomophilic nematodes, 13.3% phytophagous nematodes, and by 6.7% predators and species associated with fungi. An average frequency of occurrence of phytophagous nematodes *Bursaphelenchus sexdentati* and *Bursaphelenchus eggersi* was low in all parts of a tree, except stem part with thick bark.

The frequency of saproxylic nematodes was 4.2–6.9%in twigs, branches and under thin bark, and only 2.8% under thick bark. Predators and species associated with fungi were absent in the dead trees. The absence of *Bursaphelenchus sexdentati* and *Bursaphelenchus eggersi* in the trees of the 2nd category of health condition makes one doubt that all members of the genus *Bursaphelenchus* are phytophagous nematodes. Confinement of these nematodes the lower parts of the stem supports its association with *I. sexdentatus.*

An entomophilic nematode *Cryptaphelenchus macrogaster* f. *acuminati* was common in all parts of stem and branches. The frequency of *Parasitorhabditis acuminati* and *Fuchsia buetschlii acuminati* in colonized stem fragments with thin bark was significantly higher than in respective not colonized fragments.

References

Amezaga, I., Rodriguez, M. A., 1998: Resource partitioning of four sympatric bark beetles depending on swarming dates and tree species. Forest Ecology and Management, 109:127–135.

Andreieva, O., Zhytova, O., Martynchuk, I., 2018: Health condition and colonization of stem insects in Scots pine after ground fire in Central Polissya. Folia Forestalia Polonica, Series A – Forestry, 60:143–153.

Anonymous, 1995: Sanitary rules in the forests of Ukraine. Ministry of Forest management of Ukraine. 19 p.

Blinova, S. L., 1982: Entomopathogenic nematodes – the parasites of forest pests. Family Rhabditidae. Moscow, Nauka, 135 p.

Borkowski, A., Skrzecz, I., 2016: Ecological segregation of bark beetle (Coleoptera, Curculionidae, Scolytinae) infested Scots pine. Ecological research, 31:135–144.

Buzun, V. O., Turko, V. M., Siruk, Yu. V., 2018: A book on the forests of Zhytomyr region. Zhytomyr, O. O. Jevenok, 440 p.

Davydenko, K., Vasaitis, R., Meshkova, V., Menkis, A., 2014: Fungi associated with the red-haired bark beetle, *Hylurgus ligniperda* (Coleoptera: Curculionidae) in the forest-steppe zone in eastern Ukraine. European Journal of Entomology, 111:561–565.

Davydenko, K. V., Skrylnyk, Yu. Ye., Meshkova, V. L., 2015: Stem nematodes in declining stands of Scots pine in Volyn' Polissya. The Bulletin of Kharkiv National Agrarian University. Series Phytopathology and Entomology, 1–2: 32–37.

Davydenko, K., Vasaitis, R., Menkis, A., 2017. Fungi associated with *Ips acuminatus* (Coleoptera: Curculionidae) in Ukraine with a special emphasis on pathogenicity of ophiostomatoid species. European Journal of Entomology, 114:77–85.

Dayi, M., Akbulut, S., 2018: Survey for the detection of *Bursaphelenchus* insect-vector species in the western part of Turkey. Kastamonu University Journal of Forestry Faculty, 18:215–224.

d'Errico, G., Carletti, B., Schröder, T., Mota, M., Vieira, P., Roversi, P. F., 2015: An update on the occurrence of nematodes belonging to the genus *Bursaphelenchus* in the Mediterranean area. Forestry: An International Journal of Forest Research, 88:509–520.

Eidmann, H. H., Nuorteva, M., 1968: Der Einfluss der Siedlungsdichte und anderer Faktoren auf die Anzahl der Nachkommen von *Blustophagus piniperda* L. Ann. Ent. Fenn.*,* 34:135–148.

Grucmanová, Š., Holuša, J., 2013: Nematodes associated with bark beetles, with focus on the genus *Ips* (Coleoptera: Scolytinae) in Central Europe. Acta zoologica bulgarica, 65:547–556.

Hammer, O., Harper, D. A. T., Ryan, P. D., 2001: PAST: paleontological statistics software package for education and data analysis. Palaeontologia Electronica, 4:1–9.

Holuša, J., Lukášová, K., Hubáčková, J., Knížek, M., Wegensteiner, R., 2017: Pathogens and nematodes associated to three bark beetle species of the genus *Orthotomicus* (Coleoptera Curculionidae) in Central-South Europe. Bulletin of Insectology, 70:291–297.

Korma, O. M., Sigaryova, D. D., 2017: Complex of nematodes-xylobionts of Scots pine of the Eastern Polissya of Ukraine: features of ecology and biology. Chernihiv: Desna Polygraph, 376 p.

Kozlovsky, M. P., 2016: The pine wood nematode *Bursaphelenchus mucronatus* as the primary cause of the needle trees drying disease in Carpathians and Polissia. Proceedings of the Forestry Academy of Sciences of Ukraine, 14:185–190.

Kulinich, O. A., Ryss, A. Y., 2006: Wood nematodes of genus *Bursaphelenchus* in ther territory of Russia: extraction methods and diagnostics. Applied Nematology, p. 162–186.

Lieutier, F., Mendel, Z., Faccoli, M., 2016: Bark beetles of Mediterranean conifers. In: Paine, T., Lieutier, F. (eds.): Insects and Diseases of Mediterranean Forest Systems. Springer, Cham, 892 p.

Linnakoski, R., De Beer, Z. W., Niemelä, P., Wingfield, M. J., 2012: Associations of conifer-infesting bark beetles and fungi in Fennoscandia. Insects, 3:200–227.

Mamiya, Y., 1983: Pathology of the pine wilt disease caused by *Bursaphelenchus xylophilus*. Annual review of Phytopathology, 21:201–220.

Meshkova, V. L., 2017: Evaluation of harm (injuriousness) of stem insects in pine forest. Scientific Bulletin of UNFU, 27:101–104.

Meshkova, V. L., Skrylnik, Yu. Ye., Zinchenko, O. V., Kochetova, A. I., 2017: Seasonal development of the pine sawyer beetle (*Monochamus galloprovincialis*) in the north-eastern steppe of Ukraine. Forestry & Forest Melioration, 130:223–230.

Meshkova, V., Borysenko, O., Pryhornytskyi, V., 2018: Forest site conditions and other features of Scots pine stands favorable for bark beetles. Proceedings of the Forestry Academy of Sciences of Ukraine, 16:106–114.

Migunova, Ye. S., 1993. Forests and forest lands (Quantitative evaluation of interactions). Moscow, Ecology, 364 p.

Mota, M. M., Braasch, H., Bravo, M. A., Penas, A. C., Burgermeister, W., Metge, K. et al., 1999: First report of *Bursaphelenchus xylophilus* in Portugal and in Europe. Nematology, 1:727–734.

Nedelchev, S., Takov, D., Pilarska, D., 2008: Parasitic and associated nematodes of bark beetles in Bulgaria. Acta Zoologica Bulgarica, Suppl., 2:83–91.

Paine, T. D., Birch, M. C., Svihra, P., 1981. Niche breadth and resource partitioning by four sympatric species of bark beetles (Coleoptera: Scolytidae). Oecologia, 48:1–6.

Pernek, M., Wirth, S., Blomquist, S. R., Avtzis, D. N., Moser, J. C., 2012. New associations of phoretic mites on *Pityokteines curvidens* (Coleoptera, Curculionidae, Scolytinae). Central European Journal of Biology, 7:63–68.

Pylypenko, L. A., Kalatur, K. A., 2015: Breeding and usage of sugar beet cultivars and hybrids resistant to sugar beet nematode *Heterodera schachtii*. Agricultural Science and Practice, 1:12–22.

Ryss, A. Y., Polyanina, K. S., Popovichev, B. G., Krivets, S. A., Kerchev, I. A., 2018: Plant host range specificity of *Bursaphelenchus mucronatus* Mamiya et Enda, 1979 tested in the laboratory experiments. Parazitologiia, 52:32–40.

Saarenmaa, H., 1985: Within-tree population dynamics models for integrated management of Tomicus piniperda (Coleoptera, Scolytidae). Communicationes Instituti Forestalis Fenniae, 128:1–56.

Sauvard, D., 2007: General biology of bark beetles. In: Lieutier, F., Day, K. R., Battisti, A., Grégoire, J.-C., Evans, H. F.: Bark and wood boring insects in living trees in Europe, a synthesis. Springer, Dordrecht, p. 63–88.

Schultze-Dewitz, G., Koch, G., 2008: The anatomy of wood and bark of Scots Pine. A review of literature. Feddes Repertorium, 119:655–668.

Siitonen, J., 2014: *Ips acuminatus* kills pines in southern Finland. Silva Fennica, 48, article id 1145. 7 p.

Slonim, O., Bucki, P., Mendel, Z., Protasov, A., Golan, O., Vieira, P. et al., 2018: First report on *Bursaphelenchus sexdentati* (Nematoda: Aphelenchoididae) in Israel. Forest pathology, 48, e12431.

Southey, J. F., 1970. Principles of sampling for nematodes. Technical Bulletin. Ministry of Agriculture, Fisheries and Food, (5th ed; 2), 1-4.

Takov, D., Doychev, D., Pilarska, D., Draganova, S., Nedelchev, S., Linde, A., 2019: Occurrence of pathogens and nematodes in forest beetles from Curculionidae and Attelabidae in Bulgaria. Biologia, p. 1–9.

Wood, D. L., 1982: The role of pheromones, kairomones, and allomones in the host selection and colonization behavior of bark beetles. Annual Review of Entomology, 27:411–446.

Yaman, M., Algi, G., Unal, S., Guner, B. G., 2016: Survey of pathogens and parasites of the engraver beetle *Ips acuminatus* (Gyllenhal, 1827) (Coleoptera: Curculionidae: Scolytinae) in Turkey. Acta zoologica bulgarica, 68:127–130.

Zhao, L., Jiang, P., Humble, L. M., Sun, J., 2009: Within-tree distribution and attractant sampling of propagative pinewood nematode, *Bursaphelenchus xylophilus*: An early diagnosis approach. Forest Ecology and Management, 258:1932–1937.