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Towards understanding the role of ectomycorrhizal fungi in forest phosphorus cycling : a modelling approach

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Abstract

Many studies have shown the importance of ectomycorrhizal fungi (EM) in forests both for nutrient availability and for carbon (C) and nutrient cycling in the soil. Yet so far they are not incorporated in forest ecosystem growth and yield models. Recent research suggests phosphorus (P) shortage could be a major constraints to forest productivity in the future. For a realistic simulation of future forest ecosystem functioning, inclusion of detailed soil P cycling and the trees-EM interaction is necessary. We developed a full ecosystem P model that simulates P uptake by roots and EM, allocation within trees, physiological deficiency effects on C assimilation and allocation, release through litter decomposition, coupled with water, C and nitrogen (N) fluxes accounted for in the mechanistic forest stand model ANAFORE. Our results confirm the importance of incorporating EM in forest ecosystem models and suggest that the lack of incorporation of P in models may result in an under- or overestimation of forest growth. This new model has the potential of being used to assess the response of trees and/or stands to nutrient availability under different climate and management scenarios. With the current parameterization it is functional as a scientific research tool to investigate hypotheses.

Key words: nutrient cycling; mechanistic model; pine forest; ectomycorrhizal fungi; phosphorus

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1. Introduction

Forest models can be useful tools not only to predict forest productivity but also (and often mainly) to increase our understanding of forest ecosystem functioning. Models allow us to investigate hypothesis concerning processes and present an opportunity to run virtual experiments impossible to run at a forest scale in a reasonable timescale. To investigate and understand how changes in climate and management affect the forest ecosystem it is important that forest models take into account the main drivers. Recent findings in soil nutrient cycling and the interaction between trees and mycorrhizal fungi are not yet implemented into most forest models (Gérard et al. 2017), which limits their predictive capacity concerning some key issues, such as the nutritional status of trees under environmental changes (Hinsinger et al. 2011; Deckmyn et al. 2014).

Although increases in temperate and boreal forest productivity have been evidenced in Europe over the last decades the extent and continuity of the atmospheric CO_2 enrichment effect critically depends on nutrient availability (Nowak et al. 2004; Norby et al. 2010; Fernández-Martínez et al. 2014). The sustainability of this growth increase is questioned in areas of sustained high N deposition, such as northwestern Europe (de Vries et al. 2009). This is particularly true for many forests located on acidic soils, where P has been recognized as potential key limiting nutrient in that context (Braun et al. 2010; Vitousek et al. 2010), leading to deterioration of tree vitality (Jonard et al. 2012; Jonard et al. 2015). Moreover, forest yield is not the only important issue as other key forest functions including C storage and stabilization of nutrients in the soil are increasingly seen as key factors in sustainable forest management (Toman & Ashton 1996).

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While significant progress has been made in developing mechanistic models simulating the C and N cycles in the past decades, including the cycling of P has received less attention (Vereecken et al. 2016), except for agricultural models (Landsberg et al. 1991; Probert et al. 2000). Recently mechanistic models have been developed that include P in the litter and SOM pools (Runyan & D'Odorico 2012), though more often the representation of P uptake is simple and empirical. Most existing stand models empirically compare soil P availability with tree demand and reduce growth to available nutrient levels in case of limitation. The mineralization of organic matter is described as a function of environmental factors and litter quality only, based on decay rates, while microbial roles remain inherently incorporated and fixed in used constants.

Moreover, EM are on the whole rarely included in ecosystem models, even though hyphae extension beyond root depletion zones and their efficient absorption kinetics are vital in simulating P uptake at low soil concentrations (Read & Perez-Moreno 2003; Read et al. 2004; Deckmyn et al. 2014). In the field of EM and arbuscular mycorrhizae (AM) modeling, quite a number of models have been developed and applied showing the importance of the EM fungi and how they trade nutrients for carbon with the plant. Recently, a few of these have been linked to ecosystem models (some only for N-uptake) (Orwin et al. 2011; Meyer et al. 2012; Franklin et al. 2014). The major drawback of conventional models excluding mycorrhizae is that uptake of nutrients is only possible from mineralized sources, while in reality EM fungi are able to extract nutrients from organic sources and these nutrients become available to the host trees (Lindahl & Tunlid 2014). The lack of consideration of the P cycling, the role of mycorrhizae and the ability of plants to react to nutrient deficiency in forest ecosystem models may result in an overestimation of plant growth, and therefore failure to accurately predict forest dynamics under climate change scenarios (Fernández-Martínez et al. 2014; Jonard et al. 2015). However, including P without a realistic simulation of the interaction between EM and trees can lead to overestimation of P-limitation, as very little mineral P is present in the soil solution. Mycorrhizae also significantly affect soil aggregation (Zhenh et al. 2014). It is within this context that a complete process-based description of the P cycling and its limiting effect on tree growth in forest models becomes crucial in order to understand the magnitude and direction of forest stands response to future changes and how management can affect these.

In this paper, we describe a new process-based model that details the P cycle in forest ecosystems. This includes element fluxes such as uptake, storage and transfer by EM; uptake by fine roots, allocation and translocation within trees, and the effect of P deficiency on essential plant functions such as photosynthesis, growth and biomass allocation. This process-based model is integrated into the mechanistic forest ecosystem model ANAFORE (ANAlysis of FORest Ecosystems), in which this new module interacts with other existing modules such as the growth, C, N and soil modules (Deckmyn et al. 2008; Deckmyn et al. 2011). In order to show the application of this new module, the model is parameterized for the Scots pine (*Pinus sylvestris* L.) forest "De Inslag" in Belgium. Our aim is to provide a modeling framework to simulate P cycling in forest ecosystem models. In addition to this model description, we quantify the main pools and fluxes in the new model with emphasis on the role of mycorrhizae in the uptake of P in low soil concentrations. Furthermore, we demonstrate the simulation of seasonal changes in P allocation within the trees and the shortage effects thereof on forest growth. We also analyze the model sensitivity to mycorrhizal parameters to investigate how important EM differentiation is to the overall results and finally we show how small changes in management such as leaving branches on the site at harvest can affect the soil nutritional status.

2. Materials and methods

A new module describing the cycling of elements in forest ecosystems is integrated into the mechanistic forest ecosystem model ANAFORE (Deckmyn et al. 2008). Despite the fact that this new module is formulated in general terms, making it applicable for many elements (both nutrients and nonessential elements, here generally described as *X*), in this paper we limit ourselves to its application for P. Briefly, the previous ANAFORE model simulates stand C, water and N fluxes, tree growth, and wood tissue development by following a bottom-up approach: leaf level processes (e.g. photosynthesis and transpiration) are simulated at a half-hourly time step and implemented into a daily-operating single tree architecture and C allocation module (see Deckmyn et al. (2008) for a full description). ANAFORE was then improved by including a soil module that mechanistically simulates the organic material decay dynamics by three microorganism functional groups: bacteria, mycorrhizal fungi and non-mycorrhizal fungi (see Deckmyn et al. (2011) for a full description). This basic ANAFORE soil model is different from most existing models in that decay rates are not a function only of litter quality and environment but are simulated as an active process by competing bacteria and fungi.

2.1. Model description

2.1.1 Model pools

Three different essential pool types are considered in the model: soil pools, microorganism pools and tree pools (Fig. 1). The soil system is built up similarly to that of the main ANAFORE model (Deckmyn et al. 2011). Briefly, it consists of up to ten mineral horizons, each subdivided into layers (in equations referred to with the subscript letter *i*) with a fixed thickness of 1 – 2 cm, and a surface

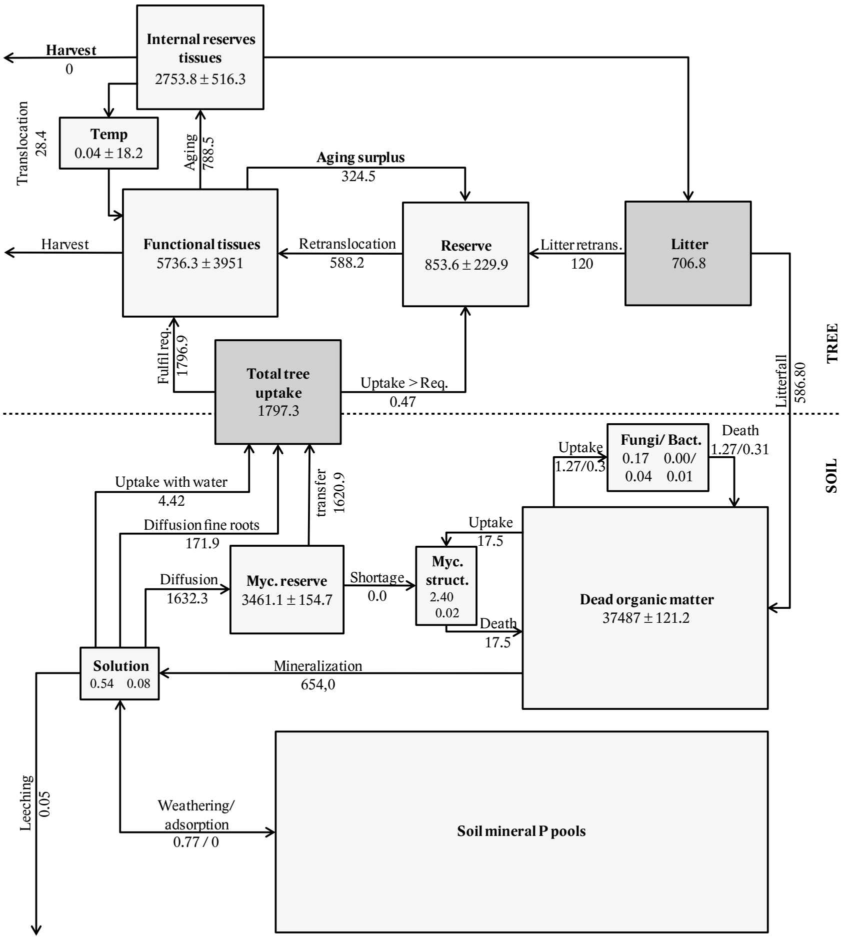

Fig. 1. Relational diagram describing the pools (light grey squares; mg P m^{-2}) and the fluxes (arrows and dark grey squares; mg P m^{-2} year^{-1}) considered in the forest ecosystem P cycling model. Average values over all 15 parameter sets are shown for the 20th year of the standard simulation, i.e. simulating actual environmental conditions. Errors show variations on the daily average pool sizes throughout the year.

organic layer that lies on top of the mineral layers and has a variable thickness depending on the amount and density of litter biomass. Every layer has a litter pool and every mineral layer has mineral P pools.

The mineral P pools are derived from a conceptual model widely and for a long time used in agriculture, and more recently applied to forest soils. It distinguishes a labile (*Plab*), an active (*Pact*) and a stable pool (*Pstab*) (fast-, medium- and slowly-reacting respectively), plus a P-containing primary mineral pool (*Pprim*) (Dzotsi et al. 2010; Jones et al. 1984; Parton et al. 1988). The labile P pool itself includes a solution (*Psolu*) and an adsorbed (*Pads*) pool, which are considered to be in equilibrium.

The litter pool in every soil layer is further divided into leaf (*leaf,* only the organic layer) and wood (including roots) litter of the following size ranks: fine (size <2 cm) (*Fin*), small (size 2 – 10 cm) (*Sm*) and coarse (size >10 cm) (*Co*). Each of these litter pools, and all derived pools, are divided into an accessible (*A*), cellulose (*Cel*) and recalcitrant (*R*) fraction. In addition to the C and N content of these pools, as described in the main ANAFORE model, we add the content of other elements (*X*), although the following description only details what is applicable to P (Table A1). This organic material is then further decomposed into fragmented pools, after which it can be humified by mycorrhizae, fungi and bacteria, and can form micro- and macroaggregates (Deckmyn et al. 2008). Hereafter there is a distinction between model equations that are applicable to all elements, equations applicable only to nutrients and equations specifically concerning P.

Both fungi and bacteria contain only one element pool each. In the case of mycorrhizae however, we consider two element pool types: (i) one mycorrhizal reserve pool (*Xmyc,res*) in which elements absorbed from the soil solution or from organic matter decay are stored and from which elements can be transferred to the host plants, and (ii) a mycorrhizal structural pool (*Xmyc,struct*). Unlike in the structural pools, the element content of the mycorrhizal reserve pool is unlimited and therefore not confined by the amount of mycorrhizal biomass. Only the element surplus in the mycorrhizal reserve pool can be transferred to trees.

Trees are divided in the following tissue pools: current year leaves or needles (*l0*), old leaves or needles of evergreen species (*l1*), dead bark of branches (*brabark*) and stem (*stembark*), current year sapwood of branches (*bra0*), stem (*stem0*) and coarse roots (*cr0*), old sapwood of branches (*bra1*), stem (*stem1*) and coarse roots (*cr1*), heartwood of branches (*braheart*), stem (*stemheart*) and coarse roots (*crheart*), fine roots (*fr*) and fruits (*fruits*). These element pools are broadly classified into two groups: (i) the functional tissue pools, that require nutrients for growth, comprising current year leaves or needles and sapwood, bark, and fruits; and (ii) the internal reserves tissue pools, comprising old leaves or needles and old sapwood, whose nutrient content can be depleted in case of nutrient deficiency. Furthermore, heartwood does not belong to either of these two categories, since it consists of dead tissue from which nutrients are retranslocated before its formation (Meerts 2002). In addition to the N content and concentration provided by the main ANAFORE model, all tissue pools are characterized by their carbon content (C_{pool}), which is also provided by ANAFORE, element content (X_{pool}) and the derived element concentration on carbon content basis ($[X]_{pool}$). In addition to the actual element concentration in the pools, the deficient ($[X]_{def,pool}$), optimal ($[X]_{opt,pool}$) and maximum ($[X]_{max,pool}$) concentrations are defined for each pool as input parameters. Besides these tissue pools we define two nonphysical pools at tree level. The first is the reserve pool (*res*) in which retranslocation from litterfall and element uptake over requirements are stored and which is only defined by its current and maximum element content (X_{res} and $X_{res,max}$ respectively). Nutrients stored in this pool are allocated to functional tissue pools in case of deficiency. The second is the temporary pool (*tem*) in which nutrients from internal reserves tissue pools are translocated before being distributed among functional tissue pools in case of severe nutrient deficiency that cannot be offset solely by the reserve pool (see also 2.1.5).

2.1.2 Mycorrhizal model

The ANAFORE mycorrhizal model can be used to describe both arbuscular and EM fungi, but the parameterization used here is specific for EM. Compared to the previous ANAFORE version (Deckmyn et al. 2008), the description of the EM fungi is further refined based on recent findings (Deckmyn et al. 2014). In the current version, user-defined parameters divide the EM biomass in fractions of rhizomorphs, hyphae and EM root tips, which have different turnover times. Furthermore the parameter "extension" (*x*) describes how far from the root tip the hyphal network reaches, so different EM types can be described (see also 2.1.4 and Table 1).

As in the previous version, the capacity of EM to degrade organic compounds is user defined and can be changed to describe a specific EM community (if enough data are known). Moreover, EM fungi can degrade complex compounds with low energy content by using plant-derived energy, to mineralize the nutrients from these compounds (Shah et al. 2016).

The interaction between the EM and the host trees is simple at this stage: a fixed fraction of the C allocated to the roots by the tree is available to the EM. Storage nutrients from the EM are available to the host plant if there is demand through a Michaelis-Menten kinetic, but under nutrient shortage (not enough structural nutrients for the EM fungi) the EM will not partition any to the tree (see also 2.1.4).

2.1.3 Model fluxes

For each specific element a series of inputs to and outputs from the system are considered. In the specific case of P we considered a single source in the system, i.e. weathering, and two pathways though which P is lost: leaching from the dissolved fraction in the lowest mineral layer, and tree harvesting (Fig. 1).

P is released in the system through weathering of the soil mineral P pools. The fluxes between the primary, labile, stable and active P pools are proportional to the pool considered and described by five parameters: *Kp1* from primary to labile, *Kp2* from labile to active, *Kp3* from active to labile, *Kp4* from active to stable, *Kp5* from stable to active. The weathering flux is the net result of these interactions. Several options are proposed to set the values of the *Kp1–5* parameters: the original equations from Jones et al. (1984) and Dzotsi et al. (2010), with an additional soil P reactivity parameter, the values given in Parton et al. (1988). In the labile P pool, the equilibrium between the solution and adsorbed P is described by a Langmuir isotherm with a maximal sorption *Pmax* and a Langmuir constant *KpLang*. A further refinement allows

Table 1. Sensitivity of the model to variations in EM parameters, harvesting or leaving branches at harvest, variations in fine root (FR) turnover and thickness.

Variable	Soil C kg ha^{-1}	Soil P g ha^{-1}	Tree stems t ha^{-1}	EM g m^{-2}	$q_{r\text{-}sh}$ /	Tree height m
Best fit parameter set	29.34	37.9	210.9	3.31	0.26	23.88
No EM	24.40	28.0	120.8	3.09	0.32	16.03
EM 10% rhizomorphs	29.40	37.8	209.4	3.26	0.26	23.88
EM 50% rhizomorphs	29.33	37.5	211.1	3.31	0.26	23.88
EM Extension 0.2 m	29.33	38.1	211.1	3.31	0.26	23.88
EM Extension 0.5 m	29.34	38.2	211.1	3.31	0.26	23.88
Leave branches	29.25	38.4	208.1	3.32	0.26	23.93
Remove all litter	29.29	37.9	210.5	3.31	0.26	23.88
FR radius 1 mm	29.18	37.7	208.3	3.38	0.25	23.93
FR turnover	30.96	40.1	198.5	3.74	0.26	23.33

accounting for the effect of pH on P sorption by making *Pmax* linearly dependent on pH (Jeppu & Clement 2012); it was not used in the present exercise.

We consider that elements in solution are absorbed by trees through three pathways (Fig. 1) (see also 2.1.4). First, fine roots absorb solutes per soil layer through a combination of diffusion and active transport (*Xup,fr,dif(i)*), hereinafter referred to as 'diffusion'. In addition dissolved elements are absorbed through the fine roots along with water uptake (*Xup,fr,sol(i)*). Finally, part of the elements taken up by the mycorrhizae is transferred from the mycorrhizal reserve pool to the host trees (*Xtrans*). Then, the absorbed element amount is allocated to the different tissue pools according to their requirements and/or nutrients are remobilized internally in case of deficiency (see also 2.1.5).

The amount of an element that is lost from each tissue pool through litterfall (*Xlit,pool*) is determined according to the litter biomass, yet a fraction of this amount is retranslocated before litterfall occurs (*Xretran_in,pool*) and allocated to the reserve pool (Fig. 1). The element contents of litter from needles, branches and stems is then added to the litter pools in the surface organic layer, while litter from roots is added to the litter pools of both the organic and the mineral soil layers. Elements are released from the litter pools in the soil system through decomposition, either in a direct pathway from organic matter to the microorganisms or through an indirect pathway to the soil solution (see Deckmyn et al. (2011) for a full explanation).

2.1.4 Element uptake

As we stressed before, we consider three pathways along which elements are taken up from the soil. Potential element uptake at tree level is then calculated as the sum of these three pathways: diffusion in mycorrhizae and fine roots, absorption along with water through fine roots and element transfer from the mycorrhizae to the host plant. Defining the soil cylinder exploited by mycorrhizae and fine roots is the first step in element uptake calculations. We assume as a starting point that every tree occupies areas of equal sizes both above and below ground between the surrounding trees (Zinke 1962). However, the horizontal area of the soil layer in which fine roots and mycorrhizae are located (*Ss(i)*) decreases with soil depth, showing a typical inverted cone distribution (Deckmyn et al. 2008). In order to include the effect of the size of the influence zone, a correction factor (*fz*) is determined for each soil layer. When the surface of the influence zone is the same size as the surface of the tree canopy, which is calculated from the canopy radius (*rcrown*), *fz* is equal to one; otherwise it is smaller, since a smaller influence area results in a decreased element uptake. The inclusion of this correction factor is therefore particularly important in the case of non-mobile elements such as P, which is why the element-specific soil to absorption surface resistance (*Rs-pool,X*) is also included in the formula. The correction factor for fine roots (*fz,fr(i)*) is then calculated as in equation [1].

$$f_{z,fr(i)} = \frac{1 - (-S_{s(i)} + \pi r_{crown}^2)}{R_{s-fr,x} - S_{s(i)} + \pi r_{crown}^2} \qquad [1]$$

In the case of the mycorrhizal correction factor (*fz,myc(i)*) the radius and thus the surface of the influence zone as defined by the fine roots is extended by the mycorrhizal extension (*x*).

Uptake processes through diffusion are described per soil layer based on the absorption surface of either mycorrhizae (*UA,myc(i)*) or fine roots (*UA,fr(i)*) as is shown in equation [2]. Both absorption surfaces are calculated based on the fine root or mycorrhizal C content per soil layer (*Cpool(i)*), the average fine root or mycorrhizal density (*ρpool*) and the average fine root or mycorrhizae radius (r_{pool}).

$$U_{A,pool(i)} = \frac{C_{pool(i)}}{\rho_{pool} + r_{pool}} \qquad [2]$$

First, half-hourly element uptake through diffusion by mycorrhizae ($X_{up,myc(i)}$) and fine roots ($X_{up,fr,dif(i)}$) is calculated per layer according to the Michaelis-Menten type equation [3] (Barber 1995). These equations depend on three element and organism specific Michaelis-Menten parameters: the maximum absorption rate per absorption surface area ($I_{max,pool}$), the Michaelis constant ($K_{m,pool}$), which is the mineral element concentration in the soil solution at which the uptake rate reaches half of the maximum absorption rate, and the element concentration in the soil solution below which element absorption does not occur ($c_{lim,pool}$). These parameters are different for mycorrhizae and fine roots (Colpaert et al. 1999; Schnepf & Roose 2006; Van Tichelen & Colpaert 2000). The uptake also depends on the dissolved concentration of the element in the soil layer ($c_{p(i)}$), which is calculated as the soluble fraction of the element in the layer ($X_{p(i)}$) divided by the water content of the layer ($\theta_{s(i)}$), which is provided by the ANAFORE soil module.

$$X_{up,pool(i)} = \frac{f_{z,pool(i)} U_{A,pool(i)} I_{max,pool} \, (c_{p(i)} - c_{lim,pool})}{K_{m,pool} + (c_{p(i)} - c_{lim,pool})} \qquad [3]$$

Next, absorption of elements along with water absorption by fine roots ($X_{up,fr,sol(i)}$) is also calculated half-hourly in each soil layer and only when water uptake ($W_{up(i)}$) is positive, as performed in equation [4].

$$X_{up,fr,sol(i)} = \frac{W_{up(i)}}{(\theta_{s(i)} + W_{up(i)})} c_{p(i)} \qquad [4]$$

Finally, element transfer from the mycorrhizae to the host plant (X_{trans}) as described in equation [5] occurs if the element concentration in the mycorrhizal reserve pool (*[X]myc,res*), calculated as the element content of the mycorrhizal reserve pool divided by the sum of the mycorrhizal biomass in all soil layers, is greater than a threshold concentration (*[X]lim,trans*). Transfer is described based on a Michaelis-Menten type equation analogous to that describing element uptake through diffusion, with the main difference that transfer varies according to the internal element concentration in the mycorrhizae rather than the soil concentration.

$$X_{trans} = \frac{I_{max,trans}([X]_{myc,res} - [X]_{lim,trans})}{K_{m,trans} + ([X]_{myc,res} - [X]_{lim,trans})} \quad [5]$$

Once uptake by mycorrhizae and fine roots is calculated, element content of the corresponding soil layers and fraction are reduced accordingly. Then, the total half-hourly potential uptake at tree level is calculated as the sum of the uptake through diffusion by fine roots, transfer of elements from mycorrhizae and the elements taken up with water uptake in each soil layer. The daily potential uptake at tree level (*Xup,T*) consists of the daily sum of the half-hourly potential element absorption.

2.1.5 Element status

The amount of elements demanded by trees is a central part of the element module because it determines the nutritional status of trees and may limit element uptake. Regarding this, we define two levels of element needs: requirement and demand. At tree level, element requirement (*Xreq,T*) is the amount of a specific element needed to support new growth at optimal concentration and to maintain the functionality of all tissues, i.e. keep all tissues at optimal concentrations, as defined in equation [6].

$$X_{req,T} = \sum\left[\left(\Delta C_{pool} \times [X]_{opt,pool}\right) + C_{pool}\left([X]_{opt,pool} - [X]_{pool}\right)\right] \quad [6]$$

Tree nutrient demand (*Xdem*) is the amount of a specific element needed to not only meet growth requirements but also to fill the reserve pool, as described by equation [7].

$$X_{dem} = X_{req,T} + X_{res,max} - X_{res} \quad [7]$$

The maximum element content of the reserves pool (*Xres,max*) is the maximum amount of elements that can be stored in this pool, as obtained through equation [8]. This is physically limited to the amount of the element that corresponds to maximum concentrations in all tree tissue pools.

$$X_{max,res} = \sum C_{pool}\left([X]_{max,pool} - [X]_{opt,pool}\right) \quad [8]$$

Five situations are considered according to the balance between on one hand element supply (element uptake and tree element reserves) and on the other hand the element requirement and demand by the tree (Fig. 2). In situation 1, the daily potential nutrient uptake exceeds the demand so the uptake is limited to the demand and the excess of elements is returned to the soil solution and mycorrhizal reserve pool proportionally to the contribution of the absorption mechanisms to the total potential uptake. In this case all tissue pools are at optimum conditions and the reserve pool is filled to maximum. In situation 2, the uptake is greater than requirements but lower than the demand. Accordingly, all tissue pools grow at optimal conditions and the rest of elements are allocated to the reserve pool. In situation 3, element uptake is lower than the demand and, therefore, retranslocation occurs from the reserve pool to the tissues pools, which will grow at optimal concentrations. In situation 4 element uptake is also lower than demand but the elements stored in the

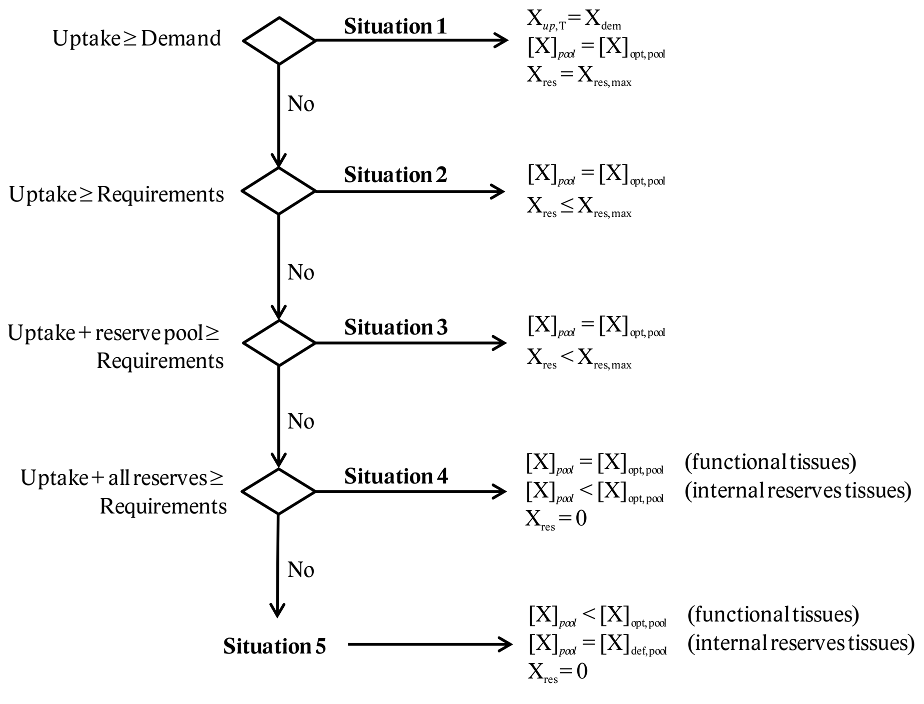

Fig. 2. Decision diagram describing the different model situations according to tree nutritional status.

reserve pool are not sufficient to meet the requirements. In this case, requirements are met by translocating elements from the internal reserves tissue pools, those tissue pools that can be depleted in case of shortage, and allocating them to the temporary pool, from where the remobilized quantity is redistributed among the functional tissue pools at the same time step. The maximum amount of nutrients that can be remobilized from these internal reserves tissue pools in one day (*Xtem*) (old leaves/needles and sapwood) is calculated according to equation [9].

$$X_{tem} = f_{x,temp} \sum C_{pool} \left([X]_{opt,pool} - [X]_{def,pool}\right) \qquad [9]$$

where *fx,temp* is a parameter that limits the amount of element that can be mobilized at each model time step from old tissues. The last situation (situation 5) implies that, in spite of all nutrients being taken from the reserves pool at tree level and the internal reserves tissue pools, the amount of nutrients supplied is not enough to achieve optimal concentrations in the functional tissue pools.

2.1.6 Phosphorus shortage effect on trees

In general the effect of element shortage, or toxicity in the case of toxic elements such as pollutants, is implemented in the model according to the degree of the shortage or toxicity. In the case of essential elements, i.e. nutrients, these effects are implemented as the modification of biomass allocation and the limitation of photosynthesis and growth. Here we explain the specific effect for P shortage. The first effect is the modification of C allocation by increasing the root to shoot growth ratio ($q_{r\text{-}sh,norm}$) up to a maximum ratio ($q_{r\text{-}sh,max}$) when the element uptake is lower than the growth requirements, even if nutrient reserves are sufficient to fulfill the deficiency. The rescaling of the root to shoot growth ratio is calculated as follows:

$$\text{if} \quad \frac{X_{req,T} - X_{up,T}}{X_{req,T}} \leq 0 \quad \text{then } q_{r-sh} = q_{r-sh,norm} \qquad [10]$$

$$\text{if} \quad 0 < \frac{X_{req,T} - X_{up,T}}{X_{req,T}} < 1 \quad \text{then}$$

$$q_{r-sh} = q_{r-sh,norm} + \left(q_{r-sh,max} - q_{r-sh,norm}\right)\frac{X_{req,T} - X_{up,T}}{X_{req,T}}$$

$$\text{if} \quad \frac{X_{req,T} - X_{up,T}}{X_{req,T}} \geq 1 \quad \text{then} \quad q_{r-sh} = q_{r-sh,max}$$

As P is essential in RuBisCo regeneration (Rao & Pessarakli 1996), P deficiency will limit net photosynthesis (A_n), even though the effect of P limitation on photosynthesis is lower compared to the effect due to N shortage (Farquhar et al. 1980). We use the empirical equation derived by Reich et al. (2009) to, first, calculate the maximum net leaf photosynthesis at optimal P and current leaf N concentrations ($A_{max,opt}$), and then to calculate it at current N and P leaf concentrations (A_{max}). Lastly, the net photosynthesis calculated by ANAFORE ($A_{n,0}$), which already includes any possible effects caused by N limitation (Deckmyn et al. 2008), is adjusted according to equation [11].

$$A_n = A_{n,0}\frac{A_{max}}{A_{max,opt}} \qquad [11]$$

The modification of the root shoot growth ratio and the reduction in photosynthesis are implemented when P concentration in leaves/needles are between deficiency and optimal concentrations. When P concentration drops below the deficiency level, and in order to reduce growth, the construction respiration costs of each pool ($R_{con,pool}$) are increased proportionally (Deckmyn et al. 2008). Given the importance of P as structural component of nucleic acids and in cell energy transfer, we also define a critical concentration (i.e. minimum P level in leaves) below which growth is stopped altogether (Mohren et al. 1986).

2.1.7 Tree tissues aging

On the first day of the year, before the start of the growing season, elements from current year sapwood pools are transferred to their corresponding old sapwood pools (i.e; *bra0, stem0* and *cr0* to *bra1, stem1* and *cr1*, resp.), from old sapwood to heartwood pools (i.e. *bra1* and *stem1* to *brabark* and *stembark*, resp.) and from current year needles (l0) to old needles (*l1*). If a sufficient amount is present in the initial tissue pool, the corresponding older pool is supplemented up to its optimal concentration. Since the optimal concentration of older tissues is typically lower (FFCT 2013; Jacobsen et al. 2003), any remaining amount from the initial tissues is then added to the tree reserves pool (*res)*. This is the only way in which elements may be temporarily added to the reserves pool in excess of this pool's maximum content ($X_{res,max}$).

2.2. Case study

2.2.1 Site description

The experimental forest 'De Inslag' (51°18'33"N and 4°31'14"E) is located in Brasschaat in the Campine region of Belgium. 'De Inslag' is a 1.3 ha plot dominated by Scots pine (*Pinus sylvestris* L.) planted in 1929, that belongs to the level-II observation plot of the European Programme for the Intensive Monitoring of Forest Ecosystems. Since 1995 several researches concerning tree physiology, cycling of nutrients, CO_2 and water fluxes, forest vitality and air pollution have been conducted in the plot (Overloop & Meiresonne 1999). The location has a temperate maritime climate, with a long term mean annual temperature of 9.8 °C and 767 mm of precipitation. The soil consists of a moderately wet sandy soil characterized by a distinct humic and/or iron B-horizon on top of an impermeable clay layer at a variable depth between 1.5 and 2 m. The soil is classified as umbric regosol (F.A.O. classification). The organic soil layer has an average P content of 446 mg kg^{-1} and the P concentration in the underlying mineral layers ranges from 62 to 20 mg kg^{-1} top down (Overloop & Meiresonne 1999).

2.2.2 Dataset

A dataset containing N, P and C content and dry weight of foliage, measured yearly on 1000 needles of ten trees from 1999 until 2011, ground vegetation and the different fractions of litterfall (needles, barks, branches, woody material, fruits and seeds), measured several times throughout the year from 1999 until 2013, was provided by the Instituut voor Natuur- en Bosonderzoek (INBO). Furthermore, this dataset also includes data on the thickness and composition of the organic and mineral soil layers down to a depth of 160 cm, which were collected in 2007.

2.2.3 Parameterization

A Bayesian parameterization was performed for the tree species parameters, following the procedure described by Deckmyn et al. (2009). All prior distributions were initialized from the parameter values derived from previous parameterizations (Deckmyn et al. 2009) and the growth of the stand over 70 years was optimized towards measured data on tree height, biomass, diameter at breast height (DBH), gross primary productivity (GPP), net primary production (NPP), soil respiration, canopy evapotranspiration and soil C. The model was set to run 10.000 times and the Bayesian procedure selected a posterior distribution of parameter sets. From the resulting posterior parameter distributions a random Latin hypercube sample consisting of fifteen samples was retained and used because using more parameter sets becomes too slow, but a random sample of 15 is too small: a Latin hypercube sample is partially random but takes more samples from the range with the higher likelihood so one gets a more representative sample (McKay et al. 1979). These fifteen posterior parameter sets were then used to carry out the simulations. Hence, unless stated otherwise, for each simulation all standard deviations and error bars present the variation on the runs based on these fifteen posterior parameter sets. The 15 sets of 140 parameters for Scots pine (*Pinus sylvestris* L.) can be obtained from the authors. A detailed analyses of the uncertainties of the ANAFORE model can be found in a publication by Horemans et al. (2016).

Parameter values with regard to optimal, maximum and deficient element concentrations were determined based on data from the Forest Foliar Coordinating Center (Vienna, Austria, operated under ICP Forests) and Jacobsen et al. (2003). Those parameters regarding the absorption of P through fine roots and mycorrhizae were estimated based on results from studies on P absorption kinetics in *Pinus sylvestris* seedlings inoculated with *Paxillus involutus* (Batsch.) Fr., *Suillus luteus* (L.:Fr.) S. F. Gray, *Suillus bovinus* (L.: Fr.) O. Kuntze or *Thelephora terrestris* Ehrh.: Fr. (Colpaert et al. 1999; Van Tichelen & Colpaert 2000). Parameters concerning the EM module were taken from the review by Deckmyn et al. (2014). Table A2 gives the parameter values used specific to the P and EM module.

2.2.4 Simulations

In order to demonstrate the functionality of the model concerning P limitations, three complete runs were performed after parameterization, each using 15 parameter sets. All simulations started from seedlings and ran for a period of 80 years.

In the first simulation (hereinafter “standard”) we simulated the real environment.

In addition to this standard simulation, we performed a second simulation (hereinafter “unlimited P”) which was identical to the standard simulation, with the sole exception that P availability remained high by artificially adding P to the solution in each soil layer of the system at the beginning of every day. Consequently, P availability remained high and no limitation effects occurred. This allowed us to compare the simulated tree growth and photosynthetic capacity under contrasting situations regarding P availability. Furthermore, in both simulations and starting from the fifteenth year, a harvesting system was applied in which half of the aboveground tree growth was harvested (which is similar to the actual management but simplified). Consequently, P was repeatedly removed from the system through harvesting. In order to illustrate how tree nutritional status and responses vary throughout the season and in addition to comparing these two simulations over the full 80-year period, we will demonstrate the model functioning in more detail based on the 20th year of the standard model simulations. This year was arbitrarily selected since, in the standard simulation, it is located in a P-deficient period from 10 – 40 years (see also 3.3).

For the third complete run, EM transfer to the trees was set to 0 as was C allocation from the trees to the EM fungi, to investigate whether the model correctly simulates plant P uptake in the absence of EM fungi. The EM fungi in this run grew as fungi getting their energy from organic matter decay.

In addition single runs (using only the “best fit” parameter set and not the Latin hypercube sample) were run to investigate the importance of specific EM parameters: the rhizomorph fraction of EM biomass was varied (0.1, 0.3 (standard) and 0.5) and the extension (0.05 m, 0.1 m (standard), 0.2 m). To compare the sensitivity of the results to fine root characteristics 2 additional runs with modified fine root turnover and modified fine root width were performed. Finally we changed the conventional harvest method to leave the branches on site (while in the standard run 60% are removed as is the conventional harvest in Belgium) or remove all.

3. Results

3.1. Tree growth

Since the species parameters were fitted towards stand growth, simulated tree height at the end of the 80-year period (23.8 m) was similar to the measured value. Tree growth is depicted in Fig. 3 for the standard and the unlimited P scenario. After 80 years trees were on average 0.16 m smaller but total aboveground wood biomass was slightly increased under unlimited P. Still, P shortage did not occur in all of the 15 runs in the standard simulation, which may suggest that this particular forest is on the edge of becoming P deficient. Due to the large variation between the different runs, none of these differences were significant. Average tree P content at the end of the simulation period was 25.4 g at an average density of 1314 trees ha^{-1} this accounts for 33.37 kg ha^{-1}. The harvesting treatment resulted in the standard simulation in a total average over all model runs of 7927 ± 660 trees harvested over a period of 80 years and a total loss of 9044 ± 116 g P ha^{-1} from the ecosystem.

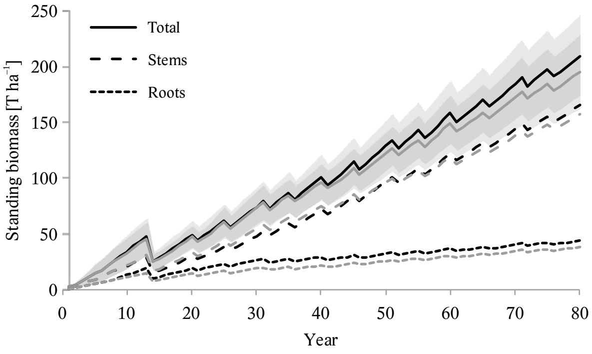

Fig. 3. Simulated total tree biomass, stem biomass and root biomass of *Pinus sylvestris* forest stand "De Inslag" over 80 years for the standard (grey) and unlimited P (black) runs. In order to preserve a clear overview, error bars are only shown for the total biomass. Error bars present the variation on the runs based on the fifteen posterior parameter sets of the Latin hypercube sample.

3.2. Phosphorus in the soil

In the 20th year of the standard simulation, the average simulated amount of P fixed to organic matter in the organic soil layer is 88.01 ± 15.83 kg P ha^{-1} whilst it was initialized at the measured value of 89.54 kg P ha^{-1}. which is similar to for example 80 ± 3 kg P ha^{-1} in organic soil in a forest of comparable age as reported by Yanai (1992). The P concentration in the soil solution is greater and more variable in the organic soil layer than in the mineral layers (1.28 ± 1.49 mg l^{-1} and 0.28 ± 0.33 mg l^{-1}, respectively, standard deviations represent the variation on the yearly average), and within the 0.001 – 1 mg P l^{-1} range reported for the soil solution by Brady and Weil (2008) (Fig. 4). The simulated yearly P mineralization rate of 6.54 ± 3.80 kg P ha^{-1} y^{-1} is also comparable to the range of 5 – 20 kg P ha^{-1} y^{-1} reported by Brady and Weil (2008). Within year variability shows that the decrease in P fixed to the organic matter in the organic layer during the growing season is paralleled by an increase in the dissolved P concentration in the same layer. This suggests that most of the available P was provided through the decomposition and mineralization of litter in the organic layer (Jonard et al. 2010).

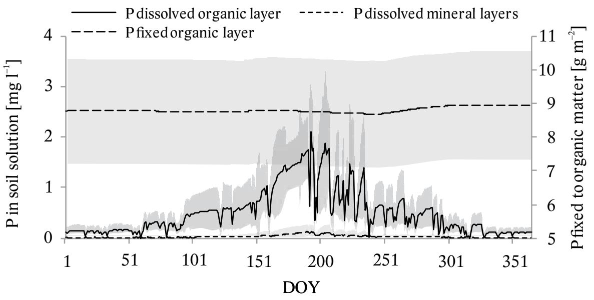

Fig. 4. Mean simulated daily amount of P fixed to organic matter in the organic soil layer; and mean simulated P concentration in the organic soil layer and in all soil mineral layers (mg P l^{-1}) during the 20th year of the standard simulation. Error bars present the variation on the runs based on the fifteen posterior parameter sets of the Latin hypercube sample.

3.3. Phosphorus uptake

P uptake rates are in line with expected values based on experimental data. The mean simulated yearly total P uptake by adult trees (40 – 80 years) is 2.01 ± 0.47 g P m^{-2} y^{-1}, which is quite high compared to the value of 0.96 g P m^{-2} y^{-1} reported by Yanai (1992) in forests of similar age and with comparable aboveground biomass. The P uptake rate through diffusion by mycorrhizae is highly correlated (R2 = 0.79) to seasonal changes in the simulated total amount of P released from litter through decomposition. In contrast, the total P uptake rate in trees show no correlation (R2 = 0.101) with the daily amount of P released from litter through decomposition. This can be explained by the fact that on average 94.29 ± 24.13% of the P released through decomposition in every time step is taken up through diffusion by the mycorrhizae and allocated to their reserve pool. Indeed, 97.87 ± 41.93% of the total P supplied to the tree (Fig. 5) is transferred from mycorrhizae to the host plants, which is consistent with global estimations that range around 90% (Deckmyn et al. 2014). In spite of P uptake through diffusion and uptake through fine roots along with water showing a similar seasonality to P uptake by mycorrhizae, their contribution to the P supply to trees is on average relatively small (2.03 ± 1.27% and 0.09 ± 0.03%, respectively, Fig. 5). These results demonstrate the importance of incorporating mycorrhizae in simulating P supply to trees. Mycorrhizae not only contribute most to P supply to trees but also supply P to the trees relatively independent of the mineralization rate, helping to overcome the sudden rise in P requirement at the beginning of the growing season.

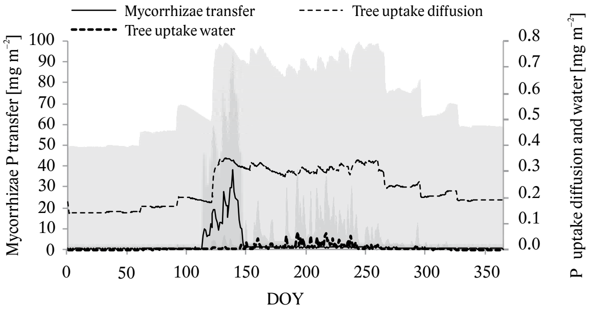

Fig. 5. Mean simulated relative contributions of P uptake through fine root diffusion and P transferred from mycorrhizae in the 20th year of the standard model run. Error bars present the variation on the runs based on the fifteen posterior parameter sets of the Latin hypercube sample.

3.4. Phosphorus in tree tissues

Seasonal variation in the allocation of P to both the physical tissue pools and the non-physical temporary reserve pool consists of a sudden drop in the P content of the tree's reserve pool and, when the translocated amount of P is insufficient to meet the requirements associated with the tree growth at the beginning of the growing season, of the internal reserves tissue pools (Fig. 6), thus corresponding to the expected pattern described by Chapin et al. (1990). P requirement is driven by tree growth, increasing at the start of the growing season due to the formation of new needles, sapwood and roots. The high amount of P needed to meet growth requirements at the start of the growing season is mainly supplied by the reserve pool of the tree. However, the within-year variability of P requirements and the level of the reserve pool are driven by the nutritional status of the tree demonstrating the ability of the model to react to contrasting nutrient availabilities. In the unlimited P simulation, the reserve pool supplies the required P, whereas in some runs of the standard simulation the reserves are completely depleted leading to an increase in requirements because tissues grew at suboptimal P concentrations. After the spring growth flush requirements decrease to basal values in the case of the unlimited P simulation. In the standard simulation, requirements remain high because of P deficiency in tree tissues, yet gradually decrease due to P supply by uptake. In autumn requirements decreased at a higher rate due to retranslocation when litterfall occurs and, when these requirements are met, the reserve pool is replenished also slowly through P uptake and more rapidly through retranslocation from litterfall.

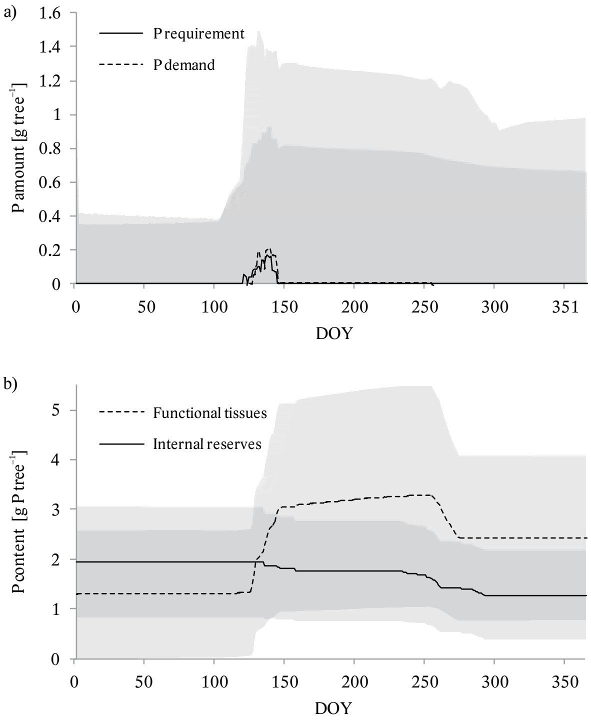

Fig. 6. (**a**) Mean simulated daily requirement and amount of P stored in the tree reserve pool, and (**b**) mean standard deviations from the Latin hypercube sample of model parameters; (**b**) Mean simulated total P content of all functional and internal reserves tissue pools in the 20th year of the standard simulation and standard deviations from the Latin hypercube sample of model parameters.

In order to illustrate how trees react to P shortage according to their nutritional status throughout the season, we arbitrarily selected the 20th year to demonstrate the functioning of the model (Fig. 1). This year is located in the P-deficient period of tree growth from 10 – 40 years (Fig. 7).

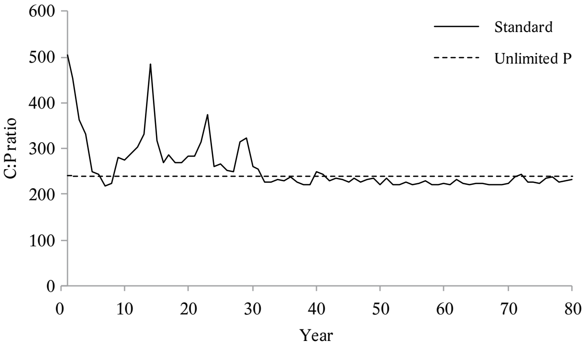

Fig. 7. Yearly average C:P ratio in current year needles for the standard simulation (full line) and under unlimited P (dashed line). In order to preserve a clear overview, no error bars are shown.

3.5. Phosphorus shortage effects

Trees respond to nutrient deficiency by increasing C allocation to roots in order to capture more nutrients (Marschner et al. 1996). In our model, root to shoot growth ratio is modified at the moment when nutrient uptake is not sufficient to meet the growth requirements, thus this effect occurs at an earlier stage than the reduction of the photosynthetic capacity, which becomes active once the P concentration is below optimum. This is true both at a small temporal scale as well as on a scale of several years when comparing yearly averages. Accordingly, under limited conditions root to shoot growth ratio suddenly increases at the beginning of the growing season as a consequence of the high P requirements. In parallel to requirements, the root to shoot growth ratio decreases in autumn when retranslocation from litterfall occurs and requirements decrease. In contrast to limited conditions, the root to shoot growth ratio under non-limited conditions remains at the initial ANAFORE value of 0.25 throughout the year after the first initial years (saplings have a higher ratio). Over the 80 year period the shortage between 10 – 40 years leads to an increased ratio but the difference decreases after 40th year when P-limitation has disappeared (Fig. 8).

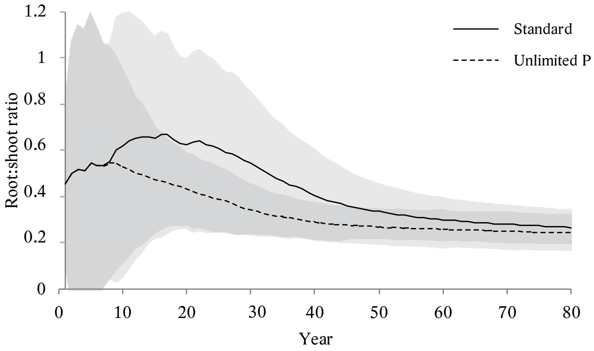

Fig. 8. Root:shoot ratio during stand growth for the standard simulation (full line) and under unlimited P (dashed line). Error bars present the variation on the runs based on the fifteen posterior parameter sets of the Latin hypercube sample.

With regards to the effect of P deficiency on photosynthesis, the maximum reduction compared to the unlimited P simulation occurs at the beginning of the growing season, when P shortage is higher (Fig. 9). Then, this effect gradually decreases with decreasing P requirements and thus shortage. Still, under non-limited conditions, there is a reduction of 9.09 ± 0.08% in photosynthetic capacity from the beginning of the year up to the moment when new needles grow (beginning of growing season), followed by a stable period during which the photosynthetic capacity is reduced by 0.25 ± 0.43%, even though P supply was sufficient to meet P requirements. This is because until bud break, only old needles were present, which have a lower optimum P concentration, and consequently a slightly lower photosynthetic capacity. This result shows that the model is not only improved through the addition of feedback effects in case of P deficiency, but also through reduction of the photosynthetic capacity due to the aging of needles.

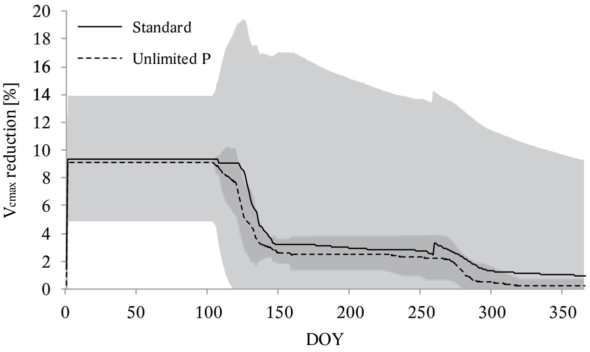

Fig. 9. Simulated daily reduction of the *Vcmax* photosynthesis parameter in the 20th year of the standard and unlimited P simulations and standard deviations from the Latin hypercube sample of model parameters.

3.6. Influence of EM

Running the model without EM interaction resulted in a significant but gradual decrease in stand growth both in terms of biomass and in terms of tree height (Table 1). In addition, soil C and P were severely reduced.

This confirms what has been suggested concerning the important role of EM not only towards plant nutrition but also towards stabilizing soil nutrient and C content. This result is of course also influenced by the parameters used. However, one less realistic outcome is that EM biomass remains quite high. 10% of plant C allocated to the roots is 'traded' with the EM in the standard run, whereas in the non-mycorrhizal run the trees do not, indicating the EM fungi as simulated in the model are able to get enough energy and C by litter decay instead of the C they normally receive from the trees.

The uptake characteristics of the EM hyphae were set equal to those of the fine roots since we had no site-specific data although one would expect them to be different in reality (see Introduction). Setting them equal is a conservative option reducing the importance of the EM. The difference in uptake efficiency is therefore simply due to the higher surface area of the hyphae.

3.7. Influence of EM parameters

Increasing or decreasing rhizomorph fraction by a factor 2 hardly changes the model outcome at an ecosystem scale (Table 1), although the turnover rate of the rhizomorphs was set at 450 days compared to 20 for the hyphae which is an extreme difference. Of course, total EM biomass is quite low (up to 500g m^{-2} have been found (Wallander et al. 2004), but data are highly variable (Deckmyn et al.

2014)). Furthermore we did not include any other effect of the rhizomorphs except a longer lifetime. Increasing the extension of the EM fungi also had no effect on the ecosystem at a 80 year time frame.

3.8. Influence of FR parameters

Fine roots are an important C sink in the forest ecosystem. Uncertainty concerning the turnover rate of fine roots is known to influence the model results and stand data generally include all roots below 2 mm in the fine root pool while some of these are known to be different concerning function (transport or uptake) and longevity (slower turnover). If we assume fine roots are 1 mm, more root area can be produced per unit invested C. However, because the uptake is dominated by the EM this has little influence on the ecosystem functioning. Increasing yearly FR turnover from 41% to 49% had a relatively important impact on the C flows and stocks in the ecosystem: stem biomass was reduced by 10% while soil C and P stocks were slightly increased (Table 1). This is important to note because the uncertainty on fine root turnover is high.

3.9. Influence of management

The harvesting treatment resulted in the standard simulation in a total average over all model runs a total loss of 9044 ± 116 g P ha^{-1} from the ecosystem. Leaving the branches on site at harvest resulted in an 1.5% increase in soil P, which could become important since soil P is close to being limiting at the particular studied site.

The largest loss is at the final harvest, which was not included in this run (this would have an effect during a second rotation) so long-term effects would be more significant.

4. Discussion

To the best of our knowledge, this is the first mechanistic model that simulates the detailed cycling of P in the whole temperate forest ecosystem, including uptake and transfer of P by EM, P allocation within the trees and feedback effects of P limitation on growth, C allocation and photosynthetic capacity. Our results confirm the importance of incorporating mycorrhizae in forest ecosystem models since they do not only increase the P availability to the trees but also buffer its availability by providing a P source relatively more independent from mineralization rates. Furthermore, the model simulates increasing tree P requirements at the beginning of the growing season and, when these requirements are not met, decreased growth and photosynthetic capacity. Therefore, our results support the need for including the cycling of P and the effect of P deficiency in forest ecosystem models (Braun et al. 2010). In view of these results and the increasing body of evidences that suggest a shift in nutrient limitation in terrestrial ecosystems from N to P (Marschner et al. 1996; de Vries et al. 2009; Peñuelas et al. 2012, 2013), the lack of consideration of P and its effect on trees in many modeling studies might lead to an overestimation of forest growth and productivity in local and global models, and therefore to an overestimation of the mitigating potential of forests under limited nutrient conditions (Fernández-Martínez et al. 2014; Jonard et al. 2015).

Nevertheless, from the large variance on simulated output variables can be inferred that for many parameters a large uncertainty exists. It is important that the expected increase in forest models that simulate the cycling of P, is accompanied by an increase in data collected from field measurements and experimental setups, particularly regarding P absorption by fine roots and mycorrhizae and transfer from mycorrhizae to trees, since these mechanisms are key in every P model but are at the same time scarce and therefore difficult to evaluate. The strong response of tree growth in the non-mycorrhizal run is impossible to evaluate since EM are common in temperate forest, and the simulated trees grow fine the first years which is the only thing one could study in an experiment.

Our results suggest that although the fractioning between EM hyphae and rhizomorphs has a large effect on the turnover of the EM, the effect on the ecosystem is marginal. Likewise the extension of the EM in a mature forest did not substantially influence soil processes. It appears that model simplification is possible for many applications unless EM are specifically investigated. However, the sensitivity of the model results to fine root turnover is cause for concern, since measured data do not only show large variation between sites and species but also between observation methods, further stressing the importance of improving empirical estimations of fine root turnover rates (McCormack et al. 2015).

Since EM infect all pine trees, one could, if the mere simulation of tree growth were the main aim of the implementation, include their characteristics such as the increased extension and surface area implicitly in the parameters of the tree fine roots by simulating thinner roots that extend further. Moreover, given the high number of parameters and the complexity of mechanistic forest models, one could parameterize a model to fit the current growth of a forest without P and/or EM. However this would not be sufficient to capture the stabilizing effect of EM on soil nutrient availability nor the capacity of EM to degrade organic compounds. The added value of the full mechanistic model is in a better understanding of the mechanisms of nutrient uptake and feedbacks, and of the true limitations to tree growth from soil nutrient limitation. In addition the possibility to understand and predict qualitatively (if not quantitatively) the effects of changes in soil biodiversity and forest management on forest nutritional status and functioning is the main goal of this model elaboration.

The successful simulation of a simple management scenario, such as harvesting, indicates that this model is a suitable tool to study the impact of different management scenarios on forest productivity within a global change context, though additional validation of this aspect is necessary. The fact that in the standard simulation not all of the runs using the different Latin hypercube parameters samples resulted in P limitation may indicate that the described forest, 'De Inslag', is on the edge of becoming P deficient. This corresponds to field measurements in this particular forest suggesting that P deficiency symptoms in the trees are latent but are expected to be amplified through time under the effect of increasing N deposition (Roskams & Neirynck 1999). Since the harvesting of trees results in a removal of P from the system, our results substantiate the concern that tree harvesting may induce or amplify this P deficit and corroborate earlier findings that small changes in conventional harvest methods such as leaving branches on site can mitigate P loss (Mälkönen 1976; Grigal 2000).

The general description of element cycling in the model provides an excellent basis to simulate different elements, other than N and P, in forest ecosystem models. Indeed, nutrients such as K, Mg, or Ca, which may become limiting in European forest ecosystems in the future (Jonard et al. 2012, 2015) or toxic elements such as Cd or Pb (among others) could be easily simulated by adapting the uptake parameters and the effect of limitation or toxicity on tree growth. However, while optimal, deficiency and maximum concentrations in plant tissues are generally well known (e.g. Jacobsen et al. 2003), only very few parameter values concerning the uptake and transfer Michaelis-Menten equations and the effects on growth and photosynthesis are specified in literature (e.g. Jongbloed 1991). Further experimental studies are therefore necessary to define these model parameters in order to incorporate these elements in forest ecosystem models.

Acknowledgments

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Appendix tables

Table A1. List of symbols.

Symbol	Unit	Definition
$[X]_{def,pool}$	kg X kg^{-1} C	Tissue pool deficiency concentration
$[X]_{lim,trans}$	kg X kg^{-1} C	Threshold concentration in mycorrhizal reserves pool for transfer to trees
$[X]_{myc,res}$	kg X kg C^{-1}	Concentration in mycorrhizal reserves pool
$[X]_{opt,pool}$	kg X kg C^{-1}	Optimal Concentration in tree tissue pool
$[X]_{pool}$	kg X kg C^{-1}	Concentration in tree tissue pool
$[X]_{max,pool}$	kg X kg C^{-1}	Toxic Concentration in tree tissue pool
A_{max}	µmol m^{-2} s^{-1}	Net photosynthesis at current leaf N and P concentrations
$A_{max,opt}$	µmol m^{-2} s^{-1}	Net photosynthesis at current leaf N and optimal P concentrations
A_n	µmol m^{-2} s^{-1}	P adjusted net photosynthesis
$A_{n,0}$	µmol m^{-2} s^{-1}	Net photosynthesis as calculated by main ANAFORE
$c_{lim,pool}$	kg X m^{-3}	Limiting soil solution concentration for uptake
$c_{p(i)}$	kg X m^{-3}	Dissolved concentration in soil layer *i*
C_{pool}	kg C	Carbon content of tree tissue pool
$C_{pool(i)}$	kg C	Fine root or mycorrhizal C content in soil layer *i*
$f_{X,temp}$	dimensionless	Fraction mobilized from old tissues
$f_{z,fr(i)}$	dimensionless	Fine root rooting zone effect for soil layer *i*
$f_{z,myc(i)}$	dimensionless	Rooting zone effect including hyphae for soil layer *i*
$I_{max,pool}$	kg X m^{-2}	Maximum absorption rate per absorption surface
$I_{max,trans}$	kg X	Maximum transfer rate from mycorrhizae to trees
$K_{m,pool}$	kg X m^{-3}	Michaelis constant for uptake through diffusion
$K_{m,trans}$	kg X kg^{-1} C	Michaelis constant for transfer from mycorrhizae to trees
K_{p1}	time^{-1}	Flux parameter from the primary to the labile soil mineral P pool
K_{p2}	time^{-1}	Flux parameter from the labile to the active soil mineral P pool
K_{p3}	time^{-1}	Flux parameter from the active to the labile soil mineral P pool
K_{p4}	time^{-1}	Flux parameter from the active to the stable soil mineral P pool
K_{p5}	time^{-1}	Flux parameter from the stable to the active soil mineral P pool
K_{pLang}	kg P m^{-3} solution	Inverse of the Langmuir affinity constant (P sorption isotherm)
P_{act}	kg P kg^{-1} soil	Active P pool in the mineral soil layers
P_{ads}	kg P kg^{-1} soil	Adsorbed P pool in the mineral soil layers
P_{lab}	kg P kg^{-1} soil	Labile P pool in the mineral soil layers
P_{max}	kg P kg^{-1} soil	Maximum soil P sorption capacity (Langmuir sorption isotherm)
P_{prim}	kg P kg^{-1} soil	P–containing primary mineral pool in the mineral soil layers
P_{solu}	kg P m^{-3} solution	Soil solution P pool
P_{stab}	kg P kg^{-1} soil	Stable P pool in the mineral soil layers
$q_{r\text{-}sh}$	dimensionless	Ratio of coarse root to shoot growth
$q_{r\text{-}sh,max}$	dimensionless	Maximum ratio of root to shoot growth under nutrient limitation
$q_{r\text{-}sh,nrom}$	dimensionless	Ratio of root to shoot growth in absence of element deficiency
$q_{s(i)}$	l	Water content of soil layer *i*
$R_{con,pool}$	kg C kg C^{-1}	Construction respiration rate per unit growth of a tissue pool
r_{crown}	m	Tree canopy radius
r_{pool}	m	Average fine root or mycorrhizae radius
$R_{s\text{-}pool,X}$	m^2	Soil to absorption surface resistance
$S_{s(i)}$	m^2	Surface of rooted area of soil layer *i*
$U_{A,fr(i)}$	m^2	Average fine root absorption surface in soil layer *i*
$U_{A,myc(i)}$	m^2	Average mycorrhizae absorption surface in soil layer *i*
$W_{up(i)}$	kg H_2O	Tree water uptake
x	m	Average hypha extension from root tip
X_{dem}	kg X	Tree nutrient demand
$X_{lit,pool}$	kg X	Element amount lost from each tissue pool through litterfall
$X_{myc,res}$	kg X	Mycorrhizal reserve pool content
$X_{myc,struct(i)}$	kg X	Mycorrhizal structural pools content in layer *i*
$X_{p(i)}$	kg X	Dissolved amount in layer *i*
X_{pool}	kg X	Element content of a tissue pool
$X_{req,T}$	kg X	Total tree nutrient requirement
X_{res}	kg X	Actual content of tree reserve pool
$X_{res,max}$	kg X	Maximum content of tree reserve pool
$X_{retran\_in,pool}$	kg X	Element amount retranslocated before and allocated to the reserve pool
X_{tem}	kg X	Amount remobilized from internal reserves tissue pools
X_{trans}	kg X	Nutrient transfer from mycorrhizae to trees
$X_{up,fr,dif(i)}$	kg X	Uptake through diffusion by fine roots in soil layer *i*
$X_{up,fr,sol(i)}$	kg X	Uptake through water absorption by fine roots in soil layer *i*
$X_{up,myc(i)}$	kg X	Uptake through diffusion by mycorrhizae in soil layer *i*
$X_{up,T}$	kg X	Total tree element uptake
$\theta_{s(i)}$	kg H_2O	Water content in layer *i*
ρ_{pool}	kg C m^{-3}	Average fine root or mycorrhizae density

Table A2. Parameter values for P and EM modules.

Parameter	Unit	Value
CP ratio	—	1400
Hyphal radius	μm	10
Mycelial extension x	m	0.05
EMM fraction	—	0.5
Rhizomorph Fraction	—	0.3
CN ratio rhizomorph	—	200
CN ratio EMM	—	10
CN roottip	—	10
Turnover Rhizomorphs	days	450
Turnover EEM	days	20
Turnover roottip	days	150
K_{pi}	—	0.1
Langmuir	—	1
P_{max}	—	400
[P]opt, stem0	mgP: gC	0.176
[P]opt,stem1	—	0.143
[P]opt,stemheart	—	0.038
[P]opt,stembark	—	0.92
[P]opt, l1	—	2.30
[P]opt,l0	—	3.00
[P]opt,cr0	—	0.401
[P]opt,cr1	—	0.1433
[P]opt,crheartwood	—	0.106
[P]opt,brabark	—	4.048
[P]opt,bra0	—	0.776
[P]opt,bra1	—	0.631
[P]opt,braheart	—	0.167
[P]opt,fr	—	1.24
$X_{retran\_in,pool}$	—	0.3
I_{max}	mg s^{-1}	2.0
C_{lim}	mg l^{-1}	5
K_m	—	0.001

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ORIGINAL PAPER

Merchantability and assortment structure of pine stands affected by root rot in the Volyn Polissya region, Ukraine

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Abstract

The study was conducted in the forests of the State Enterprise "Gorodotske Forest Economy", located in the Manevytsko-Volodymyretsky region of the Volyn Polissya in Ukraine. The annosum root rot (*Heterobasidion annosum* (Fr.) Bref.) impact on timber merchantability was investigated. The comparison of the cost estimation of stands assortment structure was carried out on the basis of the market value at current selling prices of the State Enterprise "Gorodotske Forest Economy" of the Volyn Regional Department of Forestry and Hunting as of 2017, taking into account the quality and the average length of the assortments. We present a comparative analysis of productivity, merchantability and assortment structure and financial value of timber volume by various assortments of pine and birch stands of the Volyn Polissya region affected by annosum root rot. We found that in the pine plantations, the overall productivity and the value of merchantable wood was higher by 42% in the control sites (areas between the fungal disease centers) as compared with those in the root rot disease centers. In the middle-aged birch-pine stands, the value of merchantable wood was higher than that in pine plantations of 34 the comparable age: by 9% in the disease centers and by 8% in control sites.

Key words: artificial pine stands; annosum root rot; disease center; merchantability; assortment structure; assortment value

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1. Introduction

One of important questions in forestry, concerning growing of high-yield pine stands, is a problem of root rot that is still current, as there is no efficient methods of the disease control. Scots pine (*Pinus sylvestris* L.) is most severely affected by root rot caused by the fungus *Heterobasidion annosum* (Fr.) Bref. Due to the disease globalization in the last decades, it covers all countries of Europe (CMI 1980; EPPO 2014; Vasiliauskas et al. 2002), North America (Harrington et al. 1989), Central America and Caribbean (USDA Forest Service 2002; EPPO 2014), some regions of Australia (EPPO 2014), Asia (Parmasto 1986), and Africa (Morocco) (EPPO 2014). The problem of disease appearance and spreading in Ukraine arose up in a middle of the 20th century as pine forest plantations were established in considerable areas of abandoned arable lands, pastures, and wastelands, where soils had lost forest properties (EPPO 2014). The root rot reduces the productivity of forest stands, causes their early deterioration, initiates the massive propagation of pests, increases the fire hazard, causes sanitation felling, worsens the soil-protective, water-conservation and sanitary functions of a forest, and, in general, significantly reduces a growing stock and affects the assortment structure of pine forests in Ukraine (Ladeyshchikova et al. 2001). The fungus causes a mottled rot in the lower part of the trunk, the length of which along the trunk can reach 6 – 8 m that leads to timber loss, which amounts 50% (Onyskiv & Kidyk 2008; Churakov et al. 2013; Lapitan et al. 2013).

Besides decreased profits due to reduced timber yield and deterioration in the quality, annosum root rot causes the stand increment loss (Bazzigher & Schmid 1969; Jambunathan et al. 1986; Vollbrecht et al. 1994; Brandtberg et al. 1996; Khun et al. 2011). It deteriorates the trunk form due to the thickening the lower part of the trunk (Bazzigher & Schmid 1969; Vollbrecht et al. 1994; Khun

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*Corresponding author. Oksana Tarnopylska, e-mail: tarnopilskaya@gmail.com, phone: +38 096 252 46 01 et al. 2011). However, the loss of increment of living trees affected by annosum root rot is not often taken into account in forest management planning. For example, the growing stock increment of affected trees decreases on 10% during a 5-year period as compared to healthy trees. For a longer period, the increment losses can be considerably perceptible in certain stands (Jambunathan et al. 1986). The trees affected by root rots are sensitive to wind damage (Yde-Andersen 1970; Semenkova 1971; Bendz-Hellgren et al. 1999) and to the attacks of bark beetles *Dendroctonus micans* (Froelich et al. 1978; Rasanen et al. 1985) as well.

The use of control methods to decrease the rates of the disease requires investments. Additional costs are needed for forest harvesting in a summer period for protecting measures to prevent the infection of stump surface in summer. Most of the forestry measures, in particular, lowering the felling age, controlled burning-out, grubbing and change of wood species – are also expensive. The efficiency of these measures is difficult to be foreseen because of the absence of long-term experience with the measures.

In Ukraine, annosum root rot is most prevalent in young and middle-aged pine plantations established on lands after agricultural use in Polissya, Carpathian parts and some areas of the Forest-Steppe. Considering the fact that a significant part of such lands falls on Volyn Polissya, the study of pine forests decline on former arable lands is now becoming increasingly relevant. The influence of annosum root rot on pine stands was investigated in the studies of Vedmid et al. (2013), Lapitan et al. (2013) and Mihaylichenko et al. (2014).

In Ukraine, predominantly pure pine plantations are created again on cutting areas affected by annosum root rot. According to Ladeyshchikova et al. (2001), the establishment of birch (*Betula pendula* Roth.) plantations as a pine forecrop is proposed in fresh and moist fairly infertile pine site types on the formerly arable lands in order to reduce the infectious background of the root rot and contribute to the formation of the soil microbiota natural composition. However, this provision needs to be confirmed, as there is not enough data on the growth, health condition, productivity, merchantability, and assortment structure of birch plantations on the post-agricultural lands. In Finland, birch trees appeared to be very resistant to *H. annosum* s. str. Obviously, *H. annosum* s. str. needs pine or spruce trees as a food supply to allow for infesting living birch trees (Rasanen et al. 1985).

The aim of the study was to compare the productivity, merchantability, assortment structure and value of timber volume by different types of assortments of pine stands affected by annosum root rot for trees growing in the root rot disease centers and for trees growing between the centers in the Volyn Polissya zone. Also, the aim of the study was to compare the above mentioned values for infected pine stands and for healthy birch stands in the same forest site conditions for possible substitution of pine stands by more root rot resistant birch plantations.

2. Material and methods

The study was conducted in pine forests of the State Enterprise "Gorodotske Forest Economy"; the enterprise is in a jurisdiction of State Forest Resources Agency of Ukraine and is located in Volyn Polissya of Ukraine. The climate of the region is moderate continental with mild winter and warm summer. The average temperature is −4.7 °C in January and +18.5 °C in July. The absolute minimum is −39 °C, the absolute maximum is +39 °C. The period with a temperature above +10 °C is 150 – 160 days. The sum of active temperatures for this period is 2,495 – 2,580°. Precipitations are 550 – 640 mm per a year; most of them come in summer, the least in winter.

The Volyn Polissya zone has widely occurring glacial and karst forms of relief and valley landscapes. The zone is characterized by excessive moistening and development of the water-logged lands and bogs; there are numerous (over 200) lakes and large forested areas. The bottom-lands of mixed forests zone (45%), meadow-bog landscapes (about 10%) and moraine-frontal plains are prevailing here, in particular, the Volyn range. Among pre-Quaternary deposits, cretaceous rocks are prevailing, which determine the development of karst forms of relief: lake basins, karst funnels, and humus-carbonate soil formation (Marinich et al. 1985).

The total area of forests of Volyn Polissya is over 2,300 thousand ha. The area of forest plots covered with forest vegetation in the State Enterprise "Gorodotske Forest Economy" is 28,240.5 ha. Scots pine is the main forest forming tree species; it occupies near 68% of the area covered with forest vegetation (Source: Production Association "Ukrderzhlisproekt").

To evaluate the merchantability and assortment structure of middle-aged artificial pine plantations affected by annosum root rot, 9 sample plots were established in the stands, containing infected and dead trees (disease centers); the stands were at age of 51, 61 and 75 years. Additional 9 sample plots were established as a control in a relatively healthy part (i. e. without evidence of deterioration) of these stands (the area between the disease centers) (Fig. 1).

The number of replications is three for each of three age classes (with an interval of 10 years).

Pure birch stands are resistant against annosum root rot. From this view, one sample plot was laid out on abandoned arable lands in the 51-year-old undamaged birch stand (Fig. 2) to compare health, growth and productivity characteristics with that of diseased pine stands.

For birch and pine stands affected by the root rot, assortment structure was compared and a value of timber was assessed.

The area of sample plots is 0.5 ha on average and the number of the dominant trees is above 200 trees on each plot (Anuchin 1982). The root rot disease center is an area occupied by a group of declining (severely weakened) and dying trees including clearings resulting from sanitary

Fig. 1. 75-year-old pine plantation: *a* – in annosum root rot disease center; *b* – in the area between the disease centers (control).

Fig. 2. 51-year-old birch plantations.

cutting of the trees affected by annosum root rot. The area between the disease centers is a viable part of the stand, not disordered by the pathogenic loss of growing trees. The disease-produced loss of forest comprises very weakened and dying trees and fresh and old standing dead trees.

Enumeration survey (including breast height diameter and tree height mensuration) was performed in all sample plots by 4-cm categories based on DBH (8–12–16 – 20 cm etc.; Anuchin 1982). The trees were grouped into three categories according to the merchantability, as follows: merchantable trees – the total length of merchantable part at the bottom of the trunk is 6.5 m and longer, semi-merchantable trees – the length of merchantable part at the bottom of the trunk is from 2 to 6.5 m, fuelwood trees – the length of merchantable part at the bottom of the trunk is less than 2 m.

The health condition of trees was estimated using 6 categories as follows: I – trees without evidence of decline, II – weakened trees, III – severely weakened trees, IV – dying trees, V – standing dead trees died over the present year, VI – standing dead trees died over recent years (Sanitary Forests Regulations 2016). The degree of stand damage is characterized by health indicator, which was calculated using the formula [1]:

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

where: I_c – health indicator of the stand; $K_1, \ldots, K_6$ – category of the health condition of the trees (from I to VI); $n_1, \ldots, n_6$ – the number of trees of given category of the health condition; N – the total number of trees on the sample plot.

The trunks of merchantable trees are divided into three dimensional and qualitative categories, depending on the diameter of the trunk segment in the upper section without bark: large-sized – 25 cm or more, medium-sized – from 14 to 24 cm, and small-sized – from 6 to 13 cm. Round merchantable timber logs were grouped into assortments according to their intended purpose: building timber, which is used for wooden shipbuilding, piles, bridges, poles of aerial lines of communication; saw logs, which are the raw materials for lumber production; mine timber, which is the timber for excavation support; pulpwood, which is assortment for the production of cellulose and wood pulp; veneer logs used for veneer production, which is then used in plywood, furniture and other industries.

Absolute and relative stand density was determined by using the tables according to Shvydenko et al. (1987). The total stock volume per hectare was estimated according to the tables of Nikitin (1984) and Strochinsky et al. (2007a, b) for young and middle-aged stands cruising.

Merchantability of the stands was estimated by the ratio of merchantable and fuelwood trunks and by the subsequent division of the stock into qualitative and quantitative categories (timber by size categories and grades, industrial raw materials, fuelwood, waste) (Nikitin 1984). The merchantability was estimated by the forest mensuration results, using assortment tables, which are used during the inventory evaluation of the felling areas (Nikitin 1984).

The comparison of cost estimations of the stands assortment structure was carried out on the basis of the economic benefit that can be obtained from the sale of the timber at current selling prices (Pearse 1990; Synyakevych 1996). The prices correspond to the average selling prices of the State Enterprise "Gorodotske Forest Economy" of Volyn Regional Department of Forestry and Hunting as of 2017, taking into account the quality and the average length of the assortments.

Merchantability of a stand is attributable mainly to the patterns of distribution of the number of trunks by thickness grades, depending on the average diameter of the tree stand. Therefore, the non-parametric Kolmogorov-Smirnov goodness-of-fit test (λ) (Massey 1951) was used during the studies of the merchantability of the stands. For this purpose, two series of empirical distributions of tree diameters in paired sample plots (in the root rot disease centers and in the areas between the disease centers (the control) laid out in pine plantations affected by annosum root rot were compared and their belonging to one general population was assessed according to the formula [2]:

$$\lambda = d_{max} \sqrt{\frac{n_1 \cdot n_2}{n_1 + n_2}} \quad [2]$$

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

In this case,

$$d_{max} = \sqrt{\frac{p_1}{n_1}} - \sqrt{\frac{p_2}{n_2}} \quad [3]$$

where: $\sqrt{\frac{p_1}{n_1}}$ *and* $\sqrt{\frac{p_2}{n_2}}$ – the values of the first and the second series of cumulative frequencies.

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

$$\lambda = \sqrt{\frac{1}{2}\ln\frac{2}{p}} \quad [4]$$

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

Table 1. Mensurational indices for pine plantations in the root rot disease centers and in the control (the area between the disease centers) and for birch plantations in fresh oak-pine fairly infertile site type.

Composition	Part of the stand	Part of the trees	Age [years]	Stand density [trees ha^{-1}]	Average diameter [cm]	Average height [m]	Total stand basal area [m^2 ha^{-1}]	Relative density	Stand volume [m^3 ha^{-1}]	Health indicator I_c	λ
10Sp	Disease center	living	51	770	20.5	18.5	25.47	0.59	220.1	2.0	4.62
		dead		50	18.2	17.9	1.3	0.03	10.8		
	Control	living		1 185	18.2	17.8	30.98	0.74	260.5	1.6	
		dead		21	10.1	13.7	0.17	0	1.1		
10Sp	Disease center	living	61	458	27.7	24.6	27.43	0.58	306.8	2.3	5.37
		dead		132	25.3	24.1	6.56	0.14	72.1		
	Control	living		799	27.0	26.0	45.75	0.97	541.3	1.6	
		dead		73	18.6	22.6	1.99	0.04	20.8		
10Sp	Disease center	living	75	167	37.6	25.8	18.61	0.39	228.9	2.9	6.86
		dead		80	34.6	25.0	7.52	0.16	85.5		
	Control	living		491	35.0	26.3	46.91	0.98	561.4	1.3	
		dead		5	22.6	22.0	0.2	0	2.1		
9Sb	Whole stand	living	51	724	20.2	22.0	23.04	0.76	234.5	1.5	—
		dead		21	15.6	19.6	0.39	0.01	3.5		
1Sp		living		76	20.5	22.1	2.52	0.06	25.7	1.5	
		dead		—	—	—	—	—	—	—	

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

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

During the study, mensurational characteristics of the stands were obtained in the established sample plots, where the research on merchantability and assortment structure and the monetary valuation of trunk timber volumes were made (Table 1).

3. Results

The analysis of λ value indicates that the compared populations of the trunk distribution by DBH categories, depending on the average diameter of the stand in the disease center and in the control, belong to different general populations and are described by different curves ($\lambda = 4.62...6.86 > 1.95$), that is, the probability of differences exceeds 99 % level (Table 2).

Wood losses by the total volume due to dying of trees caused by the disease increase considerably with aging. In artificial pine plantations of the age class VI, growing in the same forest site conditions, the total volume of trunk timber in the root rot disease centers is 7% less in comparison with the stand growing in the area between the disease centers; in the stands of the age classes VII and VIII, it is 39% and 57% less, respectively (Table 2). In total, in the 51-year-old pine stand, annosum root rot did not cause serious damage. In addition, the average diameter of this stand is 11% and the average height is 4% higher in the disease center than in the control.

As the age increases, the yield of the timber increased in both parts of the investigated stands: from 74% to 83% in the area between disease centers and from 74% to 78% in the disease centers. However, in the last, the yield of industrial raw materials decreases from 8% to 6% and of fuelwood, from 9% to 7%. In the areas between annosum root rot centers, the decrease is from 7% to 3% and from 9% to 5%, respectively. This difference is not significant.

In the 61-year-old pine stand, unlike other investigated stands, the yield of the timber is the maximum both in the centers of the disease (84%) and in the areas between the centers (82%), and the yield of industrial raw materials is almost the same (only 1% and 2%, respectively). This is due to the selective sanitary felling carried out in this stand a year before the laying out sample plots.

The birch-pine stand differs from other investigated stands by a considerably smaller proportion of timber – 59% only – and, respectively, a larger proportion of industrial raw materials (18%) and fuelwood (15%).

The medium-sized timber is prevalent in the pine plantations of the age classes VI – VII and in the birch-pine plantations; in the pine stands of age class VII, the large-sized timber does (Fig. 3).

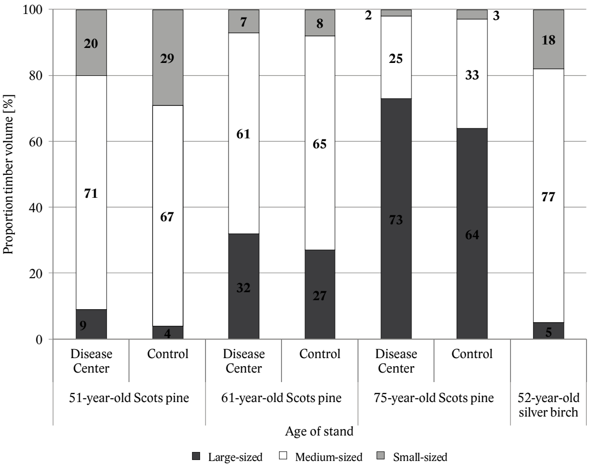

Fig. 3. Distribution of timber volume of pine and birch-pine forest plantations by size category.

As the age of pine plantations increases, the proportions of medium and small-sized timber decrease both in the disease centers (from 71 to 25% and from 20 to 2%, respectively) and in the parts of the stand between

Table 2. Merchantability and assortment structure of the investigated stands.

Age, year	Fungal infection	Tree species	Unit	Timber									Low-grade wood		Merchantable wood	Waste	Total
				Size			Timber distribution by assortments					Timber in total	Industrial raw materials	Fuelwood			
				Large	Medium	Small	Building timber	Saw log	Veneer log	Mine timber	Pulpwood						
51	Disease center	Sp	$m^3 ha^{-1}$	15	122	34	102	21	—	33	14	170	18	20	208	22	230
			%	6	53	15	44	9	—	14	6	74	8	9	91	10	100
	Control	Sp	$m^3 ha^{-1}$	7	124	53	103	15	—	49	17	184	18	21	223	25	248
			%	3	50	21	41	6	—	20	7	74	7	9	90	10	100
61	Disease center	Sp	$m^3 ha^{-1}$	85	166	20	152	88	—	19	12	271	4	16	291	33	324
			%	26	52	6	47	27	—	6	4	84	1	5	90	10	100
	Control	Sp	$m^3 ha^{-1}$	116	283	36	251	126	—	36	22	435	12	28	475	53	528
			%	22	53	7	47	24	—	7	4	82	2	6	90	10	100
75	Disease center	Sp	$m^3 ha^{-1}$	140	49	4	60	126	—	3	4	193	15	17	225	22	247
			%	56	20	2	24	51	—	1	2	78	6	7	91	9	100
	Control	Sp	$m^3 ha^{-1}$	307	157	13	172	280	—	12	13	477	15	29	521	55	576
			%	54	27	2	30	49	—	2	2	83	3	5	91	9	100
51	Whole stand	Sp	$m^3 ha^{-1}$	—	16	4	13	1	—	4	2	20	3	3	26	3	29
			%	—	55	14	45	3	—	14	7	69	10	10	89	11	100
		Sb	$m^3 ha^{-1}$	7	97	22	22	14	80	—	10	126	41	34	201	16	217
			%	3	45	10	10	6	37	—	5	58	19	16	93	7	100
		Σ	$m^3 ha^{-1}$	7	113	26	35	15	80	4	12	146	44	37	227	19	246
			%	3	46	10	14	6	32	2	5	59	18	15	92	8	100

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

the centers (from 67 to 33% and from 29 to 3%, respectively). Instead, the portion of large-sized timber grows significantly: from 9% to 73% in the disease centers and from 4% to 64% in the areas between the centers.

Merchantability structure of birch-pine plantations is dominated by the medium-sized timber (77%). The proportion of small-sized timber is 18%, and large, 5% only. However, the merchantability and assortment structure of such plantations can be significantly improved, assuming that intermediate felling is timely. In pine plantations, both in the disease centers and in the areas between the disease centers, the proportion of saw logs increases with aging – from 12 to 65% and from 8 to 59%, respectively. The yield of small-sized wood assortments decreases: for the mine timber, from 19 to 2% and from 27 to 2%, respectively, and for the building timber, from 60 to 31% and from 56 to 36%, respectively. In birch-pine plantations, veneer logs and building timber prevail among assortments, which account for 55% and 24%, respectively. The share of saw logs is only 10% of the timber volume. The value of the pine stand volume in the disease centers is reduced due to the negative impact of the root rot and is much smaller compared to that for the part of stand between the centers (Table 3).

The difference between the values of pine stand volume in the centers of forest decline and in the sites between the centers increases with age. It is 1% in the stand of age class VI, 36% in the stand of the age class VII and amounts to 57% in the VIII age class forest stand in favor of the healthy part of the stands (Table 4). In absolute terms, the difference in the volume values for affected and healthy parts of the stands increases with aging – from 40.7 EUR in the stands of the age class VI to 9471.6 EUR in the stands of the age class VIII.

The main part of the value structure of all studied plantations is the timber, which is the most valuable. With the aging, the value of the timber of pine plantations grows both in absolute and in relative terms. The share of the timber value increases from 90 to 95% in the centers of annosum root rot disease and from 90 to 97% in the part of the stands between the centers.

The proportion of the timber value in birch-pine plantations (83%) is lower than that in artificial pine plantations of the appropriate age, while the parts of industrial raw materials and fuelwood (9% and 8%, respectively), on the contrary, are higher (see Table 3).

Table 3. Monetary valuation of trunk timber volumes by 1 ha of pine and birch stands, EUR.

Age [years]	Part of the stand	Species	Characteristic	Timber						Industrial raw materials	Fuelwood	Total
				Assortments					Timber in total			
				Building timber	Saw log	Veneer log	Mine timber	Pulpwood				
51	Disease center	Sp	Volume [m³]	102	21	—	33	14	170	18	20	208
			Cost [EUR]	24.8	41.2	—	13.5	12.5	—	12.8	9.6	—
			Value [EUR]	2 529.6	865.2		445.5	175.0	4 015.3	230.4	192.0	4 437.7
	Control	Sp	Volume [m³]	103	15	—	49	17	184	18	21	223
			Cost [EUR]	24.8	41.2	—	13.5	12.5		12.8	9.6	—
			Value [EUR]	2 554.4	618.0		661.5	212.5	4 046.4	230.4	201.6	4 478.4
61	Disease center	Sp	Volume [m³]	152	88	—	19	12	271	4	16	291
			Cost [EUR]	24.8	41.2	—	13.5	12.5	—	12.8	9.6	—
			Value [EUR]	3 769.6	3 625.6		256.5	150.0	7 801.7	51.2	153.6	8 006.5
	Control	Sp	Volume [m³]	251	126	—	36	22	435	12	28	475
			Cost [EUR]	24.8	41.2	—	13.5	12.5	—	12.8	9.6	—
			Value [EUR]	6 224.8	5 191.2	—	486.0	275.0	12 177.0	153.6	268.8	12 599.4
75	Disease center	Sp	Volume [m³]	60	126	—	3	4	193	15	17	225
			Cost [EUR]	24.8	41.2	—	13.5	12.5	—	12.8	9.6	—
			Value [EUR]	1 488.0	5 191.2	—	40.5	50.0	6 769.7	192.0	163.2	7 124.9
	Control	Sp	Volume [m³]	172	280	—	12	13	477	15	29	521
			Cost [EUR]	24.8	41.2	—	13.5	12.5	—	12.80	9.6	—
			Value [EUR]	4 265.6	11 536.0		162.0	162.5	16 126.1	192.0	278.4	16 596.5
51	Whole stand	Sb	Volume [m³]	22	14	80	—	10	126	41	34	201
			Cost [EUR]	25.4	29.8	31.2	—	11.6	—	10.0	10.3	—
			Value [EUR]	558.8	417.2	2496.0	—	116.0	3 588.0	410.0	350.2	4 348.2
		Sp	Volume [m³]	13	1	—	4	2	20	3	3	26
			Cost [EUR]	24.8	41.2	—	13.5	12.5	—	12.8	9.6	—
			Value [EUR]	322.4	41.2	—	54.0	25.0	442.6	38.4	28.8	509.8
		Σ	Value [EUR]	881.2	458.4	2 496.0	54.0	141.0	4 030.6	448.4	379.0	4 858.0

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

Table 4. Comparison of the values of pine stands volumes in the disease centers and the control (areas between the disease centers) in euro.

Commercial grade	Age [years]								
	51			61			75		
	Disease center	Control	Difference	Disease center	Control	Difference	Disease center	Control	Difference
Timber	4 015.3	4 046.4	31.1	7 801.7	12 177.0	4 375.3	6 769.7	16 126.1	9 356.4
Industrial raw materials	230.4	230.4	—	51.2	153.6	102.4	192.0	192.0	—
Fuelwood	192.0	201.6	9.6	153.6	268.8	115.2	163.2	278.4	115.2
Total	4 437.7	4 478.4	40.7	8 006.5	12 599.4	4 592.9	7 124.9	16 596.5	9 471.6

In artificial pine plantations, the total value of merchantable wood in the part of stands in the areas between root rot disease centers is 42% higher compared with that in the disease centers. For the period from VI to VII age class, the value of merchantable wood of the first generation pine plantations increases in 1.6 – 1.8 times in the disease centers and in 3.7 times in the control.

4. Discussion

Our results suggest a significant influence of annosum root rot on absolute and relative indicators of assortments yield and value of pine stands. These findings comply with the results of the other studies. For example, Lapitan et al. (2013) who conducted research in the neighboring region, Novgorod-Siverske Polissya, noted that in maturing and mature pine stands, the stock volume had decreased by an average of 24% and 33%, respectively, in the centers of the disease. Our data show, however, that in Volyn Polissya, the total yield and the value of merchantable wood in the disease centers of artificial pine plantations affected by the root rot are even less, by 42% as compared with the part of the stands between the disease centers. All researchers agree that this negatively affected the distribution of assortments yield. Thus, Lapitan et al. (2013) indicate that in the disease centers, the yield of saw logs had decreased, on average, by 41% in maturing pine stands and by 50% in mature ones compared with that in sites between the disease centers. Instead, fuelwood yield had increased by 44% and 38%, respectively. In general, losses from annosum root rot damage are 40% of the total value of the wood in maturing stands and 49% in the mature ones. According to our study in maturing stands in the Volyn Polissya zone, this indicator is similar to that obtained by Lapitan et al. (2013) and makes 42%. The studies conducted in Eastern Polissya of Ukraine (Vedmid et al. 2013) testify that the growing stock and timber value of pine stands decrease even more, by 1.5 – 2 times, in the root rot centers in comparison with that in the part of the stand between the centers.

According to Vedmid et al. (2013), birch stands have a better health condition as compared with the pine plantations in the declined sites, but the value of the "realizable" volume of their trunk timber is 1.2 – 1.9 times less. At the same time, the authors note that the practicability of growing first-generation birch plantations in the formerly arable lands could be justified in the relation of forestry and biology as a preventive measure to create the preconditions for the further development of indigenous pine forest stands. Our results in Volyn Polissya indicate the higher value of merchantable wood of the middle-aged (51 years old) birch-pine plantations as compared with pine stands of the same age: by 9% in the disease centers and by 8% in the areas between the disease centers (see Table 3). This is due to the high value of birch veneer log, which is the main product getting during the birch stands cultivation, while the proportion of saw logs in pine stands of the age class VI is small.

Since birch plantations are almost not established at the enterprise "Gorodotske Forest Economy", a comparative analysis of merchantability and assortment structure of artificial plantations for other age classes is not possible. Comparison of the merchantable structure of pine plantations with natural birch stands, the area of which at the enterprise is 6%, is incorrect.

Consequently, all researchers agree that annosum root rot essentially affects the state, productivity, merchantability, and assortment structure of pine stands.

Thus, analysis and synthesis of the results obtained allow recommending the creation and cultivation of birch-pine plantations in Polissya on cutting areas after pine stands affected by annosum root rot. These plantations have the higher productivity and value of merchantable wood as compared with pure pine plantations of the appropriate age. Provided that the intermediate felling is done in a timely way, the productivity of the mixed birch-pine plantations and, consequently, the economic efficiency of their cultivation can be improved greatly. Creation of pure pine plantations on the cutting areas after pine stands affected by annosum root rot is inadvisable, since there is a danger of re-infection of the tree stands (Ladeyshchikova et al. 2001, Mikhailichenko et al. 2014).

5. Conclusion

Annosum root rot negatively affects the productivity, merchantability and assortment structure of artificial pine stands of Volyn Polissya. The total yield and the value of merchantable wood of artificial pine plantations affected by annosum root rot are 42% less in the disease centers than that in the areas between the disease centers. The value of merchantable wood volume is higher on average by 8.5% in the middle-aged birch-pine plantations than in pine stands of the appropriate age affected by the disease. In Volyn Polissya, it is useful to establish and grow birch-pine plantations on the cutting areas after pine plantations affected by annosum root rot.

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ORIGINAL PAPER

The energy intensity of the production of energy chips from dendromass stands on long-term uncultivated agricultural land

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Abstract

The aim of this work was to investigate the energy intensity of the fuel wood chips production on unused agricultural land. The unused agricultural land, overgrown with forest trees, also called white areas, is the result of the end of the traditional intensive management of agricultural land by the natural succession of forest stands and pioneers' wood species on the borders of forest and non-forest land. These stands are advantageously localized due to previous method of the land utilization, accessible and therefore very interesting from the point of view of obtaining fuel dendromass. The logging and subsequent dendromass processing was carried out for the purpose of further land use as pasture land and also for the production of fuel wood chips and their subsequent sale to the end user. With the utilization of technology chain saw-forwarder-chipper, the energy intensity of each operation, expressed in terms of the amount of fuel consumed per unit of produced wood fuel, was determined. The share of energy consumed in the energy value of the harvested tree dendromass in the evaluated sites ranged from 0.43 to 0.62%, approximately 0.64 to 0.88% and the chipping 0.42 to 0.54%. The total amount of energy consumed after calculation the chipper transfers to an average distance of 180 km was within 1.46 to 2.11%. The average weight of the harvested trees caused the biggest impact on the energy intensity of the production process.

Key words: wood chips; biomass transportation; energy ratio; dendromass; unused agricultural land

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1. Introduction

Fuel wood biomass belongs to significant renewable energy sources (RES) in Slovakia. Currently, its largest consumers are energy sources in cities and used in the form of fuel chips (Oravec 2015). It is obtained, in particular, from raw wood of inferior quality logged on forest land, from raw wood logged on unused agricultural land with wood species, residues and waste after wood processing in the wood-processing industry and residues after mechanical treatment (debarking) of pulpwood in the pulp and paper industry (Oravec et al. 2016). The unused agricultural land, overgrown with wood species, called white areas, is the result of the end of the traditional intensive management of agricultural land by the natural succession of forest stands and pioneers' on the borders of forest and non-forest land. The assortment structure of these stands is compared with the forest stands with a higher proportion of fiber and wood for energy use. These stands, whose area exceeded 270,000 ha in Slovakia in 2006 (Šmelko & Šebeň 2009) are advantageously localized, well accessible and therefore very interesting from the point of view of obtaining fuel dendromass. The production of fuel wood chips on this land consists of a number of working operations such as trees felling, wood skidding, dendromass drying, chipping and transportation. However, as is the case with most other RES, it is, to some extent, dependent on the use of non-renewable resources (fossil fuels) (Timmons & Mejía 2010).

Taking into the consideration the current increasing demand for fuel wood biomass, research of its production becomes increasingly important. One option to reduce the dependence of RES on fossil fuels is to introduce innovations and more modern, efficient technologies and technological processes into the practice. The low efficiency of work with the simultaneous abandonment of the largest ecological footprint is an accompanying phenomenon of obsolete technology and obsolete technological processes of wood production (Enache et al. 2016).

The aim of this research was to investigate the energy intensity of the production of fuel wood chips on unused agricultural land and the factors affecting it. With the utilization of chain saw-forwarder-chipper, the energy intensity of each operation, expressed in terms of the

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Corresponding author. Milan Oravec, e-mail: oravec@nlcsk.org amount of fuel consumed per unit of produced wood fuel, was determined. The aim of the research was the impacts assessment of the above-ground tree biomass stock, tree species structure of the stands and the skidding distance on the energy intensity of the individual operations of the fuel chips production and on the overall energy intensity of the production process.

2. Material and methods

Tests of the technological process of the production of fuel wood biomass were carried out on unused agricultural land. Stands logging and subsequent processing of dendromass were carried out for the purpose of further land use as pasture land and also for the purpose of obtaining a fuel wood chip and its subsequent sale to an energy source. Measurements were carried out within three localities (Očová, Ľubietová, Liptovská Teplička) in Central Slovakia. The reason for selecting these sites is the diversity of terrain and climate conditions as well as the woody structure of the harvested stands affecting the production conditions of the logging, skidding and dendromass chipping. The production conditions of the evaluated sites are typical for most of the area of woody plantations on non-forested land in the conditions of Slovakia. The energy consumption of the entire production process was evaluated on the basis of the calculated energy value of the fuel consumed by the individual technologies. The following parameters have been evaluated for the need to meet the set objectives in the technological process of energy chip production:

- stock of above-ground wood biomass, wood species structure, slope of the terrain, skidding distance,
- wood felling – working time, fuel consumption, performance,
- wood skidding – fuel consumption, work (machine loading), working time (hours) – (particularly: drive to the stands, drive with load, load structure, stowage, downtime), performance,
- natural drying of dendromass – time (day), humidity, weight,
- wood chipping – working time, performance, fuel consumption,

The stock of above-ground tree biomass was measured at each of the three sites within an area of 1.5 hectares with dimensions of 100 × 150 m. The age of the trees in the evaluated stands ranged from 20 to 40 years. The volume of wood biomass was calculated on the basis of the thickness and height of the wood, including the main branches. The thickness of all the trees was measured on a stand of height 1.3 m. Trees height, stem thickness, and branches diameters were measured on logged samples selected on the basis of the observed thickness structure and the wood species composition of the stand. The stems and branches diameters were measured at 1 m interstice. Due to the number, thickness and height structure of the trees in the evaluated stands, 3% of the total number of trees as samplers were used on each area. The weight of the wood was measured by weighing the slices cut into pieces weighing less than 20 kg. The assimilation organs were not removed prior to the measurement of the mass of above-ground tree biomass samples. These were part of the mass and energy balances of the energy chips production process. The humidity of the fresh biomass was determined from the samples taken by hygrometer Testo 606 and the energy value was indicated by calorimetry.

The wood felling on the measured areas was carried out with STIHL MS 231 type saws. During the felling, the time of work was measured including woodcutting, transfers within the workplaces, chainsaws maintenance and necessary breaks. Fuel consumption was indicated by determining the volume and its weight in the bins before the start and finalization of the work. For the calculation of energy consumption, the low heating value of fuel consumption 43 535 KJ kg^{-1} was used. Felling performance and energy consumption were calculated using mass data of above-ground wood biomass on the measured areas

Skidding of wood biomass was carried out by the JD 810 D forwarder. The average skidding distance to the place of storage and subsequent chipping within particular stands was determined as the distance between the centre of the measured area and the stock. Time and distance of work activities, drive to the stand, raw material handling, transfers within the stand, drive with the load, unloading of raw materials and downtime were measured. Fuel consumption was measured with a fuel consumption flow meter. For calculation of energy consumption, the low fuel consumption of 41 868 KJ kg^{-1} was used. Skidding performance and measured power consumption were calculated using data on the mass of above-ground tree biomass on measured areas reduced by loss. Skidding losses were measured by measuring the weight of raw material left on the logging area and on the skidding path.

Wood biomass skidded to the stock was freely stored for 91 days. At 7 day intervals, biomass samples were taken and their humidity measured using the same method as for fresh biomass. The number of samples taken at the same time was 50 – 60, depending on the thickness and wood structure of the biomass. The energy value of the samples was measured by the calorimetric method.

The wood biomass chipping at the stock was carried out by a Biber 92 drum chipper. Produced chips were filled by chipper into a 40 m^3 container removal set and then transported to the stock of end user. During the chipping, the total duration of the working time, including maintenance of the chipper, downtime, necessary breaks as well as the net time of the chipper, was measured. Fuel consumption was measured using a consumption flow meter. The measured values were compared to the total recorded fuel consumption. When calculating the energy consumption, the same fuel heat was used as for the skidding. In addition, fuel consumption of chipper transfer to the workplace was also included in the assessment of the energy intensity of the chipping. The total duration of transfers within the evaluated sites was 108 to 228 km. For an objective comparison of the results, the energy intensity was also calculated on an average distance of 180 km. The chipping power and the actual energy consumption were calculated using the energy value of the raw material, fuel consumption and the weight of the chips measured by the final customer as the difference in the weight of the loaded and emptied removal set. There was no loss of raw material mass during chipping due to its leaving in stock. The measured and calculated data were used to assess the impact of the logged stands structure and the production conditions on the time and energy intensity of the work activities as well as the influence of the storage duration of the wood biomass in the unchipped state on the overall energy balance of the production process.

3. Results

3.1. The tree species structure, stock and energy value of logged stands

The tree species structure, stock, moisture and energy value of woody biomass of the logged stand in Liptovská Teplička are presented in the Table 1. The total stock of above-ground wood biomass was 229.3 m^3, calculated per 1 ha 152.8 m^3. The largest stock was represented by spruce wood of 166.0 m^3 and its share within the total stock was 72.4%. The stock of other wood species, such as hazel, fir, beech and other wood species, ranged from 11.5 to 20.9 m^3.

The total mass of wood biomass in the fresh state was 185.0 t. The largest mass was spruce 128.3 t with 69.4% share of the total weight. The weight of raw materials of other wood was 12.3 to 18.7 t. The share of the weight of wood biomass of particular wood species is involved in Figure 1.

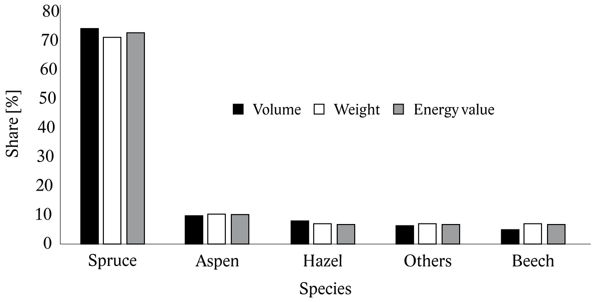

Fig. 1. Shares of volumes, weight and energy values of particular tree species, Liptovská Teplička.

Differences in the density of particular wood species have been revealed, which has increased the weight ratio of the hardwood compared to the volume structure of the tree species. The absolute humidity of the fresh-cut wood was 77.0 to 82.5% on average 79.75% and the energy value 8.41 to 8.91 MJ kg^{-1}, at an average of 8.66 MJ kg^{-1}. The highest energy value was measured for beech wood and the lowest one for the hazel. The total energy value of the stand was 1623.8 GJ. The share of the energy value of particular tree species is given in Figure 1. The total number of harvested trees was 2482, the highest number of hazels was 1214, and lowest the fir 84. The average volume of wood species was 0.092 m^3. The average weight of the wood was 0.075 t, most of the spruce and fir 0.157 resp. 0.147 t and the lowest one for hazel 0.015 t.

The tree species structure, stock, moisture and energy value of wood biomass of logged stand in Ľubietová are given in Table 2. The total stock of above-ground wood biomass was 217.8 m^3, with 145.0 m^3 per 1 ha. The largest stock was of the spruce wood of 105.7 m^3 and its share in the total stock was 48.5%. The stock of other tree species, including aspen, hazel, beech and other wood plants, ranged from 4.6 to 59.5 m^3. The share of wood biomass volumes of individual trees is shown in Figure 2.

The total mass of biomass in the fresh state was 184.7 t. The highest weight of the spruce was 82.3 t with

Table 1. Tree species structure, stock, moisture and energy value of the wood biomass of the logged stand in Liptovská Teplička.

Parameter	Thickness with bark, cm	Tree species					Total
		Spruce	Fir	Beech	Hazel	Other	
Wood biomass stock [m^3]	up to 8.0	53.9	5.3	4.4	18.0	7.7	89.4
	8.1 – 20.0	74.8	6.2	5.3	2.9	6.7	95.9
	20 and more	37.2	4.9	1.8	0.0	0.0	44.0
Total, [m^3]	—	166.0	16.5	11.5	20.9	14.4	229.3
Average stock per ha [m^3]	—	110.6	11.0	7.7	13.9	9.6	152.8
Wood biomass weight [t]	up to 8.0	42.3	4.1	5.1	16.2	6.7	74.4
	8.1 – 20.0	57.6	4.6	6.0	2.5	5.8	76.5
	20 and more	28.4	3.6	2.1	0.0	0.0	34.1
Total [t]	—	128.3	12.3	13.2	18.7	12.5	185.0
Wood biomass absolute humidity [%]	up to 8.0	82.6	85.7	79.4	82.9	81.1	n/a
	8.1 – 20.0	79.1	81.1	75.6	81.2	78.9	n/a
	20 and more	77.2	79.5	73.1	0.0	0.0	n/a
Biomass average humidity [%]	—	79.8	82.2	77.0	82.5	80.1	n/a
Energy value of wood biomass in fresh state [MJ kg^{-1}]	—	8.87	8.43	8.91	8.41	8.59	8,78
Total energy value of the wood biomass in fresh state [GJ]	—	1 138.2	104.0	117.6	156.9	107.1	1623.8
Number of harvested trees [pcs]	—	818	84	102	1214	265	2482
Average volume of harvested trees [m^3]	—	0.203	0.197	0.112	0.017	0.054	0.092
Average weight of harvested trees [t]	—	0.157	0.147	0.129	0.015	0.047	0.075

a share of the total weight of 44.6%. The weight of raw materials of other wood was 4.1 to 51.7 t. The share of the weight of the raw material of particular trees is shown in Figure 2.

Even in this locality, the influence of lower measured spruce weights has been shown, as compared to hardwood, especially beech. The absolute humidity of fresh-cut wood was 76.9 to 111.9% in average 94.4% and the energy value was 5.84 to 8.98 MJ kg^{-1}, an average of 7.77 MJ kg^{-1}. Extremely high humidity in fresh state compared to other wood species has aspen, which causes a low energy value of the raw material. The total energy value of the stand was 1435.4 GJ. The share of the energy value of particular wood species is given in Figure 2.

The total number of harvested trees was 2959 pcs, the highest number of hazel, 1582 pieces and the least other species 86. The average volume of tree species was 0.074 m^3. The average weight of the tree species was 0.062 t, the highest for the spruce and aspen 0.183 resp. 0.124 t and the smallest one for hazel 0.022 t. Tree species structure, stock, moisture and energy value of wood biomass in harvested stand in Očová are given in Table 3.

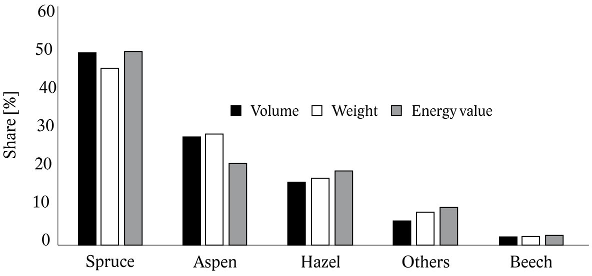

Fig. 2. Shares of volumes, weight and energy values of particular tree species, Ľubietová.

The total stock of above-ground wood biomass was 171.7 m^3, calculated per 1 ha 114.5 m^3. The largest stock had aspen wood 67.3 m^3 and its share in the total stock was 39.2%. The stock of other wood species, such as hazel, beech, oak and other wood species, ranged from 12.0 to 42.1 m^3. The share of wood biomass volumes of particular wood species is involved in Figure 3.

The total fresh biomass mass was 155.5 t. The largest weight was 58.3 t for aspen with a share of the total weight of 37.5%. The weight of raw materials of other tree species was 13.5 to 35.1 t. The share of the weight

Table 2. Tree species structure, stock, moisture and energy value of wood biomass of harvested stand in Ľubietová.

Parameter	Thickness with bark [cm]	Tree species					Total
		Spruce	Aspen	Hazel	Beech	Others	
Wood biomass stock [m^3]	up to 8.0	33.8	17.9	28.7	4.7	2.9	88.0
	8.1 – 20.0	45.7	36.7	6.1	5.2	1.7	95.4
	20 and more	26.2	4.9	0.0	3.4	0.0	34.4
Total, [m^3]	—	105.7	59.5	34.8	13.3	4.6	217.8
Average stock per ha [m^3]	—	70.4	39.6	23.2	8.8	3.0	145.0
Wood biomass weight [t]	up to 8.0	26.8	16.1	25.9	5.5	2.6	76.8
	8.1 – 20.0	35.5	31.6	5.4	6.0	1.5	80.0
	20 and more	20.1	4.0	0.0	3.8	0.0	27.9
Total [t]	—	82.3	51.7	31.3	15.2	4.1	184.7
Wood biomass absolute humidity [%]	up to 8.0	84.1	119.5	84.1	80.6	85.2	n/a
	8.1 – 20.0	80.9	109.8	82.7	76.1	81.7	n/a
	20 and more	78.1	101.3	0.0	74.0	0.0	n/a
Biomass average humidity [%]	—	81.2	111.9	83.7	76.9	84.1	n/a
Energy value of wood biomass in fresh state [MJ kg^{-1}]	—	8.51	5.84	8.26	8.98	8.31	7.77
Total energy value of the wood biomass in fresh state [GJ]	—	700.6	295.6	268.2	136.9	34.1	1435.4
Number of harvested trees [pcs]	—	852	325	1582	114	86	2959
Average volume of harvested trees [m^3]	—	0.124	0.183	0.022	0.116	0.053	0.074
Average weight of harvested trees [t]	—	0.097	0.159	0.019	0.133	0.048	0.062

Table 3. Tree species structure, stock, moisture and energy value of wood biomass of the harvested stand in Očová.

Parameter	Thickness with bark [cm]	Tree species					Total
		Aspen	Oak	Beech	Hazel	Others	
Wood biomass stock [m^3]	up to 8.0	22.3	4.8	3.6	26.9	15.5	73.1
	8.1 – 20.0	41.1	7.4	4.4	6.9	23.1	82.8
	20 and more	4.0	4.3	4.1	0.0	3.5	15.8
Total, [m^3]	—	67.3	16.5	12.0	33.8	42.1	171.7
Average stock per ha [m^3]	—	44.9	11.0	8.0	22.5	28.1	114.5
Wood biomass weight [t]	up to 8.0	19.8	5.4	4.0	24.2	13.1	66.6
	8.1 – 20.0	35.2	8.2	5.0	6.1	19.1	73.6
	20 and more	3.3	4.6	4.5	0.0	2.9	15.3
Total [t]	—	58.3	18.3	13.5	30.3	35.1	155.5
Wood biomass absolute humidity [%]	up to 8.0	117.4	78.7	81.3	83.0	84.1	n/a
	8.1 – 20.0	108.7	75.9	76.8	81.8	80.3	n/a
	20 and more	101.1	73.2	73.9	0.0	77.8	n/a
Biomass average humidity [%]	—	111.1	75.9	78.6	82.9	81.5	n/a
Energy value of wood biomass in fresh state [MJ kg^{-1}]	—	5.88	9.20	8.91	8.37	8.67	7.65
Total energy value of the wood biomass in fresh state [GJ]	—	342.6	168.1	120.5	253.7	304.5	1189.5
Number of harvested trees [pcs]	—	446	135	124	1208	1002	2914
Average volume of harvested trees [m^3]	—	0.151	0.122	0.097	0.028	0.042	0.085
Average weight of harvested trees [t]	—	0.131	0.135	0.109	0.025	0.035	0.053

of the raw material of particular wood species is given in Figure 3.

The influence of the higher density of hardwoods in comparison with other trees was revealed. The absolute humidity of the freshly grown tree species was 75.9 to 111.1% in average 93.5% and the energy value was 5.88 to 9.20 MJ kg^{-1}, in average 7.65 MJ kg^{-1}. There was high humidity and low energy value of aspen. The total energy value of wood biomass of the stand was 1189.5 GJ. The share of the energy value of particular tree species to its total value is given in Figure 3.

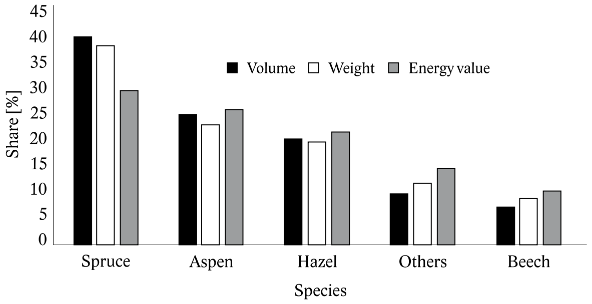

Fig. 3. Shares of volumes, weight and energy values of particular wood species, Očová.

The total number of harvested trees was 2914, the highest number of hazel 1208 pieces, and the smallest one the beech 124. The average volume of tree species was 0.085 m^3 and the average weight was 0.053 t. The largest average mass was oak 0.135 t and smallest hazel 0.025 t.

In order to compare the energy intensity of the chips production on the evaluated sites, the thickness structure of the biomass stocks is important in terms of the thickness levels share of 8 cm, 8.1 to 20 cm and over 20 cm and the number of trees with an average weight of 0.1 and above (Table 1 – 3). In harvested stands, the weight of wood biomass with a thickness of up to 8 cm ranged within a narrow range of 40.2 – 42.9%. The smallest share was measured in Liptovská Teplička and highest one in Očová. The share in the thickness of 8.1 to 20.0 cm was 41.4 to 47.3%. The smallest share was in Liptovská Teplička and highest in Očová. The largest differences were in the weight proportions of raw material with a thickness of over 20 cm. The largest share of 18.4% was measured in Liptovská Teplička and the smallest one in Očová. The structure of the weight proportions in the thickness steps at the individual sites is given in Figure 4.

The highest share of the number of wood species with a weight over 0.1 t was in Ľubietová 43.6%. In Liptovská Teplička, the share was 40.4% and in Očová only 24.2%.

In Liptovská Teplička, the biomass mass was up to 8 cm (36.9%) in Očová (39.7%). The share of raw material with a thickness of over 20 cm was 20.5% in Liptovská Teplička and only 11.4% in Očová. Differences in the thickness structure affected the increase of measured fuel consumption in comparison with Liptovská Teplička, in Ľubietová by 5.2% and in Očová by 18.5%. As a result of the growth of the thin mass, the average hourly performance in Ľubietová decreased by 4.8% and Očová by 13.9%.

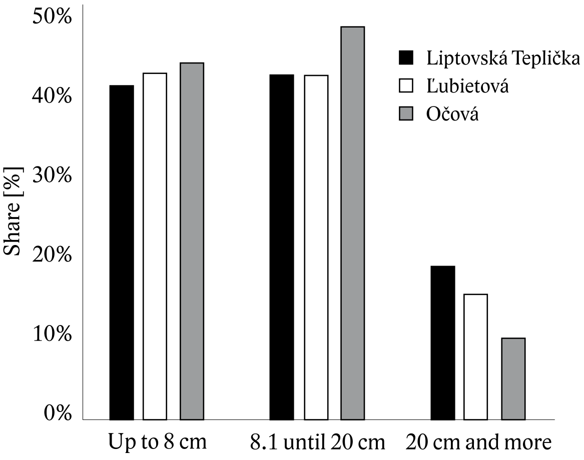

Fig. 4. Mass shares of wood biomass in thickness levels on particular sites.

3.2. Loss of wood biomass during the skidding and weight decreasing during storage of wood

The size of wood biomass losses in skidding when loading the skidding vehicle and during drive to the stock and weight loss during storage in Liptovská Teplička are involved in Table 4, in Ľubietová in Table 5 and in Očová in Table 6.

Table 4. Loss of wood biomass during the skidding to the stock and loss of storage weight, Liptovská Teplička.

Parameter	Tree species					Total
	Spruce	Fir	Beech	Hazel	Others	
Skidding losses [t]	9.4	0.6	0.7	3.6	1.3	15.6
Drying weight losses [t]	16.5	1.6	1.2	2.5	1.9	23.8

Table 5. Loss of wood biomass during the skidding to the stock and weight loss during the storage, Ľubietová.

Parameter	Tree species					Total
	Spruce	Aspen	Hazel	Beech	Others	
Skidding losses [t]	5.7	3.5	6.5	0.7	0.4	16.9
Drying weight losses [t]	10.9	8.3	4.0	1.0	0.7	24.9

Table 6. Loss of wood biomass during the skidding to the stock and weight loss during the storage, Očová.

Parameter	Tree species					Total
	Aspen	Oak	Beech	Hazel	Others	
Skidding losses [t]	4.0	0.6	0.5	5.2	3.8	14.1
Drying weight losses [t]	9.6	1.6	1.1	4.1	5.3	21.7

Mass losses by skidding in Liptovská Teplička reached 15.6 t, which represented 8.4% of the mass logged in the stand. The largest losses were 9.4 t for the spruce with a share of 7.3%. The largest share of losses was found for the hazel 19.3% and the smallest one for the fir 4.9% and beech 5.3%. From the point of view of the thickness structure losses during the skidding, there were the largest for biomass with a thickness of up to 8 cm (11.1 t), which represented 15.2% of the logged mass of mentioned thickness. Zero losses were in the case of raw material with a thickness of over 20 cm.

During the storage, a total of 23.8 tonnes of water was evaporated from biomass, representing 14.1% of the raw material weight skidded to the stock. The greatest intensity of water loss was in biomass with a thickness of up to 8 cm with a share of 15.20% and the smallest one in the raw material with thickness over 20 cm (12.6%). For particular wood species, the largest share of water loss was for the hazel and other wood species (16.6% resp. 16.9%) and the smallest for beech (9.6%).

The total water loss due to the skidding and evaporation losses were 39.4 t, and their share of logged biomass in the stand reached 21.3%. Weights losses of up to 8 cm thickness were 20.7 i.e. 27.8%, biomass with a thickness of 8.1 to 20 cm 14.4 t (19.0%) and at a thickness above 20 cm 4.3 t (12.3%). The largest share of total losses was 33.2% for the hazel, 26.4% for other wood species and the smallest one 14.4% for beech.

Mass losses by skidding in Ľubietová reached 16.9 t, which represented 9.1% of the weight harvested in the stand. The biggest losses were for the hazel 6.5 t, where the largest share of losses of 20.8% of all harvested trees was recorded. The lowest share of losses was 4.6% for the beech, 6.8% for the aspen and 6.9% for the spruce. From the point of view of the thickness structure losses during the skidding, they were the largest for biomass with a thickness of up to 8 cm (11.6 t), which represented 15.1% of the harvested mass of mentioned thickness. Zero losses were in the case of raw material with a thickness of over 20 cm.

During the storage, a total of 24.9 tonnes of water was evaporated from the biomass, which was 15.0% of the raw material skidded to the stock. The greatest intensity of water loss was in biomass with a thickness of up to 8 cm with a share of 16.1% and the smallest one for the raw material with a thickness exceeding 20 cm (12.5%). The largest share of water loss was found for the hazel and other wood species (16.1% and 18.9% respectively) and the smallest one for the beech (9.0%).

Total losses by skidding and water evaporating were 42.1 t, and their share within the harvested biomass reached 22.8%. Mass losses with a thickness of up to 8 cm were 22.1 i.e. 28.8%, for the biomass with a thickness of 8.1–20 cm 16.4 t (20.5%) and for the biomass with a thickness of over 20 cm 3.5 t (12.9%). The largest share of total losses was hazel 33.5%, 26.8% in the other wood species and 13.2% for the beech trees.

Mass losses by skidding in Očová reached 14.1 t, which represented 9.1% of the weight harvested in the stand. The biggest losses were for the hazel 5.2 t, which had the largest share of losses of all harvested wood species 17.2%. The lowest share of losses was for the oak 3.3% and beech 3.7%. From the point of view of the thickness structure losses during skidding, they were the largest for biomass with a thickness of up to 8 cm (9.6 t), which represented 14.4% of the harvested mass of mentioned thickness. Zero losses were for raw material with a thickness of over 20 cm.

During the storage, a total of 21.7 tonnes of water was evaporated from the biomass, which was 15.6% of the raw material skidded to the stock. The largest intensity of water loss was for the biomass with a thickness up to 8 cm with a share of 16.5% and the smallest one for the raw material with a thickness exceeding 20 cm (11.1%). The largest weight share of water loss was for aspen (17.7%), other wood species (16.9%) and hazel (16.3%). The smallest one was for the beech (8.5%).

The total water loss due to the skidding and evaporation losses were 35.8 t and their share of harvested biomass reached 23.2%. Mass losses for a thickness of up to 8 cm were 19.0 i.e. 28.8%, for the biomass with a thickness of 8.1 to 20 cm 15.1 t (20.7%) and biomass with a thickness of over 20 cm 1.7 t (11.1%). The largest share of total losses was 31.0% for the hazel, 26.2% for other wood species and 23.3% for aspen. The smallest losses were for the oak and beech (12.1 resp. 12.6%). In spite of the different skidding distances, the losses due to the skidding were in a narrow range of 8.4 to 9.1%. Small overall differences were also found in weight and total losses and losses of wood biomass mass.

Differences in the size of loss shares due skidding were found, water evaporation, and the total sum of these values for individual trees at all sites. Losses by the skidding of hardwoods were in the range of 3.3 to 5.3%, for conifers 4.9 to 7.3% and for aspen 6.7 to 6.8%. For hazel and other harvested wood species these losses were 9.8 to 20.8%. The reason for this is a substantially higher proportion of biomass thinner than 8 cm, which makes difficult to fill the skidding vehicle hydraulically on the logging surface and also causes mass losses during the drive to the stock. The weight loss by water evaporation during storage was between 8.5 and 9.6% for hardwoods, 13.8% to 14.2% for conifers, 17.2% to 17.7% for aspen and for hazel and other logged wood species 16, 1 to 18.9%. The reason of differences is other physical properties of particular wood species (especially biomass density, moisture and water evaporation intensity are also affected by thickness).

3.3. Energy intensity of the biomass production

The tree species structure, weight, moisture and energy value of the chipped wood biomass in the Liptovská Teplička stock is given in Table 7.

The total weight of wood biomass was 145.6 t with an average humidity of 53.8% and an energy value of 1 805.0 GJ. During storage this value increased by 11.1%. The biomass energy value of particular wood species ranged from 11.27 to 13.1 MJ kg^{-1}. The average value

Table 7. The wood species structure, weight, moisture and energy value of the chipped wood biomass in the Liptovská Teplička stock.

Parameter	Thickness with bark [cm]	Tree species					Total
		Spruce	Fir	Beech	Hazel	Other	
Wood biomass weight [t]	up to 8.0	31.0	3.1	4.2	10.6	4.8	53.7
	8.1 – 20.0	46.6	3.8	5.2	1.9	4.5	62.0
	20 and more	24.8	3.2	1.9	0.0	0.0	20.7
Total [t]	—	102.4	10.0	11.3	12.5	9.2	145.6
Biomass absolute humidity [%]	up to 8.0	55.6	57.9	60.8	52.1	49.7	n/a
	8.1 – 20.0	54.3	55.8	59.9	52.8	48.9	n/a
	20 and more	54.2	55.5	58.7	0.0	0.0	n/a
Biomass average humidity [%]	—	54.8	56.3	60.2	52.3	49.3	53.8
Energy value of biomass in the dry state [MJ kg^{-1}]	—	12.31	11.98	11.27	12.63	13.1	12.1
Total energy value of the biomass [GJ]	—	1 261	120	127	159	100	1 805

Table 8. The tree species structure, weight, moisture and energy value of the chipped wood biomass in the Ľubietová stock.

Parameter	Thickness with bark [cm]	Tree species					Total
		Spruce	Aspen	Hazel	Beech	Other	
Wood biomass weight [t]	up to 8.0	20.1	11.7	16.6	4.5	1.8	54.7
	8.1 – 20.0	28.3	24.8	4.1	5.2	1.2	63.6
	20 and more	17.4	3.4	0.0	3.5	0.0	24.3
Total [t]	—	65.8	39.9	20,7	13.2	3.0	142.6
Biomass absolute humidity [%]	up to 8.0	56.9	77.2	53.8	61.7	52.1	n/a
	8.1 – 20.0	55.1	74.9	54.7	60.5	50.9	n/a
	20 and more	54.8	71.3	0.0	59.3	0.0	n/a
Biomass average humidity [%]	—	55.6	75.262	53.979	60.591	51.625	59.4
Energy value of biomass in the dry state [MJ kg^{-1}]	—	12.18	9.27	12.33	11.25	12.96	11.32
Total energy value of the biomass [GJ]	—	801	370	256	148	39	1614

was 12.1 MJ kg^{-1}. The tree species structure, weight, moisture and energy value of chipped wood biomass in Ľubietová stock are given in Table 8.

The total wood biomass weight was 142.6 t with an average humidity of 59.4% and an energy value of 1 613.7 GJ. During storage this value increased by 12.4%. The energy value of particular wood species biomass ranged from 9.27 to 12.96 MJ kg^{-1}. The average value was 11.32 MJ kg^{-1}.

Tree species structure, weight, humidity and energy value of chipped wood biomass in the stock Očová are given in Table 9.

The total weight of wood biomass was 119.4 t with an average humidity of 59.1% and an energy value of 1333 GJ. During storage this value increased by 12.1%. The biomass energy value of particular wood species ranged from 9.42 to 12.93 MJ kg^{-1}. The average value was 11.3 MJ kg^{-1}. There was no loss of raw material mass during chipping due to its leaving in the stock.

Table 9. The tree species structure, weight, moisture and energy value of the chipped wood biomass in the Očová stock.

Parameter	Thickness with bark [cm]	Tree species					Total
		Aspen	Oak	Beech	Hazel	Others	
Wood biomass weight [t]	up to 8.0	14.3	4.5	3.4	16.3	9.0	47.4
	8.1 – 20.0	27.6	7.3	4.4	4.7	14.5	58.4
	20 and more	2.8	4.2	4.1	0.0	2.5	13.6
Total [t]	—	44.7	16,0	11.8	20.9	25.9	119.4
Biomass absolute humidity [%]	up to 8.0	75.5	60.9	63.7	52.2	51.4	n/a
	8.1 – 20.0	72.6	60.1	61.0	53.6	50.7	n/a
	20 and more	70.1	57.9	58.6	0.0	49.9	n/a
Biomass average humidity [%]	—	73.4	59.6	60.8	52.4	50.8	59.1
Energy value of biomass in the dry state [MJ kg^{-1}]	—	9.42	11.39	11.12	12.56	12.93	11.3
Total energy value of the biomass [GJ]	—	421	182	132	263	335	1333

Table 10. Performance, Fuel Consumption and Energy Intensity of Wood Felling in Assessed Locations.

Parameter	Locality		
	Liptovská Teplička	Ľubietová	Očová
Number of harvested trees [pcs]	2 482	2 959	2 914
Volume of harvested dendromass [m^3]	229.3	217.8	171.7
Performance [m^3 h^{-1}]	10.71	8.68	7.31
The energy value of harvested mass [GJ]	1 623.8	1 435.4	1 189.5
The weight of the dendromass [t]	185	184.7	155.5
Average weight of wood [t]	0.075	0.062	0.053
Total fuel consumption [kg]	160.72	186.93	168.76
Measured energy consumption [MJ t^{-1}]	37.83	44.07	47.26
Measured fuel consumption [kg t^{-1}]	0.87	1.01	1.09
Overall performance [t h^{-1}]	8.64	7.35	6.62
Duration of work [h]	21.4	25.1	23.5
Number of motor saws [pcs]	4	4	4
Average hourly saw performance [t h^{-1}]	2.16	1.84	1.65
Total energy consumption [MJ]	6 998.6	8 139.9	7 348.7
Share of energy consumed on the energy value of the extracted dendromass [%]	0.43	0.57	0.62

3.4. Trees felling

Data on performance, fuel consumption and energy intensity of stands felling in the evaluated sites are involved in Table 10.

The total time of felling at assessed sites in areas with a size of 1.5 ha ranged from 21.4 to 23.5 hours. The average hourly performance in the conversion to the chainsaw was 1.65 to 2.16 t h^{-1}. Total fuel consumption reached 160.72 to 186.93 kg, with a consumption rate of 0.87 to 1.09 kg t^{-1}. The total energy consumption was 9 668.6 to 7348.7 MJ representing the share of energy consumption 0.43 to 0.62%.in the fresh biomass energy value of the harvested stand. The highest performance and the lowest measured fuel consumption and the share of the energy value of harvested biomass were achieved in Liptovská Teplička. The least favorable parameters were measured in Očová.

3.5. Wood skidding

The total skidding time on the assessed sites ranged between 19.5 and 20.97 hours and net skidding time of 17.52 to 8.33 hours. The total fuel consumption including the trailer transfers was 20.97 to 244.69 kg and the fuel consumption for the skidding was 168.24 to 179.55 kg. Fuel consumption for the transfers was 34.73 to 73.11 kg. The total actual energy consumption was 8498.0 to 10 244.7 MJ and, for the same transfer distance, it was 9 472.3 to 9 976.2 MJ. Measured fuel consumption for skidding was 1.01 to 1.19 kg t^{-1} and the total measured consumption calculated for the equal transfer distance of 1.35 to 1.60 kg t^{-1}. The share of total energy consumption for the skidding and transfers to the equal distance related to the energy value of the skidded wood biomass to the stock was 0.64 – 0.88%. After recalculation for the equal transfer distance, the highest was the performance, the lowest measured consumption and the share of the energy value of the skidded wood biomass reached in Liptovská Teplička were calculated. The least favorable skidding parameters were measured in Očová. Based on the measurements, the factors influencing the performance and the energy process were analyzed. The overall performance of technology significantly affected the harvesting of wood biomass freely laid in the work area. Due to its character (thin, whole non-branched stems), it was problematic to use the load-carrying capacity of the vehicle set as much as possible. The dependence of performance during the skidding on the time required to stop cargo at the Ľubietová ($r^2 = 0.6361$, $P = 0.001$) site is shown in Figure 5.

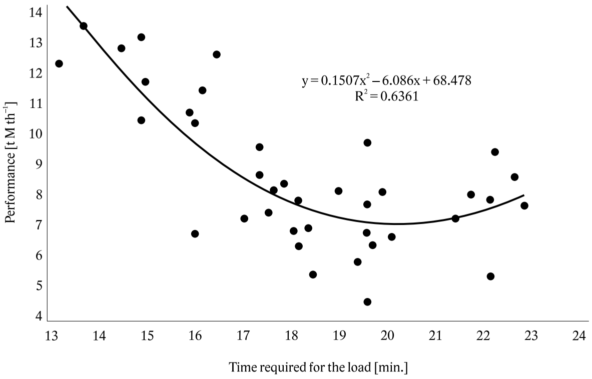

Fig. 5. Achieved technology performance, depending on time required for the load time in Ľubietová.

Performance data, data of fuel consumption and energy intensity of wood biomass skidding at assessed sites are given in Table 11.

3.6. Wood chipping

The total chipping time at assessed sites ranged from 21.1 to 2 hours and net chipping time was 18.4 to 19.9 hours. The average hourly performance in terms of networking time was 6.05 to 7.93 t h^{-1}. Total fuel consumption, including the transfers was 171.64 to 181.89 kg, fuel consumption for chipping 113.17 to 139.7 kg, fuel consumption for transfers was 31.94 to 68.32 kg. The total measured power consumption was 7186.2 to 7 615, and after the recalculation to the equal transfer distance due to the mutual comparability of results 713.3 to

Table 11. Performance, fuel consumption and energy intensity of skidding at assessed sites.

Parameter	Unit	Liptovská Teplička	Ľubietová	Očová
Total mass of skidded fresh biomass	t	169.40	167.80	141.40
Network time	h	18.08	18.81	17.52
Average hourly performance	t h^{-1}	8.33	8.00	7.24
Total duration of work	h	20.34	20.97	19.53
Average hourly performance in net time	t h^{-1}	9.37	8.92	8.07
Fuel consumption for skidding	kg	171.58	179.55	168.24
Measured fuel consumption for the skidding	kg t^{-1}	1.01	1.07	1.19
Transfers duration	km	228.00	156.00	108.00
Fuel consumption for transfers	kg	73.11	50.26	34.73
Measured fuel consumption for the transfers	kg t^{-1}	0.43	0.30	0.25
Total fuel consumption	kg	244.69	229.81	202.97
Total measured fuel consumption	kg t^{-1}	1.44	1.37	1.44
Total measured fuel consumption per average transfers travel distance of 180 km	kg t^{-1}	1.35	1.42	1.60
Energy value of skidded dendromass	GJ	1 486.80	1 302.40	1 079.20
The share of actual energy consumed in the energy value of the skidded biomass	%	0.69	0.74	0.79
Total actual energy consumption	MJ	10 244.70	9 621.70	8 498.00
Total energy consumption for an average transfers travel distance of 180 km	MJ	9 574.80	9 976.20	9 472.30
The share of energy consumption in the energy value of the skidded biomass	%	0.64	0.77	0.88

8 077.6 MJ. Measured fuel consumption for chipping was 0.78 to 1.17 kg t^{-1} and the total measured consumption was recalculated to the equal transfer distance of 1.15 to 1.62 kg. The share of total energy consumed for chipping and transfers to the equal distance to the energy value of the chipped wood biomass in the stock was 0.39 – 0.61%. After the recalculation to equal distance, the highest performance, the lowest specific consumption and the share of the energy value of the chipped biomass was reached in Liptovská Teplička. The least favorable chipping parameters were measured in Očová.

Performance data, data of fuel consumption and energy intensity of wood biomass chipping at assessed sites are given in the Table 12.

The energy consumption in the process of fuel chips production consisting of wood felling, wood biomass skidding to the stocks and its subsequent chipping was compared with the biomass energy values found in the logged stands and the biomass of these stands in the form of chips. The energy values of fuel chips made from stored raw material are higher due to moisture loss during storage on the assessed sites by 11.1 to 12.4%. For this reason, the share of the total energy consumed for the production of fuel chips is lower (1.05 to 1.52%) compared to the energy value of fresh biomass in logged stands (1.16 – 1.69%).

If we do not consider energy consumption for transfers of skidding vehicles and chippers between the workplaces, we found comparable energy values of the felling and skidding, whose shares of energy consumption on fresh biomass ranged between 0.43 and 0.61% and the value of fuel chips 0.39 up to 0.55%. After the transfers energy consumption calculation the energy intensity of the skidding has increased, and the share of energy on the value of fresh biomass has risen to 0.59 to 0.80% and the value of fuel chips 0.53 to 0.71%. Shares of energy consumption for chipping, including the transfers on fresh biomass value were 0.43 – 0.68% and fuel chips value 0.39 – 0.61%. Shares of energy consumption per chipping were 0.29 to 0.49%, respectively 0.26 to 0.44%.

The lowest energy intensity of the production process was achieved in Liptovská Teplička. Shares of energy consumption on energy biomass were higher in Ľubietová by 23.5% and 44.7% in Očová.

4. Discussion and conclusion

The energy intensity of the logging, skidding and chipping of above-ground tree dendromas has been investigated in the stands of wood species growing on long-term uncultivated agricultural land. These occur as a result of the end of the traditional intensive management of agricultural land through the natural succession of forest stands and pioneers'' wood species (Oravec & Slamka 2014). The experimental areas in terms of their wood species composition corresponded to the result of Šebeň (2008). The resulting product of the evaluated production process are fuel wood chips. These are currently the preferred form of biomass in terms of size and transport options (Manzone 2015). The energy intensity of the production was evaluated on the basis of fuel consumption using the technology chain saw – forwarder – chipper.

In spite of the attempt to replace gradually risk moto-manual felling of trees by machines (Moravčík et al. 2009), it is routine technology of the wood production combined with other mechanization means still used (Borz & Ciobanu 2013). We have found that the average weight of the wood is an important factor that affects the performance and energy intensity of the felling. With the decreasing average weight of the wood in Ľubietová by 17.3% and Očová 29.3%, compared to Liptovská Teplička, the energy intensity of the felling increased by 16.1, respectively 25.3%. Due to its decline, the average hourly performance in Ľubietová also decreased by 14.8% and Očová by 23.6%. In these stands on non-forest land, advantageously localized and well available with respect to the previous land use method (Oravec & Slamka 2014), consideration should be given to utilization of other available and more efficient technologies. The issue of dendromass processing on uncultivated agricultural land is actual also in the surrounding states on different levels. These are, in particular, countries where land ownership change and agricultural restructuralization (e.g. V4 countries) were implemented. Due to the terrain and climatic conditions and the tree structure of the harvested stands, the results can be used as follows:

- location Liptovská Teplička – mountain regions of Bohemia and southern Poland with a spruce prevalence,

Table 12. Performance, fuel consumption and energy intensity of chipping at assessed sites.

Parameter	Unit	Liptovská Teplička	Ľubietová	Očová
Energy value of the harvested stand biomass	GJ	1 623.8	1 435.4	1 189.5
Energy value of the fuel chips	GJ	1 804.9	1 613.7	1 332.8
Energy consumption in wood felling	MJ	6 998.6	8 139.9	7 348.7
Share of felling energy consumption in energy value of harvested stand	%	0.43	0.56	0.61
Share of felling energy consumption in energy value of chips	%	0.39	0.5	0.55
Energy consumption in wood biomass skidding calculated for the equal transfers distance	MJ	9 574.8 (7 183.7)	9 976.2 (7 517.4)	9 472.3 (7 043.9)
Share of skidding energy in energy value of harvested stand biomass	%	0.59 (0.44)	0.70 (0.52)	0.80 (0.59)
Share of skidding energy in energy value of chips	%	0.53 (0.40)	0.62 (0.47)	0.71 (0.53)
Energy consumption in wood biomass chipping calculated for equal machine transfers distances	MJ	7 013.3 (4 755.0)	7 631.3 (5 373.3)	8 077.6 (5 849.0)
Share of chipping energy consumption in energy value of harvested stand biomass	%	0.43 (0.29)	0.53 (0.37)	0.68 (0.49)
Share of chipping energy consumption in energy value of the chips	%	0.39 (0.26)	0.47 (0.33)	0.61 (0.44)
Total energy consumption	MJ	23 586.7 (18 937.3)	25 747.4 (21 030.6)	24 898.6 (20 241.6)
Share of total energy consumption in energy value of harvested stand biomass	%	1.45 (1.16)	1.79 (1.45)	2 009 (1.69)
Share of total energy consumption in energy value of the chips	%	1.31 (1.05)	1.59 (1.30)	1.87 (1.52)

Note: The figures in brackets indicate energy consumption and their shares in the case of no calculation of energy consumption for transfers.

- locality Ľubietová – mountain regions of Bohemia, Poland and northern Hungary, with mixed hardwood and softwood stands,
- locality Očová – the territory of Hungary and South-East Bohemia with mixed areas of soft and hard broadleafs.

Wood was skidded by JD 810 D forwarder with a load of 9 t and a reach of 8.7 m. Although these machines are designed for the export of logs, in practice they are used for the export of logging residues and energy wood in spite of the insufficiently utilized capacity (Hakkila 2004; Slotta & Spevár 2010; Klvač 2011). The JD 810 D belongs to the class of small forwarders and the producer recommends it to be used especially for shorter skidding distances, but the effect of their utilization is influenced by several factors (Macrì et al. 2016). Since the production of energy wood was only the added value of the intention and the main reason for the logging was the need for the restoration of the original pastures, the whole trees were harvested. This method is increasingly being used on forest land due to the increase in demand for wood chips, however there are fears of excessive loss and withdrawal of nutrients (Hytönen & Moilanen 2014). The results of particular time-demanding work operations of the skidding by the forwarder in these natural-production conditions are comparable with the results of Dvorak (2000), Slamka (2009) and Slamka & Radocha (2010) which evaluated the harvesting residues of forest stands. In the case of freely scattered and thin wood mass, the load structure is a time-consuming operation that can affect the performance of the machine and hence the energy intensity of the whole process. However, the opposite effect may also occur. The dependence presented in Figure 5 is not of a linear path, and over the 20-minute limit for the load there was rising trend for the performance in comparison with so far decreasing performance. This situation arises in cases where, at the expense of the time of loading, a better utilization of the loading area and load-bearing capacity of the technology is used. Another influencing factor of the skidding is the thickness structure of the extracted biomass. The impact of the skidding distance on energy intensity was insignificant, due to a small share of transfers between stands and biomass stocks. The share of driving times in Liptovská Teplička on the networking time was 18.1% at the skidding distance of 370 m and in Očová 15.0% at the skidding distance of 160 m.

Concentrated mass was in heaps stored and dried 95 to 128 days at particular locations. This is the split technological process in which the continuity and interlink of the chips production operations interrupted for a certain period in order to reduce the moisture content of the wood by its natural drying in the stand either in the heaps or at the place of removal (Simanov 1995). The moisture content of a tree depends on the type of wood species, the part of the tree and the seasons, the highest being in the spring and the lowest one at the end of the vegetation in the winter period (Dzurenda & Banski 2016). Together with the dimensions, it is one of the most important factors affecting the efficiency of the energy conversion of the chips (Pari et al. 2013). Another important factor is the degree of their biodegradation, while all factors influence to a large extent the storage method (Pettersson & Nordfjeld 2007; Oravec et al. 2012). From the point of view of the inclination to microbial degradation, especially relatively young plant material derived from fast-growing wood species is particularly demanding (Jirjis 2005).

The natural dendromass drying method, which was also used in the tests performed, is in terms of increasing the energy efficiency of Röser et al. (2011) sufficiently effective. Although Brand et al. (2011) as well as Afzal et al. (2010) point to the need to select a suitable annual period for mining and subsequent storage, Filbakk et al. (2011) have also achieved satisfactory results in the wetlands of Norway, where most of the small heating plants are designed to burn wood chips with a moisture content of 35%. In the Mediterranean climate of Italy, the moisture content of the poplars for energy purposes was reduced from 59% below 30% after 100 days of natural drying, and the analyzes confirmed that air temperature is the main driving force (Pari et al. 2013). Simanov (1995) states that the time required to reduce the relative humidity is three or more months. On the other hand, if the storage time of dendromass is too long before chipping, it may have a negative impact on the quality of the chips, as Pochi et al. (2015) discovered for the poplars. Drying in the combustion process is according to Gebreegziabhera et al. (2013) a costly process whose economy affects the dimensions of the produced wood chips. From the point of view of the final quality, the biggest demands on the producers are given by the small heat plant operators, due to the more demanding provision of efficient operation and minimization of maintenance costs (Röser et al. 2011).

In terms of the energy intensity of wood chips production, most of the studies published as input energy refer to the energy value of diesel directly used in their production and transport. According to the results of Timmons & Mejía (2010), the dependence on it is not extreme and the share of input energy does not exceed 2% of the total potential energy of wood chips. The share of input power to 5% was published by Börjesson in 1996. Using the same comparison criterion, i.e. fuel consumption, the input energy needed to produce wood chips from experimental areas did not exceed 2% of their energy value. We have found that with decreasing weight and thickness of wood species, the energy and time demand of work operations is increasing. An important influence factor is also the duration of the mechanisms transfers between the workplaces. In order to achieve the energy efficiency of the logging and production activities it is necessary to optimize the choice of workplaces with an emphasis on works concentration.

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Forest biodiversity and production potential of post-mining landscape: opting for afforestation or leaving it to spontaneous development?

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Abstract

Land reclamation of post-mining sites strongly influences not only diversity and biomass of frequently studied ground vegetation, but also diversity of forest ecosystem. In most cases, spoil heaps are afforested after coal mining, but some reclaimed sites are left to spontaneous development, such as our study locality – surroundings of the Sokolov town, Czech Republic. Structure, species diversity and production potential were studied on three heap sites, artificially afforested by pedunculate oak (*Quercus robur* L.), black alder (*Alnus glutinosa* [L.] Gaertn) and silver birch (*Betula pendula* Roth) stands, and compared with three permanent research plots (PRP) left to natural succession processes with prevailing European aspen (*Populus tremula* L.), goat willow (*Salix caprea* L.) and also with silver birch. The timber production increased from the willow stand (28 m^3 ha^{-1}) to birch ones (97 m^3 ha^{-1}, all 45 years old). The mean stand volumes were significantly higher on afforested PRPs (74 m^3 ha^{-1}) than on succession PRPs (51 m^3 ha^{-1}), just as tree diameters. However, in terms of production quality, occurrence of breaks was significantly higher on afforested PRPs (15%) compared to succession PRPs (7%), while the opposite situation was observed in the stem quality. Horizontal structure of trees was regular on afforested PRPs, while spatial pattern on succession PRPs was aggregated. The highest differences in favor of succession PRPs was found in species richness and total stand diversity. These results imply a need for combined approaches in post-mining landscape management to support economic benefit and especially ecological value.

Key words: natural succession; forestry reclamation; ecological value; Antonín-Sokolov spoil heap; Czech Republic

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1. Introduction

The environment is being increasingly influenced by human activity that has, so far, significantly transformed more than a half of the Earth's surface (WWF 2016). On the entire planet Earth, forests, pastures, wetlands and other habitats are being transformed into an agricultural and urbanized landscape. The resulting loss of habitats is a serious driving force leading to a significant reduction in biodiversity (Tittensor et al. 2014; Lanz et al. 2018). Soil conversion also affects watercourses and the biogeochemical cycle of carbon, nitrogen and phosphorus and other important elements (Erisman et al. 2013). While individual cases of surface change occur locally, combined results have implications for Earth processes on a global scale (Brandi 2015).

The main reason for the change in landscape utilization in previous centuries was agricultural management (Ellis & Ramankutty 2008; Feurdean et al. 2017; Ustaoglu & Williams 2017). One of increasingly discussed changes is the transformation of the landscape by mining minerals (Hildon 2002; Hendrichová & Kabrna 2016). Mining activities influence vast areas, for example in Germany, brown-coal mining affected approximately 1550 km^2 (Katzur & Haubold-Rosar 1996); in the Czech Republic, approximately 400 – 420 km^2 of land was transformed (Kupka & Dimitrovský 2011).

In the Czech Republic, the area around the town of Sokolov represent such a large devastated land. In this area, there are about 9,250 hectares of land on which mining activities have already ended, or are still under way or are planned in the future (Kubát 2008). The total area of the Sokolov lignite basin is 219 km^2 (Sklenička & Charvátová 2003). The lives of people in the landscape, degraded in space and time by surface coal mining, are inextricably linked to the existence of greenery, water and air (Šťýs 2001; Kubát 2008; Kupka & Dimitrovský 2011). Recovery of these natural phenomena is a very complex

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**Corresponding author. Zdeněk Vacek, e-mail: vacekz@fld.czu.cz* and costly issue (Simon et al. 2005). Changes in the landscape structure caused by surface coal mining are crucial; mining is one of humanity's historical activities that create irreversible changes in the landscape (Slonecker & Benger 2001; Hendrichová & Kabrna 2016).

The long-term goal of restoration of the territory devastated by surface coal mining should be gradual creation of a mosaic-like landscape, which would meet various requirements, such as: production (forestry and agricultural reclamation), social (tourism) and non-productive, i.e. aesthetic, soil-protective and other requirements (Buček & Lacina 2001; Hendrichová & Kabrna 2016). Among the most important elements of a harmonious cultural landscape are forest ecosystems, representing potential climax communities with specific biodiversity in the Central European landscape (Prach 1995).

The forestry reclamation in the conditions of anthropogenically generated relief by mining in the Antonín forestry arboretum is to be considered, on the one hand, as a "controlled succession", where the tree species were planted as the key species of target forest ecosystems. On the other hand, a part of the arboretum area was left to spontaneous succession (Dimitrovský et al. 2007, 2010). The distinguishing features of the ligneous components of ecosystems lie in the way they affect the physical space in which other species live, and their direct effects may last longer than the life of an organism (Hastings et al. 2007). Organisms that predominantly direct courses of artificial ecosystem life are entering similar stages of ecological succession (Prach et al. 2016). The reclaimed soil and nitrogen-poor substrates in temperate zones are covered by forest areas in a relatively short time if a seed bank of pioneer trees is available (Rebele & Lehmann 2016).

Forestry reclamation should not only be aimed at arbitrary planting the land with any trees, as used to be the case in the past (Štýs 2001; Knoche 2005). It is desirable to create sustainable and ecologically stable forest ecosystems, especially with the use of suitable, target autochthonous or introduced tree species (Vacek et al. 2009; Kupka & Dimitrovský 2011). The use of native plant species with mycorrhiza is an excellent ecological engineering which strives to initiate and accelerate the re-colonization and stabilization of soils and raw materials stored in the landscape (Graf & Frei 2013; Sýkorová et al. 2016). In general, site-suitable tree species can be considered as physical ecosystem engineers because they favorably modify their habitat and stand environment (Paz-Kagan et al. 2016; Prausová et al. 2017), especially by their beneficial effects on the soil environment and microclimate, including air cleanliness (Sádlo & Tichý 2002). They contribute to overall restoration or regeneration of severely degraded, damaged or completely new habitats (Prach et al. 2016).

The aim of this paper, representing the first results of the Antonín spoil heap afforestation, was to evaluate biodiversity and production (quantity and quality) of the forest ecosystem after 45 years of post-mining landscape. Two types of stands were compared, namely stands established by a managed succession – by afforestation with autochthonous deciduous trees compared – with spontaneous succession by trees with pioneering growth strategy. The secondary aim was to determine differences in structure and production among stands with the different dominant deciduous tree species.

2. Material and methods

2.1. Study area

The study was conducted in six forest stands in the Antonín-Sokolov Forest Arboretum in post-mining landscape of the Sokolov area, in the west part of the Czech Republic (Table 1, Fig. 1). According to Czech Hydrometeorological Institute Sokolov station (4 km SW from town Sokolov, 402 m a. s. l.), the average annual temperature in study area is 7.3 °C. The highest altitude of the Antonín Arboretum is 444 m a. s. l., the elevation to the surrounding terrain is 48 m (Dimitrovský et al. 2007, 2010). Long-term annual precipitation ranges from 327 to 658 mm, the average sum in the Sokolov station is $611\ \mathrm{mm\ y^{-1}}$. The most precipitation falls in July (78 mm), and the least in March (34 mm). The growing season ranges between 220 – 227 days. The study territory is characterized by warm dry summers and cool dry winters with a narrow annual temperature range (Cfb) according to Köppen climate classification (Köppen 1936).

The soils in Forest Arboretum are currently in the initial stages of development (Dimitrovský et al. 2016). Initial dynamics of ground vegetation shows the trend towards potential association of *Querceto-Fagetum acidophilum* and *Querceto-Fagetum lapidosum acidophilum* forest site type according to Viewegh et al. (2003), despite a significant proportion of ruderal species in the first period of spontaneous succession. In waterlogged areas, the vegetation development corresponds to the association *Querceto-Abietum variohumidum acidophilum* and *Fraxineto-Alnetum alluviale* (Glos 2016). Forest site type

Table 1. Summary of basic site and stand characteristics of permanent research plots 1 – 6.

PRP	Forest origin	Species[1]	Altitude [m]	Exposure	Slope [°]	Herbal cover [%]	Forest type	GPS coordinates
1A	Afforestation	QR, BP	410	SW	7	6–25	Acidic Oak-Beech	50°9'52"N 12°37'16"E
2A	Afforestation	AG, FE	415	S	6	51–75	Acidic Oak-Beech	50°9'47"N 12°37'22"E
3A	Afforestation	BP	425	S	7	51–75	Acidic Oak-Beech	50°9'51"N 12°37'30"E
4S	Succession	BP, SC, AG	420	S	1	76–100	Acidic Oak-Beech	50°9'49"N 12°37'25"E
5S	Succession	SC, AG, FE	415	S	6	76–100	Acidic Oak-Beech	50°9'48"N 12°37'24"E
6S	Succession	PT, BP, AG, SC, TC	420	S	4	76–100	Acidic Oak-Beech	50°9'50"N 12°37'30"E

Notes: [1] QR – *Quercus robur*, BP – *Betula pendula*, AG – *Alnus glutinosa*, FE – *Fraxinus excelsior*, SC – *Salix caprea*, PT – *Populus tremula*, TC – *Tilia cordata.*

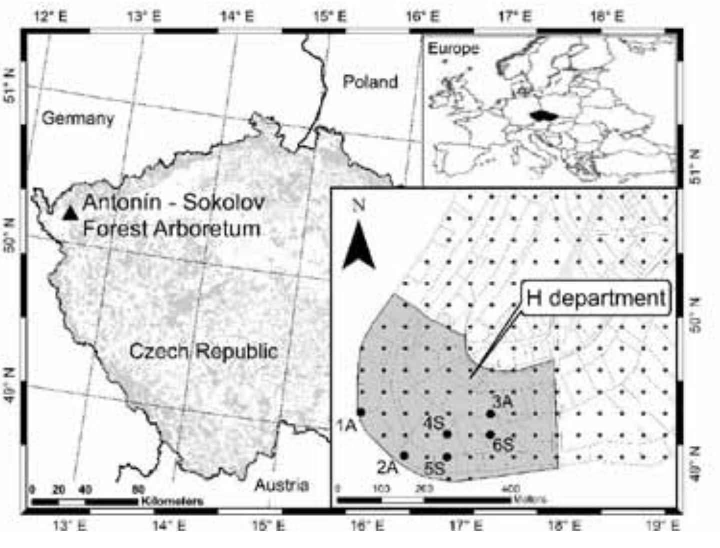

Fig. 1. Location of Antonín-Sokolov Forest Arboretum with plot network and study permanent research plots (1A – 3A, 4S – 6S) falling within H department highlighted by gray color.

of permanent research plots is in the forest management plan described like Acidic Oak-Beech.

Historically, the Antonín-Sokolov coal mine was in operation between 1881 and 1965 (until 1945 the mine was named Luipold), first as a deep, later as a surface coal mine. In the last 20 years (1945–1965) 22.5 million t of coal and 10.8 million m^3 of overburden materials were mined (Jiskra 1997). After its closure in 1965, the coal mine was gradually filled up by overburden material from the coal mine Medard and by ash from a nearby power plant, so the surface of the spoil heap is structurally and texturally petrographically unordered. Most of the area consists of mild slopes interrupted by platforms providing anti-erosion measures. The dewatering of the spoil heap surface is made by open, unpaved ditches in the north to northwest direction. In some places, several smaller water areas and wetlands have emerged, which are currently in decline (Dimitrovský 2001). The study Antonín-Sokolov Forest Arboretum was established in 1969–1974 on the Antonín coal spoil heap (dump) close to the town of Sokolov. Technical operations, i.e. transporting and spreading the topsoil, were completed in 1971–1972, followed by forest reclamation. A wide assortment of 220 species, ecotypes and phenotypes of trees and shrubs and over than 30 introduced tree species were gradually planted on the study area of 165 ha, where a part of spoil heap was left to self-development to spontaneous succession. Resulting forest stands of Arboretum were left without silviculture intervention, and thinning was directed focused only to sublevel (Dimitrovský et al. 2007, 2010).

2.2. Data collection

The FieldMap technology (IFER-Monitoring and Mapping Solutions Ltd.) was used to establish six permanent research plots (PRPs) of 10×15 m in size in 2017. PRPs were randomly (RNG in MS excel) chosen from a plot network of 50×50 m in measured department H (consisting of 55 PRPs), each representing different deciduous tree species (Table 1, Fig. 1). PRPs were network-based in the direction perpendicular to the slope or in the north-south direction on a plane terrain situated in one forest stand. Study three PRPs were established by managed afforestation (PRP 1A–3A) and three PRPs were left to spontaneous succession (PRP 4S–6S). Using the FieldMap system, the position and crown projections at a minimum of four directions perpendicular to each other were measured in the tree layer with diameter at breast height (DBH) > 4 cm. In the tree layer, DBH was measured with a metal calliper (1 mm accuracy) and the total height and height to crown base with a Vertex laser hypsometer (0.1 m accuracy). The methodology of tree measurement was based on the National Forest Inventory (ÚHÚL 2003). The IUFRO tree classification and the Schädelin tree classification (Schädelin 1931) was used for evaluation of coenotic position (dominant, intermediate, suppressed tree), vitality (lush growth, average, dying), stem quality (ductile straight, slightly curved, poor-quality curved stem) and crown quality (good large symmetric, average, defective small asymmetric crown). Tree damage was evaluated using the modified methodology of the Institute of Forest Ecosystem Research, Ltd. (IFER) (Černý et al. 2009). The following damage was classified: game barking (yes, no), mechanical damage of stem (yes, no) and stem breaks caused by abiotic factors (no damage; top crown break – in the top third of the crown; crown break – in the other two thirds of the crown; stem break – below the live crown). Except the tree layer, natural regeneration (density, species, height) and herb cover (%) were inventoried in accordance with the Forest Management Institute practice (ÚHÚL 2003).

2.3. Data analysis

Growth parameters, production, biodiversity, horizontal and vertical structure were evaluated for all individuals in the tree layer on the PRPs. Tree volume was estimated by using volume equations published by Petráš & Pajtík (1991). Stand density index (SDI) and crown closure (CC) were calculated by Reineke (1933), respectively Crookston & Stage (1999). Height curves were constructed using Näslund height–diameter function (Näslund 1936) in R software (© R Core Team).

To evaluate various aspects of biodiversity, the following diversity indices were computed by Sibyla 10 software (© Fabrika & Pretzsch): species heterogeneity index (Shannon 1948), species evenness index (Pielou 1975), species richness index (Margalef 1958), Arten-profile index (Pretzsch 2006), index of diameter and height differentiation (Füldner 1995), and total stand diversity index (Jaehne & Dohrenbusch 1997). In the Table 2 are described the criteria of structure, species and complex diversity indices.

To evaluate the spatial pattern of the stands aggregation index (Clark & Evans 1954), index of non-randomness (Mountford 1961) and *L*-function (Ripley 1981) were calculated. The PointPro 2 program (© Zahradnik & Pus) was used to compute the characteristics that describe the horizontal distribution of individuals across a plot. The test of significance of deviations from the values expected for the random point pattern was performed by means of Monte Carlo simulations. The mean values were estimated as arithmetic means computed for 999 randomly generated point structures.

Statistical analyses were processed in the Statistica 12 software (© StatSoft, Tulsa). Data were log-transformed to acquire normal distribution (tested by Shapiro-Wilk test). Differences in production parameters between the types of forest origin were separately tested by one-way analysis of variance (ANOVA). A principal component analysis (PCA) was carried out in CANOCO 5 software (© Leps & Smilauer) to assess the relation among the stand characteristics, biodiversity and type of forest origin. Data were centred and standardized before the analysis. The results from PCA were visualized in the form of an ordination diagram. Tree damage and production quality by type of forest origin was statistically evaluated using the method of multiple comparison of *P* parameters of binomial distribution (Anděl 1998). Variances are shown by standard deviation (SD).

3. Results

3.1. Growth parameters, stand production and quality

The density ranged between 933 – 3267 trees ha^{-1}, both in spontaneous-succession stands, and the stand density index was 0.89 – 0.99 (Table 3). Tree density on afforested plots was relatively balanced (1733 – 2600 trees ha^{-1}). The total mean stand volume on succession plots was 51 m^3 ha^{-1} (± 25 SD), and 76 m^3 ha^{-1} (± 20 SD) on afforested plots. The highest stand volume on succession plots (78 m^3 ha^{-1}) was on PRP 6S with dominant European aspen (*Populus tremula* L.; 61.5%) and the lowest (28 m^3 ha^{-1}) on PRP 5S with prevailing goat willow (*Salix caprea* L.; 96.4%). The highest stand volume on afforested plots (97 m^3 ha^{-1}) was found on PRP 3A with 100% silver birch (*Betula pendula* Roth) composition and the lowest (57 m^3 ha^{-1}) on PRP 2A with prevailing black alder (*Alnus glutinosa* [L.] Gaertn; 60.3%). On PRP 1A stand was formed mainly by pedunculate oak (*Quercus robur* L.; 71.6%) and on PRP 4S silver birch was dominant tree species (91.5%). Among other admixed tree species occurring on PRPs there was European ash (*Fraxinus excelsior* L.) and small-leaved lime (*Tilia cordata* Mill.).

Mean annual increment of stands currently fluctuated in the range of 0.62 (PRP 5S) – 2.13 (PRP 3A) m^3 ha^{-1} y^{-1}. The total stand basal area ranged between 10.4 and 19.7 m^2 ha^{-1} on succession plots and 16.2 – 22.3 m^2 ha^{-1} on afforested plots (Table 3). Crown closure was in the range of 0.25 – 0.66 and showed higher variability on succession plots, such as in other growth parameters. A comparison of the growth parameters on afforested PRPs and succession PRPs showed that the mean DBH was significantly higher on afforested plots (9.9 cm) than on succession PRPs (8.1 cm; $P < 0.05$), such as tree volume (A – 0.034 m^3, S – 0.027 m^3; $P < 0.05$), while the mean height (A – 10.2 m, S – 9.5 m) was similar ($P > 0.05$).

The diameter distribution clearly shows another difference between the particular types of origin (Fig. 2). In the succession stands the mean number of trees was relatively balanced in the first three small-diameter classes where on PRP 2A the highest number of trees was in the second diameter class (8 – 12 cm). Strong left-sided shape of diameter classes with a typical selection structure and the highest density of trees in the first diameter of 4 – 8 cm was typical of succession plots. On these plots, we observed diameter classes of range

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

Criterion	Quantifiers	Label	Reference	Evaluation
Species diversity	Heterogeneity	H' (Shi)	Shannon (1948)	minimum $H' = 0$, higher H' = higher values
	Evenness	E (Pii)	Pielou (1975)	range 0 – 1; minimum $E = 0$, maximum $E = 1$
	Richness	D (Mai)	Margalef (1958)	minimum $D = 0$, higher D = higher values
Horizontal structure	Aggregation index	R (C&Ei)	Clark & Evans (1954)	mean value $R = 1$; aggregation $R < 1$; regularity $R > 1$
	Index of non-randomness	α (Pi&Mi)	Mountford (1961)	mean value $\alpha = 1$; aggregation $\alpha > 1$; regularity $\alpha < 1$
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 diff.	TM_d (Fi)	Füldner (1995)	range 0 – 1; low $TM_d < 0.3$; very high differentiation $TM_d > 0.7$
	Height diff.	TM_h (Fi)		
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. Basic stand characteristics of permanent research plots 1 – 6.

PRP	t [y]	dbh [cm]	h [m]	f	v [m^3]	N [trees ha^{-1}]	G [m^2 ha^{-1}]	V [m^3 ha^{-1}]	HDR	MAI [m^3 ha^{-1} y^{-1}]	CC	SDI
1A	45	10.5	7.90	0.414	0.028	2600	22.3	74	75.2	1.64	0.66	0.96
2A	45	10.9	9.30	0.382	0.033	1733	16.2	57	85.3	1.27	0.44	0.98
3A	45	10.8	14.46	0.377	0.050	1933	17.7	97	133.9	2.13	0.48	0.96
4S	45	9.9	11.27	0.311	0.027	1733	13.3	47	113.8	1.04	0.37	0.95
5S	45	12.1	8.54	0.310	0.030	933	10.4	28	70.6	0.62	0.25	0.89
6S	45	8.8	8.95	0.441	0.024	3267	19.7	78	101.7	1.73	0.57	0.99

Notes: t – average stand age, dbh – mean quadratic breast height diameter, h – mean height, f – form factor, v – mean tree volume, N – number of trees, G – basal area, V – stand volume, HDR – height to diameter ratio, MAI – mean annual increment, CC – canopy closure, SDI – stand density index.

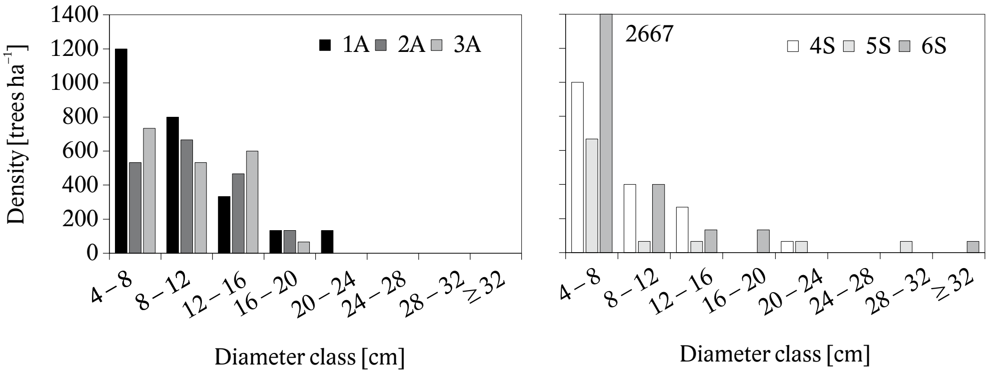

Fig. 2. Histogram of the diameter classes of the tree layer of afforested (left) and spontaneous-succession (right) stands on permanent research plots 1 – 6.

28 – 36 cm, while on afforested plots no trees exceeded DBH ≥ 24 cm. On the succession PRPs the aspen tree reached the greatest diameter (34.1 cm), followed by a willow tree (28.3 m). Contrary alder on afforested PRP reached maximum DBH of only 16.2 cm at the same age of 45 year. Maximum DBH of oak and birch were similar (22.1 cm, resp. 21.1 cm).

The tallest on the afforested PRPs was a birch (21.1 m), followed by an ash tree (15.2 m). Similarly, the maximum height on succession PRPs for aspen was 22.3 m, and 16.1 m for birch. The height of the crown base of trees varied considerably, especially on succession PRPs. From aspect of relation of diameter at breast height to tree height, considerable stand differentiation with regard to stand origin and prevailing tree species was observed on PRPs (Fig. 3). The highest coefficient of determination (R^2) was found on the afforested birch PRP 3A, while the highest height variability was on the succession poplar and willow PRP 6S, respectively 5S. HDR decreases with DBH while a more pronounced decrease, with the higher variability in afforested trees, was observed in the thinnest trees when the variance of values was maximum.

In terms of production quality, occurrence of all the types of breaks (top, crown, stem) was significantly ($P < 0.05$) higher on afforested PRPs (15%) compared to succession PRPs (7%). The largest break damage was found in afforested PRP 2A with dominant alder (22%) compared to the smallest occurrence of breaks on succession PRP 4S with birch (4%). Tree vitality and crown quality did not show significant differences ($P > 0.05$). The average tree vitality on the afforested PRPs reached

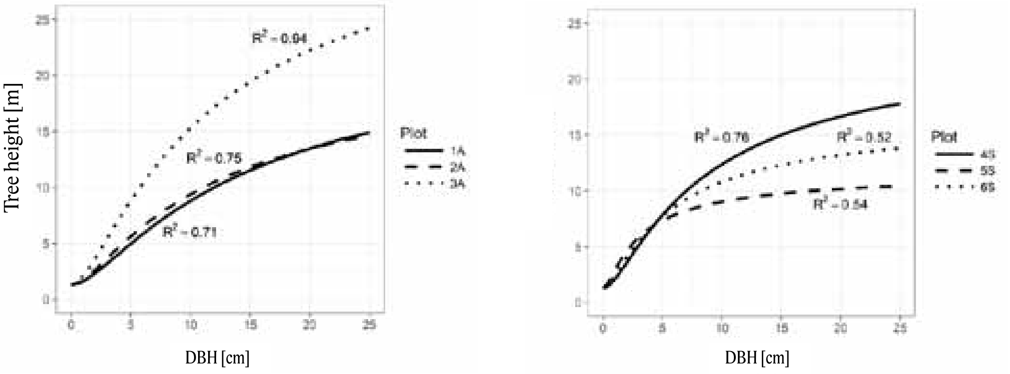

Fig. 3. The relationship between DBH and tree height of the tree layer of afforested (left; parameter *a* 0.98 – 1.57, *b* 0.17 – 0.22) and spontaneous-succession (right; *a* 0.64 – 0.95, *b* 0.21 – 0.29) stands on permanent research plots 1 – 6 with coefficient of determination (R^2).

64%, respectively the average crown quality was 50%, similarly such as on the succession PRPs (values 61% and 44%). Conversely, stem quality was significantly ($P < 0.05$) higher on afforested PRPs (the best quality with straight stem – 28%, the worst quality with large curved stem – 22%) compared to succession PRPs (the best quality – 21%, the worst quality – 40%).

3.2. Biodiversity and structure of tree layer

Species richness ranged from low diversity ($D = 0.000 – 0.134$) on afforested PRPs to medium diversity ($D = 0.268 – 0.371$) on succession PRPs (Table 4). Similarly, species heterogeneity was at a low level ($H' = 0.000 – 0.265$) on afforested PRPs compared to a high level on succession PRP 6S ($H' = 0.532$). Species evenness ranged from none to very high ($E = 0.000 – 0.884$) diversity, again reaching its maximum on RPP 6S. The vertical structure according to A index was moderately to strongly-varied ($A = 0.447 – 0.744$). Diameter differentiation was low to medium ($TM_d = 0.112 – 0.315$), but height differentiation was only at a low level ($TM_h = 0.108 – 0.261$). A generally higher structural diversity was observed in afforested stands. Total stand diversity B suggested a prevailing even structure on PRPs ($B = 4.689 – 5.704$) except for a more diverse structure on PRP 6S ($B = 8.183$).

The horizontal structure was regular on afforested PRPs, while the spatial pattern on succession PRPs was significantly ($P < 0.05$) aggregated (Table 4, Fig. 4). The exception was PRP 2A and 6S, where, according to the R and α index, the distribution of tree layer individuals was random. On afforested birch PRPs (3A) there was a mostly regular distribution of tree layer individuals, while the most aggregated spatial pattern was found on a willow succession plot (5S) with the lowest tree density. According to the tree distance as follows from Ripley's L-function, on PRP 1A and 3A the spatial pattern was aggregated at a distance shorter than 1.5 m. On the other hand, the regular spatial pattern of the tree layer occurred at 1 – 2 m distances on PRP 4S and more than 2.5 m on PRP 5S. On PRP 2A and 6S, L-function also confirmed a random horizontal structure (Fig. 4).

Table 4. Indices of the tree layer biodiversity on permanent research plots 1 – 6.

PRP	D (Mai)	H' (Si)	E (Pii)	R (C&Ei)*	α (P&Mi)*	A (Pri)	TM_d (Fi)	TM_h (Fi)	B (J&Di)
1A	0.127	0.227	0.754	1.200	0.804^R	0.649	0.304	0.256	5.473
2A	0.134	0.265	0.880	1.112	1.040	0.631	0.227	0.171	4.854
3A	0.000	0.000	0.000	1.469^R	0.712^R	0.744	0.315	0.261	4.698
4S	0.268	0.250	0.524	0.774^A	1.300	0.560	0.219	0.196	5.564
5S	0.292	0.224	0.469	0.606^A	4.335^A	0.447	0.112	0.108	5.704
6S	0.371	0.532	0.884	1.071	1.061	0.706	0.253	0.207	8.183

Notes: D – species richness index, H' – species heterogeneity index (entropy), E – species evenness index, α – index of non-randomness, R – aggregation index, A – Arten-profile index, TM_d – diameter differentiation index, TM_h – height differentiation index, B – total diversity index; * statistically significant$^{A, R}$ ($P < 0.05$; A – aggregation, R – regularity).

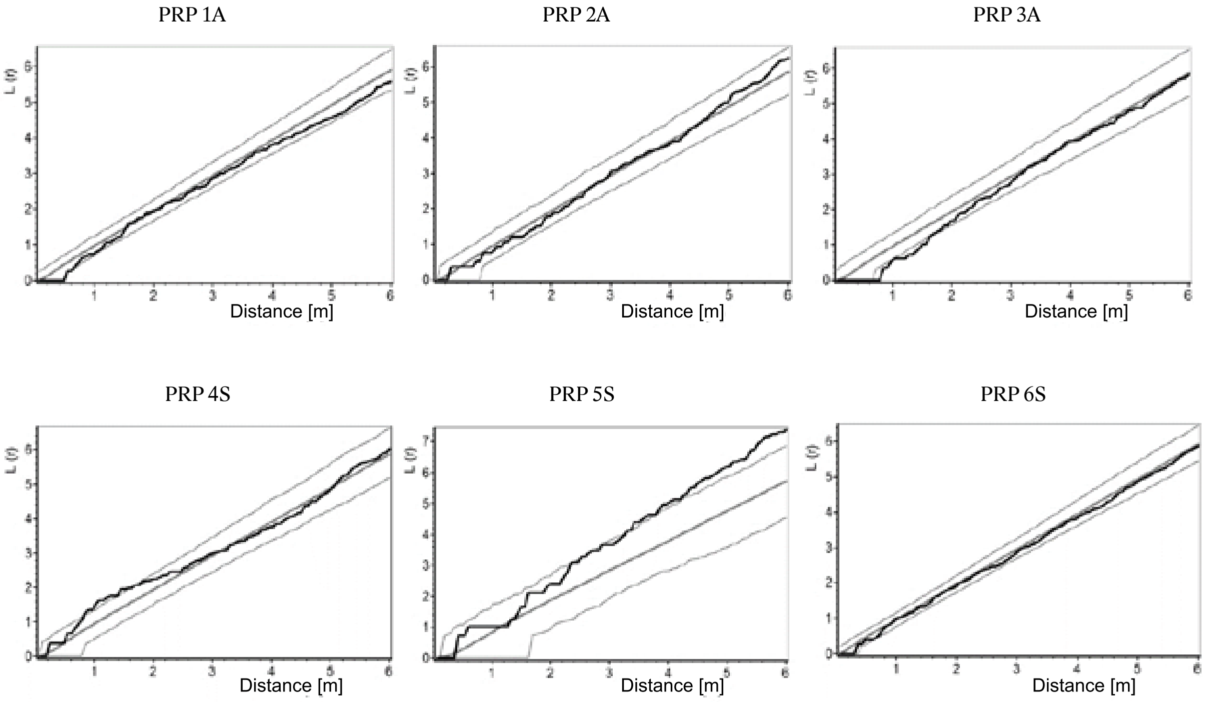

Fig. 4. Horizontal structure of the tree layer on permanent research plots 1 – 6 expressed by L-function; the bold grey line represents the mean course for random spatial distribution of trees and the two thinner central curves represent the 95% interval of reliability; when the bold black line of tree distribution on the plot drops below this interval, it indicates a tendency of trees toward regular distribution; if above this interval, they tend toward aggregation.

3.3. Relationships among stand characteristics, biodiversity and type of forest origin

The results of PCA are depicted by an ordination diagram in Fig. 5. The first ordination axis explains 54.9%, the first two axes 84.6% and first four axes the total of 98.5% of data variability. The x-axis represents the stand volume, Arten-profile index and diameter differentiation. The y-axis represents complex diversity and species evenness and heterogeneity. Canopy closure is positively correlated with the number of trees and stocking, while these parameters are negatively correlated with the mean DBH. All study structural indices representing vertical and horizontal structure, diameter and height differentiation have positive relationship with the stand volume. The species diversity (evenness, richness, heterogeneity) is positively correlated with the total stand diversity, while these parameters are negatively correlated with the height and also with HDR, but its contribution is relatively small.

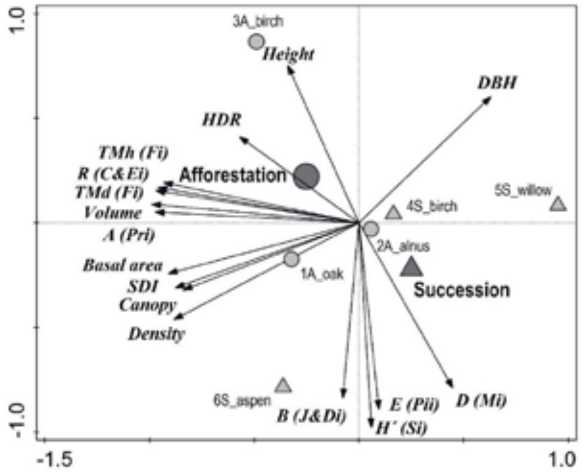

Fig. 5. Ordination diagram showing results of the PCA analysis of relationships between stand characteristics (Volume, Basal area, DBH – diameter at breast height, Height, Canopy – canopy closure, Density – number of trees, HDR – slenderness ratio, SDI – stand density index/stocking), structural diversity (*A* – Arten-profile index, *TMd* – diameter differentiation, *TMh* – diameter differentiation, *R* – aggregation index), species diversity (*E* – evenness, *D* – richness, *H´* – heterogeneity), complex diversity (*B* index) and type of stand origin (● afforestation/planted, ▲ succession/left to self-development); Codes indicate plots with the type of origin and prevailing tree species.

The type of stand origin shows a low effect on mutual relationships among production parameters compared to great differences among diversity indices. The diagram also shows large differences among plots due to predominant tree species. Differences of types of origin are remarkable especially for the spontaneous-succession stand as marks of each record are relatively distant from one another whereas marks for planted stands are close together in the diagram. Plots with different type of origin are different from one another – the succession plots with high species and complex diversity occupy the right down part of the diagram, while the high stand volume and regular spatial pattern were typical for artificially afforested stands.

4. Discussion

In the examined area of Antonín-Sokolov reclamation site the number of trees on average reached 1978 trees ha^{-1} on succession plots with the stand volume of 51 m^3 ha^{-1}, while the density on afforested plots was on average 2089 trees ha^{-1} and the stand volume ranged about 76 m^3 ha^{-1} at age of 45 years. The highest stand volume was measured on the plot afforested by silver birch. Comparison of basic stand characteristics on afforested reclamation sites in Europe is complicated because of the lack of data for particular tree species. Reclamation sites were mostly afforested with Scots pine (*Pinus sylvestris* L.) (Heinsdorf 1996; Katzur & Haubold-Rosar 1996; Knoche 2005; Bacia & Barzdajn 2007; Pietrzykowski 2014; Likus-Cieślik & Pietrzykowski 2017), for example there were 780 trees ha^{-1} in a 66 years old pine forest and the total stand volume was 330 m^3 ha^{-1} (Knoche 2005), but this stand's characteristics are given for different age and tree species. Comparing to studied tree species, the stand volume on succession plots in reclaimed open-cast mining areas in Estonia show a significantly higher value (3 – 5 times) only at the age of 30 years. The stand volume of alder plots was 280 m^3 ha^{-1} and even 340 m^3 ha^{-1} in birch stands (Pensa et al. 2004). The study from reclaimed mining sites (Kuznetsova et al. 2011) also confirmed a high production potential of alder stands compared to other tree species, but in our study the alder stand reached the lowest production from all afforested plots. In Poland, stand productivity of the English oak in the conditions of a reclaimed external dump of Piaseczno sulphur mine ranged between 103 – 176 m^3 ha^{-1} with tree density of 846 trees ha^{-1} at age of 40 years (Pietrzykowski et al. 2015), but in our study at similar age oak volume reached only 74 m^3 ha^{-1} with density of 2400 trees ha^{-1}. Similar stand volume was observed in same country from external spoil bank of the Bełchatów brown coal mine (66 m^3 ha^{-1}) only at the age of 20 years, where black poplar (*Populus nigra* L.) and black locust (*Robinia pseudoacacia* L.) were characterized by the best productivity compared to lowest volume in black alder (Pająk et al. 2004), such as in our study.

Compared with the overall condition of birch stands in the Czech Republic, the birch succession plots near the thermal power plant in Poříčí (near Trutnov, northeast Bohemia) showed significantly higher production quantities and slightly higher production quality, both in forest stands (*Fagetum acidophilum*) and reclaimed spoil heaps

(*Fagetum lapidosum acidophilum*). The stand volume per hectare ranged from 198 – 238 m^3 in 35-year-old stands (Vacek et al. 1987; Vacek 1991). A higher stand volume of 113 – 147 m^3 ha^{-1} was also found on birch and alder (45 years) succession plots created on degraded soils of an air shooting range in eastern Bohemia (Vacek et al. 2009). When compared to similar age groups (47 – 53 years) on former agricultural land in the Orlické hory Mts., the stand volume of birch succession stands ranged from 244 – 309 m^3 ha^{-1}, and in artificially established alder stands it even reached 354 m^3 ha^{-1} (Vacek et al. 2009, 2016). Comparable production was found only at reclaimed Jirásek and Breňany localities in west Bohemia, where ash and birch stands reached 75 – 106 m^3 ha^{-1} (Vacek et al. 2009) but the average age of the stand was 20 years less than in the studied Antonín-Sokolov locality. Ones of the main reasons for the low production of the stand on the studied site is caused, among other reasons, mainly by unfavorable soil conditions and insufficient silvicultural interventions

The diameter distribution shows also different trends: on succession plots, the highest frequency was found in the first diameter class (4 – 8 cm) with a strong decline in the following classes, while approximately balanced numbers of trees in first three diameter classes was observed on afforested plots (Vacek et al. 2009). Quality of production is also related to the origin of forest stands. Stem quality was significantly higher in the artificially afforested stands where the best quality with straight stems reached 28% of stems and the worst quality was found in 22% stems, while on the succession plots was the best quality found in 21% and the worst quality in 40%.

Evaluation of biodiversity and structure of tree layer also show important characteristics of stands. Tree species richness ranged from low diversity (D = 0.00 – 0.13) on afforested PRPs to medium diversity (D = 0.27 – 0.37) on succession PRPs. Similarly, on Estonian spoil heaps, the species diversity was the largest in the succession areas and the smallest in the birch plantation (Pensa et al. 2004). In the Antonín-Sokolov spoil heap, aggregated distribution prevailed on the successive areas, and random and regular distribution in the artificially afforested stands, in the similar way as on former agricultural lands in the Orlické hory Mts. (Vacek et al. 2009). A comparison of the spoil heap and the forest land in Trutnov brought similar results (Vacek 1991). The succession forest stands also showed a larger overall stand diversity than the afforested stands. In the Orlické hory Mts., up to twice the diversity of the succession stands with dominating alder and birch (B = 8.26 – 10.26) was found in comparison with the artificially afforested stands (B = 5.97). This is due to the fact that the growth of these stands is temporally and spatially highly differentiated (Vacek et al. 2018). Trees that colonize postindustrial sites are, thus, natural tools that contribute to mitigating microclimatic stress, improving the quality of the substrate and purifying the air (Prausová et al. 2017). Their existence influences other organisms. Their biological activity (leaf fall and underground and above-ground biomass growth) gradually cultivates habitat and subsequently the environment (Byers et al. 2006). In the first stage of development, however, the seedlings and juveniles of pioneer tree species (*Betula pendula, Populus tremola, Salix caprea* etc.) are very sensitive to any kind of stress, especially summer drought, overheating and frost (Kovář 2004). In unfavorable situations, their mortality is high (Kovář & Herben 2004) but decreases with the growing density of vegetation (Matějíček & Kovář 2015). A favourable effect of the ecological cover of shrubs on the growth of trees in the juvenile stage is widely known (Gómez-Aparicio 2009; Rejzek et al. 2016). The extreme environment thus has a great influence on the biodiversity of the succession stands on immature soils (Prausová et al. 2017).

It is important is to reflect the aim of reclamation by afforestation. Forest stands production plays only a minor role in this case and the timber quantity and quality cannot compete with standard forest stands. Future management of forest stands, growing on these poor spoil heap sites, is another issue to be addressed. One of the possibilities is to improve the stand conditions by fertilizers, which were already tested on reclamation sites, e.g. dolomite fertilization (Bacia & Barzdajn 2007) or brown coal ash (Katzur & Haubold-Rosar 1996). It is also possible to use fertilizers tested on standard forest stands (Podrázský et al. 2003; Ferreiro-Domínguez et al. 2011; Cukor et al. 2017a, b). Successful amelioration requires exploration of soil conditions that identify limiting soil parameters on reclamation sites (Katzur & Haubold-Rosar 1996). Another alternative is to reduce the basal area of pioneer tree species by strong thinning and, subsequently, to underplant them with hardwood trees as *Fagus sylvatica* (L.) or *Quercus* spp. (Knoche 2005). All the discussed forest stands parameters are interesting from the future point of view, because afforestation is still one of the cheapest solution of reclamation (Kubát 2008) assumed to be used further ahead.

5. Conclusion

Afforested stands in Antonín spoil heaps in the Sokolov vicinity show a higher stand volume and quality production compared to forest stands originated by natural succession. However, non-homogenous conditions and small number of the compared plots, due to the inception of this long-term research, must be considered when interpreting the present results. Timber production and economic benefit do not constitute the primary function of afforested reclamations; forest stands have positive effect on the soil and microclimatic conditions and offer other non-market functions, e.g. ecological, social, aesthetical etc. The Antonín-Sokolov Forestry Arboretum is therefore very important as it represents a sole recreational and suburban educational forest in the area, which was strongly affected by coal mining in the surroundings of the Sokolov town. From the scientific point of view, Antonín-Sokolov is a unique place with more than 220 species and cultivars of original and introduced tree species and their growth in specific conditions brings unique results. For the above-mentioned reasons, the spoil heap afforestation and its development will raise a number of new questions and encourage further research in the future.

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ORIGINAL PAPER

Is cable yarding a dangerous occupation? A Survey from the public and private sector

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Abstract

Cable yarding is a physically demanding and dangerous occupation in forest harvesting. Currently, the technology is gaining interest due to its low environmental impacts compared to the ground based technologies. This paper was focused on comparing the subjective opinions regarding occupational safety and work environment with objective findings found in the literature. We used a questionnaire with 33 questions, divided into three main parts: (i) personal traits of the participants; (ii) occupation description; and (iii) the occupational risks identified the participants. The sample consisted of 92 workers who operated cable yarders from both the public and the private sector. Our survey showed that 90% of public and 75% of private sector employees view their work as physically very demanding. Regarding risky behaviour, 50% of public, and 54% of private employees stated they risked only when the circumstances forced them to. However, more than 41% of public and 50% of private employees stated they suffered an occupational accident in the last ten years of working with this technology. Considering the workers worked in unstable climatic conditions, on unstable terrain, and the work environment presents other hazards, such as the loads, sharp tools and equipment, this result was not surprising.

Key words: occupational accident; occupational risks; cable yarding; public and private sector; questionnaire

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1. Introduction

Forest harvesting is, from multiple views, a dangerous occupation (Bentley et al. 2005; Lindroos & Burström 2010) It is considered on of the most dangerous occupations in the world (Lilley et al. 2002; Klun & Medved 2007). In all countries, where comparable statistics are available, forestry has one of the highest frequency of occupational accidents per employee compared to other sectors of the economy (Ozden et al. 2011). Forest harvesting is especially dangerous on steep slopes (Tsioras et al. 2014). Slovakia, with 41% of forest area, is one of the most forested countries in Europe. Production-wise, forest harvesting is complicated in Slovakia (Bugoš & Stanovský 2009). Aside from other factors, such as tree species composition, soil bearing capacity, there is the fact that about 40% of Slovak forests are located in areas with slope steeper than 40% (Ministry of Agriculture and Rural Development of the Slovak Republic, National Forest Centre 2015).

Steep slopes and rugged terrain are conditions, which favour using cable yarding. Difficult conditions reflect in demanding work environment, which negatively affects workers when operating the yarders and requires skilled workers and their effective teamwork (Mologni et al. 2016). Effective teamwork requires good coordination of the team members, good communication, and good relationships within the team. According to West (2012) an effective team should meet the following criteria: task effectiveness (the extent to which the team is successful in achieving its task-related objectives), team member well-being (refers to factors such as the well-being or mental health, growth and development of team members), team viability (the likelihood that a team will continue to work together and function effectively), team innovation (the extent to which the team develops and implements new and improved processes, products and procedures), and inter-team cooperation (the effectiveness of the team in working with other teams in the organization with which it has to work in order to deliver products or services).

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Besides the need of cooperation, cable yarding is demanding physically and requires both static and dynamic muscle power, since it imposes hard labor of intense loads on the musculoskeletal system of forestry workers (Bovenzi et al. 2004; Yovi et al. 2015). Given that cable yarding operations need appropriate planning and dimensioning to respect safe working conditions (Mologni et al. 2016). It is a very difficult work, which can lead to serious accidents, especially on steep slopes (Tsioras et al. 2011). There is a lack of information on the complex analysis of cable yarding from the view of the workers who actually work with the technology.

This paper is focused on the overview of the physical demands, risks, and negative factors affecting workers employed in cable yarding. The research is conceived as a questionnaire survey aimed at the employees of both the large Slovak state forest enterprise (further in text: employees of the public sector; PU), as well as the employees of private contractors who carry out cable yarding (further in text: employees of the private sector; PR). We hypothesize that the number of occupational accidents per employee and the connected standard of occupational safety is higher in case of the PU employees. Public employees work in a large company, with elaborated safety standard and ergonomic risk management system. Smaller private companies that provide services in cable yarding usually do not emphasize occupational safety and health as much as larger companies.

2. Material and methods

Forests of the Slovak Republic, (FSR) works with the most cable yarders in Slovakia. During the year 2015, FSR owned 20 cable yarders on total and employed 80 people in cable yarding. The annual output of the cable yarders owned by the FSR was 100 000 m^3. The total amount of timber yarded in the FSR was higher though, about 400 000 – 500 000 m^3 per year (about 10% of the total annual fellings), the remaining volume of felled timber was yarded by private contractors. Public employees used the following cable yarders: Larix Kombi H, Larix 550, Larix Lamako, Larix 3T, Steyr KSK 16, and Mounty 4000, whereas PR employees used: Mounty 4100, Syncrofalke, KMS 12, Lanor 3, and Vlu 5 cable yarders. On total, 68 PU employees and 24 PR emplyees participated in our study. The personal characteristics of the participants are available in Table 1.

To evaluate the subjective views of the workers on working with cable yarders, we used a questionnaire containing 33 questions on the workers themselves and their work. The questionnaire was divided into three segments: (i) Personal traits: age, weight, experience, occupation; (ii) Work itself: physical demands, performance, work shift duration, communication within the team, usage of personal protective devices; (iii) Risks: individual factors of the work environment, operations, occupational accidents occurrence, injured bodyparts. The questions were multiple choice, the participants were able to select one of the choices. For better clarity, we selected fourteen most important questions for further inspection.

Table 1. Relative distribution of the workers who participated in the survey based on their age, practical experience, and weight.

Category	Class	Public employees [%]	Private employees [%]
Age [years]	≤30	22.4	20.8
	31–40	29.9	50
	41–50	31.3	12.5
	>50	16.4	16.7
Experience* [years]	<1	5.9	0
	1–5	41.2	16.7
	6–10	35.3	37.5
	>10	17.6	45.8
Weight [kg]	≤70	10.6	8.3
	71–90	50	58.4
	>90	39.4	33.3

*Number of years of practice by cable yarders.

We assessed the results of the questionnaire survey through a series of χ^2 tests (Scheer & Sedmák 2007). The tests served for detecting the effects of various variables on the number of occupational accidents occurring during cable yarding. The tests were elaborated independently for PU and PR employees. In the first χ^2 test, we focused on the relationship between the occupation (V_{1PU} or V_{1PR}) and the number of occupational accidents (Y_{PU} or Y_{PR}), in the second test, we tested the duration of the shift (V_{2PU} or V_{2PR}) on number of occupational accidents (Y_{PU} or Y_{PR}), then we tested effect of the quality of communication in the teams (V_{3PU} or V_{3PR}) on Y_{PU} or Y_{PR}. The fourth χ^2 test served to analyse the effect of using personal protective equipment (PPE) (V_{4PU} or V_{4PR}) on Y_{PU} or Y_{PR}. Further analysis was a multiple regression and correlation analysis, through which we observed the relationship between the duration of practical experience of the employees (V_{5PU} or V_{5PR}), the monthly volume of yarded timber (V_{6PU} or V_{6PR}), and the duration of the work shift (V_{7PU} or V_{7PR}) on either Y_{PU} or Y_{PR}. We used MS Excel, and STATISTICA 12.0 software to analyze the data.

3. Results

The overview of employees in particular occupations is depicted in Table 2. From the data, it is visible that in both PU and PR group, most employees had multiple occupations. In case of PU employees, it was 63% and in case of PR employees it was 50% of employees. Rotation of occupations was important mainly to reduce monotony, thus preventing occupational accidents.

We tested the relationship between occupation and occupation accidents. The results of the statistical analysis (χ^2) test showed, both for PU and PR employees, no statistically significant relationship between the occupation (V_{1PU} or V_{1PR}) and the occupational accidents (Y_{PU} or Y_{PR}) (χ^2_{PU} – 4.70; df – 4; p – 0.32 > 0.05; χ^2_{PR} – 2.48; df – 4; p – 0.65 > 0.05).

Table 2. Relative distribution of the workers, who participated in the survey based on their occupation, the operation they perceive as the most dangerous, and the season they perceive as the most dangerous.

Category	Conditions	Public employees [%]	Private employees [%]
Occupation	Yarder operator	19.1	4.2
	Choker setter	4.4	4.2
	Feller	1.5	29.2
	Skidder operator	11.8	12.4
	Combination	63.2	50
Hazards operations	Field preparation	25	20.8
	Mounting/Dismounting	3.6	8.3
	Yarding	37.5	29.2
	Combination	28.5	16.7
	Other	5.4	25
Hazards season	Spring	1.5	0.0
	Summer	4.4	12.5
	Fall	5.9	0.0
	Winter	88.2	87.5

Another important factor, affecting the occurrence of occupational accidents, is the duration of the shift. Our results show that 44% of the PU employees and 42% PR employees worked more than five hours per day, 56% of the PU employees and 50% of the PR employees stated they worked more than eight hours per day. In case of the PR employees, 8% stated that they worked more than 12 per day. The χ^2 test did not show a statistically significant relationship between V_{2PU} and Y_{PU}, or V_{2PR} and Y_{PR} (χ^2_{PU} – 0.45; df – 1; 0.51 > 0.05; χ^2_{PR} – 1.29; df – 2; 0.52 > 0.05). We can therefore state that there is no significant relationship between the length of the shift and the occurrence of an occupational accident.

From the view of the physical demands of working with a cable yarder, 90% of the PU employees and 75% of the PR employees identified the work as physically very demanding. About 10% of PU and 21% of PR employees identified the work as moderately physically demanding, and 4% of the PR employees identified the work as physically non-demanding.

The experience of the employees who suffered an occupational accident, is shown in Fig. 1.

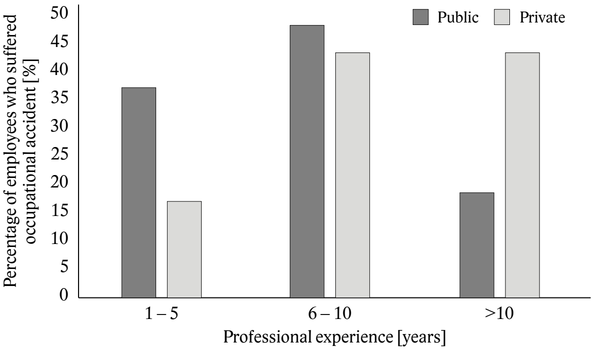

Fig. 1. Relative distribution of the public and private employees who suffered an occupational accident during the last ten years, based on practical experience.

The graph shows that there were some differences between the PU and PR employees regarding the practical experience of workers who suffered occupational accidents. Within the PU employee group, the most accidents occurred to employees with 6 – 10 years experience (46%). As for the PR employees, 42% of accidents occurred to both the class with 6 – 10 years experience and the class with more than 10 years experience (84% on total). The age structure of the employees who stated they suffered an occupational accidents is shown in Fig. 2.

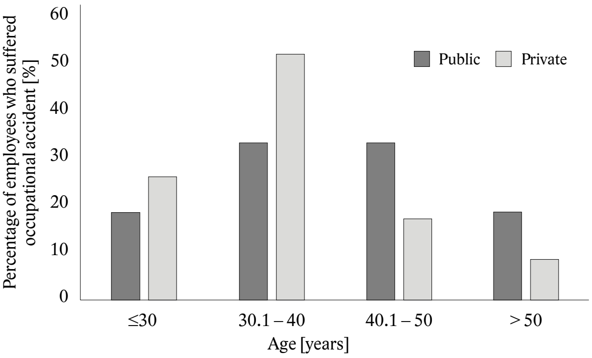

Fig. 2. The age structure of the public and private employees who sufferd an occupational accident in the last ten years.

It shows that for the PU employees, the most accidents happened to employees aged 30.1 – 40 and 40.1 – 50 years (32% each). In case of the PR employees, the most accidents (50%) occurred to employees aged between 30.1 to 40 years.

Suffcient, and appropriate communication within the team decreases the risk of an occupational accident occurring. From Table 3, we can see that the largest share of employees from both groups stated that the communication within the team was good (57% PU and 38% PR employees).

In case of the PU employees, another 25% stated the communication within the team was very good, and another 18% stated it was good with occasional conflicts. Private sector employees saw the state of communication within the team differently – 29% of the PR employees stated that the communication was good with occasional conflicts, 21% stated it was very good, and 13% stated that communication within the team was bad. We statistical analyzed communication within the team and occupational accidents. We tested the relationship between V_{3PU} and Y_{PU}, or V_{3PR} and Y_{PR} through the χ^2 test. In both the PU and the PR employee groups, the relationship did not prove to be statistically signiffcant (χ^2_{PU} – 0.45; df – 1; p – 0.50 > 0.05; χ^2_{PR} – 1.08; df – 2; p – 0.58 > 0.05).

The tendency of the employees towards risky behaviour can be seen in Table 3. In both the PU and PR employee group, the largest share stated they risk only when forced to by the circumstances (50% PU and 54% PR employees). The second most frequent answer was "I risk all the time" (27% PU and 33% PR employees). This fact might be the explanation of some occupational accidents in cable yarding. Only 24% of the PU employees and 13% of the PR employees stated that they do not risk at all during their work.

Using PPE is very important to ensure safe work. More than 94% of the PU employees stated they use prescribed PPE, and about 6% stated, they only use them when necessary. A similar structure was found within the PR employee group. Seventy-eight percent of employees stated that they use the prescribed PPE, and 22% stated they use them only when necessary. We statisticaly tested using of prescribed PPE and number of occupational accidents. To assess the relationship between the V_{4PU} and Y_{PU}, or V_{4PR} and Y_{PR}, we used a χ^2 test. We found no statistically significant relationship between the variables ($\chi^2_{PU} – 1.39$; df – 2;p – 0,50 > 0.05; $\chi^2_{PR} – 3.31$; df – 3; p – 0.35 > 0.05).

Almost every second PU employee (41%) suffered an occupational accident in the last ten years. Similar outcome was found in case of the PR employees, 50% suffered an occupational accidents (Table 4).

The most frequently injured bodypart were lower extremities (50%), upper extremities (27%), head and neck (10%), and spine (10%). The least injured bodypart was torso (3%). Private sector employees reported similar results: 36% were injuries of the lower extremities, 27% were injuries of both upper extremities, and head and neck each. The remaining 9% were injuries of the spine. These injuries are characteristic for working with a cable yarder (Table 4).

Table 5 shows the distribution of occupational accidents according to the operations during which they occurred. The answers of the PU employees show that 57% of accidents occured during felling and delimbing, and 27% occurred during yarding. Operations such as bucking, maintenance, or mounting and dismounting the yarder constituted about 17% of all occupational accidents. Similar structure was found for the PR employees, where 46% of all occupational accidents occurred during felling and delimbing, 36% during yarding, and 18% during bucking, maintenance, or mounting and dismounting the yarder. However, the employees considered yarding to be the most dangerous operation (38% PU and 29% PR employees). Yarding was followed by a groupt that considered multiple operations to be similarly dangerous (29% PU and 17% PR employees).

One quarter of the PU employees, and 21% of the PR employees thought that preparation of the forest stand for yarding was the most dangerous (Table 2). In case of the PR employees, 25% stated that "other" operations were the most dangerous. Regarding the season of yarding, both the PU and the PR employees thought winter was

Table 3. Relative distribution of the workers, who perticipated in the survey, based on their attitude towards risky behaviour, and the perceived quality of communication within the squads.

Category	Status	Public employees [%]	Private employees [%]
Communication within the group	Very good	25	20.8
	Good	57.4	37.5
	Occasional arguments	17.6	29.2
	Bad	0.0	12.5
Risky behaviour	I risk when I am forced to	50	54.2
	I risk all time at work	26.5	33.3
	I do not risk at work	23.5	12.5

Table 4. Number of accidents in the last ten years and the bodyparts the workers injured when the occupational accidents occured.

Category	Status	Public employees [%]	Private employees [%]
Accidents in the last ten years	Yes	41.2	50.0
	No	58.8	50.0
Bodypart injured	Upper extremity	26.7	27.3
	Lower extremity	50.0	36.3
	Head and neck	10.0	27.3
	Spine	10.0	9.1
	Torso	3.3	0.0

Table 5. Relative distribution of the operations during which the occupational accidents occured, the perceived significance of a particular factor of the work environment on the total risk from the work environment.

Category	Status	Public employees [%]	Private employees [%]
Share of particular operation	Felling/Delimbing	56.6	45.5
	Yarding	26.7	36.3
	Bucking	3.3	0.0
	Mounting/Dismounting	6.7	9.1
	Maintenance	6.7	9.1
Factors of the work environment	High and low temperatures	11.8	12.5
	Terrain	44.1	45.9
	Physical exertion	2.9	8.3
	Moving stems	5.9	8.3
	Combination	35.3	25.0

the most dangerous (Table 2). The reason for increased danger of working in winter was the instability of the terrain due to snow, ice, etc. Public sector employees considered fall, summer, and spring (in order). Private sector employees considered only summer to be dangerous besides winter, due to high temperatures.

The most dangerous factor of the work environment was, according to almost half (44%) of the PU employees, the terrain (Table 5), followed by a combination of multiple factors (35% of the PU employees), and microclimatic conditions at the work-place (12% of the PU employees). Employees from the private sector stated, similarly as the PU employees, that the terrain is the most dangerous factor of the work environment (46%), 25% considered a combination of multiple factors as the most dangerous, and 13% stated that microclimatic conditions were the most dangerous. We used a regression and correlation analysis to study the relationship between V_{5PU}, V_{6PU}, V_{7PU}, and Y_{PU}, or V_{5PR}, V_{6PR}, V_{7PR}, and Y_{PR}. Both analysises were inconclusive, no statistically significant relationship was found (R_{PU} – 0.22; p – 0.38; R_{PR} – 0.35; p – 0.49).

4. Discussion

Synwoldt & Gellerstedt (2003) state that the health of workers is at risk and the probability of an occupational accident increases when workload is high in the long term. Gallis (2006) during his study of forestry workers in Greece found that the mean age is about 45 ± 14 years and the mean workshift duration is nine ± two hours, and the workweek lasted six ±one day per week. Lilley et al. (2002) state that workers in forest harvesting work more than nine hours per day on average. These results correspond with our results, the majority of participants stated they work longer than the standard eight hour shift. Gandaseca & Yoshimura (2001) state that 73% of the workers in forest harvesting in Turkey does not wear the prescribed PPE, and the remaining 27% uses protective gloves, boots, glasses, and hearing protectors. On the other hand, Enez et al. (2014) found in his study that 54% of workers in forest harvesting in Turkey uses gloves, 9% uses boots, and 2% uses helmet. To compare, the participants in our study stated they use all prescribed PPE.

Tsioras et al. (2014) states that in Austria 19% of the total amount of occupational accidents occurr during timber extraction from the forest stand to the roadside on average. In timber yarding, 15% of all occupational accidents occurr during yarding itself. Compared to other countries, this share is low, e.g. in Slovinia, Enez et al. (2014) state that 24% of occupational accidents occurr during yarding, in New Zealand it is 22% (Gaskin & Parker 1993), in Sweden it is 20% (Engsås 1995). Most of the injuries that the employees suffered were located on the extremities in our case, though in case of the PR employees, head and neck was a frequent injury location. Our results correspond with what other authors found: Tsioras et al. (2011) – 64% of injuries were located on the extremities, Potočnik et al. (2009) – 66% of injuries were located on the extremities and (KWF 2011) in Germany – 64% of injuries were located on the extremities . In China, Wang et al. (2003) state that the share of injuries located on extremities was 51%, and in Louisiana, Lefort et al. (2003) state a similar 50% share of injuries located on extremities. Enez et al. (20014) in their study state that the most injured bodyparts during forest harvesting were feet and toes (41%), spine (30%), legs (20%), torso (14%), and hands and fingers (11%). Acar & Sentürk (1999) state that the most injured bodyparts were feet and arms (17%) and head and neck (9%).

When considering the operations during which the occupational accident occurred, more than half of the PU employees stated that they were injured during felling and delimbing, followed by yarding, maintenance and repairs of the yarder, and mounting and dismounting the yarder. The answers of the PR employees had similar distribution. During an objective analysis of occupational accidents, Tsioras et al. (2011) state that occupational accidents occurr mainly during yarding (43%), and mounting and dismounting the yarder (33%), followed by repairs and maintenance of the yarder. Tsioras et al. (2011) also state that broken supports, oscilating cables, anchoring trees, falling objects, and tree stems cause more than two thirds of all occupational accidents. Machine failures are a frequent source of occupational accidents in forest harvesting, as well as not using safe practices during work (Bentley et al. 2005).

Assessing the seasonal effects on the occurrence of occupational accidents showed that the most employees consider winter the most dangerous season. However, when compared to objective data by Tsioras et al. (2011) on seasonal occurrence of occupational accidents, we see that the most occupational accidents occurr in October, followed by March, June, and November.

Enez et al. (2014) states that 39% of the workers described terrain at the time when the occupational accident happened as steep, out of which 82% stated that the soil surface was moist and slippery. This corresponds to our results, as both PU and PR employees stated they consider terrain to be the dominant factor of the work environment.

5. Conclusion

High rate of occupational accidents during forest harvesting is well known. From the results we reached it can be seen that worker consider cable yarding to be physically demanding occupation with high risk of an occupational accident occurring. In this study, 41% of the PU employees and 50% of the PR employees stated that they suffered an occupational accident during the last ten years. This result is not surprising, considering the workers work in unstable climatic conditions, on unstable terrain, and the work environment presents other hazards, such as the loads, sharp tools and equipment, etc. For this reason, it is vital to ensure the workers are well informed about the individual factors of the work environment, and the potential hazards they present during work, and the proper working procedures in cable yarding. Only by ensuring that the workers know what is the toll for using improper (dangerous) tools or working techniques and enforcing the workers to adhere to safety protocols we can limit the number of occupational accidents in cable yarding, or forest harvesting as a whole.

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ORIGINAL PAPER

Species diversity of fungi on damaged branches and leaves of ashes (*Fraxinus* spp.) in different types of stands in Slovakia

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Abstract

The diversity of fungi on branches and leaves of ashes (*Fraxinus angustifolia*, *F. excelsior*, *F. ornus*) in Slovakia was studied. Symptomatic material collected in Slovakia during the period of 2013 to 2017 and herbarium specimens previously collected were examined. In total, 30 fungal taxa (15 Deuteromycetes, 14 Ascomycetes and one Basidiomycetes) were recorded. Twenty-three of them have never been recorded on ashes in the country. The most frequently occurring fungi were *Hymenoscyphus fraxineus* (anamorph *Chalara fraxinea*) that causes necrosis of shoots and branches, and *Phyllactinia fraxini*, a foliar pathogen that causes powdery mildew disease. Fungal diversity on ashes growing in different types of stands was compared. Species richness was the greatest in seed orchards (20 fungal taxa) compared to private gardens, which contained the lowest (two fungal taxa). Species diversity in forest stands comprised 18 fungal taxa and the urban greenery was represented by 10 fungal taxa. Nine fungal taxa were recorded in tree alley along the road. The widest fungal species spectrum was recorded on *F. excelsior*.

Key words: mycobiota; ash dieback; plant pathogens; saprophytes

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1. Introduction

Three native ash species, European ash (*Fraxinus excelsior* L.), narrow-leafed ash (*F. angustifolia* Vahl) and manna ash (*F. ornus* L.) occur on the territory of Slovakia. Ashes compose an important part of Slovak forests, and they are often planted as ornamental trees in the urban greenery. Although *Fraxinus* has relatively low representation in our forests (1.6%), ash wood remains industrially important (Anonymous 2015). This woody plant is sensitive to climatic fluctuations, especially to late frosts.

In the 1990s, an extensive outbreak of ash dieback occurred in north-eastern Europe. Due to the spread of the causal agent, *Hymenoscyphus fraxineus* (anamorph *Chalara fraxinea*) in recent years, ash trees of all ages are severely damaged across Europe. Some of the major symptoms of the disease are leaf necrosis, premature leaf abscission, and necrosis of the bark, cambium, and phloem, leading to the dying of shoots and branches. This disease causes a widespread mortality of ash trees. Thus, ash dieback threatens the existence of *Fraxinus* on the European continent (Vasaitis & Enderle 2017). *Fraxinus excelsior* has been registered in the Sweden's Red list of plants since 2010. *Hymenoscyphus fraxineus* attacks mainly *F. excelsior* and *F. angustifolia*. The following susceptible hosts have also been recorded: black (*F. nigra* Marshall), green (*F. pennsylvanica* Marshall), white (*F. americana* L.), Manchurian (*F. mandshurica* Rupr.), manna (*F. ornus*) and Chinese (*F. chinensis* subsp. *rhynchophylla* (Hance) E. Murray) ash trees (Drenkhan & Hanso 2010; Kirisits & Schwanda 2015; Gross & Han 2015). In Slovakia, the first evidence of the disease occurred more than 10 years ago (Kunca et al. 2006) and the identity of the fungal pathogen on *F. excelsior* and *F. angustifolia* was confirmed by molecular techniques (Adamčíková et al. 2015; Kádasi-Horáková et al. 2017). Due to the massive dieback of ashes at the present time, forest managers prefer culling or completely eliminating whole ash groups (Longauerová et al. 2017).

Although *H. fraxineus* is considered to be the main cause of dying ash trees, many other fungal genera (*Cytospora*, *Diplodia*, *Fusarium*, *Phomopsis*) colonizing ash shoots and branches are associated with their damage (Griffith & Boddy 1988; Przybyl 2002; Kowalski & Łukomska 2005; Kowalski & Czekaj 2010; Kowalski

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Corresponding author. Katarína Pastirčáková, e-mail: katarina.pastircakova@ife.sk, phone: +421 37 6943 358 et al. 2016). In Slovakia, previous authors (Juhásová et al. 2003, 2004) recorded 10 fungal taxa on ashes during the assessment of the status of woody plant health in urban greenery. There has been no further data on the detailed composition of mycobiota of ashes in Slovakia recorded since the first appearance of the ash dieback in the country.

The aim of the present study was to determine species diversity of fungi colonizing and damaging branches and leaves of our native *Fraxinus* species growing in different types of stands in Slovakia.

2. Material and methods

From 2013 to 2017, symptomatic ash branches and leaves (*F. angustifolia*, *F. excelsior*, *F. ornus*) were collected at selected localities in the urban and extra-urban vegetation of Slovakia. Samples (one sample was material taken from one tree) were examined by means of a stereo microscope (Olympus SZ61, Tokyo, Japan) and standard light microscope (Olympus BX51, Tokyo, Japan). Fungi that have formed reproductive structures on the studied material were identified on the basis of their morphological characteristics using taxonomic manuals for fungi (Arx & Müller 1954; Dennis 1978; Sutton 1980; Sivanesan 1984; Ellis & Ellis 1985; Kiffer & Morelet 2000).

In addition to the direct identification of mycobiota on the examined material, an *in vitro* cultivation on artificial culture media was used to detect the presence of microscopic fungi. The selected material was surface-sterilized using 70% ethanol for 1 min, 2% sodium hypochlorite for 10 min, flushed with sterile distilled water, and then cultured on culture medium (potato-dextrose agar). The cultures were incubated in the dark at 22 ±2 °C in a climate chamber MLR-351H (Sanyo, Japan). Isolated fungi were identified based on their cultural and morphological characteristics using the above literature.

In order to find out the spectrum of fungi previously found on *Fraxinus* spp. in Slovakia in the past (before 2013), herbarium specimens deposited in the Plant Pathology Herbarium (herbarium code: NR) of the Institute of Forest Ecology SAS Zvolen, Branch for Woody Plant Biology in Nitra were examined and revised. Herbarium specimens were collected by Gabriela Juhásová after 1980.

Based on the sampling sites, the samples were categorized according to the type of stand (A – tree alley along the road, F – forest, G – private gardens, O – seed orchard and arboretum, P – public parks and inter-block greenery). The frequency (%) of occurrence of the fungal taxa was calculated.

3. Results

In our study, we focused on identifying microscopic fungi associated with damage of ash leaves and branches, as well as withering of ashes in forests, orchards and urban vegetation. A total of 287 samples were analysed. Samples were collected from branches and leaves of *Fraxinus* spp. growing at 82 sampling sites in different parts of Slovakia (Fig. 1). The sampling sites represented different types of ash stands with different levels of management (42 public parks and inter-block greenery, 18 forest stands, 14 tree alleys, 4 seed orchards including one arboretum, and 4 private gardens).

A total of 30 fungal taxa (15 Deuteromycetes, 14 Ascomycetes, and 1 Basidiomycetes) were identified on branches and leaves of *F. angustifolia, F. excelsior*, and *F. ornus*. The data overview and the frequency of the recorded fungi was given in Table 1. Twenty-three of the fungal taxa

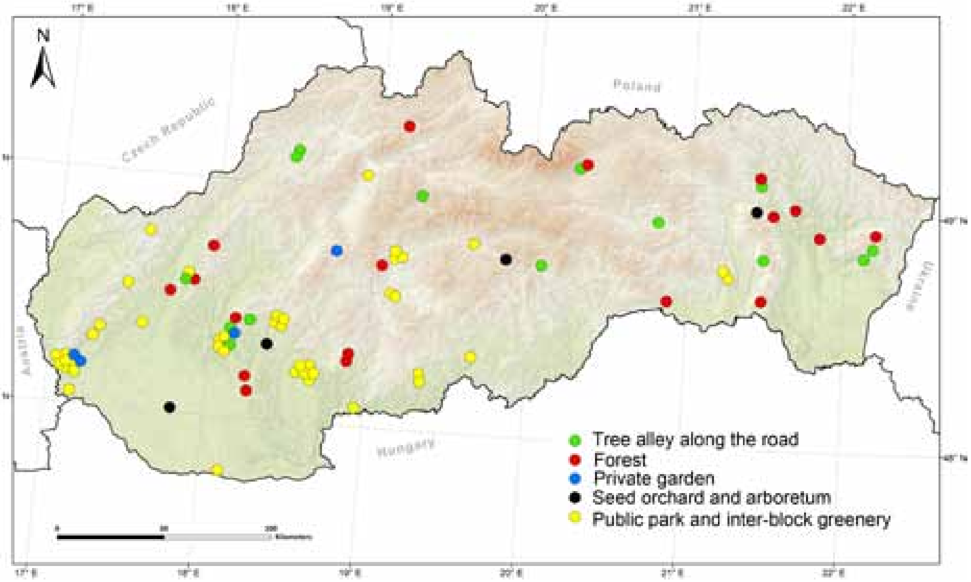

Fig. 1. Localization of sampling sites in Slovakia.

had never been recorded on *Fraxinus* in Slovakia. The novel taxa were marked with an asterisk (*) in Table 1. Fifteen species, namely *Botryosphaeria dothidea, Camarosporium orni, Coniothyrium fuckelii, Cryptosphaeria eunomia, Cucurbitaria obducens, Diaporthe eres, Didymosphaeria decolorans, Diplodia fraxini, Discula fraxinea, Dothiorella sarmentorum, Gloeosporidiella turgida, Hypoxylon fraxinophilum, Hysterographium fraxini, Immotthia atrograna*, and *Microdiplodia fraxini*, were not included in the checklist of fungi of Slovakia (Lizoň & Bacigálová 1998). The present paper documents the occurrence of these fungal species for the first time in Slovakia.

Under the *in vitro* conditions, the following 12 fungal taxa were isolated from ash shoots and branches: *Alternaria alternata*, *Botryosphaeria dothidea*, *Botrytis cinerea*, *Camarosporium orni*, *Cladosporium cladosporioides*, *Clonostachys rosea*, *Coniothyrium fuckelii*, *Diplodia fraxini*, *Dothiorella sarmentorum*, *Fusarium* sp., *Phomopsis* sp., and *Sordaria* sp.

Species richness (20 fungal taxa) was the greatest in seed orchards (monoculture plots). There were 18 fungal species found on ashes growing in forest stands (both single-tree species and mixed-tree species forest plots), 10 species in public parks and inter-block greenery, nine species in tree alleys along the road, and two species in private gardens (Fig. 2). The most common fungi occurring in all types of ash stands were *Hymenoscyphus fraxineus* causing necrosis of ash shoots and branches, and *Phyllactinia fraxini* causing powdery mildews. *Hymenoscyphus fraxineus* occurred very sporadically in urban ash plantations, presumably due to low quality of maintenance of a stand. The occurrence of the major pathogen, *H. fraxineus*, in the ash stands lead to the progressive withering and death of the trees. Rarely (only in one type of stand), 16 fungal taxa were recorded. There were 28 fungal taxa that colonized the bark and branches and 4 taxa were found on leaves, while two of them (*H. fraxineus* and *Phomopsis* sp.) occurred on the bark, branches, and the leaves. The list of fungi found on three species of *Fraxinus* in Slovakia is shown in Table 2. The widest fungal species spectrum was recorded on *F. excelsior*. The results showed that, in necrotic ash tissue, numerous fungi may occur, although only a few species are very frequent. Known plant pathogenic fungi present in a stand of dead ashes, such as: *Botryosphaeria dothidea, Cytospora sp., Diaporthe eres, Diplodia fraxini, Gibberella baccata*, and *Tubercularia vulgaris*, may represent a noticeable threat to young or stressed and weakened ash trees. These fungi

Table 1. The frequency of occurrence of fungal taxa on *Fraxinus* spp. in different type of stands in Slovakia.

Fungus	Mode of life	Substrate	Number of sampling sites[a]	Number of samples[b]	Frequency[c] [%]	Type of stand[d]
Ascomycetes						
**Botryosphaeria dothidea* (Moug.) Ces. & De Not.	parasite	branch	1	1	0.3	O
**Cryptosphaeria eunomia* (Fr.) Fuckel	parasite	branch	3	4	1.4	A, F, O
**Cucurbitaria obducens* (Schumach.) Petr.	saprophyte	branch	3	3	1.0	A, F
**Diaporthe eres* Nitschke	parasite	branch	2	2	0.7	F, P
**Didymosphaeria decolorans* Rehm	saprophyte	branch	1	3	1.0	F
Gibberella baccata (Wallr.) Sacc.	parasite	branch	1	1	0.3	P
Hymenoscyphus fraxineus (T. Kowalski) Baral, Queloz & Hosoya; anamorph *Chalara fraxinea* T. Kowalski	saprophyte, parasite	leaf, branch	25	120	41.8	A, F, G, O, P
**Hypoxylon fraxinophilum* Pouzar	saprophyte	branch	1	8	2.8	F
**Hysterographium fraxini* (Pers.) De Not.	saprophyte	branch	3	9	3.1	A, F, O
**Immotthia atrograna* (Cooke & Ellis) M.E. Barr	mycoparasite	branch	1	1	0.3	F
Neonectria ditissima (Tul. & C. Tul.) Samuels & Rossman (=*Nectria galligena* Bres.)	saprophyte	branch	3	6	2.1	F, O, P
Phyllactinia fraxini (DC.) Fuss (=*P. guttata* (Wallr.) Lév.)	parasite	leaf	41	73	25.4	A, F, G, O, P
**Sordaria* sp.	saprophyte	branch	1	2	0.7	O
**Xylaria longipes* Nitschke	saprophyte	branch	1	1	0.3	F
Basidiomycetes						
**Trametes versicolor* (L.) Lloyd	saprophyte	branch	1	1	0.3	P
Deuteromycetes						
**Alternaria alternata* (Fr.) Keissl.	endophyte	branch	1	2	0.7	O
**Botrytis cinerea* Pers.	endophyte	branch	1	1	0.3	O
**Camarosporium orni* Henn.	saprophyte	branch	3	5	1.7	A, F, O
**Cladosporium cladosporioides* (Fresen.) G.A. de Vries	endophyte	branch	1	1	0.3	O
**Clonostachys rosea* (Link) Schroers, Samuels, Seifert & W. Gams	mycoparasite	branch	1	1	0.3	O
**Coniothyrium fuckelii* Sacc.	saprophyte	branch	1	1	0.3	O
**Cytospora* sp.	parasite	branch	5	15	5.2	A, F, O, P
**Diplodia fraxini* (Fr.) Fr.	parasite	branch	5	9	3.1	A, F, O, P
**Discula fraxinea* (Peck) Redlin & Stack	parasite	leaf	1	1	0.3	F
**Dothiorella sarmentorum* (Fr.) A.J.L. Phillips, A. Alves & J. Luque	parasite	branch	1	2	0.7	O
Fusarium sp.	parasite	branch	1	1	0.3	O
**Gloeosporidiella turgida* (Berk. & Broome) B. Sutton	parasite	branch	3	3	1.0	F, O, P
**Microdiplodia fraxini* Died.	saprophyte	branch	1	1	0.3	F
Phomopsis sp. (=*Phyllosticta fraxinicola* Sacc.)	parasite	leaf, branch	6	7	2.4	F, O, P
Tubercularia vulgaris Tode	parasite	branch	2	2	0.7	A, O

[a] Number of sampling sites on which the occurrence of identified fungi was recorded.
[b] Number of samples in which the identified fungi were present (out of 287 examined samples).
[c] Frequency of the occurrence of fungi in total collection of 287 examined samples.
[d] A – tree alley along the road, F – forest, G – private gardens, O – seed orchard and arboretum, P – public parks and inter-block greenery.
*Fungal taxa not recorded on *Fraxinus* to date in the country.
The name on the original herbarium label is indicated in bracket.

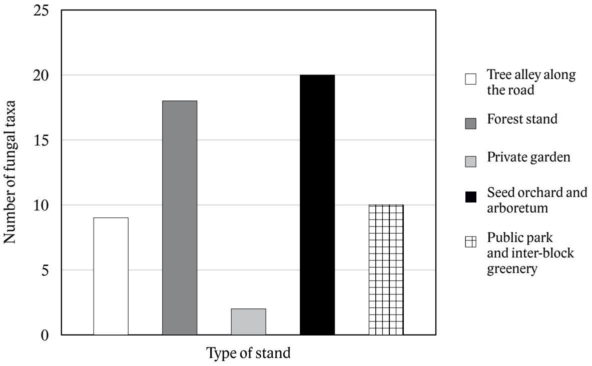

Fig. 2. Number of fungal taxa by type of ash stand in Slovakia.

possess a broad host spectrum that also places other tree species at risk of disease.

The fungi that we recorded on ash branches and leaves represent the taxa with different heterotrophy, such as saprophytes feeding on the dead or decaying substrates (e.g. *Cucurbitaria*, *Didymosphaeria*, *Hymenoscyphus*, *Hypoxylon*, *Hysterographium*, *Neonectria*, *Sordaria*, *Trametes*, *Xylaria*), parasites that prefer to colonize living plant tissues (e.g. *Chalara*, *Diplodia*, *Gloeosporidiella*, *Phomopsis*, *Phyllactinia*, *Tubercularia*), and endophytes (*Alternaria*, *Botrytis*, *Cladosporium*). Also mycoparasitic fungi, *Immotthia atrograna* parasitic on *Hypoxylon fraxinophilum* and *Clonostachys rosea* parasitic on *Sordaria* sp., were recorded on dead branches of *F. excelsior*.

Fungal specimens obtained during this study were preserved as a collection of herbarium materials (NR), as a data source for studying the geographical distribution of fungi and as the source of DNA of the fungi for molecular taxonomic analyses.

Table 2. The spectrum of fungi found on *Fraxinus* spp. in Slovakia.

Host	Fungus	Location of sampling sites
F. angustifolia	*Alternaria alternata*	Trstice[c]
	Botryosphaeria dothidea	Trstice[c]
	Botrytis cinerea	Trstice[c]
	Camarosporium orni	Trstice[c]
	Cladosporium cladosporioides	Trstice[c]
	Coniothyrium fuckelii	Trstice[c]
	Diplodia fraxini	Trstice[c]
	Dothiorella sarmentorum	Trstice[c]
	Fusarium sp.	Trstice[c]
	Hymenoscyphus fraxineus	Trstice[b], Vieska nad Žitavou[b]
	Hysterographium fraxini	Trstice[b]
	Phomopsis sp.	Trstice[c]
	Phyllactinia fraxini	Bratislava[a,b], Nitra[a,b]
	Sordaria sp.	Trstice[c]
F. excelsior	*Alternaria alternata*	Trstice[c]
	Camarosporium orni	Považská Teplá[b], Stará Lesná[b]
	Clonostachys rosea	Trstice[c]
	Cryptosphaeria eunomia	Kuková[b], Podhorany (Nitra District)[b], Vieska nad Žitavou[b]
	Cucurbitaria obducens	Kuková[b], Podhorany (Nitra District)[b], Stará Lesná[b]
	Cytospora sp.	Kuková[b], Nitra[b], Piešťany[b], Podhorany (Nitra District)[b], Stará Lesná[b]
	Diaporthe eres	Nitra[b], Stará Lesná[b]
	Didymosphaeria decolorans	Kuková[b]
	Diplodia fraxini	Kostoľany pod Tríbečom[b], Kuková[b], Nitra[b], Piešťany[b]
	Discula fraxinea	Kuková[b]
	Dothiorella sarmentorum	Trstice[c]
	Gibberella baccata	Nitra[a]
	Gloeosporidiella turgida	Kuková[b], Trstice[b]
	Hymenoscyphus fraxineus	Badín[b], Brekov[b], Černík[b], Hermanovce nad Topľou[b], Hôrka nad Váhom[b], Kuková[b], Kvakovce[b], Ladzany[b], Lipníky[b], Podsuchá[b], Poruba pod Vihorlatom[b], Považská Teplá[b], Remetské Hámre[b], Štitáre[b], Topoľčianky[b], Trstice[b], Turňa nad Bodvou[b], Úľany nad Žitavou[b], Vieska nad Žitavou[b], Zázrivá[b], Zbojská[b]
	Hypoxylon fraxinophilum	Kuková[b]
	Hysterographium fraxini	Kuková[b], Stará Lesná[b], Trstice[b]
	Immotthia atrograna	Kuková[b]
	Microdiplodia fraxini	Stará Lesná[b]
	Neonectria ditissima	Kostoľany pod Tríbečom[b], Kuková[b]
	Phyllactinia fraxini	Banská Bystrica[a], Bratislava[a,b], Brezno[b], Handlová[a], Herľany[a], Horné Lefantovce[a], Komárno[a], Košice[a], Levice[a], Modra[a], Muráň[b], Myjava[a], Nitra[a,b], Pezinok[a], Slanec[a], Šahy[a], Topoľčianky[b], Trnava[a], Trstice[a], Trstín[b], Veľké Kostoľany[a], Vieska nad Žitavou[a,b], Zvolen[a]
	Phomopsis sp. *(=Phyllosticta fraxinicola)*	Banská Bystrica[a], Košice[a], Kuková[b], Nitra[b], Vieska nad Žitavou[a]
	Sordaria sp.	Trstice[c]
	Trametes versicolor	Pezinok[a]
	Tubercularia vulgaris	Spišské Vlachy[b], Trstice[b]
	Xylaria longipes	Považský Inovec[b]
F. ornus	*Gloeosporidiella turgida*	Bratislava[a]
	Hymenoscyphus fraxineus	Vieska nad Žitavou[b]
	Neonectria ditissima (=Nectria galligena)	Bratislava[a]
	Phyllactinia fraxini	Bratislava[a,b], Martin[a], Nitra[a,b], Veľký Krtíš[a]

[a] Herbarium specimens deposited in the Plant Pathology Herbarium (NR) collected before 2013.

[b] Samples collected in 2013–2017.

[c] Fungal isolates on culture media (*in vitro*).

The name on the original herbarium label is indicated in bracket.

4. Discussion

The results show that the mycobiota associated with ash trees in Slovakia are very rich in species diversity. In previous papers (Juhásová et al. 2003, 2004), 10 fungal taxa on ashes growing in urban greenery have been recorded. Twenty-three other fungal taxa on ashes growing in five different types of stands were recorded in the present paper. Representative material of previously published findings of some fungi on ashes from Slovakia, *Cercospora fraxini* Ellis & Kellerm., *Gibberella baccata* (anamorphic stage of *Fusarium lateritium* Nees) and *Mycosphaerella fraxini* (Niessl) Lindau (Juhásová et al. 2003, 2004) were not preserved. We did not record any wood-decaying fungi on the ashes examined from 2013 to 2017. The only herbarium specimen, *Trametes versicolor*, on *F. excelsior* is stored in NR herbarium. *Ganoderma adspersum* (Schulzer) Donk, *G. applanatum* (Pers.) Pat. (=*G. lipsiense* (Batsch) G.F. Atk.), *G. carnosum* Pat., and *G. pfeifferi* Bres. have been recorded on *Fraxinus* spp. in Slovakia (Juhásová et al. 2003; Gašparcová et al. 2017). The basidiomycete *Inonotus hispidus* (Bull.) P. Karst. causes an intense white rot and ash wood degradation in Slovak forests (Zúbrik et al. 2017). Longauerová et al. (2013) recorded an occurrence of *Armillaria cepistipes* Velen. and *A. gallica* Marxm. & Romagn. on trees weakened by *H. fraxineus*. Wilt disease caused by *Verticillium dahliae* Kleb. and leaf blotch caused by *Kabatiella apocrypta* (Ellis & Everh.) Arx, responsible for the mortality of ash trees in nurseries in Germany (Schröder & Dujesiefken 2001), were not recorded in Slovakia. In our study, we noticed a rare occurrence of the fungus *Discula fraxinea* that causes anthracnose disease of ashes, premature leaf abscission, and the defoliation and disfigurement of infected branches in North America (Jacobs & Danielson 2002).

In an extensive study of the mycobiota in declining ashes in Polish forests, Kowalski et al. (2016) identified more than 70 fungal taxa on stems and twigs in initial and advanced stages of dieback. They recorded *H. fraxineus* in almost 60% of the samples analysed, as well as the following frequently occurring fungi: *Alternaria alternata*, *Diaporthe eres*, *Diplodia mutila* (Fr.) Mont., *Fusarium avenaceum* (Fr.) Sacc., *F. lateritium*, and *Phomopsis* spp. Griffith & Boddy (1988) recorded the species *Phomopsis platanoidis* (Cooke) Died., *Libertella fraxinea* Oganova, *Peniophora lycii* (Pers.) Höhn. & Litsch., *F. lateritium* and *Acremonium* sp. on dead branches in ash crowns. Bakys et al. (2009) confirmed the pathogenicity in four of 24 isolated fungal species and reported symptomatic necrosis of the bark and cambium were caused by *A. alternata*, *Epicoccum nigrum* Link, *Chalara fraxinea* and *Phomopsis* sp. Przybyl (2002) observed the necrosis of the tissue on young *Fraxinus* seedlings inoculated with *Diplodia mutila* and *F. solani* (Mart.) Sacc. *Diplodia fraxini*, which we isolated from *F. angustifolia* and *F. excelsior* collected from five localities in Slovakia, is a species belonging to the *Diplodia* species complex associated with cankers and branch dieback on *Fraxinus* spp. in Europe. Alves et al. (2014) recorded *D. mutila*, *D. pseudoseriata* C.A. Pérez, Blanchette, Slippers & M.J. Wingf., *D. seriata* De Not., *D. subglobosa* A.J.L. Phillips, Deidda & Linald. and *D. fraxini* on all three native *Fraxinus* species. In the taxonomic revision of the genus *Phyllosticta*, van der Aa & Vanev (2002) re-examined the material previously published as *Phyllosticta fraxini* Ellis & G. Martin and *Phyllosticta fraxinicola* on *Fraxinus* spp. and designated the taxa as *Phomopsis* sp., the anamorphic stage of *Diaporthe eres*. The pathogenicity of *Phomopsis controversa* (Desm.) Traverso and *P. scobina* Höhn. isolated from necrotic ash shoots have not been confirmed (Przybyl 2002).

Powdery mildew disease caused by *Phyllactinia fraxini* occurs commonly on all three native species of *Fraxinus* in Slovakia (Table 2). Paulech (1995) recorded *P. fraxini* also on *F. americana* (Hurbanovo, Sesíleš, park). An Asian powdery mildew fungus, *Erysiphe salmonii* (Syd. & P. Syd.) U. Braun & S. Takam., recently introduced to Europe and found on *F. excelsior* and *F. pennsylvanica* in Ukraine (Heluta et al. 2017), was not recorded in our country until now.

Diverse forests can contribute to reduced susceptibility of trees to disease and fungal infection, and a subsequent increase in plant survival and growth (Keesing et al. 2006; Hantsch et al. 2014). According to Keesing et al. (2006), non-host trees can reduce fungal disease risks. When the density of these heterospecific trees increases, the proportion of host trees then becomes diluted in mixed stands. Our results showed a richer diversity of fungal taxa in seed orchards (monoculture plots) and both single-tree species and mixed-tree species forest plots. The invasive pathogenic fungus, *H. fraxineus*, caused devastating damage to the ashes growing in forests, seed orchards and tree alleys. We assume that very sporadic findings of *H. fraxineus* in urban ash plantations are a consequence of the quality of maintenance of urban greenery. The presence of the pathogen confirmed in seeds of *F. excelsior* (Cleary et al. 2013) is of great concern to phytosanitary protection authorities in countries outside the current zone of infestation.

Ash with extensive dieback symptoms rarely recovers under field conditions. There is very low proportion of trees tolerating infection by *H. fraxineus* in current common ash populations. Clonal seed orchards composed of dieback-tolerant clones appear to be the most efficient tool for management of ash dieback. The results of experiments on the selection and testing of candidate hyposensitive clones for new ash seed orchards are only preliminary (Longauerová et al. 2017). There have been early steps in propagating and screening a wide range of *Fraxinus* species and selection of tolerant *F. excelsior* genotypes for a new breeding program (Clark & Webber 2017). There is currently no information on an effective control method for *H. fraxineus*. The maintenance of high tree vigor using cultural practices such as destroying fallen diseased leaves, pruning out dead branches and covering wounds with fungicide-augmented dressings is recommended.

5. Conclusion

The results of species diversity of fungi colonizing three native *Fraxinus* species in Slovakia are presented. A rich diversity of fungi on ashes represents a total of 30 fungal taxa. Although numerous fungi occur in necrotic ash tissue, only a few taxa are very frequent. Some of plant pathogenic fungi that are present in the stand of dead ashes may represent a noticeable threat to young or stressed and weakened ash trees. Other tree species may also be at risk of disease since these pathogenic fungi possess broad host spectrums. We assume other species of pathogenic fungi could also be present in dying ashes and thus contribute to dieback. Further mycological surveys are needed to identify fungal species that benefit from the initial infection by *H. fraxineus* or contribute to progress of ash dieback disease.

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