SILVER FIR (*ABIES ALBA* MILL.) ECTOMYCORRHIZA ACROSS ITS AREAL – A REVIEW APPROACH

EKTOMIKORIZNI SIMBIONTI BELE JELKE (*ABIES ALBA* MILL.) NA NARAVNEM OBMOČJU RAZŠIRJENOSTI - PREGLED

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ABSTRACT

Silver fir (*Abies alba* Mill.) ectomycorrhiza across its areal – a review approach

Silver fir is a long-living ecologically valuable and indigenous conifer species. In temperate forests it is considered as a ″stabilization tree species″. Currently, knowledge of silver fir ectomycorrhiza community is manly based on morphological-anatomical description of ectomycorrhizal fungi and their fruiting bodies. Only recently few studies were published in which authors identified ectomycorrhizal symbionts of silver fir with an aid of molecular (DNA-based) markers. We analysed the silver fir ectomycorrhiza diversity and species richness from different geographic areas and stand types. From all together nine original studies we calculated average species richness as well as a Bray-Curtis similarity index. The highest species diversity was observed in studies where a combination of morphological-anatomical and molecular approaches were used for identification. Bray-Curtis similarity index indicated highest dissimilarity of the southern sites comparing to other areas. We correlated the observed outcome to differences in soil conditions, climate, and only basic identification approach.

Keywords: Silver fir, ectomycorrhiza, literature review, community composition, site conditions, species diversity, species richness

IZVLEČEK

Ektomikorizni simbionti bele jelke (*Abies alba* Mill.) na naravnem območju razširjenosti – pregled

Bela jelka je vednozelena drevesna vrsta, ki ima v naravnih gozdovih ekološko pomembno vlogo, saj velja za stabilizacijsko drevesno vrsto. Podatki o ektomikoriznih simbiontih bele jelke pretežno temeljijo na morfološko-anatomskih opisih ektomikoriznih gliv in njihovih trosnjakov. Šele v zadnjih letih je bilo objavljenih nekaj študij, v katerih so avtorji združbo ektomikoriznih gliv bele jelke analizirali z molekularnimi pristopi. V preglednem članku smo analizirali rezultate pestrosti ektomikorize bele jelke z devet lokacij in preračunali povprečne vrednostmi vrstne pestrosti ter Bray-Curtisov indeks podobnosti združb. Največjo vrstno pestrost smo ugotovili za vzhodni del areala bele jelke. Poleg ugodnih rastiščnih razmer k temu predvidoma doprinesejo tudi kombinacija uporabljenih metod za identifikacijo. Bray-Curtisov indeks podobnosti združb kaže, da med zastopanimi regijami znotraj areala (centralna, vzhodna in južna) po vrstni sestavi najbolj odstopajo rastišča v južnem arealu bele jelke. Odstopanja vrstne sestave lahko povežemo z razlikami v pH tal, s tipom tal in s toplejšo, za belo jelko manj primerno klimo.

Ključne besede: bela jelka, ekomikoriza, pregledni članek, združba ektomikorize na jelki, rastišči pogoji, bogastvo vrst, vrstna pestrost

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1 INTRODUCTION

Although in recent years few studies, focusing on ectomycorrhizae of silver fir (*Abies alba* Mill.) have been published, little is known about ectomycorrhiza species richness of silver fir along its geographic areal. Silver fir is a long-living conifer and the largest tree (up to 60 m) in the genus *Abies* in Europe. The distribution area is limited mainly to the mountainous regions of eastern, western, southern and central Europe (Figure 1) (Westergren et al. 2010). Silver fir is also an ecologically valuable and indigenous tree species (Eberhardt et al. 2000). It is considered as a ″stabilization tree species" as well as a key tree species, without which maintenance of selection structure in forest communities would be difficult (Klopčič et al. 2009).

As most European forest tree species, silver fir forms an ectomycorrhiza, a symbiosis with fungi from Ascomycota and Basidiomycota (Schirkonyer et al. 2013). Beside the exchange of nutrients and metabolites between symbiotic ectomycorrhizal fungi and plant host, formation of ectomycorrhizae on tree roots alters root growth (Smith & Read 2008) and protects them against root diseases, which increases the survival rate of silver fir seedlings (Schirkonyer et al. 2013).

Currently ectomycorrhizal communities on silver fir remain poorly identified. Most silver fir ectomycorrhiza descriptions were based on morphological and anatomical characteristics (Comandini et al. 2004, Pacioni et al. 2001, Cremer 2009) and characterized without the exact identification of fungal symbiont (Rudawska et al. 2016). In addition, some potential ectomycorrhiza fungi were connected to silver fir based on proximity of sporocarps occurrence (Lagana et al. 2000, 2002). Until now only few studies have been published in which authors had identified ectomycorrhiza on silver fir applying molecular (DNA-based) markers (Eberhardt et al. 2000, Cremer 2009, Wazny 2014, Schirkonyer et al. 2013, Rudawska et al. 2016, Wazny & Kowalski 2017).

Ectomycorrhiza diversity and community structure, tree age, rooting depth, soil characteristics, and other characteristics can be used as a prediction data for potentially altered tree responses in given environments. To evaluate the significance of the ectomycorrhiza community shifts, a base knowledge on the ectomycorrhiza diversity and community structure is required. For this reason, we reviewed all published studies that focused ectomycorrhiza on silver fir to assess and analyse the species richness and its variation on geographic gradient, and under generalized site conditions from the currently analysed locations.

2 MATERIALS AND METHODS

2.1 Collection of mycorrhizal occurrence data

The review is based on published studies of ectomycorrhiza on silver fir (Table 1) where at least the list of identified types of ectomycorrhiza and basic site characteristics such as soil pH, soil type, stand type and location of the study were given.

Authors from reviewed studies have analysed ectomycorrhizal taxa either in pure adult natural silver fir stands, mixed stands with variable share of silver fir as well as from planted silver fir stands. Reviewed stands differ soil conditions, climatic condition, altitude and in tree species composition. Although most studies provided the stand characteristics, not all were readily available thus missing values for soil pH were gained either from online soil databases (soilgrids.org) or from other studies performed at the same study sites.

Ectomycorrhiza studies on silver fir covered three general parts of the silver fir distribution areal in Europe. The areal was also the rationale for grouping them into representative areas, namely southern, eastern and central Europe. No studies were available for western part of its areal. The position of studied location in areal as well as silver fir distribution in Europe is given in Figure 1.

2.2 Data analyses

From published papers the following variables have been extracted: number of ectomycorrhizal species of silver fir per study/site, basic soil characteristics (if given) such as soil pH and soil type, as well as type of stand in which ectomycorrhizal fungal of silver fir were analysed.

To compare species richness between geographic areas, average species richness per geographic area was calculated (Atlas & Bartha 1981). To show similarity of communities among geographic areas we calculated a Bray-Curtis similarity index for species richness (Bray & Curtis 1957).

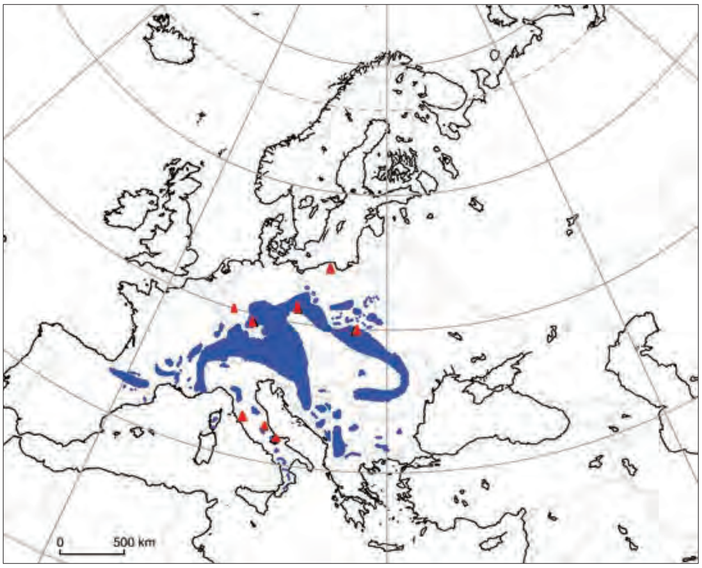

Figure 1: The location of reviewed stands and silver fir (Abies alba Mill.) distribution (source: EUFORGEN database).
Slika 1: Lokacije analiziranih sestojev bele jelke (Abies alba Mill.) in območje razširjenosti bele jelke (vir: podatkovna baza EUFORGEN).

3 RESULTS

3.1 Ectomycorrhizal fungal symbionts overview

The review of published works on ectomycorrhiza on silver fir revealed nine studies where sufficient data and metadata were available, to be included in the review. Studies covered only central, eastern and southern part of the silver fir areal (Table 1, Figure 1).

Table 1: Studies included in review.
Tabela 1: Študije vključene v pregled.

Geographic area	Data
Southern Europe	Comandini et al. 2001
	Lagana et al. 2002
	Pacioni et al. 2006
Central Europe	Schirkonyer et al. 2013
	Cremer, 2009
Eastern Europe	Wazny 2014
	Rudawska et al. 2016
	Wazny and Kowalski 2017
	Kowalski 2008

The average number of different types of ectomycorrhiza on silver fir was high, overall 85 different ectomycorrhizal types have been identified (Table 2). In eastern Europe 62 different ectomycorrhiza fungal taxa have been identified, however 5 ectomycorrhiza fungal taxa remained identified only at genus level. For southern Europe 12 out of 18 different ectomycorrhiza taxa of silver fir were identified to a species level and the rest to a genus level. However, there were still 13 ectomycorrhiza fungal taxa that remained as unidentified ectomycorrhiza. In central Europe, authors managed to identify 17 different ectomycorrhiza fungal taxa at a species level and 3 at a genus level.

Table 2: Number of different identified ectomycorrhiza fungal taxa on silver fir and number of different identified ectomycorrhiza taxa recorded per geographic area.
Tabela 2: Število različnih določenih ektomikoriznih glivnih taksonov bele jelke in število različnih določenih ekotmikoriznih glivnih taksonov zabeleženih po geografskih območjih.

Overall number	Southern Europe	Eastern Europe	Central Europe	Unidentified species
85	18	62	20	13

By comparing emerging ectomycorrhiza fungal taxa among areas only few species were present at all areas, namely *Byssocorticium atrovirens, Cenococcum geophilum* and *Laccaria amethystina*. Southern Europe differed most in terms of ectomycorrhiza taxa diversity while eastern and central Europe have much more species in common compared to southern Europe (Table 3).

Table 3: Identified ectomycorrhiza fungal taxa in symbiosis with silver fir based on area their occurrence. + indicates present of the species in particular area.
Tabela 3: Določeni ektomikorizni glivni taksoni v simbiozi z belo jelko na podlagi njihovega območja pojavljanja. + označuje prisotnost vrste na posameznem območju.

Fungal species	Present at eastern Europe	Present at southern Europe	Present at central Europe
Amanita rubescens	+		
Amanita spissa	+		
Amphinema byssoides	+		+
Boletus edulis	+		+
Boletus badius	+		
Boletus pruinatus	+		+
Byssocorticium atrovirens	+	+	+
Cantharellus sp.	+		
Cenococcum geophilum	+	+	+
Clavulina cristata	+		+
Clavulina rugosa	+		
Cortinarius anomalus			+
Cortinarius casimiri			+
Cortinarius fulvescens	+		
Cortinarius malachius	+		
Cortinarius semisanguineus	+		
Cortinarius sp.		+	
Craterellus lutescens	+		
Elaphomyces muricatus	+		
Entoloma sp.	+		
Genea sp.	+	+	
Geopora cervina	+		
Hydnotrya bailii	+		
Hydnotrya tulasnei	+		
Hydnum repandum	+		
Hydnum rufescens	+		
Hygrophorus pudorinues		+	
Hysterangium sp.		+	
Imleria badia	+		
Inocybe geophylla	+		
Inocybe terrigena	+		
Inocybe sp.		+	
Laccaria amethystina	+	+	+
Laccaria laccata	+		
Laccaria maritima	+		
Lactarius aurantiacus	+		
Lactarius camphoratus	+		
Lactarius ichoratus		+	
Lactarius intermedius		+	
Lactarius lignyotus	+		
Lactarius necator	+		
Lactarius rufus	+		
Lactarius salmonicolor	+	+	

Fungal species	Present at eastern Europe	Present at southern Europe	Present at central Europe
Lactarius scrobiculatus		+	
Lactarius subericatus		+	
Lactarius subdulcis			+
Lactarius sp.			+
Melanogaster variegatus			+
Meliniomyces variabilis			+
Mycena galopus			+
Paxillus involutus	+		+
Phellodon niger		+	
Piloderma byssinum	+		
Piloderma fallax	+		
Piloderma sp.			+
Pseudotomentella tristis	+		
Russula amethystina	+		
Russula cyanoxantha	+		
Russula fellea	+		
Russula integra	+		
Russula nigricans	+		
Russula ochroleuca	+		+
Russula olivacea	+		
Russula puellaris	+		
Russula vesca	+		
Russula xerampelina	+		
Russula sp.		+	
Scleroderma citrinum			+
Sebacina sp.	+		
Thelephora terrestris	+		+
Tomentella albomarginata	+		
Tomentella botryoides	+		
Tomentella ellisii	+		
Tomentella stuposa	+		
Tomentella sublilacina	+		
Tomentella terrestris	+		
Tomentella sp.			+
Tomentellopsis sp.	+		
Tuber puberulum	+		
Tuber sp.		+	
Tricholoma bufonium		+	
Tricholoma saponaceum		+	
Tylopilus felleus	+		
Tylospora asterophora	+		
Tylospora fibrillosa	+		

3.2 Stands characteristic and ectomycorrhizal fungal species richness

All reviewed studies have analysed pure silver fir stands as well as mixed or planted stands. The southern Europe stands deviate from other areas mainly by the average pH values which are significantly higher, compared to eastern and central Europe (Table 3). As well as pH also soil type differed between reviewed areas, although for southern Europe we could not gain information from original papers about soil characteristics.

The highest average species richness was calculated for eastern Europe sites and the lowest for central European sites (Figure 2). High standard deviation within areas indicates high variability among sites and individual soil samples.

Table 4: Generalised characteristics of reviewed stands.
Tabela 4: Splošne značilnosti analiziranih sestojev.

Geographic generalized area	Reviewed stand type	Soil characteristics	pH
Eastern Europe	pure silver fir and mixed stands	acid brown	4.46 ± 0.4
Southern Europe	natural and planted silver fir stands	not specified	6.1 ± 1.13
Central Europe	pure silver fir and mixed stands	middle-red sandstone	4.28 ± 0.17

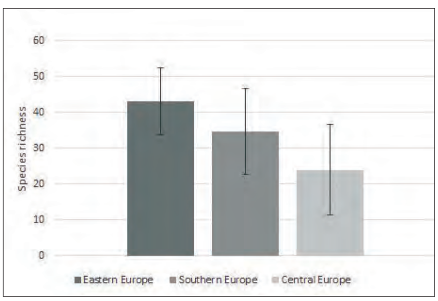

Figure 2: Average ectomycorrhiza fungal taxa richness analysed for eastern, southern and central Europe.
Slika 2: Povprečna pestrost ektomikoriznih glivnih taksonov analiziranih za območje vzhodne, južne in osrednje Evrope.

As average species richness, specifically a standard deviation calculated for individual areas showed high differences inside the same area, we compared species richness by a stand type (Table 4). Except in central Europe, pure (monospecific) silver fir stands showed higher species richness than mixed stands and plantation stands. In central Europe species richness in mixed stands with silver fir was higher compared to natural silver fir stands, where have been detected half less species compared to mixed stands.

Table 5: Average species richness for stand type and geographic area.
Tabela 5: Povprečna vrstna pestrost po tipih sestojev in geografskih območjih.

Stand type / Av. spec.richn.	Monospecific silver fir stands	Mixed stands with silver fir	Plantation silver fir stands
Eastern Europe	33.5	26.7	20
Southern Europe	27	/	21
Central Europe	15	33	/

To show similarity of communities among reviewed geographic areas, Bray-Curtis similarity index was calculated. The highest species richness similarity was calculated among eastern and central Europe, while southern Europe differed more from eastern and from central Europe (Table 5). The result coincides with pattern of ectomycorrhizal fungal species occurrence.

Table 6: Bray-Curtis similarity index for species richness.
Tabela 6: Bray-Curtisov indeks podobnosti za vrstno pestrost.

Geographic areas	Bray-Curtis similarity index
Eastern & southern Europe	0.13
Eastern & central Europe	0.24
Southern & central Europe	0.16

4 DISCUSSION

4.1 Silver fir ectomycorrhiza has high diversity potential that remains underexploited

Silver fir ectomycorrhiza is not among better studied topics, what is reflecting in results of the review. From nine studies a relative high number of ectomycorrhizal taxa per site was retrieved, indicating a high potential for ectomycorrhiza diversity in silver fir stands. A high potential for hidden ectomycorrhiza taxa diversity on silver fir is also indicated with high number of types of ectomycorrhiza that remained unknown or identified only at genus level either due to lack of recognizable features or due to an insufficient identification method. Both indicate a need to study additional silver fir sites along the species distribution gradient in particular areas, where Silver fir ectomycorrhiza was not studied yet.

4.2 The silver fir ectomycorrhiza community differs among areas

In this review, published studies have been grouped into three general parts, which were further compared based on species occurrence, species richness, environmental propertied as well as based on ectomycorrhizal species similarity.

Bray-Curtis similarity index for species richness showed higher similarity between eastern and central

Europe, compared to southern Europe, which stands out. This could be a consequence of different climatic and environmental condition, as southern Europe is more characterized by Mediterranean conditions while silver fir prefers relatively high elevated areas (above 500 m a.s.l.) and requires high moisture conditions throughout the year (Tinner et al. 2013). This all can put silver fir in permanent stress conditions and a selection toward more resistant / pioneer types of ectomycorrhiza among which we identified at least genera *Cenococcum, Genea, Hysterangium* and *Tuber*.

Silver fir tolerates a wide variety of soil types with different nutrient content and alkalinity conditions (Ruosch et al. 2015) associated ectomycorrhiza community reacts to differences among site soils as only three ectomycorrhizal species were present at all areas, namely *B. atrovirens, C. geophilum* and *L. amethystina*. Several other types of ectomycorrhiza were present at two areas – eastern Europe and central Europe, namely *Genea* sp., *Clavulina cristata*, *Russula ochroleuca*, *Thelephora terrestris* etc. which favour conditions as well as on stand types in common for eastern and central sites. These species can also be regarded as generalist as they occur at two different geographic areas.

Species richness analysis showed the highest ectomycorrhizal species richness in eastern Europe and on lowest species richness in central Europe. This result could be a consequence of either lower sampling intensity in central Europe or either of insufficient ectomycorrhizas identification. As the sampling intensity of studies was in general between four till six-week period, we can assume that beside the differences in environmental properties, the identification method was the mainly reason for a large ectomycorrhizas species richness differences between geographic areas. Analysis success of ectomycorrhiza fungal diversity based on morphological descriptions is often low and only rarely allows sufficient identification of mycorrhizas at the fungal species level (Rudawska et al. 2016).

Only for eastern Europe sites DNA-based identification approaches were used for ectomycorrhiza identification thus we assume, that higher number of ectomycorrhiza fungal species is a result of combination of methods used for identification (Suz et al. 2008).

The ectomycorrhiza species richness differ also between stand types. The species richness was higher at natural pure fir stands compared to mixed stands and plantation fir stands. Although it is generally accepted that co-occurrence of different host tree species within a stand promotes ectomycorrhiza diversity at the local scale (Rudawska et al. 2016), the ectomycorrhiza communities can be highly diverse even in a mono-specific stands (Cremer 2009). Many studies have shown that relevant factors determining the composition of the ectomycorrhizal fungi are age of the associated host trees and stand history (PACIOni et al. 2001, Lagana et al. 2002). Cremer (2009) indicated that adult silver fir trees on average, host higher number of different ectomycorrhiza than juvenile trees suggesting an increase of the ectomycorrhiza species richness over time. In case of other conifers, a rapid increase was shown in species richness and sporocarp productivity during first 30-40 years of the stand and a more gradual decrease to a constant level afterwards (Comandini et al. 2004). This explains observations where the individual tree increased its ectomycorrhiza community richness in time by allowing multi-mycorrhization of its expending root systems (Cremer 2009). Lack of some silver fir ectomycorrhizal fungi in analysed stands could be also a result of unfavourable site characteristics such as pH, litter and soil quality, climate, etc. (Rudawska et al. 2016). This explains the higher ectomycorrhiza species richness at natural fir stands compared to planted sites supporting the idea to focus diversity studies on either more natural or combination of natural and planted sites (Lagana et al. 2002).

4.3 Specialists versus generalist ectomycorrhiza species on silver fir

At all investigated silver fir stands, *Cenococcum geophilum* was present in most soil samples. The species is known to be one of the most widely distributed ectomycorrhizal fungal species in various ectomycorrhiza forests (Hrenko et al. 2009). Predominance of *C. geophilum* can indicate thick organic layer or high fluctuations of soil temperature and moisture content as it is regarded as stress tolerant species and can persist as ectomycorrhiza up to 10 times longer compared to other ectomycorrhiza species (Lobuglio 1999). In such conditions, *C. geophilum* is a highly competitive ectomycorrhizal fungus. Similar *Tomentella stuposa* can be regarded as common ectomycorrhiza symbiont of silver fir with long list of ectomycorrhiza plant partners (Cremer 2009, Wazny 2014).

Among silver fir specialist ectomycorrhizal fungi is *Lactarius salmonicolor* (Pillukat 1996). This ectomycorrhiza was found at silver fir stands in southern and eastern Europe, but was not recorded in central Europe. Other species that exhibit some level of silver fir preference are also *L. albocarneus, L. intermedius* and *Russula* spp. (Rudawska et al. 2016). From mentioned *Lactarius* species, only *L. intermedius* has been identified in southern Europe. Absence of other silver fir-specialist ectomycorrhizal fungi in southern Europe can be a result of distinct climate and soil conditions or of an insufficient (e.g. only ectomycorrhiza morphology-based) identification.

The occurrence of several other species and be related to the area or forest type characteristics. *Laccaria amethystina* was also found in ectomycorrhiza with silver fir occurring regardless to the age of the stand, although it was previously regarded as an early stage ectomycorrhizal species (Cremer 2009). Occurrence of *Clavulina cristata* at stands in eastern and central Europe may indicate at high concentrations of Ca- and Mg-cations in the soil, as high cation concentrations positively affected the development of *C. cristata* in spruce and beech stands (Wazny 2014).

CONCLUSSIONS

All together nine studies were conducted focusing the ectomycorrhiza of silver fir. Observed differences in silver fir stands between analysed areas (eastern, southern and central Europe) reflect some of the general site characteristics while the strong bias cannot be excluded and likely related to insufficient sampling effort and use of identification approaches and sampling strategies with poor discriminative power.

POVZETEK

Bela jelka je vednozelena drevesna vrsta iz rodu *Abies*, katere območje razširjenosti je omejeno na vzhodno, zahodno, južno ter centralno Evropo. Tako kot večina evropskih drevesnih vrst, tvori tudi bela jelka ektomikorizno simbiozo z več vrstami gliv. Mikorizna simbioza je stalen simbiotski odnos med korenino rastline in glivo, pri katerem prihaja do dvosmernega pretoka hranil. Do sedaj je bilo objavljenih le nekaj študij v kateri so avtorji analizirali pestrost ektomikoriznih simbiontov bele jelke. Trenutno, znanje o ektomikorizah bele jelke povečini temelji na morfološko-anatomskih opisih ektomikoriznih gliv in njihovih trosnjakov. V zadnjih letih je bilo objavljenih tudi nekaj študij, v katerih so avtorji za identifikacijo ektomikoriznih glivnih vrst uporabili tudi analize molekularnih markerjev.

V članku smo povzeli rezultate objavljenih študij in z analizami vrstne pestrosti in podobnosti združb, med seboj primerjali posamezna geografska območja ter tipe sestojev.

Največja vrstna pestrost ektomikoriznih simbiontov bele jelke je bila ugotovljena za območje vzhodne Evrope, medtem ko je južna Evropa najmanj vrstno pestra glede na število vrst ektomikoriz bele jelke. Ugotovljena razlika je najverjetneje posledica izbire identifikacijskih metod, saj so samo na območju vzhodne Evrope, avtorji študij za identifikacijo ektomikoriznih gliv bele jelke uporabili tudi molekularne metode identifikacije – analize molekularnih markerjev.

Vrstna pestrost se razlikuje tudi med posameznimi analiziranimi tipi sestojev. V naravnih sestojih bele jelke je vrstna pestrost ektomikoriznih gliv večja v primerjavi z umetnimi oz. mešanimi sestoji. Zraven starosti sestojev so najverjetnejši vzroki za ugotovljeno razliko neugodni okoljski dejavniki.

Pri primerjavi prisotnosti ektomikoriznih glivnih simbiontov na posameznem geografskem območju smo ugotovili, da se v vseh analiziranih sestojih pojavljajo nekateri generalisti, kot npr. *B. atrovirens, C. geophilum* in *L. amethystine*. Kljub prisotnosti nekaterih generalistov, se v analiziranih sestojih bele jelke pojavljajo tudi vrste, ki preferirajo sestoje bele jelke, *Lactarius salmonicolor, Lactarius intermedius* ipd. Na podlagi prisotnosti nekaterih ektomikroiznih glivnih vrst lahko ocenimo tudi starost sestojev ter lastnosti tal.

Skupaj smo analizirali devet objavljenih študij, v katerih so se avtorji osredotočili na analize pestrosti ektomikoriznih gliv bele jelke. Ugotovljene razlike so zraven vpliva različnih lastnosti sestojev, najverjetneje rezultat uporabe identifikacijskih metod, kot tudi različnih metod ter časovne dinamike vzorčenja, katerih so se v svojih študijah poslužili avtorji.

7 REFERENCES - LITERATURA

Atlas, R. & R. Bartha, 1981: *Introduction to microbiology.* Boston.

Bray, J. R. & J. T. Curtis, 1957: *An ordination of upland forest communities of southern Wisconsin.* Ecological Monographs (Washington) 27(4): 325-349. http://dx.doi.org/10.2307/1942268

Comandini, O., I. Haug, A. C. Rinaldi & T. W. Kuyper, 2004: *Uniting Tricholoma sulphureum and T. bufonium.* Mycological Research (London) 108(10): 1162-1171. https://doi.org/10.1017/S095375620400084X

Cremer, E., K. Donges, S. Liepelt, K. H. Rexer, G. G. Vendramin, I. Leyer, G. Kost & B. Ziegenhagen, 2009: *Ontogenetic and genotypic effects of silver fir (Abies alba Mill.) on associated ectomycorrhizal communities.* In: Cremer, E. (ed): *Population genetics of silver fir (Abies alba) in the Northern Black Forest-preconditions for the recolonization of wind throw areas and associated ectomycorrhizal communities.* Phillipps-Universität Marburg, Biologie (Marburg, pp. 62-83).

Eberhardt, U., F. Oberwinkler, A. Verbeken, A. C. Rinaldi, G. Pacioni & O. Comandin, 2000: *Lactarius ectomycorrhizae on Abies alba: morphological description, molecular characterization, and taxonomic remarks.* Mycologia (Oxfordshire) 92(5): 860-873. https://doi.org/10.2307/3761582

Euforgen database, 2017. EUFORGEN Secretariat. Rim.
http://www.euforgen.org/forest-genetic-resources/poplars-clones-database/

Hrenko, M., B. Štupar, T. Grebenc & H. Kraigher, 2009: *Mycobioindication method simplified : Sclerotia of Cenococcum geophilum Fr. as indicators of stress in forest soils.* V: Himmelbauer, M. (Ed.): *Short paper abstracts : 7th ISRR Symposium root research and applications.* Institute of Hydraulics and Rural Water Management (Vienna, p. 116).

Klopčič, M., K. Jerina & A. Bončina, 2009: *Long-term changes of structure and tree species composition in Dinaric uneven-aged forests: are red deer an important factor?* European Journal of Forest Research (Berlin) 129(3): 277-288. https://doi.org/10.1007/s10342-009-0325-z

Kowalski, S., 2008: *Mycorrhizaef of the European silver fir (Abies alba Mill.) seedlings from natural and artificial regeneration in forests of the Karkonosze National Park.* In: Barzdajn, W. & A. Raj (eds): *Silver fir in the Karkonosze National Park.* Karkonoski National Park (Jelenia Góra, 175–212 pp.).

Lagana, A., E. Salerini, C. Barluzzi, C. Perini & V. De Dominicis, 2000: *Mycocoenology in Abies alba Miller woods of central-southern Tuscany (Italy).* Acta societatis Botanicorum Poloniae (Varšava) 69(4): 293-298. https://doi.org/10.5586/asbp.2000.039

Lagana, A., C. Angioli, S. Loppi, E. Salerini, C. Perini, C. Barluzzi & V. De Dominicis, 2002: *Periodicity, fluctuations and successions of macrofungi in fir forests (Abies alba Miller) in Tuscany, Italy.* Forest Ecology and Management (Amsterdam) 169(3): 187-202. https://doi.org/10.1016/S0378-1127(01)00672-7

Lobuglio, K. F., 1999: *Cenococcum.* In: Cairney J. W. G & S. M. Chambers (eds.): *Ectomycorrhizal fungi: key genera in profile.* Springer-Verlag Berlin. (Berlin, 287–309 pp.). https://doi.org/10.1007/978-3-662-06827-4

Pacioni, G., O. Comandini & A. C. Rinaldi, 2001: *An assessment of below-ground ectomycorrhizal diversity of Abies alba miller in central Italy.* Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology (Firenze) 135(3): 337-350. https://doi.org/10.1080/11263500112331350960

Pillukat, A., 1996: *Lactarius salmonicolor R. Heim &Leclair + Abies alba Mill.* Descr Ectomyc (Schwäbisch Gmünd) 2: 59–64. https://doi.org/10.2307/3761582

Rudawska, M., M. Pietras, I. Smutek, P. Strzelisnki & T. Leski, 2016: *Ectomycorrhizal fungal assemblages of Abies alba Mill. outside its native range in Poland.* Mycorrhiza (Berlin) 26(1): 57-65. https://doi.org/10.1007/s00572-015-0646-3

Ruosch, M., R. Spahni , F. Joos, P. D. Henne, W.O. Van der Knaap & W. Tinner, 2015: *Past and future evolution* of *Abies alba forests in Europe – comparison of a dynamic vegetation model with paleo data and observations.* Global Change Biology (Switzerland) 22: 727-740. https://doi.org/10.1111/gcb.13075

Schirkonyer, U., C. Bauer & G. M. Rothe, 2013: *Ectomycorrhizal diversity at five different tree species in forests of the Taunus Mountains in Central Germany.* Open Journal of Ecology (Berlin) 3(1): 66-81. https://doi.org/10.4236/oje.2013.31009

Smith, S. E. & D. J. Read, 2008: *Mycorrhizal Symbiosis.* London.

Suz, L. M., A. M. Azul, M. H. Morris, C. S. Bledsoe & M. P. Martin, 2008: *Morphotyping and Molecular Methods to Characterize Ectomycorrhizal Roots and Hyphae in Soil.* In: Nautiyal C. S. & P. Dion (Eds.): *Molecular Mechanisms of Plant and Microbe Coexistence.* Heidelberg: Springer Berlin Heidelberg. (Berlin, 437-474 pp.). https://doi.org/10.1007/978-3-540-75575-3

Tinner, W., D. Colombaroli, O. Heiri, P. D. Henne, M. Seitnacher, J. Untenecker, E. Vescovi, J. R. M. Allern, G. Carro, M. Conedera, F. Joos, A. F. Lotter, J. Luterbacher, S. Sanartin & V. Valsecchi, 2013: *The past ecology of Abies alba provides new perspectives on future responsesn of silver fir forests to global warming.* Ecological Monographs (Washington) 83(4): 419-439. https://doi.org/10.1890/12-2231.1

Wazny, R., 2014: *Ectomycorrhizal communities associated with silver fir seedlings (Abies alba Mill.) differ largely in mature silver fir stands and in Scots pine forecrops.* Annals of Forest Science (Paris) 71(7): 801-810. https://doi.org/10.1007/s13595-014-0378-0

Wazny, R. & S. Kowalski, 2017: *Ectomycorrhizal fungal communities of silver-fir seedlings regenerating in fir stands and larch forecrops.* Trees (Berlin): 1-11. https://doi.org/10.1007/s00468-016-1518-y

Westergren, M., A. Poljanec & H. Kraigher, 2010: *Tehnične smernice za ohranjanje in rabo genskih virov : bela jelka : Abies alba : Sloveenija.* Gozdarski vestnik (Ljubljana) 68 (10): 491-494.