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Soil fungal communities in nurseries producing *Abies alba*

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Abstract

Silver fir is an important forest-forming species in the mountain and upland parts of Poland. It was determined that fir lost the possibility of spontaneous return to the forests of the region. That is why the Polish State Forests has launched a programme to restore its resources in the Sudetes. Until now, fungi and their relationship with fir have not been fully addressed in the Sudetes Restitution Programme, therefore this study was undertaken. The aim of this study was to determine the species composition of soil fungi from quarters producing silver fir seedlings. The research material was rhizosphere soil collected from 3-year-old saplings produced in forest nurseries of the Międzylesie Forest District. Fungal composition was determined by Next-Generation sequencing (Illumina NextSeq 500). The total number of OTUs obtained (638 435) included sequences of cultivated horcultured fungi (433 412 OTUs = 52.7%), non-cultivable fungi, that is which cannot be cultured (97 108 OTUs = 22.41%) and potential fungi with no reference sequence in UNITE (73 419 OTUs = 16.93%) and non-fungal organisms (34 496 = 7.96%). The following taxa as *Mortierella* sp. (8.23%), *Tylospora* sp. (6.68%) and *Russula* sp. (3.76%) had the largest share in the soil fungal communities. The results of the study indicate the dominance of saprotrophic and mycorrhizal fungi in the communities of fir roots, which proves that saplings are of good quality. Small share of pathogens sequences suggests that soil-born fungal pathogens are not a major threat to fir seedlings in nurseries.

Keywords: mycorrhizal fungi, nursery, *Abies alba*, seedlings, Międzylesie Forest District

Introduction

Fungi constitute a significant part of the soil microorganism community. It is estimated that they take approximately 1.33% of the soil volume and 0.2% of its weight, and that in 1 g of soil there are up to 10 million microorganism cells, including 75–1500.000 fungal spores (Watanabe 2002, Behnke-Borowczyk and Kwaśna 2010). The taxa of fungi that live in the soil are present in the roots and seeds. The most common soil fungi are species of the following genera: *Absidia* Tiegh., *Acremonium* Link, *Alternaria* Nees, *Aspergillus* P. Micheli ex Haller, *Botrytis* P. Micheli ex Haller, *Chaetomium* Kunze, *Cladosporium* Link, *Cylindrocarpon* Wollenw., *Fusarium* Link, *Mucor* Fresen., *Penicillium* Link, *Rhizophus* Ehrenb. and *Stemphylium* Wallr. (Waksman 1916, 1917, Behnke-Borowczyk and Kwaśna 2010, Frąc et al. 2018). Considering the relationship with plants, pathogenic, antagonistic to plant pathogenic, mycorrhizal, saprotrophic and parasitic fungi can be distinguished (Behnke-Borowczyk and Kwaśna 2010, Frąc et al. 2018).

The soil fungal biodiversity has a great impact on given tree species, especially at the nursery production stage, where it influences quality of the planting material. Silver fir (*Abies alba* Mill.) is an important forest-forming species in the mountain and upland parts of Poland. In 1998, its share in the forests of the Polish part of the Sudetes was below 0.4% and it was resolved that fir lost the possibility of spontaneous return to the forests of the region (Barzdajn 2000, 2012, Barzdajn and Kowalkowski 2012). It was why the Polish State Forests have launched a forest restoring programme in the Polish part of the Sudetes. Until now, fungi and their relationship with fir has not been fully addressed in the Sudetes Restitution Program, therefore this study was undertaken (Barzdajn 2000, 2012, Barzdajn and Kowalkowski 2012). Previous studies of the fir fungal communities were mainly focused on mycorrhizae (Kowalski 1982, Comandini et al. 2001, Laganà et al. 2002, Kowalski 2008, Ważny 2011, 2014, Rudawska et al. 2016, Terhonen et al. 2019) and pathogens (Puddu et al. 2003, Oliva and Colinas 2007, Łakomy et al. 2007, Niemtur et al. 2014, Chomicz-Zegar et al. 2016, Terhonen et al. 2019). On the other hand, soil fungal communities accompanying fir in nursery production were not investigated. The aim of this study was to determine the species composition of soil fungi from quarters producing silver fir seedlings. It was assumed that mycorrhizal fungi and saprotrophs will have a dominant share in such communities.

Materials and methods

In June 2017 thirty soil samples were taken from nurseries located in Międzylesie Forest District, where 3-year-old fir trees grew. The soil samples (in five repetitions) were collected as follows: 1) from under Scots pine canopy, 2) from under spruce canopy, 3) from under fir canopy (natural regeneration), 4) from Kosturkiewicz's containers, in which fir grew in nursery fields, 5) from open bed, and 6) from under fir trees that have been replanted after two seasons. Samples were taken randomly, from the topsoil to a depth of 25 cm (every 20 m). Thirty individual samples were placed in a container, mixed thoroughly and approx. 0.5 kg of such prepared soil was taken to the laboratory. Six samples of approximately 300 mg were taken from the later sample for further analysis.

DNA extraction was performed using DNeasy PowerSoil Kit (QIAGEN, Hilden, Germany) according to the manufacturer's protocol. The ITS1, 5.8S rDNA region was used to identify the fungal species, and the analysis was carried out with ITS1FI2 5′-GAACCWGCGGARGGATCA-3′ (Schmidt et al. 2013) and 5.8S 5`-CGCTGCGTT CTTCATCG-3` primers (Vilgalys et al. 1990). Each amplification reaction was carried out in a final volume of 25.0 µL containing 2 µL DNA, 0.2 µL of each primer, 10.1 µL deionized water and 12.5 µL 2X PCR MIX (A&A Biotechnology, Gdynia, Poland). Initial denaturation was carried out at 94°C for 5 min. Cycling conditions were: primer annealing at 56°C for 30 s elongation at 72°C for 30 s and final elongation at 72°C for 7 min. 35 cycles were carried out. The PCR product was then checked on a 1% agarose gel stained with Midori Green Advance DNA (Genetics, Dueren Germany). The resulting PCR product was purified and sequenced with the use of Illumina SBS technology (Genomed S.A. Warsaw, Poland).

The results were subjected to bioinformatic and statistical analysis according to Behnke-Borowczyk et al. (2019). The resulting sequences were compared with the reference sequences deposited in the UNITE community database (https://unite.ut.ee/, Nilsson et al. 2018) using BLAST algorithm.

Abundance of fungi was defined as the number of OTUs in a sample. Frequency of an individual taxon was defined as percentage (%) of OTUs in the total number of OTUs. Diversity was defined as the number of species in a sample.

The role of the detected fungal species in the community was determined based on literature data, and the Information System for Characterization and DEtermination of EctoMYcorrhizae (DEEMY) (Agerer and Rambold 2004–2014, Rudawska et al. 2016).

Results

The total number of OTUs obtained (638 435) included sequences of cultivated or cultured fungi (433 412 OTUs = 52.7%), non-culturable fungi that is which cannot be cultured (97 108 OTUs = 22.41%) and potential fungi with no reference sequence in UNITE (73 419 OTUs = 16.93%) and non-fungal organism (34 496 = 7.96%). Taxa belonging to the following clusters were identified in the study: Ascomycota (15.54%), Basidiomycota (24.16%), Mucoromycota (9.48%), Zoopagomycota (1.995%), Chytridiomycota (0.22%), Glomeromycota (0.08%), Rozellomycota (1.14%), non-cultivated fungi (22.41%) and representatives of the other Kingdoms (7.96%). Sequences that were not represented in the NCBI database (16.94%) were also present (Table 1).

The *Mortierella* sp. (8.23%). *Tylospora* sp. (6.68%) and *Russula* sp. (3.76%) had the largest share in the different soil fungal communities (Table 1).

The soil fungal communities were dominated by saprotrophic (28.6%), mycorrhizal (19.11%) and those unrecognized (18.97%) fungi. Pathogens (4.9%), antagonists in relation to forest tree pathogens (3.19%) and a small percentage of parasitic and lichen-forming fungi were also present. Among the mycorrhizal fungi and endophytes that were isolated *Tylospora* sp. (6.68%), *Russula* sp. (3.76%), *Amanita* sp. (1.95%), *Tricholoma* sp. (1.2%), and *Piloderma* sp. (1.11%) were identified. The most common mycorrhizal fungi and endophytes in the studied fungal community were: *Tylospora* sp. (6.68%). The most common pathogens were: *Chalara* (Corda) Rabenh. (0.82%), *Malassezia* Baill. (0.51%), *Fusarium* Link (0.41%) and antagonists in relation to pathogens: *Solicoccozyma* Xin Zhan Liu, F.Y. Bai, M. Groenew. et Boekhout (0.62 %).

Discussion

In the last two decades, numerous studies on the diversity of soil microorganisms, e.g. fungi or bacteria and their association with plants have been conducted. The abundance and diversity of microorganisms in soil from several common plant species, 'model plants', and their wild relatives were studied. Many of them play an important role in agriculture and forestry (Terhonen et al. 2019). However microorganisms associated with silver fir have not been fully studied and recognized, especially in Poland. So far, stand regeneration (Filipiak and Komisarek 2005), eutrophication (Lasota et al. 2015), effects of soil properties, and preparation on the growth of trees (Kucerová et al. 2013, Kobala et al. 2015, Kormanek et al. 2015)

Table 1. Taxa occurring in the communities of soil fungi, which share in the collection exceeded 0.01%

Dominant taxa are marked in bold. Symbols of trophic groups M – mycorrhizal fungi; S – saprotrophic fungi; A – antagonistic fungi; P – pathogenic fungi; L – lichens according to DEEMY (Agerer and Rambold 2004–2014, Rudawska et al. 2016). Colors of the last column contain the collected taxa data in the community: red – the smallest share; green – the largest share of the taxon in the community (the scale is attached below).

Taxons	Trophic group	Order	Similarity [%]	Frequency [%]
Ascomycota				
Acephala sp. + ***A. applanata*** Grünig & T.N. Sieber + *A. macrosclerotiorum* Münzenb. & Bubner	M	Helotiales	99–100	0.103
***Acremonium* sp.** + *A. alternatum* + *A. rutilum* W. Gams	S	Hypocreales	98–99	0.047
Alatospora acuminata Ingold + *A. flagellata* (Gönczöl) Marvanová	S	Leotiales	99–100	0.052
Apodus deciduus Malloch & Cain	S	Sordariales	98	0.013
***Archaeorhizomyces* sp.** + *A. borealis* Menkis. T.Y. James & Rosling	S	Archaeorhizomycetales	98–99	0.362
Archaeorhizomycetes			100	0.014
Arthrobotrys conoides Drechsler + *A. oligosporus* Fresen.	A	Orbiliales	99	0.035
Ascobolus sp.	S	Pezizales	98	0.214
Ascomycota			100	1.509
Aspergillus sp. + *A. costiformis* H.Z. Kong & Z.T. Qi + *A. inflatus* (Stolk & Malla) Samson. Frisvad. Varga. Visagie & Houbraken + *A. kassunensis* Baghd. + *A. parvulus* G. Sm. + *A. pseudodeflectus* Samson & Mouch. + ***A. tardus*** Bissett & Widden	A	Eurotiales	98–100	0.146
Byssonectria fusispora (Berk.) Rogerson & Korf		Pezizales	99	0.058
***Cadophora* sp.** + *C. finlandica* (C.J.K. Wang & H.E. Wilcox) T.C. Harr. & McNew + *C. orchidicola* (Sigler & Currah) M.J. Day & Currah	P	Helotiales	98–99	0.096
Caloplaca obscurella (J. Lahm) Th. Fr.		Teloschistales	98	0.015
Capnodiales			100	0.046
Cenococcum sp. + ***C. geophilum*** Fr.	M	Mytilinidiales	98–99	0.393
Chaetomiaceae	S	Sordariales	98	0.107
***Chaetomium* sp.** + *Ch. grande* Asgari & Zare	S	Sordariales	99–100	0.057
Chaetosphaeria sp. + ***Ch. vermicularioides*** (Sacc. & Roum.) W. Gams & Hol. Jech.	S	Chaetosphaeriales	98–99	0.026
Chaetosphaeriaceae		Chaetosphaeriales	100	0.016
Chaetothyriales			100	0.063
Chalara sp. + ***Ch. hyalocuspica*** Koukol + *Ch. longipes* (Preuss) Cooke + *Ch. piceaeabietis* Hol. Jech.	P	Microascales	99–100	0.819
Chloridium sp.	S	Chaetosphaeriales	100	0.012
Ciliophora sp.	S	Incertae sedis	100	0.191
Citeromyces siamensis Nagats. H. Kawas. Limtong. Mikata & T. Seki		Saccharomycetales	98	0.041
***Cladophialophora* sp.** + *C. chaetospira* (Grove) Crous & Arzanlou + *C. minutissima* M.L. Davey & Currah	P	Chaetothyriales	98–100	0.086
Cladorrhinum brunnescens W. Gams + *C. bulbillosum* W. Gams & Mouch + *C. flexuosum* Madrid. Cano. Gené & Guarro	A	Sordariales	98–100	0.028
Colletotrichum antirrhinicola Damm + ***C. cliviae*** Yan L. Yang. Zuo Y. Liu. K.D. Hyde & L. Cai	S	Incertae sedis	99–100	0.028
Crocicreas sp.	S	Helotiales	100	0.013
Cryptosporiopsis sp.	P	Helotiales	100	0.016
Dendryphion nanum (Nees) S. Hughes	S	Pleosporales	98	0.059
Dermateaceae		Helotiales	100	0.308
Devriesia sp.	S	Incertae sedis	100	0.016
Didymella dactylidis (Aveskamp. Gruyter & Verkley) Qian Chen & L. Cai + *D. protuberans* (Lév.) Qian Chen & L. Cai	S	Pleosporales	99	0.203
Dothideomycetes			100	0.272
Elaphomyces granulatus Fr. + *E. muricatus* Fr.	M	Elaphomycetales	99–100	0.198
Fusarium sp. + *F. asiaticum* O'Donnell. T. Aoki. Kistler & Geise + *F. concolor* Reinking + ***F. oxysporum*** Schltdl.	P	Hypocreales	98–100	0.413
Geomyces sp. + *G. asperulatus* Sigler & J.W. Carmich. + ***G. auratus*** Traaen	S	Helotiales	99	0.142
Gyoerffyella sp. + *G. entomobryoides* (Boerema & Arx) Marvanová	S	Incertae sedis	98–99	0.961
Halokirschsteiniothelia maritima (Linder) Boonmee & K.D. Hyde	S	Mytilinidiales	99	0.044
Harzia cameroonensis Crous & Jol. Roux + ***H. sphaerospora*** (Matsush.) D.W. Li & N.P. Schultes	S	Melanosporales	98–99	0.030
Helotiaceae		Helotiales	100	0.203
Helotiales			100	1.176
Herpotrichiellaceae		Chaetothyriales	99	0.033
Hyaloscyphaceae		Helotiales	99	0.116
Hymenoscyphus sp.	S	Helotiales	98	0.026
Hypocreales			100	0.528
Hypomyces sp. + ***H. microspermus*** Rogerson & Samuels + *H. ochraceus* (Pers.) Tul. & C. Tul	A	Hypocreales	98–99	0.052
Ilyonectria morspanacis (A.A. Hildebr.) A. Cabral & Crous + ***I. robusta*** (A.A. Hildebr.) A. Cabral & Crous	P	Hypocreales	99–100	0.044
Knufia peltigerae (Fuckel) Réblová & Unter.	L	Incertae sedis	99	0.017
Lasiosphaeriaceae		Sordariales	99	0.105
***Lecanicillium* sp.** + *L. primulinum* Kaifuchi. Nonaka & Masuma	A	Hypocreales	99–100	0.145
Lecanoromycetes	A		100	0.033
Lecythophora fasciculata (J.F.H. Beyma) E. Weber. Görke & Begerow	P	Coniochaetales	99	0.032
Leotia lubrica (Scop.) Pers.	L	Helotiales	99	0.061
Leotiomycetes sp.	L		100	0.213
***Leptodontidium* sp.** + *L. trabinellum* (P. Karst.) Baral. Platas & R. Galán	P	Incertae sedis	98–99	0.020
Leptosphaeria sp.		Pleosporales	98	0.051
Lophodermium conigenum (Brunaud) Hilitzer + ***L. piceae*** (Fuckel) Höhn. + *L. pinastri* (Schrad.) Chevall. + *L. seditiosum* Minter. Staley & Millar	P	Rhytismatales	98–100	0.069
Maasoglossum sp.	S	Helotiales	99	0.012
Mariannaea elegans (Corda) Samson	S	Hypocreales	99	0.025
Meliniomyces bicolor Hambl. & Sigler + ***M. variabilis*** Hambl. & Sigler + *M. vraolstadiae* Hambl. & Sigler	S	Incertae sedis	98–99	0.013
Metapochonia bulbillosa (W. Gams & Malla) Kepler. S.A. Rehner & Humber	S	Hypocreales	99	0.082
Metarhizium anisopliae (Metschn.) Sorokīn + *M. carneum* (Duché & R. Heim) Kepler. S.A. Rehner & Humber		Hypocreales	98–99	0.061
Microascus restrictus Sand. Den. Gené & Deanna A. Sutton	S	Microascales	98	0.015
Minutisphaera parafimbriatispora Raja. Oberlies. Shearer & A.N. Mill.	A	Minutisphaerales	98	0.040
Mycopappus sp.		Helotiales	98	0.010
Mycosphaerellaceae		Incertae sedis	100	0.015
Nadsonia commutata Golubev	S	Saccharomycetales	99	0.012
Nectria sp.	P	Hypocreales	100	0.070

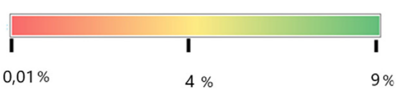
Table 1. Taxa occurring in the communities of soil fungi, which share in the collection exceeded 0.01% (continued)

Taxons	Trophic group	Order	Similarity [%]	Frequency [%]
Nectriaceae	P	Hypocreales	99	0.098
Neobulgaria sp + ***N. pura*** (Pers.) Petr	S	Helotiales	98–99	0.072
Neocosmospora solani (Mart.) L. Lombard & Crous	S	Hypocreales	98	0.020
Neonectria **sp.** + *N. candida* (Ehrenb.) Rossman. L. Lombard & Crous	P	Hypocreales	98–99	0.010
Ocellularia punctulata (Leight.) Zahlbr.		Ostropales	99	0.219
Ochroconis sp.	S	Venturiales	100	0.010
Oidiodendron sp. + *O. chlamydosporicum* Morrall + *O. echinulatum* G.L. Barron + *O. majus* G.L. Barron + *O. pilicola* Kobayasi + ***O. rhodogenum*** Robak	S	Incertae sedis	98–100	0.763
Orbiliaceae	S	Orbiliales	99	0.014
Penicilium amaliae Visagie. Houbraken & K. Jacobs + *P. arianeae Visagie. Houbraken & K. Jacobs* + *P. atrovenetum* G. Sm. + *P. bialowiezense* K.W. Zaleski + *P. brasilianum* Bat. + *P. cairnsense* Houbraken. Frisvad & Samson + *P. caperatum* Udagawa & Y. Horie + *P. chrysogenum* Thom + *P. citreonigrum* Dierckx + *P. glandicola* (Oudem.) Seifert & Samson + *P. lanosum* Westling + *P. lapidosum* Raper & Fennell + *P. nodositatum* Valla + *P. onobense* C. Ramírez & A.T. Martínez + *P. penicillioides (*Delacr.) Vuill. + *P. riverlandense* Visagie & K. Jacobs + *P. senticosum* D.B. Scott + *P. simplicissimum* (Oudem.) Thom + ***P. singorense*** Visagie. Seifert & Samson + *P. subrubescens* Houbraken. Mansouri. Samson & Frisvad + *P. vasconiae* C. Ramírez & A.T. Martínez	A	Eurotiales	98–100	0.363
Pezizaceae			100	0.011
Pezizales			100	0.043
Phacidium grevilleae Crous & M.J. Wingf.	S	Phacidiales	100	0.124
Phialocephala fortinii C.J.K. Wang & H.E. Wilcox + *P. fusca* W.B. Kendr.	P	Helotiales	98–100	0.023
Plectosphaerella cucumerina (Lindf.) W. Gams	P	Glomerellales	98	0.022
Pleosporales			100	0.166
Pleotrichocladium opacum (Corda) Hern.Restr. R.F. Castañeda & Gené	S	Pleosporales	99	0.449
Pleuroascus nicholsonii Massee & E.S. Salmon	S	Incertae sedis	97	0.020
Pleurophoma ossicola Crous. Krawczynski & H.G. Wagner	S	Xylariales	99	0.096
Pochonia sp. + ***P. cordycipiticonsociata*** H. Huang. Mu Wang & L. Cai	S	Hypocreales	98–99	0.021
Podospora sp. + ***P. appendiculata*** (Auersw. ex Niessl) Niessl	S	Sordariales	99–100	0.043
Pseudogymnoascus verrucosus A.V. Rice & Currah	S	Incertae sedis	100	0.151
Pseudopenidiella pini (P.M. Kirk & Minter) P.M. Kirk	S	Incertae sedis	99	0.071
Pseudosigmoidea ibarakiensis Diene & Narisawa	P	Incertae sedis	98	0.014
Pyronemataceae		Pezizales	98	0.042
Rhodoveronaea varioseptata Arzanlou. W. Gams & Crous	S	Incertae sedis	100	0.011
Robillarda sessilis (Sacc.) Sacc.	R	Incertae sedis	99	0.066
Saccharomyces cerevisiae (Desm.) Meyen	A	Saccharomycetales	99	0.035
Saccharomycetales	A		100	0.014
Sagenomella diversispora (J.F.H. Beyma) W. Gams + *S. striatispora* (Onions & G.L. Barron) W. Gams	S	Eurotiales	98	0.023
Sordariales			99	0.014
Sordariomycetes		Sordariales	99	0.179
Sphaerodes fimicola (E.C. Hansen) P.F. Cannon & D. Hawksw.	S	Hypocreales	98	0.070
Sphaerostilbella aureonitens (Tul. & C. Tul.) Seifert. Samuels & W. Gams	A	Hypocreales	99	0.224
Sporormiaceae		Pleosporales	100	0.026
Sporothrix sp. + ***S. brunneoviolacea*** Madrid. Gené. Cano & Guarro + *S. dimorphospora* (Roxon & S.C. Jong) Madrid. Gené. Cano & Guarro	P	Ophiostomatales	98–100	0.018
Tetracladium **sp.** + *T. setigerum* setigerum (Grove) Ingold	S	Helotiales	99	0.196
Trichocomaceae	A	Eurotiales	100	0.023
Trichoderma sp. + *T. alcalifuscescens* (Overton) Jaklitsch & Voglmayr + *T. asperellum* Samuels. Lieckf. & Nirenberg + ***T. crassum*** Bissett + *T. cremeum* P. Chaverri & Samuels + *T. foliicola* (Jaklitsch & Voglmayr) Jaklitsch & Voglmayr + *T. fomiticola* Jaklitsch + *T. longipilis* Bissett + *T. martiale* Samuels + *T. neokoningii* Samuels & Soberanis + *T. nothescens* Samuels & Jaklitsch + *T .pachypallidum* Jaklitsch + *T. parapiluliferum* (B.S. Lu. Druzhin. & Samuels) Jaklitsch & Voglmayr + *T. pleuroti* S.H. Yu & M.S. Park + *T. pubescens* Bissett + *T. rossicum* Bissett. C.P. Kubicek & Szakács + *T. spirale* Bissett + *T. stellatum* (B.S. Lu. Druzhin. & Samuels) Jaklitsch & Voglmayr + *T. theobromicola* Samuels & H.C. Evans	A	Hypocreales	97–100	0.320
Tuber sp.	M	Pezizales	99	0.036
Valdensinia heterodoxa Peyronel	P	Helotiales	100	0.013
Venturia **sp.** + *V. hystrioides* (Dugan. R.G. Roberts & Hanlin) Crous & U. Braun	P	Venturiales	99–100	0.085
Venturiaceae	P	Venturiales	100	0.080
Verrucaria sp. + ***V. elaeomelaena*** (A. Massal.) Arnold	L	Verrucariales	99	0.015
Verticillium leptobactrum W. Gams	P	Glomerellales	98	0.014
Xenopolyscytalum pinea Crous	P	Helotiales	97	0.057
Xylariales			100	0.021
Frequency of Ascomycota isolates				**15.5411**
Basidiomycota				
Agaricales			100	0.841
Agaricomycetes sp.		Agaricales	100	0.145
Amanita sp. + *A. beckeri* Huijsman + *A. fulva* Fr. + *A. muscaria* (L.) Lam. + ***A. rubescens*** Pers.	M	Agaricales	97–100	1.954
Apiotrichum dulcitum (Berkhout) Yurkov & Boekhout	S	Trichosporonales	99	0.022
Atheliaceae		Atheliales	99	0.061
Auriculariales			100	0.163
Basidiomycota				0.715
Boletaceae	M	Boletales	100	0.013
Boletus edulis Bull.	M	Boletales	100	0.107
Cantharellales	M		100	0.183
Cantharellus decolorans Eyssart. & Buyck	M	Cantharellales	99	0.102
Ceratobasidiaceae	S	Cantharellales	100	0.173
Clavariaceae		Agaricales	99	0.052
Clavulina sp. + ***C. coralloides*** (L.) J. Schröt.	M	Cantharellales	98–99	0.455
Clavulinopsis sp.	M	Agaricales	97	0.034
Conocybe echinata (Velen.) Singer + *C. semiglobata* Kühner & Watling	M	Agaricales	99–100	0.029
Coprinopsis narcotica (Batsch) Redhead. Vilgalys & Moncalvo	S	Agaricales	100	0.017
Cortinarius sp.+ *C. croceus (*Schaeff.) Gray + *C. fulvoconicus* M.M. Moser + ***C. semisanguineus*** (Fr.) Gillet	M	Agaricales	98–100	0.053
Cronartium pini (Willd.) Jørst.	P	Pucciniales	98	0.040
Entoloma byssisedum (Pers.) Donk + *E. conferendum* (Britzelm.) Noordel. + *E. juncinum* (Kühner & Romagn.) Noordel. + ***E. sericeum*** Quél.	M	Agaricales	98–100	0.023

Table 1. Taxa occurring in the communities of soil fungi, which share in the collection exceeded 0.01% (continued)

Taxons	Trophic group	Order	Similarity [%]	Frequency [%]
Erythrobasidiales			100	0.011
Flagelloscypha minutissima (Burt) Donk	S	Agaricales	99	0.045
Galerina sp. + *G. atkinsoniana* A.H. Sm. + ***G. fallax*** A.H. Sm. & Singer + *G. nana* (Petri) Kühner + *G. pseudocamerina* Singer + *G. stylifera* (G.F. Atk.) A.H. Sm. & Singer	S	Agaricales	97–100	0.903
Geminibasidium sp.		Geminibasidiales	99	0.055
Gymnopilus decipiens (Sacc.) P.D. Orton + *G. penetrans* (Fr.) Murrill	S	Agaricales	99–100	0.141
Hygrocybe sp. + *H. appalachianensis* (Hesler & A.H. Sm.) Kronaw. + ***H. intermedia*** (Pass.) Fayod	M	Agaricales	99	0.050
Hygrophoraceae	M	Agaricales	100	0.355
Hymenogaster boozeri Zeller & C.W. Dodge + *H. huthii* Stielow. Bratek & Hensel + ***H. olivaceus*** Vittad.	M	Agaricales	98–100	0.068
Hypochnicium sp. + ***H. geogenium*** (Bres.) J. Erikss. + ***H. punctulatum*** (Cooke) J. Erikss.	S	Polyporales	97–100	0.018
Inocybe sp. + *I. curvipes* P. Karst. + *I. flocculosa* Sacc. + ***I. napipes*** J.E. Lange + *I. nitidiuscula* (Britzelm.) Lapl. + *I. rimosa* (Bull.) P. Kumm. + *I. rufoalba* Sacc.	M	Agaricales	98–100	0.312
Lactarius musteus Fr. + ***L. necator*** (Bull.) Pers. + *L. quietus* (Fr.) Fr. + *L. rufus* (Scop.) Fr. + *L. tabidus* Fr.	M	Russulales	98–100	0.772
Lepiota echinella Quél. & G.E. Bernard + ***L. fuscovinacea*** F.H. Møller & J.E. Lange	S	Agaricales	98–99	0.018
Leucosporidiales			100	0.016
Leucosporidium sp. + ***L. drummii*** Yurkov. A.M. Schäfer & Begerow + *L. fasciculatum* Babeva & Lisichk. + *L. fellii* Gim. Jurado & Uden + *L. golubevii* Gadanho. J.P. Samp. & R. Bauer		Leucosporidiales	99–100	0.013
Lycoperdon nigrescens Pers. + ***L. perlatum*** Pers. + *L. pratense* Pers. + *L. subumbrinum* Jeppson & E. Larss.	S	Agaricales	97–100	0.016
Malassezia sp. + *M. cuniculi* J. Cabañes & G. Castellá + *M. globosa* Midgley. E. Guého & J. Guillot + ***M. restricta*** E. Guého. J. Guillot & Midgley + *M. sympodialis* R.B. Simmons & E. Guého	P	Incertae sedis	98–100	0.507
Microbotryomycetes			100	0.057
Minimedusa polyspora (Hotson) Weresub & P.M. LeClair		Cantharellales	99	0.082
Russula sp. + *R. amethystina* Quél. + *R. badia* Quél + *R. chloroides* (Krombh.) Bres. + *R. firmula* Jul. Schäff. + *R. fragilis* Fr. + ***R. ionochlora*** Romagn. + *R. nigricans* Fr. + *R. ochroleuca* Fr. + *R. paludosa* Britzelm. + *R. puellaris* Fr. + *R. sapinea* Sarnari + *R. veternosa* Fr.	M	Russulales	100	3.760
Russulaceae	M	Russulales	100	0.040
Sebacina sp.	M	Sebacinales	100	0.020
Sebacinaceae	M	Sebacinales	100	0.013
Sebacinales	M		100	0.016
Sistotrema sp.	S	Cantharellales	99	0.014
Solicoccozyma fuscescens (Golubev) Yurkov + *S. phenolica* (Á. Fonseca. Scorzetti & Fell) Yurkov + ***S. terrea*** (Di Menna) Yurkov + *S. terricola* (T.A. Pedersen) Yurkov	A	Filobasidiales	99	0.621
Sporidiobolales			100	0.168
Thelephoraceae	M	Thelephorales	99	0.392
Tomentella sp.	M	Thelephorales	98	0.079
Trechispora sp. + ***T. hymenocystis*** (Berk. & Broome) K.H. Larss. + *T. invisitata* (H.S. Jacks.) Liberta + *T. stevensonii* (Berk. & Broome) K.H. Larss.	S	Trechisporales	98–100	0.147
Trechisporales	S		100	0.066
Tremellales	S		99	0.027
Tremellomycetes sp.	S	Tremellales	99	0.071
Tricholoma sp. + ***T. fulvum*** (DC.) Bigeard & H. Guill. + *T. saponaceum* (Fr.) P. Kumm.	M	Agaricales	99–100	1.195
Trichosporon sp.	A	Tremellales	99	0.157
Tubulicrinis sp.	S	Hymenochaetales	98	0.011
Tylospora sp. + ***T. asterophora*** (Bonord.) Donk	M	Atheliales	98–99	6.681
Paraglomus sp.	M	Paraglomerales	99	0.002
Scutellospora alterata Oehl. J.S. Pontes. Palenz. I.C. Sánchez & G.A. Silva	M	Diversisporales	99	0.002
Frequency of Glomeromycota isolates				**0.082**
Rozellomycota				
Rozellomycota				1.142
Frequency of Rozellomycota isolates				**1.142**
Mucoromycota				
Absidia sp. + *Absidia caerulea* Bainier + ***A. cylindrospora*** Hagem + *A. glauca* Hagem	S	Mucorales	97–100	0.037
Mortierella sp.	S	Mucorales	100	8.226
Mortierellaceae	S	Mucorales	99	0.384
Mortierellales	S		100	0.610
Mucor abundans Povah + *M. bainieri* B.S. Mehrotra & Baijal + *M. circinelloides* Tiegh. + *M. hiemalis* Wehmer + *M. moelleri* (Vuill.) Lendn.	S	Mucorales	99	0.040
Umbelopsis sp.	S	Umbelopsidales	100	0.183
Frequency of Mucoromycota isolates				**9.480**
Zoopagomycota				
Basidiobolaceae	S		100	0.009
Basidiobolales	S		100	0.01
Basidiobolus ranarum Eidam	S	Basidiobolales	99	1.79
Piptocephalis graefenhanii H.M. Ho + *P. tieghemiana* Matr.	S	Zoopagales	98	0.013
Syncephalis sp.	S	Zoopagales	98	0.173
Frequency of Zoopagomycota isolates				**1.995**
uncultured fungus				22.4055
No sequence in the UNITE database				16.9346
Number of isolates				577013
Number of fungus isolates				433 412

Scale:



have been studied, taking soil from fir nursery beds into consideration.

Functional groups of fungi in forest soils include free-living saprotrophs and mycorrhiza (Smith and Read 2008). Functional groups of fungi inhabiting forest soils include mycorrhizal fungi and free-living saprotrophs (Smith and Read 2008). It is often difficult to determine the function of the latter. Many fungal species show phenotypic plasticity and depending on the prevailing conditions, adopt different life strategies – from saprotrophs to endophytes. Their role in the community is not always clear (Vasiliauskas et al. 2007, Kowalski 2008, Kuo et al. 2014, Jaber et al. 2014, Unuk et al. 2019). For example, the classification of the *Mycena* genus is very ambiguous. According to Unuk et al. (2019), *Mycena* spp. are saprotrophs however Kowalski (2008) classified *Mycena galopus* (Pers.) P. Kumm. as an ectomycorrhizal species. In this study *Mycena* were grouped with mycorrhizal fungi.

In soil of silver fir nursery, the fungal communities were dominated by saprotrophs involved in the processing of decayed organic matter.

Fungal communities determined in the study were dominated by saprotrophs that play an important role in the processing of decayed organic matter. *Rozellomycota* with saprotrophic *Mortierella* species accounted for 8.23% of the whole community. Mucoromycota and Ascomycota (*Archaeorhizomyces* sp., *Ascobolus* sp., *Ciliophora* sp., *Didymella* sp., *Geomyces* sp., *Gyoerffyella* sp., *Oidiodendron* sp., *Phacidium* sp., *Pleotrichocladium* sp., *Pseudogymnoascus* sp., *Tetracladium* sp., *Gyoerffyella* spp., *Oidiodendron* spp., and *Pleotrichocladium opacum* (Corda) Hern. Restr., R.F. Castañeda et Gené.) accounted for 15.54%, whereas Basidiomycota accounted for 24.16% of the whole community. The results of this research partly coincide a study by Sun et al. (2016), in which authors have detected 86 OTUs belonging to the Ascomycota phylum, and accounted for 3% of the total sequence reads; 234 OTUs from the Basidiomycota phylum (56% of the reads). The frequency of Basidiomycota in this study was much higher than Ascomycota. Among other Basidiomycota fungi many mycorrhizal species were detected, for example *Amanita, Boletus, Cantharellus, Clavulina, Cortinarius, Elaphomyces, Hygrophoraceae, Lactarius, Phellodon, Piloderma, Russula, Sebacina, Thelephora, Tomentella, Tricholoma, Tylospora* and *Xerocomellus*. Also, usually widely spread decay fungi from Amphinema genera were found. This taxon was earlier described by Smutek et al. (2010) in their study.

The above-mentioned species are common in boreal forests and temperate zones in Europe, including Poland (Kennedy et al., 2003, Nara 2006, Kowalski 2008). Some of these species (*Russula* and *Piloderma*) were however found in warmer climate – in Mexico (Argüelles-Moyao and Garibay-Orijel 2018). The fungi often form mycorrhiza with *Abies* (Matsuda and Hijii 1999, 2004, Eberhardt et al. 2000, Ishida et al. 2007, Cremer et al. 2009, Kranabetter et al. 2009, Smutek et al. 2010, Argüelles-Moyao and Garibay-Orijel 2018) and occur in silver fir nursery soil, younger and older fir stands (Korkama et al. 2006, Kowalski 2008, Wallander et al. 2010, Kyaschenko et al. 2017).

To date 13 species of ectomycorrhizal fungi (ECM) associated with the genus *Abies* have been included in DEEMY: *Abierhiza fascicularis* Haug et R. Weber, *A. tomentosa* Haug et R. Weber, *Cortinarius odorifer* Britzelm., *Lactarius caespitosus* Hesler et A.H. Sm., *L. deliciosus* (L.) Gray, *L. intermedius* Krombh. ex Berk. et Broome, *L. salmonicolor* R. Heim et Leclair, *L. subsericatus* Kühner et Romagn. ex Bon, *Polyporoletus sublividus* Snell, *Russula brevipes* Peck, *R. ochroleuca* Pers., *R. silvicola* Shaffer and *Tricholoma bufonium* (Pers.) Gillet, of which only *R. ochroleuca* was found in the sampled soil fungal community. The presence of *Cenococcum geophilum* and *Thelephora stuposa* was not significant in the study which is in opposition to the research done by Rudawska et al. (2016). The list of mycorrhizal species detected in silver fir soils includes: *Amanita, Amphinema, Boletus, Cenococcum*, *Clavulina* J. Schröt., *Cortinarius*, Elaphomyces, *Hydnum* L., *Inocybe* (Fr.) Fr., *Lactarius*, Leotiomycetes O.E. Erikss. et Winka, *Piloderma, Pseudotomentella* Svrček, *Russula, Sebacina, Thelephora* and *Tylospora* that were earlier described in Poland by Wojewoda (2003). *Byssocorticium* Bondartsev et Singer ex Singer, *Laccaria* Berk. et Broome, *Paxillus* Fr., *Tomentellopsis* Hjortstam and *Xerocomus* Quél were not detected in the study. The above-mentioned species were found in fir nursery soil by Schirkonyer et al. (2013), Ważny (2014) and Unuk et al. (2019).

Glomeromycota and Ascomycota (*Acephala, Cenococcum*) mycorrhizal or root-associated fungi were not as abundant as Basidiomycota. Members of Glomeromycota form arbuscular mycorrhizas (AMS) with mosses and roots of land vascular plants (Parniske 2008). They form symbioses with the roots of most plant species (>80%). *Cenococcum* is one of the most common ectomycorrhizal fungal species encountered in forest ecosystems. *Cenococcum geophilum* and *Thelephora stuposa* were not significantly frequent in the studied soil, and this again is in opposition with Rudawska et al. (2016).

A few phytopathogens, e.g. *Chalara, Malassezia* and *Fusarium* were detected in the study. The above-mentioned pathogens are typical examples of soil-borne pathogens (Werner 2012, Lazreg et al. 2014, Orr and Nelson 2018, Theelen et al. 2018, Kowalska et al. 2017). Their frequency was low, and several ones, e.g. *Malassezia* (common pathogen of mammals, Theelen et al. 2018) are not dangerous for trees. In sampled soils fungi antagonistic to phytopathogens, including species of *Penicillium* (0.36%) and *Trichoderma* (0.32%) were also present. The low frequency of pathogens and relatively high frequency of their antagonists, apart from forming the high frequency of mycorrhizal fungi, gave the chance to produce the healthy and good-quality planting material.

Using the Illumina sequencing technique 3.072 fungal taxa were found in the material sampled in this study. Argüelles-Moyao and Garibay-Orijel (2018) obtained 1,746 species from *Abies religiosa* (Kunth) Schltdl. et Cham. soil in central Mexico. The results of mycological studies still do not present the actual microbial situation in soil. Despite the advanced techniques used, the detection and identification of many taxa is still impossible. This affects taxon sequences that are not deposited in databases, and fungi non-cultivated on artificial media. In this study, the frequency of the former and the latter was 17% and 20%, respectively.

Conclusion

This study led to recognising the spectrum of saprotrophic, mycorrhizal, and pathogenic fungi characteristic for the soil, in which 3 year old *Abies alba* grew.

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References

Agerer, R. and Rambold, G. 2004–2014. DEEMY – An Information System for Characterization and Determination of Ectomycorrhizae. München, Germany. Available online at: www.deemy.de [First posted on 2004-06-01; Most recent update: 2019-09-15].

Argüelles-Moyao, A. and Garibay-Orijel, R. 2018. Ectomycorrhizal fungal communities in high mountain conifer forests in central Mexico and their potential use in the assisted migration of *Abies religiosa*. *Mycorrhiza* 28(5–6): 509–521.

Barzdajn, W. 2000. Strategia restytucji jodły pospolitej (*Abies alba* Mill.) w Sudetach [Restitution strategy of the common fir (*Abies alba* Mill.) in the Sudetes]. *Sylwan* 144 (2): 63–77.

Barzdajn, W. 2012. Restytucja jodły pospolitej w Sudetach. Program działania dla sudeckich nadleśnictw Regionalnej Dyrekcji Lasów Państwowych we Wrocławiu [Restitution of silver fir in the Sudetes. Action program for Sudeten Forest Districts of the Regional Directorate of State Forests in Wrocław]. Wydanie I. Ośrodek Rozwojowo-Wdrożeniowy Lasów Państwowych w Bedoniu, 92 pp. (in Polish).

Barzdajn, W. and Kowalkowski, W. 2012. Restytucja jodły pospolitej (*Abies alba* Mill.) w Sudetach. Charakterystyka drzew zachowawczych [Restitution of Fir (*Abies alba* Mill.) in the Sudetes. Characteristics of conservative trees]. *Forestry Letters* 103: 7–16 (in Polish with English abstract).

Behnke-Borowczyk, J. and Kwaśna, H. 2010. Grzyby glebowe i ich znaczenie [Soil fungi and their significance]. *Sylwan* 154(12): 846–850 (in Polish with English abstract).

Behnke-Borowczyk, J., Kwaśna, H. and Kulawinek, B.J. 2019. Fungi associated with *Cyclaneusma* needle cast in Scots pine in west of Poland. *Forest Pathology* 49(2): e12487. https://doi.org/10.1111/efp.12487.

Chomicz-Zegar, E., Niemtur, S., Kapsa, M. and Ambroży, S. 2016. Butt rot occurrence in plus trees of Silver fir *Abies alba* Mill. and Norway spruce *Picea abies* (L.) from the Carpathians. *Leśne Prace Badawcze / Forest Research Papers* 77(3): 212–220. https://doi.org/10.1515/frp-2016-0023.

Comandini, O., Pacioni, G. and Rinaldi, A.C. 2001. An assessment of belowground ectomycorrhizal diversity of *Abies alba* Miller in central Italy. *Plant Biosystems* 135: 337–350.

Cremer, E., Donges, K., Liepelt, S., Rexer, K.H., Vendramin, G.G., Leyer, I., Kost, G. and Ziegenhagen, B. 2009. Ontogenetic and genotypic effects of silver fir (*Abies alba* Mill.) on associated ectomycorrhizal communities. Manuscript. In: Cremer, E. Population genetics of silver fir (*Abies alba*) in the Northern Black Forest – preconditions for the recolonization of wind throw areas and associated ectomycorrhizal communities. Dissertation zur Erlangung des Doktorgrades der Naturwissenschaften (Dr. rer. nat.). Fachbereich Biologie, Philipps-Universität Marburg, Marburg/Lahn, 93 pp. Available online at: https://archiv.ub.uni-marburg.de/diss/z2009/0130/pdf/dec.pdf.

Eberhardt, U., Verbeken, A., Rinaldi, A.C., Pacioni, G. and Comandini, O. 2000. *Lactarius* ectomycorrhizae on *Abies alba*: morphological description. molecular characterization and taxonomic remarks. *Mycologia* 92: 860–873.

Filipiak, M. and Komisarek, J. 2005. Regeneration of the European silver fir (*Abies alba* Mill.) in the Sudety Mountains on soils with different physico-chemical properties. *Dendrobiology* 53: 17–25.

Frąc, M., Hannula, S.E., Bełka, M. and Jędryczka, M. 2018. Fungal Biodiversity and their Role in Soil Health. *Frontiers in Microbiology* 9: 707.

Ishida, T.A., Nara, K. and Hogets, T. 2007. Host effects on ectomycorrhizal fungal communities: insight from eight host species in mixed conifer-broadleaf forests. *New Phytologist* 174: 430–440.

Jaber, E., Xiao, C. and Asiegbu, F.O. 2014. Comparative pathobiology of *Heterobasidion annosum* during challenge on *Pinus sylvestris* and *Arabidopsis* roots: An analysis of defensin gene expression in two pathosystems. *Planta* 239: 717–733.

Kennedy, P.G., Izzo, A.D. and Bruns, T.D. 2003. There is high potential for the formation of common mycorrhizal networks between understorey and canopy trees in a mixed evergreen forest. *Journal of Ecology* 91: 1071–1080.

Korkama, T., Pakkanen, A. and Pennanen, T. 2006. Ectomycorrhizal community structure varies among Norway spruce (*Picea abies*) clones. *New Phytologist* 171: 815–824.

Kobala, M., Grčman, H., Zupan, M., Levanič, T., Simončič, P., Kadunc, A. and Hladnik, D. 2015. Influence of soil properties on silver fir (*Abies alba* Mill.) growth in the Dinaric Mountains. *Forest Ecology and Management* 337(2): 77–87.

Kormanek, M., Banach, J. and Leńczuk, D. 2015. Influence of soil compaction on the growth of silver fir (*Abies alba* Mill.) under a forest canopy. *Ecological Questions* 22: 47–54.

Kowalska, B., Smolińska, U., Szczech, M. and Winciorek, J. 2017. Application of organic waste material overgrown with *Trichoderma atroviride* as a control strategy for *Sclerotinia sclerotiorum* and *Chalara thielavioides* in soil. *Journal of Plant Protection Research* 57(3): 205–211.

Kowalski, S. 1982. Role of mycorrhiza and soil fungi community in natural regeneration of fir (*Abies alba* Mill.) in Polish Carpathians and Sudetes. *European Journal of Plant Pathology* 12: 107–112.

Kowalski, S. 2008. [Mycorrhizae of the European Silver fir (*Abies alba* Mill.) seedlings from natural and artificial regeneration in forests of the Karkonosze National Park]. In: Barzdajn, W. and Raj, A. (Eds.) Jodła pospolita w Karkonoskim Parku Narodowym [Silver fir in the Karkonosze National Park]. Karkonoski Park Narodowy, Jelenia Góra, p. 175–212 (in Polish).

Kranabetter, J.M., Durall, D.M. and MacKenzie, W.H. 2009. Diversity and species distribution of ectomycorrhizal fungi along productivity gradients of southern boreal forest. *Mycorrhiza* 19: 99–111.

Kuceravá, B., Dobrovolný, L. and Remeš, J. 2013. Responses of *Abies alba* seedlings to different site conditions in *Picea abies* plantations. *Dendrobiology* 69: 49–58.

Kuo, H.C., Hui, S., Choi, J., Asiegbu, F.O., Valkonen, J.P.T. and Lee, Y.H. 2014. Secret lifestyles of *Neurospora crassa. Scientific Reports* 4: 5135.

Kyaschenko, J., Clemmensen, K.E., Hagenbo, A., Karltun, E. and Lindahl, B.D. 2017. Shift in fungal communities and associated enzyme activities along an age gradient of managed *Pinus sylvestris* stands. *ISME Journal* 11: 863–874.

Laganà, A., Agnolini, C., Loppi, S., Salerni, E., Perini, C., Barluzzi, C. and De Dominicis, V. 2002. Periodicity. fluctuations of macrofungi in fir forests (*Abies alba* Mill.) in Tuscany. Italy. *Forest Ecology and Management* 169: 187–202.

Lasota, J., Błońska, E. and Zwydak, M. 2015. Warunki glebowe eutroficznych lasów jodłowych Beskidu Niskiego oraz Sądeckiego [Soil conditions of eutrophic fir forests of the Low Beskids and Sądecki]. *Sylwan* 159(9): 767–777 (in Polish with English abstract).

Lazreg, F., Belabid, L., Sanchez, J., Gallego, E. and Bayaa, B. 2014. Pathogenicity of *Fusarium* spp. associated with diseases of Aleppo-pine seedlings in Algerian forest nurseries. *Journal of Forest Science* 60(3): 115–120.

Łakomy, P., Broda, Z. and Werner, A. 2007. Genetic diversity of *Heterobasidion* spp. in Scots pine. Norway spruce and European silver fir stands. *Acta Mycologica* 42(2): 203–210.

Matsuda, Y. and Hijii, N. 1999. Ectomycorrhizal morphotypes of naturally grown *Abies firma* seedlings. *Mycoscience* 40: 217–226.

Matsuda, Y. and Hijii, N. 2004. Ectomycorrhizal fungal communities in an *Abies firma* forest with special reference to ectomycorrhizal associations between seedlings and mature trees. *Canadian Journal of Botany* 82: 822–829.

Nara, K. 2006. Ectomycorrhizal networks and seedling establishment during early primary succession. *New Phytologist* 169: 169–178.

Niemtur, S., Chomicz, E. and Kapsa, M. 2014. Occurrence of the silver fir (*Abies alba* Mill.) butt rot in protected area. *Leśne Prace Badawcze* 75(4): 343–352.

Nilsson, R.H., Larsson, K-H., Taylor, A.F.S., Bengtsson-Palme, J., Jeppesen, T.S., Schigel, D., Kennedy, P., Picard, K., Glöckner, F.O., Tedersoo, L., Saar, I., Kõljalg, U. and Abarenkov, K. 2018. The UNITE database for molecular identification of fungi: handling dark taxa and parallel taxonomic classifications. *Nucleic Acids Research* 47(D1): D259–D264. https://doi.org/10.1093/nar/gky1022.

Oliva, J. and Colinas, C. 2007. Decline of silver fir (*Abies alba* Mill.) stands in the Spanish Pyrenees: Role of management. historic dynamics and pathogens. *Forest Ecology and Management* 252: 84–97.

Orr, R. and Nelson, P.N. 2018. Impacts of soil abiotic attributes on *Fusarium* wilt. focusing on bananas. *Applied Soil Ecology* 132: 20–33.

Parniske, M. 2008. Arbuscular mycorrhiza: The mother of plant root endosymbioses. *Nature Reviews Microbiology* 6: 763–775.

Puddu, A., Luisi, N., Capretti, P. and Santini, A. 2003. Environmental factors related to damage by *Heterobasidion abietinum* in *Abies alba* forests in Southern Italy. *Forest Ecology and Management* 180(1-3): 37–44.

Rudawska, M., Pietras, M., Smutek, I., Strzeliński, P. and Leski, T. 2016. Ectomycorrhizal fungal assemblages of *Abies alba* Mill. outside its native range in Poland. *Mycorrhiza* 26: 57–65.

Schirkonyer, U., Bauer, Ch. and Rothe, G.M. 2013. Ectomycorrhizal diversity at five different tree species in forests of the Taunus Mountains in Central Germany. *OJE* 3(1): 66–81. https://doi.org/10.4236/oje.2013.31009.

Smith, S.E. and Read, D.J. 2008. Mycorrhizal Symbiosis. 3rd ed. Academic Press, London, 800 pp.

Smutek, I., Rudawska, M. and Leski, T. 2010. Ektomikoryzy – ukryty potencjał w badaniach mikobioty drzew leśnych na przykładzie drzewostanów jodłowych [Ectomycorrhizas – hidden potential in mycobiotics of forest trees on the example of fir stands]. http://www.czlowiekiprzyroda.eu/Ksiazki/74.pdf. Presentation (in Polish). Retrieved from: https://czlowiekiprzyroda.eu/wp-content/uploads/2017/07/74.pdf.

Sun, H., Terhonen, E., Kovalchuk, A., Tuovila, H., Chen, H., Oghenekaro, A.O., Heinonsalo, J., Kohler, A., Kasanen, R., Vasander, H. and Asiegbu, F.O. 2016. Dominant tree species and soil type affect the fungal community structure in a boreal peatland forest. *Applied and Environmental Microbiology* 82: 2632–2643.

Schmidt, P.-A., Bálint, M., Greshake, B., Bandow, C., Römbke, J. and Schmitt, I. 2013 Illumina metabarcoding of a soil fungal community. *Soil Biology & Biochemistry* 65: 128–132. https://doi.org/10.1016/j.soilbio.2013.05.014.

Theelen, B., Cafarchia, C., Gaitanis, G., Bassukas, I.D., Boekhout, T. and Dawson, T.L. Jr. 2018. *Malassezia* ecology, pathophysiology and treatment. *Medical Mycology* 56: 10–25.

Terhonen, E., Blumenstein, K., Kovalchuk, A. and Asiegbu, F.O. 2019. Forest Tree Microbiomes and Associated Fungal Endophytes: Functional Roles and Impact on Forest Health. *Forests* 10: 42.

Unuk, T., Martinović, T., Finžgar, D., Šibanc, N., Grebenc, T. and Kraigher, H. 2019. Root-Associated fungal communities from two phenologically contrasting Silver fir (*Abies alba* Mill.) Groups of Trees. *Frontiers in Plant Science*. https://doi.org/10.3389/fpls.2019.00214.

Vasiliauskas, R., Menkis, A., Finlay, R.D. and Stenlid, J. 2007. Wood decay fungi in fine living roots of conifer seedlings. *New Phytologist* 174: 441–446.

Vilgalys, R. and Gonzalez, D. 1990. Organisation of ribosomal DNA in the basidiomycete *Thanatephorus praticola. Current Genetics* 18: 277–280.

Wallander, H., Johansson, U., Sterkenburg, E., Brandstrom, D.M. and Lindahl, B.D. 2010. Production of ectomycorrhizal mycelium peaks during canopy closure in Norway spruce forests. *New Phytologist* 187: 1124–1134.

Watanabe, T. 2002. Pictorial atlas of soil and seed fungi: morphologies of cultured fungi and key to species. 2nd ed. CRC Press, Boca Raton – London – New York – Washington, D.C., 486 pp. https://doi.org/10.1201/9781420040821.

Ważny, R. 2011. Mycorrhizas of *Abies alba* Mill. natural regeneration from forest stands in Experimental Forestry Unit in Krynica. *Episteme* 12(II): 89–96.

Ważny, 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* 71: 801–810.

Waksman, S.A. 1916. Soil fungi and their activities. *Soil Science* 2: 103–155.

Waksman, S.A. 1917. Is there any soil fungus flora in the soil? *Soil Science* 3: 565–589.

Werner, E.H. 2012. A new method of quantitative detection of *Chalara elegans* and *C. thielavioides* in soils using carrot discs. *Journal of Plant Diseases and Protection* 119 (5/6): 169–173.

Wojewoda, W. 2003. Checklist of Polish Larger Basidiomycetes. [Krytyczna Lista wielkoowocnikowych grzybów podstawkowych Polski]. Series: Biodiversity of Poland, vol. 7. 'W. Szafer' Institute of Botany, Kraków. 812 pp.