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PO Box 117
221 00 Lund
+46 46-222 00 00

Ectomycorrhizal fungi: Their role in nitrogen retention and carbon sequestration in northern coniferous forests

Adam Bahr



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Faculty opponent:
Prof. Thom W. Kuyper
Wageningen University
Department of Soil Quality
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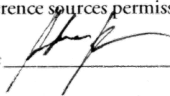
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<p>Abstract</p> <p>Almost all northern forest tree species live in symbioses with ectomycorrhizal fungi (EMF). The trees allocate up to half of the photoassimilated C through the roots to EMF. In return EMF deliver nutrients from both inorganic and organic sources in the soil, as well as water. Most of the nutrients trees need are assimilated through EMF, which thus play a potentially important role in retaining nitrogen (N) in the soil. However, it is still not clear to what extent they contribute to the total N retention capacity of northern forest soils. This thesis shows that recently produced (within 4 months) mycelium of EMF was capable to assimilate a substantial amount of inorganic N (6 kg-1 ha-1 month-1). If the total standing biomass of EMF mycelium were to be taken in to account, the total EMF N assimilation would likely be much larger. On the other hand, an abundant network of EMF mycelium was not sufficient to prevent a flush of N leaching that followed immediately after N fertilization, but it may be sufficient to retain more moderate additions of N. Leaching of N has been reported in N saturated northern forests, and further research is needed to reveal the role of N retention by EMF in relation to N assimilation by other microorganisms or directly by the tree roots, under various levels of N input in forest soil.</p> <p>Northern forest soils have been reported as a major terrestrial carbon (C) pool. This is typically explained by slow decomposition due to low temperatures, and recalcitrant litter from the coniferous trees that dominate these forests. A less discussed source to the C pool is the one originating from roots and root associated microorganisms. Since about half of the photoassimilated C is allocated belowground in coniferous forests, this is a potentially important process affecting the C sequestration. Previous studies have highlighted the potential of EMF as an important contributor to C sequestration. This is based on observations of substantial production of EMF mycelium, and that EMF tissue contains recalcitrant compounds. One of the conclusions in this thesis was that most of the soil organic C (SOC) in late successional stages originates from belowground inputs from roots and root associated fungi. This contrasts the focus on aboveground plant production in other studies where changes in forest C storage have been examined. Other results emphasize the important role of EMF in the build-up of soil organic matter: up to more than half a ton of EMF mycelium was produced during only four months, and the average C sequestration by EMF mycelium in a large scale field survey was calculated to more than 300 kg C ha-1 y-1.</p> <p>Carbon sequestered by EMF may however be sensitive to additions of N, which typically repress EMF growth. There have been many observations of reduced EMF mycelium production after large additions of inorganic N (typically 100 kg-1 ha-1 y-1), but we show that the moderate (less than 20 kg-1 ha-1 y-1) and continuous addition from elevated N deposition in many northern forest regions is sufficient for the repressive effect to occur. Consequently, C sequestration by EMF may be reduced by N deposition. This opposes the positive effect that N addition has on C sequestration due to other processes that are based on aboveground C inputs and degradation of soil organic matter. Even though previous research indisputably show that large N additions increase the C sequestration in forest soils, the effect is lacking at moderate N inputs. Thus, an important question that still remains to be answered is how low levels of anthropogenic N deposition affect the C cycle in northern forest regions. Further, the belowground contribution to SOC is often neglected, but necessary to include for accurate modeling of the C cycle in northern forests, particularly given the evidence that belowground inputs can make a larger contribution to SOC than aboveground inputs.</p>		
<p>Key words: Ectomycorrhizal fungi, Carbon sequestration, Nitrogen deposition, Nitrogen leakage, Field survey, Boreo-nemoral forest, Boreal Forest, Ergosterol, Free ergosterol, Mesh-bags, Multivariate analysis</p>		
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Department of Biology
Microbial Ecology Group
Faculty of Science
Lund University
Ecology Building
SE - 223 62 Lund, Sweden

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LIST OF PAPERS

In the thesis, the papers are referred to the roman numerals.

- Paper I** Wallander, H., Ekblad, A., Godbold, D.L., Johnson, D., Bahr, A., Baldrian, P., Björk, R.G., Kieliszewska-Rokicka, B., Kjøller, R., Kraigher, H., Plassard, C., Rudawska, M., 2013. Evaluation of methods to estimate production, biomass and turnover of ectomycorrhizal mycelium in forests soils – A review. *Soil Biology and Biochemistry* 57, 1034-1047.
- Paper II** Bahr, A., Ellström, M., Akselsson, C., Ekblad, A., Mikusinska, A., Wallander, H., 2013. Growth of ectomycorrhizal fungal mycelium along a Norway spruce forest nitrogen deposition gradient and its effect on nitrogen leakage. *Soil Biology and Biochemistry* 59, 38-48.
- Paper III** Sterkenburg, E., Bahr, A., Brandström-Durling, M., Clemmensen, K.E., Lindahl, B.D., Shift in composition and functioning of the fungal community along a natural boreal forest nutrient gradient (Manuscript)
- Paper IV** Clemmensen, K.E., Bahr, A., Ovaskainen, O., Dahlberg, A., Ekblad, A., Wallander, H., Stenlid, J., Finlay, R.D., Wardle, D.A., Lindahl, B.D., 2013. Roots and associated fungi drive long-term carbon sequestration in boreal forest. *Science* 339, 1615-1618.
- Paper V** Bahr, A., Ellström, M., Bergh, J., Wallander, H., Evaluation of soil N retention capacity by ectomycorrhizal fungi in a Norway spruce forest fertilized with nitrogen and phosphorus (Manuscript)

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List of contribution

- Paper I** Contributed to the discussion and writing of the paper, regarding ergosterol methods.
- Paper II** Main responsibility for the planning of the study. Shared responsibility in setting up the design and performing the fieldwork. Main responsibility for analysis and writing of the paper.
- Paper III** Responsible for analysis and interpretation of ergosterol. Contributed to statistics, discussion and writing of the paper.
- Paper IV** Contributed to fieldwork and shared responsibility regarding sample preparation. Main responsibility for analysis and interpretation of ergosterol. Contributed to the discussion and writing of the paper.
- Paper V** Main responsibility for the planning of the study and setting up the design. Shared responsibility in performing the fieldwork. Main responsibility for analysis and writing of the paper.

ABSTRACT

Almost all northern forest tree species live in symbioses with ectomycorrhizal fungi (EMF). The trees allocate up to half of the photoassimilated carbon (C) through the roots to EMF. In return EMF deliver nutrients from both inorganic and organic sources in the soil, as well as water. Most of the nutrients trees need are assimilated through EMF, which thus play a potentially important role in retaining nitrogen (N) in the soil. However, it is still not clear to what extent they contribute to the total N retention capacity of northern forest soils. This thesis shows that recently produced (within 4 months) mycelium of EMF was capable to assimilate a substantial amount of inorganic N ($6 \text{ kg}^{-1} \text{ ha}^{-1} \text{ month}^{-1}$). If the total standing biomass of EMF mycelium were to be taken in to account, the total EMF N assimilation would likely be much larger. On the other hand, an abundant network of EMF mycelium was not sufficient to prevent a flush of N leaching that followed immediately after N fertilization, but it may be sufficient to retain more moderate additions of N. Leaching of N has been reported in N saturated northern forests, and further research is needed to reveal the role of N retention by EMF in relation to N assimilation by other microorganisms or directly by the tree roots, under various levels of N input in forest soil.

Northern forest soils have been reported as a major terrestrial C pool. This is typically explained by slow decomposition due to low temperatures, and recalcitrant litter from the coniferous trees that dominate these forests. A less discussed source to the C pool is the one originating from roots and root associated microorganisms. Since about half of the photoassimilated C is allocated belowground in coniferous forests, this is a potentially important process affecting the C sequestration. Previous studies have highlighted the potential of EMF as an important contributor to C sequestration. This is based on observations of substantial production of EMF mycelium, and that EMF tissue contains recalcitrant compounds. One of the conclusions in this thesis was that most of the soil organic C (SOC) in late successional stages originates from belowground inputs from roots and root associated fungi. This contrasts the focus on aboveground plant production in other studies where changes in forest C storage have been examined. Other results emphasize the important role of EMF in the build-up of soil organic matter: up to more than half a ton of EMF mycelium was produced during only four months, and the average C sequestration by EMF mycelium in a large scale field survey was calculated to more than $300 \text{ kg C ha}^{-1} \text{ y}^{-1}$.

Carbon sequestered by EMF may however be sensitive to additions of N, which typically repress EMF growth. There have been many observations of reduced EMF mycelium production after large additions of inorganic N (typically $100 \text{ kg}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$), but we show that the moderate (less than $20 \text{ kg}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$) and continuous addition from elevated N deposition in many northern forest regions is sufficient for the repressive effect to occur. Consequently, C sequestration by EMF may be reduced by N deposition. This opposes the positive effect that N addition has on C sequestration due to other processes that are based on aboveground C inputs and degradation of soil organic matter. Even though previous research indisputably show that large N additions increase the C sequestration in forest soils, the effect is lacking at moderate N inputs. Thus, an important question that still remains to be answered is how low levels of anthropogenic N deposition affect the C cycle in northern forest regions. Further, the belowground contribution to SOC is often neglected, but necessary to include for accurate modeling of the C cycle in northern forests, particularly given the evidence that belowground inputs can make a larger contribution to SOC than aboveground inputs.

BACKGROUND

Carbon cycle

Global warming is a widely accepted phenomena, and it has been ascribed to increased anthropogenic greenhouse gas (GHG) emissions (Bernstein et al., 2008). The most important GHG is carbon dioxide (CO_2), which has increased from a preindustrial concentration of 280 ppm to 389 ppm in 2010 (Tarasova et al., 2012). Even though the main cause of the atmospheric increase in CO_2 is combustion of fossil fuel, inappropriate management of boreal forests may result in a considerable elevation of these values, due to degradation and respiration of soil C. Boreal forests cover about 10 % of the land (Bonan and Shugart,

1989; Watson and Change, 2000) and together they constitute one of the largest terrestrial C pools, predominantly due to the large soil C stock (Fig. 1). Actually, the C stored in boreal forest soils has been estimated to be at level with the combined C storage in tropical forest vegetation and soils, even though the latter biome covers a larger area (Watson and Change, 2000). These estimates are based on C content in the upper one meter of the soil (Dixon et al., 1994), and it should be noted that recent findings show that much C is bound to minerals in deep soils. However, the very deep C stocks are more stable (Fang and Moncrieff, 2005) and less sensitive to changes in climate or management than the upper part (Brady and Weil, 2008).

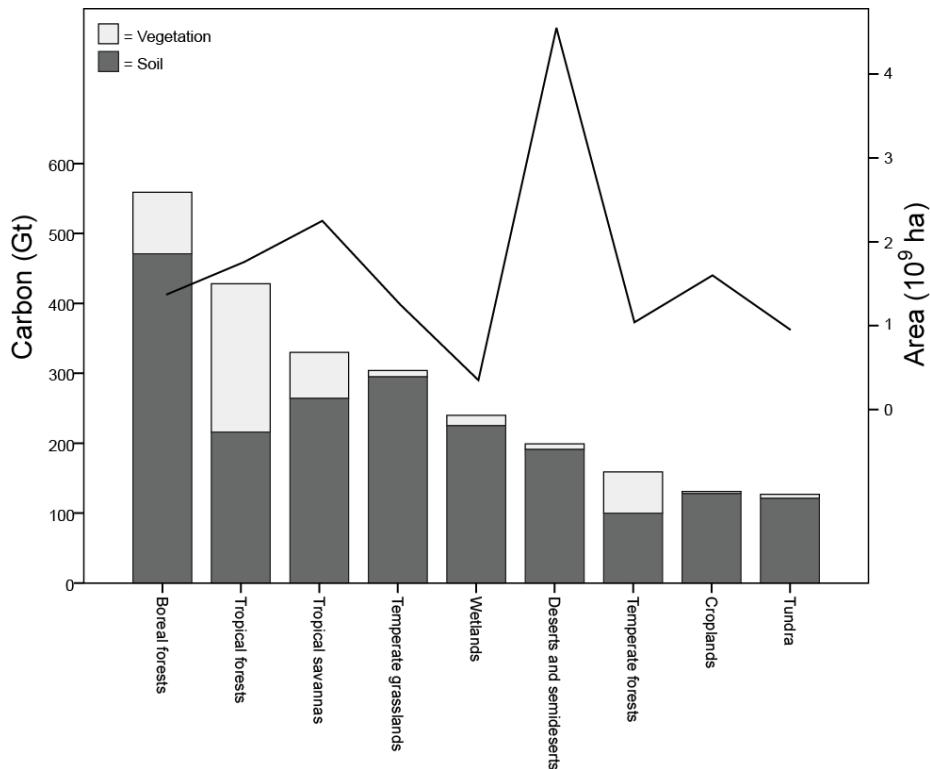


Figure 1: Global terrestrial carbon (C) stocks in vegetation and top-soils (1 m deep) in different biomes (Watson and Change, 2000). The line illustrates the total area covered by the different biomes. Due to ambiguity in the definition of biomes there is considerable uncertainty in the data, but it provides an overview of the distribution of the terrestrial C stocks and highlights the magnitude of C stored in soils.

It is well known that slow decomposition due to low temperatures, low pH and recalcitrant litter from the coniferous trees that dominate the boreal forests are important factors contributing to the build-up of soil C in the boreal region (rev. by Deluca and Boisvenue, 2012). However, a less understood source of the soil C pool is the autotrophic belowground input from roots and root associated microorganisms (Hyvönen et al., 2007). About half of the photoassimilated C is allocated belowground in coniferous forests, but the proportion is highly dependent on nutrient status and relatively less C is allocated belowground during sufficient nutrient supply (rev. by Litton et al., 2007). Thus, it is important to put more emphasis on trying to understand the contribution to the soil C pool by belowground allocated C.

Nitrogen cycle

There has been a growing concern about the environmental effects of anthropogenic alteration of the nitrogen (N) cycle (Gimeno et al., 2001; Hyvönen et al., 2007; Reay et al., 2008; Jacobson, 2009; Rockström et al., 2009), which has been identified, together with climate change and biodiversity loss, as one of totally nine planetary systems where the boundary for a sustainable use has been passed (Rockström et al., 2009). Threats from anthropogenic N emissions include soil acidification, eutrophication and N leakage (Vitousek et al., 1997). Political regulations regarding emissions of air pollutants have resulted in a decrease of deposited N in the end of the 20th century (Bertills et al., 2007). Although, deposition of N can still reach 50-100 kg ha⁻¹ y⁻¹ in some Central European areas, while remote forests at higher latitudes receive considerably less (rev. by Hyvönen et al., 2007). Elevated N deposition has also been reported from Swedish forests; during the period 2003-2007 N deposition ranged

from about 16 kg ha⁻¹ yr⁻¹ in the south to values close to the natural background deposition of about 2 kg ha⁻¹ yr⁻¹ in the north (Akselsson et al., 2010). Nitrogen, which is one of the most important nutrients for primary production has a substantial impact on forest growth globally (LeBauer and Treseder, 2008), and is generally the limiting nutrient for productivity in temperate and boreal forests (Vitousek and Howarth, 1991). However, if the N addition rates exceed the boreal forest N retention capacity it may result in N leaching (Aber et al., 1998). Research regarding the N retention capacity of boreal forests is not only important to prevent N leaching and improving the efficiency of possible fertilization in forest management, but also to better understand the C cycle which is highly connected to the N cycle. Since boreal forest trees assimilate most of the N through symbiotic microorganisms (Smith and Read, 2008), it is important to focus on their function to better understand the N retention mechanisms.

ECTOMYCORRHIZAL FUNGI

Anatomy

Almost all boreal and northern temperate forest tree species live in symbiosis with ectomycorrhizal fungi (EMF) (Smith and Read, 2008). The mycelium of EMF attaches to the fine roots of the trees and encases them in a structure called a mantle (Fig. 2). Within the mantle, fungal hyphae penetrate the root cortex and grow as a network, called the hartig net, between the cortical cells. From the outer mantle, the ectomycorrhizal extramatrical mycelium (EMM) extends into the soil, where it assimilates nutrients from both inorganic and organic sources as well as water. Apart from the sporocarps (the mushrooms),

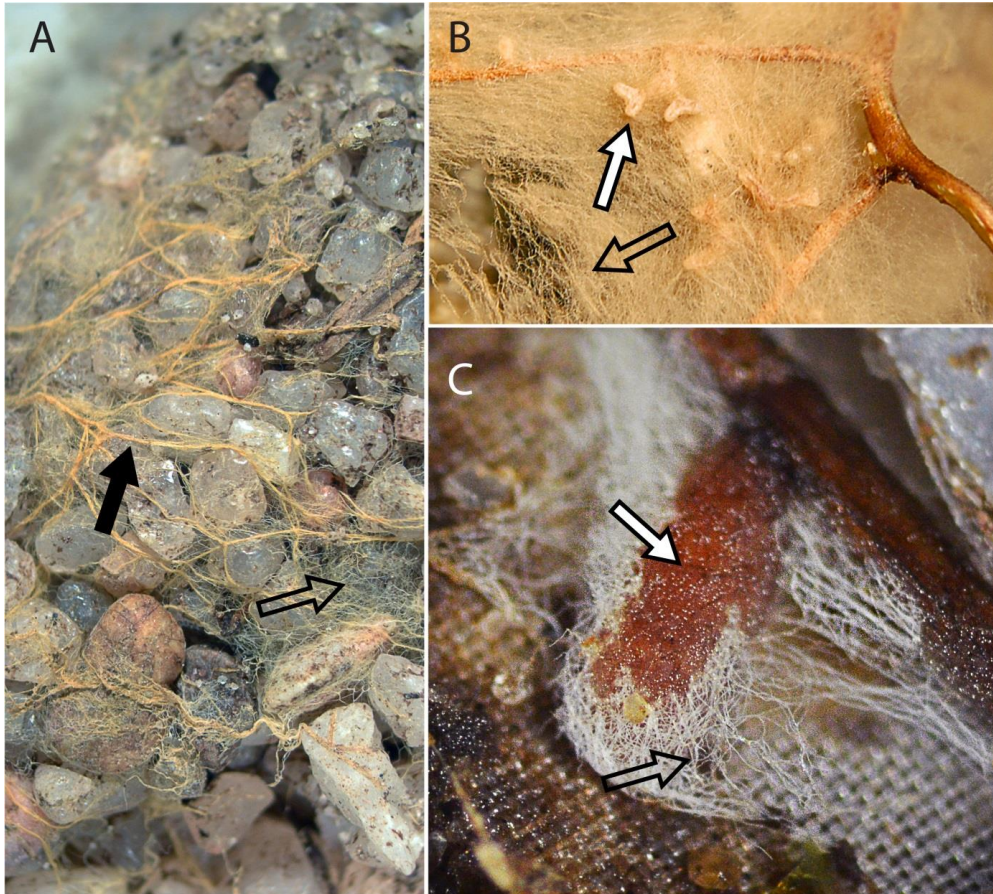


Figure 2: Mycelium of ectomycorrhizal fungi colonize fine tree roots and encapsulates them in a structure called the mantle (white arrows). From the mantle the extramatrical mycelium of the fungi extends into the soil with fine hyphae (transparent arrows) and rhizomorphs (black arrow). Picture C shows a colonized fine root on the outside of a mesh-bags, the mesh in the background has a pore size of 50 μm and prevents in-growth of tree roots while the fine hyphae of the fungi can penetrate into the bag. Picture A shows the interior of a harvested bag with abundant mycelium aggregating the sand.

EMF consists of the EMM, mantles and hartig nets. It has been estimated that within one single gram of humus soil hundreds of meters of EMM can be found (Söderstrom, 1992), and that the absorptive surface area of the tree roots can be increased by two orders of magnitude by the symbiosis (Smith and Read, 2008). The formation of EMM varies between different species, and Agerer (2001) divided EMF into the following exploration types depending on the structure of the EMM: contact, short-distance, medium-

distance and long-distance. The contact exploration type have a very limited growth of EMM and is hypothetically less C demanding than the distance exploration types which have thick bundles of hyphae (rhizomorphs) reaching far out in the soil (Fig.3) (Hobbie and Agerer, 2010). The difference in biomass and distance, of the EMM connected to one mantle, between different exploration types can be 15-fold (Weigt et al., 2012).

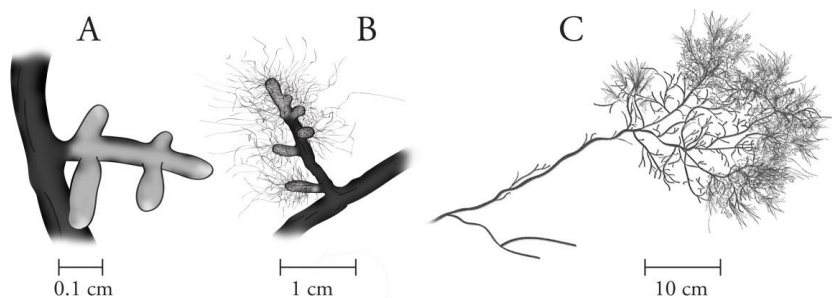


Figure 3: Agerer (2001) divided ectomycorrhizal fungi (EMF) into the different exploration types depending on the structure of the extramatrical mycelium (EMM). Contact exploration types (A) mainly form mantles and have almost no EMM. Short distance exploration types (B) have fine hyphae extending into the close surrounding area of the mantles. In contrast to the previous types long distance exploration types (C) have rhizomorphs (thick aggregated bundles of hyphae, likely more involved in transport than in uptake and only produced by some EMF species) stretching far into the soil. From the rhizomorphs, fine hyphae typically forms fan like structures.

Nutrient assimilation

The EMF are dependent on photo-assimilated C allocated belowground by the trees (Smith and Read, 2008). In exchange, they provide the trees with nutrients and water that are efficiently assimilated from the soil solution by extensive hyphal networks of EMM (Smith and Read, 2008). The relationship may however be more or less mutual (Karst et al., 2008), since the assimilated N may be retained in the EMF mycelium (Näsholm et al., 2013) and invested in the production of EMF biomass rather than allocated to the host plant. EMF can directly assimilate inorganic nutrients and simple forms of organic nutrients (such as amino acids), and also release extra-cellular enzymes that facilitate the release and uptake of nutrients bound up in macromolecules (such as proteins) or organic compounds (such as plant cell walls) (Smith and Read, 2008). Typically, more than 90 % of the fine tree roots are ectomycorrhizal (Taylor et al., 2000) and thus, most nutrients that are assimilated by the trees go through EMF. The trees allocate 10-50 % of the photoassimilated C (Simard et al., 2002) to the EMF. It has several times been shown

that EMF affects both the C cycle and N cycle of boreal and temperate forests (rev. by Smith and Read, 2008; Ekblad et al., 2013), but still there is a lack of knowledge regarding the extent to which they contribute to the globally important C sequestration of boreal forests as well as the N retention.

Carbon sequestration

Respiration by EMF is generally considered autotrophic since it is driven by photosynthetically assimilated C, and EMF are dependent on the symbiosis with a plant to acquire C (rev. by Ekblad et al., 2013). Heterotrophic C assimilation by EMF through degradation of soil organic matter (SOM) has been found in laboratory experiments (Read and Perez-Moreno, 2003), but typically only at one order of magnitude less than saprotrophic fungi. At least some species of EMF have the ability to modify and perhaps solubilize SOC (Rineau et al., 2012) by exudation of extra-cellular enzymes with the likely purpose of scavenging for other nutrients (Rineau et al., 2013). Autotrophic soil respiration may in contrast to heterotrophic respiration reflect

allocation of C to the soil, since it constitutes a portion of recent photoassimilated C allocated belowground.

Carbon allocation to EMF is regulated by environmental parameters affecting the production and the root:shoot ratio of the trees, i.e. there have been many reports of repressed EMM production after addition of inorganic N to the soil (e.g. Arnebrant, 1994; Nilsson and Wallander, 2003; Kjoller et al., 2012). Up to 50 % of the photoassimilated C is allocated through the roots to EMF (Simard et al., 2002). Even though 16-71 % of that C is directly respired by EMF (rev. by Leake et al., 2004), a large part is incorporated into fungal biomass (Bidartondo et al., 2001), of which about 10 % consists of the cell wall component chitin (Ekblad and Näsholm, 1996). Chitin is generally considered recalcitrant to soil degradation processes (rev. by Ekblad et al., 2013) and thus have the potential to accumulate in the soil. This was however questioned in a recent study (Fernandez and Koide, 2011), indicating that other components and factors such as low N content (Koide and Malcolm, 2009), hydrophobicity and rhizomorph abundance rather influence the recalcitrance of EMF residues (Ekblad et al., 2013). Still, further research is needed to understand the properties affecting the turnover of EMF.

There have been many reports pointing out that N addition leads to enhanced C sequestration in boreal forests, due to enhanced primary production, increased litter fall and reduced degradation of SOM by heterotrophic microorganisms (rev. by Janssens et al., 2010). There are however still uncertainties about a possible N induced C sequestration, especially in regard to the contribution from belowground inputs of C from roots and root associated

microorganisms. The belowground allocation of C links activity in the forest canopy to the activity in the soil, and provides a flow of organic C from shoots to soil via fine roots and mycorrhizal hyphae. The pathways by which this organic C can contribute to soil organic carbon (SOC) are complex, involving biomass turnover (Godbold et al., 2003), biomass grazing (Setälä et al., 1999) and turnover of low molecular weight exudates from roots and fungal hyphae (van Hees et al., 2005). The determination of the pools and fluxes of biomass inputs from fine roots and mycorrhizal fungi provides a major scientific challenge. Some studies (e.g. Wallander et al., 2004) suggest that biomass pools and inputs from fine roots and mycorrhizal hyphae are in the same order of magnitude. It is crucial to assess the role of EMF in the buildup of SOC in boreal and temperate forest soils, and to quantify their relative contribution to SOC in relation to litter and plant roots. If EMF is a main player in the C sequestration of northern forest soils, a different approach in forest management may be needed to maintain the large C pool. However, estimates of fungal inputs rely on methods and conversion factors with large uncertainty that needs to be considered, and precise measurements of standing biomass, production and turnover of EMM are essential in order to accurately describe the C cycle of terrestrial ecosystems.

Effect of nitrogen

Several studies have shown that the net primary production of boreal forests is enhanced by N deposition or N fertilization (Bergh et al., 2008; Brockley, 2010; Jacobson and Pettersson, 2010), while added N has been observed to have a negative influence on EMF biomass, growth and colonization in pot/microcosm studies (e.g.

Beckjord et al., 1985; Wallander and Nylund, 1992; Arnebrant, 1994; Runion et al., 1997) as well as in field studies (e.g. Arnebrant and Söderström, 1992; Nilsson and Wallander, 2003; Nilsson et al., 2007; Högberg et al., 2011; Kjoller et al., 2012). Addition of N in N limited forests typically results in a reduced root:shoot ratio (Ericsson, 1995), since the plant invest more C in above ground production, while relatively less is allocated belowground to facilitate the N assimilation by roots and EMF.

Reduced belowground allocation of C at high N availability may result in a shift of the EMF community towards less C demanding exploration types (Fig. 3). In support for this, Nilsson and Wallander (2003) found reduced growth of EMM in N fertilised plots where the amount of fungal biomass on roots were unchanged, and Kjoller et al. (2012) found that relative abundance of contact exploration types increased with N deposition while long distance exploration types decreased.

Most of the field experiments on the effect of N addition on EMM production have been designed to examine the consequences of fertilization, with additions of about 50–100 kg ha⁻¹ y⁻¹ (e.g. Nilsson and Wallander, 2003; Wallander et al., 2011). Even though deposition of N can reach such high levels, remote forests at higher latitudes receive considerably less (reviewed by Hyvönen et al., 2007). Moderate N deposition (0.27 – 2.44 kg ha⁻¹ 60 d⁻¹) has been found to affect the composition of the EMF community (Lilleskov et al., 2002), but there is still a

lack of studies on the effects of continuous low dose addition of N on EMM production.

Nitrogen retention

Even though N is generally considered well retained in the N poor boreal and boreo-nemoral forest soils (Gundersen and Rasmussen, 1995), leaching of N may occur if the N retention capacity is exceeded due to extensive N input (Aber et al., 1998; Gundersen et al., 2006; Akselsson et al., 2010). Elevated N leaching has been recorded in boreo-nemoral forests as a result of N deposition (Nilsson et al., 2007; Akselsson et al., 2010), N fertilization (Berden et al., 1998) and clear-cutting (Akselsson et al., 2004).

Since most of the plant nutrients are assimilated through EMF (Smith and Read, 2008), it is likely that high abundance of EMM increase the N retention capacity of the soil. The coincidence of elevated N leaching and impaired EMM production found after N deposition or fertilization has led to suggestions that EMF growth prevents N losses (Nilsson et al., 2007; Nilsson et al., 2012). However, the capacity of EMF to reduce N leaching still remains uncertain since the effect of impaired EMM production, typically seen after N addition (Arnebrant and Söderström, 1992; Nylund and Wallander, 1992; Nilsson and Wallander, 2003; Nilsson et al., 2007; Högberg et al., 2011; Kjoller et al., 2012; Nilsson et al., 2012), has not been separated from the direct effect from an increased N pool in the soil as well as other environmental variables.

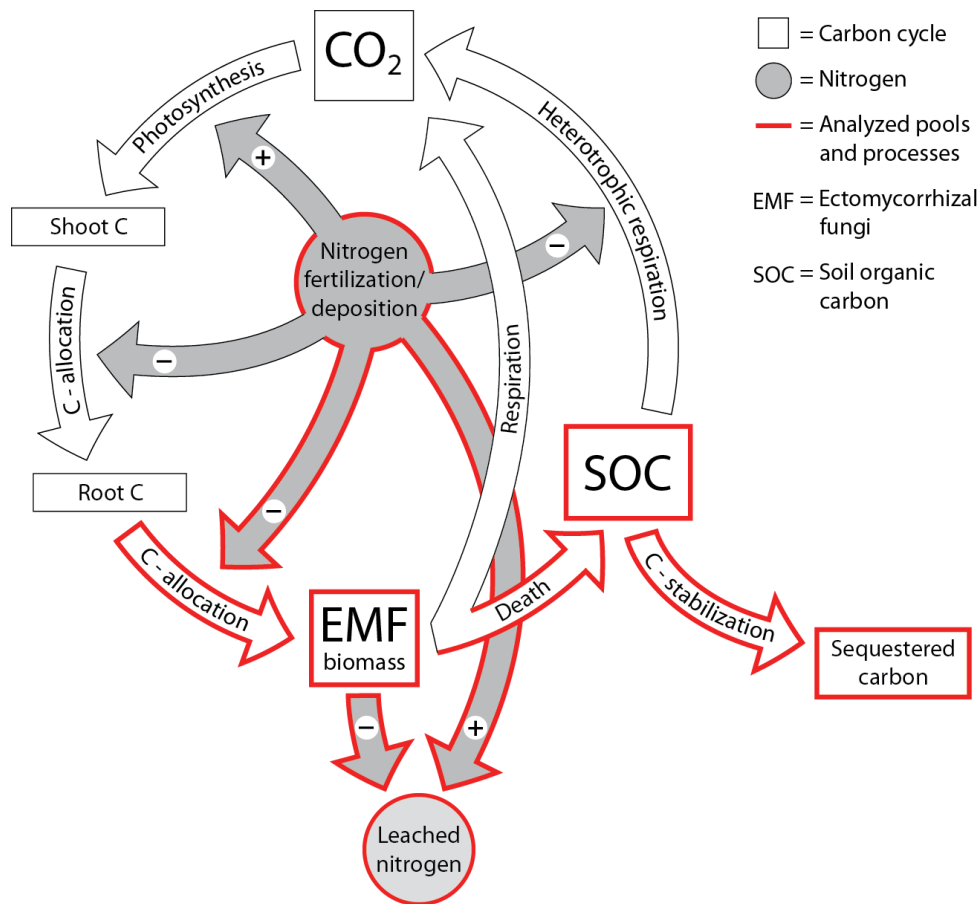


Figure 4: An overview of the main processes (arrows) and pools (boxes and circles) of carbon (C) and nitrogen (N) that affects or are affected by the production, standing biomass and turnover of ectomycorrhizal fungal (EMF) mycelium. Addition of N have several times been shown to increase the primary production of boreal forests resulting in increased photosynthesis and reduced belowground allocation of C to roots and EMF (grey arrows on the left side). However, N addition to severely N limited forests may result in a larger total amount of C being allocated belowground even though the relative allocation belowground decrease, due to an extensive increase in primary production. Nitrogen deposition has the potential to increase N leaching through two processes: (1) directly by enhancing the pool of inorganic N in the soil and indirectly (2) by repressing the EMF production and thus the assimilation capacity in the soil (grey arrows in the bottom). Elevated levels of N have been shown to slow down the heterotrophic degradation of complex molecules in the soil organic carbon (SOC) (grey arrow in the upper right) but, on the other hand, it may also reduce the production, and thus the necromass, of EMF mycelium and shift the EMF community to exploration types with different recalcitrance. Analyzed processes and pools in the current thesis are highlighted with red borders.

AIMS

The present thesis focuses on the role that EMF plays in the C and N cycles in northern forests (Fig. 4). My aim has been to analyze how EMF growth is affected by additions of inorganic N, and if EMF contribute significantly to the N retention and C sequestration in forest ecosystems.

Briefly, in my studies I expected to find that:

- (1) EMM is an important contributor to the accumulation of SOC in northern forest soils.
- (2) Nutrient assimilation by EMM is an important process for the N retention capacity of northern forest soils.
- (3) A continuous low dose addition of N through deposition is sufficient to repress the production of EMM.

METHODS

This is a brief overview and discussion of the main methods I have worked with during my PhD; a thorough review of methods for analyzing EMF is given in **Paper I**. I have studied different processes in field experiments and surveys to analyze the applicability and ecological importance of previous findings and hypotheses when other environmental variables were taken into account. Performing controlled laboratory experiments is necessary to find and explain underlying mechanisms, while the inclusion of the natural variation in the field enables a more realistic testing of ecological theories (rev. by Underwood, 2009). However, the large variation in environmental variables, due to lack of control and regulation, in field studies makes it necessary to put particular attention to the experimental design.

Field sites

The projects were restricted to Swedish boreal and boreo-nemoral forests (Fig. 5). Given the large south to north geographical distribution, Sweden covers a large portion of the climate, fertility and anthropogenic deposition found in boreal and boreo-nemoral forests globally.

The Swedish Throughfall Monitoring Network (SWETHRO) - Production of EMM in managed Norway spruce forests along a gradient of anthropogenic N deposition was analyzed in a large scale experiment, stretching over more than 600 km, in the south part of Sweden (**Paper II**).

Central Sweden pH gradient - The effects of soil fertility and pH on EMM production and community were analyzed in unmanaged Norway spruce and Scotch pine forests, only exposed to natural background deposition of N, in central Sweden (**Paper III**).

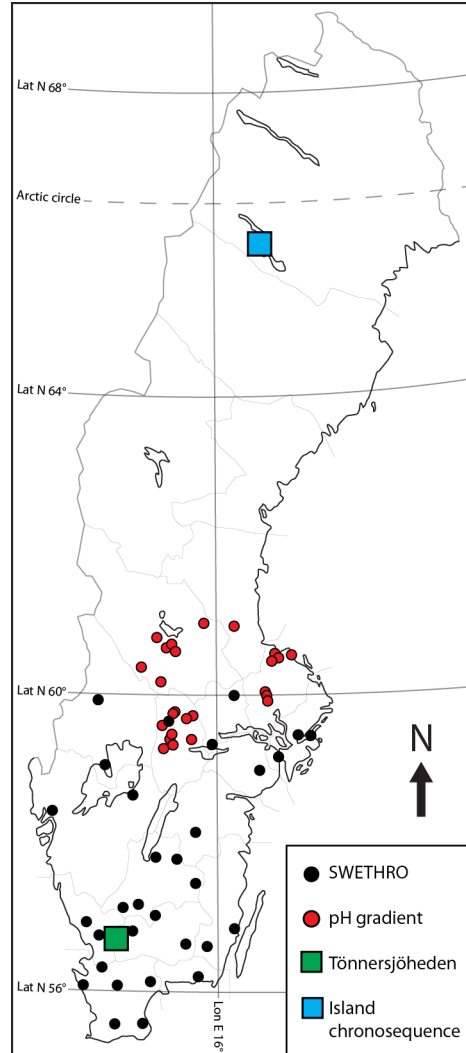


Figure 5: A map of Sweden with location of the field sites of the different experiments in this thesis.

Northern Sweden island chronosequence - The role of roots and root associated microorganisms in the buildup of a humus layer was studied in forested islands, largely unaffected by human activities, in North Sweden. The forests constituted a successional chronosequence, ranging from a few hundred years to several thousand years (**Paper IV**).

Tönnersjöheden fertilization project - To verify the patterns found in the SWETHRO survey (Paper II) of EMM N retention and a repressive effect from both N and P on EMM production, we manipulated the nutrient regimes of a managed Norway spruce forest in South Sweden. Apart from EMM production, we analyzed N leakage as well as N assimilation by EMM (Paper V).

Production of ectomycorrhizal fungi

In general, it is problematic to analyze soil microbial processes without exposing the natural soil environment to a major disturbance. This becomes even further complicated when analyzing the activity of EMF mycelium, since they are dependent on the symbiosis with trees (i.e. if a soil sample is taken the EMF growth ceases due to broken connections to the trees). Further, a key problem in the determination of mycorrhizal hyphal production is a lack of methods to distinguish growth of mycorrhizal hyphae from that of saprotrophic fungi. As EMF fungi do not form a monophyletic clade (Hibbett et al., 2000; Tedersoo et al., 2010) no single biochemical or DNA based marker can be found to quantify this group in the complex soil environment. PCR and qPCR can be used to identify known EMF species from DNA or RNA, but further development of molecular methods are needed to enable a stable quantification of the EMF biomass (Paper I).

Mesh-bags

One solution to analyze the production of EMM in the field is to incubate sand filled ingrowth mesh-bags (Fig. 6 and 7) in the soil (Wallander et al., 2001). A fine nylon mesh (pore size: 50 µm) allows for EMM ingrowth while it prevents tree roots from penetrating into the bag (Fig. 2) (Wallander et al., 2001). A lack of organic C in the sand filled

mesh-bags hypothetically reduces ingrowth of saprotrophic fungi, while the EMM has an external C source from the trees. The fungal communities that colonize the mesh bags are usually dominated by mycorrhizal hyphae which has been verified in trenching experiments (Wallander et al., 2001) and with DNA-analyses (Kjøller, 2006; Korkama et al., 2007; Parrent and Vilgalys, 2007; Hedh et al., 2008; Wallander et al., 2010). Ingrowth mesh-bags were used to determine the EMM production in Paper II and V.

In the SWETHRO survey (Paper II), triangular mesh-bags (side: 6 cm) were installed in the interface between the mineral soil and the organic horizon, where mycorrhizal growth is usually most active (Lindahl et al., 2007). They were incubated for one year in the soil during two consecutive years.

In the fertilization experiment at Tönnersjöheden (Paper V) the mesh-bags were cylindrical (length: 16 cm, diameter: 2 cm) to cover most of the active EMM region. This form of bag simplifies extrapolation of EMM production to a per area basis that covers a specific soil depth. The design also allows the comparison of adjacent soil and/or root samples taken with the same volume. Further, it is suitable for sequential harvests since the mesh bags can be replaced in the same hole, with minimal disturbance. In this project sequential harvesting was done with incubation periods of 4 months during a period of 16 months.

Possible shortcomings of the mesh-bag method are an initial delay before the EMM has the potential to extend into the whole bag and that the sand constitutes an unoccupied space where competition is lacking. The former would lead to an underestimation of EMM production while the latter could cause an overestimation.

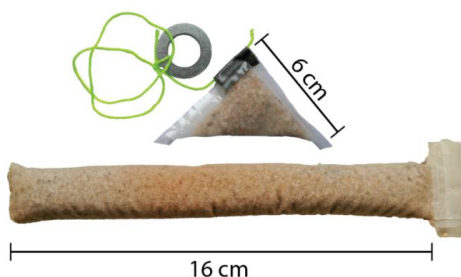


Figure 6: Ingrowth mesh-bags were installed in the soil during different periods to analyze production of ectomycorrhizal mycelium (**Paper II** and **IV**).

Further, there has been criticism about the use of pure quartz sand in the mesh bags since they contain a substrate that in many cases is different from the surrounding soil. It has been shown that mycelial in-growth can be higher when natural soil is used rather than pure sand (Hendricks et al., 2006), indicating that the use of pure sand likely gives an underestimation of the production. This has to be considered in regard to quantification and extrapolation of the fungal biomass and production, but is less important for relative differences between treatments.

Estimating fungal biomass

We used different approaches to quantify the ingrowth of EMM into the mesh-bags. The mycelial content was estimated visually with a stereo microscope (**Paper II** and **V**) according to a 6 graded scale (similar to Wallander et al., 2001), and the frequency of hyphae present in mesh holes was counted in vertical rows of 100 mesh holes (**Paper V**) (enabling quantitative analysis). Fungal content was then estimated chemically by analysing the fungal biomarker ergosterol (**Paper II** and **V**). Ergosterol is a cell membrane component specific to fungi that can be used as a quantitative indicator of fungal biomass (Nylund and Wallander, 1992). Frequency of hyphae and visual EMM estimation gave somewhat different

results than ergosterol (**Paper II** and **V**). Even though ergosterol content usually correlate well with other methods for fungal quantification (**Paper I**), inconsistencies have been reported (Högberg, 2006; Wallander et al., 2011), and the methods likely represent different aspects of fungal biomass. The visual method may be better to estimate the proliferation and aggregation of fine hyphae while ergosterol content to a larger extent is sensitive to the abundance of rhizomorphs (thick aggregated bundles of hyphae, likely more involved in transport than in uptake and only produced by some EMF species). It is also possible that ergosterol accumulates in the mesh-bags during the incubation time, while visual estimation gives a snap shot of the current situation. Ergosterol was found to accumulate in soil during late successional stages (**Paper IV**), and it has been suggested to be less prone to degradation following N addition and reduced belowground C allocation (Zhao et al., 2005). Ergosterol content has also been shown to differ between different EMF species (Bermingham et al., 1995), and may thus be affected by differences in the environment (e.g. soil fertility) affecting the EMF community composition (Kjøller et al., 2012). Ergosterol is either “free” (unesterified) or “bound” (esterified), since ergosterol becomes bound in sterol esters during degradation (Yuan et al., 2008). We analyzed both free and total (including both free and bound) ergosterol in an attempt to separate the living fungi from the necromass, since the free part has been suggested to better resemble living fungal mycelium (**Paper I**). For the same reason, total ergosterol and free ergosterol were also analyzed in soil samples (**Paper III** and **IV**).

The ratio of the stable isotopes ^{15}N and ^{13}C was used to interpret the ectomycorrhizal origin of organic material in mesh-bags and in soils in the forests of the Northern

Sweden chronosequence (**Paper IV**). Plant C allocated belowground is in relation to aboveground tissue enriched in ^{13}C , and this enrichment is further enhanced during C transfer to mycorrhizal fungi (Hobbie and Werner, 2004). Mycorrhizal fungi also have higher $\delta^{15}\text{N}$ signatures than their host plants, because they supply N to their hosts that is ^{15}N -depleted relative to that retained in their own mycelium (Högberg, 1997). Thus, analyses of ^{13}C and ^{15}N can give an indication of the contribution of EMF to SOM in northern forests. Although, the results has to be interpreted with caution since other soil processes also discriminate between different isotopes. Saprotrophic fungi are generally further elevated in ^{13}C than EMF (Högberg et al., 1999). However, growth of saprotrophic fungi is typically largest in the litter layer at the surface, while EMF have been shown most active close to

the border between the humus and mineral layer (Lindahl, 2007). Changes in the isotopic ratio induced by EMF activity may thus be expected occur in the deeper soil region. In regard to ^{15}N , other discriminating processes such as nitrification and denitrification are very limited in boreal forests (Schulze, 2000), and EMF activity is probably a main contributor to increased ^{15}N content with depth.

In the Tönnersjöheden fertilization project, N enriched in ^{15}N was added to EMM ingrowth mesh bags a few days before harvest. This enabled tracking and detection of ^{15}N assimilated by EMM (Clemmensen et al., 2008), while the amount of labeled N not taken up by the EMM network in the mesh-bags was collected at the bottom of the mesh-bags in ion exchange resins and used as a proxy for N leaching.

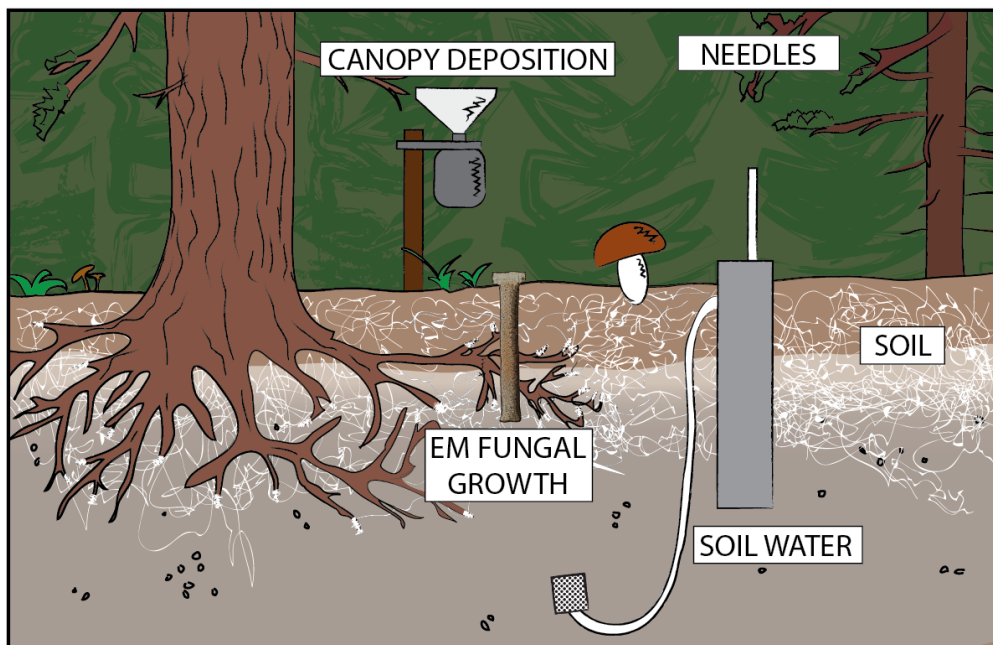


Figure 7: Overview of field sampling in this thesis. Production of ectomycorrhizal (EM) mycelium was analyzed by installing ingrowth mesh-bags in the soil. Soil samples were analyzed for chemistry, isotopic signatures of carbon and nitrogen, and the fungal specific membrane component ergosterol. Needles were analyzed for chemicals to interpret the nutrient status. Soil water was collected in suction lysimeters with ceramic filters and analyzed for pH and chemistry. Canopy deposition was sampled with funnels and analyzed for chemistry.

Soil water sampling

Ceramic cup suction lysimeters were used for soil water sampling (Paper II and V). The lysimeters consisted of 2 l cylindrical containers connected with plastic tubing to ceramic filters put at 50 cm depth (Fig. 7). The lysimeters were set to approximately 0.6 bar vacuum pressure and then left for two days (Paper II) or one month (Paper V). Shorter sampling periods gives a more consistent vacuum pressure in the lysimeters, but are, on the other hand, sensitive to temporary changes in soil water percolation (i.e. after heavy rainfall or during snowmelt). Thus, short sampling intervals spread out during the year may be better for instantaneous quantification of root available nutrients, while continuous long term sampling may be better to detect relative differences between treatments. Sampled soil water was quantified and analyzed for pH and N (Paper II and V) as well as other nutrients (Paper II).

ENVIRONMENTAL VARIABLES AFFECTING PRODUCTION OF ECTOMYCORRHIZAL FUNGI

Nitrogen

In the fertilization experiment at Tönnersjöheden (Paper V) we found repressed EMM production within four months after N fertilization (Fig. 8). Repressed EMM growth after N fertilization has been found in many earlier observations, although these measurements have usually been performed after several years of exposure to elevated levels of inorganic N (e.g. Nilsson and Wallander, 2003; Nilsson et al., 2007; Kjoller et al., 2012). The reduction in EMM growth may be due to a greater demand of photoassimilated C for above ground plant production, resulting in relatively less C being allocated belowground to support nutrient assimilation (Hobbie, 2006). In support of this Högborg et al. (2010) found a reduction in belowground

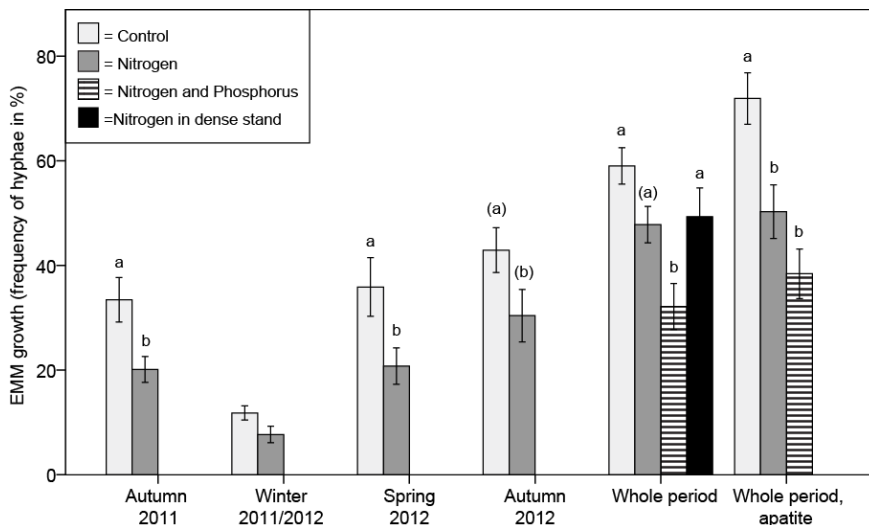


Figure 8: Tönnersjöheden fertilization experiment (Paper V). Growth of ectomycorrhizal extramatrical mycelium (EMM), during 4 month incubation periods as well as during the whole period of the study, according to counting of mycelium along the mesh of the ingrowth bags. Shadings and patterns illustrate fertilization regimes. Apatite refers to mesh-bags amended with the phosphorus (P) containing mineral that has been shown to enhance EMM production during P deficiency. Samples from the same period that do not share letters are significantly different (tendencies are shown within parenthesis) and the error bars represent standard error.

C allocation to soil biota of more than half after N fertilization of a pine forest in northern Sweden. In addition, the C that is allocated to EMF will, to a larger extent, be used for energy purposes and as C skeletons for amino acid production during elevated N availability, resulting in less C being available for fungal growth (Wallander, 1995). Reduced production of EMM at elevated N input may also be related to changes in the EMF community. For example, the contact exploration type (Fig. 3), described by Agerer (2001), have a very limited growth of EMM in contrast to distance exploration types (Hobbie and Agerer, 2010). Kjølner et al. (2012) found that relative abundance of contact exploration types increased with N deposition while distance exploration types decreased. Reduced growth of EMM at high N availability may thus be an effect of a shift to less C demanding exploration types.

Even though high N availability often has been observed to reduce the EMM production (e.g. Beckjord et al., 1985; Wallander and Nylund, 1992; Arnebrant, 1994; Runion et al., 1997; Nilsson and Wallander, 2003; Nilsson et al., 2007; Kjølner et al., 2012), these observations are mainly from experimental studies with rather high N addition rates (e.g. Nilsson and Wallander 2003, with an annual addition of 100 kg N ha⁻¹ during 13 years). In the SWETHRO survey (**Paper II**) we show during two consecutive years that reduction of EMM production also occurs when moderate levels (< 10 kg N ha⁻¹ yr⁻¹) of N are added by atmospheric deposition (Fig. 9). By including a comprehensive dataset of environmental variables regarding canopy throughfall, soil water, soil chemistry and needle chemistry in a multivariate analysis (Fig. 10) we concluded that N deposition was the most important abiotic variable controlling EMM production. This suggests

that the moderate deposition of N found in many boreal and boreo-nemoral regions, is not only sufficient to repress EMM production but also the main controlling abiotic variable.

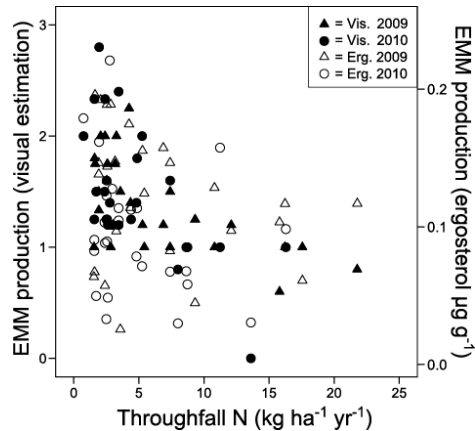
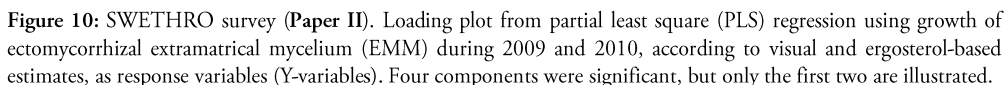


Figure 9: SWETHRO survey (**Paper II**). A negative correlation between nitrogen deposition and ectomycorrhizal extramatrical mycelium growth was found during both 2009 ($r_s = -0.58$, $P = 0.001$) and 2010 ($r_s = -0.61$, $P < 0.001$) according to visual estimation, but this could not be verified by ergosterol analyses (2009: $R^2 = 0.234$, $P = 0.221$; 2010: $R^2 = 0.257$, $P = 0.195$).

Phosphorus

Apart from N, elevated allocation to EMF has also been found in response to P deficiency in pot studies (Wallander and Nylund, 1992; Ekblad et al., 1995) and also in the field (Berner, 2013), indicating a strong role of plant P status in controlling C allocation to EMF. The importance of P provision by EMF in controlling plant C allocation to EMF was illustrated by using EMF ingrowth mesh-bags amended with the P containing mineral apatite, resulting in enhanced EMM production in P limited forests (Wallander and Thelin, 2008; Berner et al., 2012). Northern forests are generally considered N limited, and in the SWETHRO survey (**Paper II**) only one of the localities had a needle content of P below



Wallander and Nylund (1992) showed in pot studies that EMM production was repressed by excess N treatment when P levels was adequate, however if P was deficient no repression of EMM production was found after N addition. In the fertilization experiment at Tönnersjöheden (**Paper V**) we show that this also occurs under field conditions, since production of EMM was further repressed when N was added in combination with P (Fig. 8). This

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however only occur when the trees are originally P limited and further studies of P addition effects on EMM growth are needed in order to test if a general effect can be expected.

pH

Although most of the variation in production of EMM in the SWETHRO survey (**Paper II**) could be explained by N availability, inclusion of needle nutrient status and pH increased the predictability further (from $Q^2 = 0.27$ to $Q^2 = 0.36$). Together, these variables seem to be the most important ones since inclusion of additional variables did not contribute to any further increase of the predictability. Strong positive correlations were found between pH and EMM production in the SWETHRO survey (**Paper II**) as well as in the study of the Central Sweden pH gradient (Fig. 11, **Paper III**).

A low pH may become stressful for fungi. Even though fungal abundance usually increase with low pH (Rousk and Bååth, 2011), Rousk et al. (2011) found reduced saprotrophic fungal growth at pH less than 4.5. Only a few field studies have analysed the effects of a reduction in pH on EMF, but it has been observed that simulated acid rain did not affect formation of mycorrhizas (Meier et al., 1989; Nowotny et al., 1998) or EMF morphotypes (Meier et al., 1989). On the other hand, liming to counteract soil acidification has a strong effect on the composition of the EMF community (Erland and Söderström, 1991; Lehto, 1994; Andersson and Söderström, 1995; Wallander et al., 1997; Bakker et al., 2000), while species richness (Kjøller and Clemmensen, 2009) and diversity (Rineau et al., 2010) seem to be rather unaffected by liming. It is often reported that species with well developed EMM increase in abundance after liming (Bakker et al., 2000; Kjøller and

Clemmensen, 2009) and highly competitive ubiquitous species are more common at higher pH (Rineau et al., 2010).

Robust and long-lived plant leaves are usually associated with stressful conditions (Wright et al., 2004). Correspondingly, in fungi, long-lived mycelial structures may enable more economic resource utilization. To retain mycelium for a long time, it needs to be protected against fungivores and harsh abiotic conditions, e.g. by impregnation of cell walls with melanin and hydrophobic compounds (rev. by Ekblad et al., 2013). Fungi associated with stressful environments are often ascomycetes having traits considered adaptations to harsh conditions such as drought and acidity (Gostinčar et al., 2010). Lehto et al. (1994) found that the reduction of contact exploration type EMF was mainly due to increased pH and ionic strength. Thus the positive relation between pH and EMM production in the SWETHRO survey (**Paper II**) and the study of the Central Sweden pH gradient (**Paper III**) could be related to the composition of the EMF community.

A positive correlation between pH and EMM may, however, not imply a causal effect. Increasing the pH in acidic forest soils has been found to promote microbial activity (Bååth and Arnebrant, 1994) and, in general, to elevate nutrient availability and N mineralization. Nevertheless, the effects of liming on the N cycle in N limited, acidic soils are complex, and reduced N mineralisation after liming has also been reported (reviewed by Formánek and Vranová, 2003). The positive correlation between pH and EMM growth observed in the SWETHRO (**Paper II**) survey may be due to the acidifying effect of N deposition. Nilsson et al (2007) also found lower EMM production in areas with elevated N deposition, which also had the lowest pH

values. The narrow pH gradient and a dispersed pattern of pH-related variables (according to PLS regression, Fig. 10) in the SWETHRO survey, indicates that canopy throughfall of N was the most important variable affecting EMM growth, and probably the cause of the pH trend.

On the other hand, a positive correlation between pH and EMF biomass was also found in the study of the Central Sweden pH gradient (**Paper III**) where the forests only received natural background deposition of N. The underlying cause was most likely increased availability of nutrients at higher pH, since the most important predictor of ergosterol according to multivariate analysis as well as multiple regression was the C:N ratio of humus. We suggest that, without elevated N input through atmospheric

deposition or fertilization, N availability rarely becomes sufficient to reduce the belowground allocation of C. Rather, the belowground allocation of photoassimilated C increases with fertility due to alleviation of severe nutrient limitation. Positive responses of EMF to N additions, both in terms of mycelial growth and abundance, have been observed previously in low-productive arctic heathland (Clemmensen et al., 2006). Thus, we postulate that negative effects of high N-availability on mycorrhizal fungi are primarily found at the higher inorganic N-levels associated with fertilizer addition or elevated atmospheric deposition, but that this relationship is not valid within the range of variation commonly found in undisturbed boreal forests not exposed to artificial or anthropogenic N-deposition.

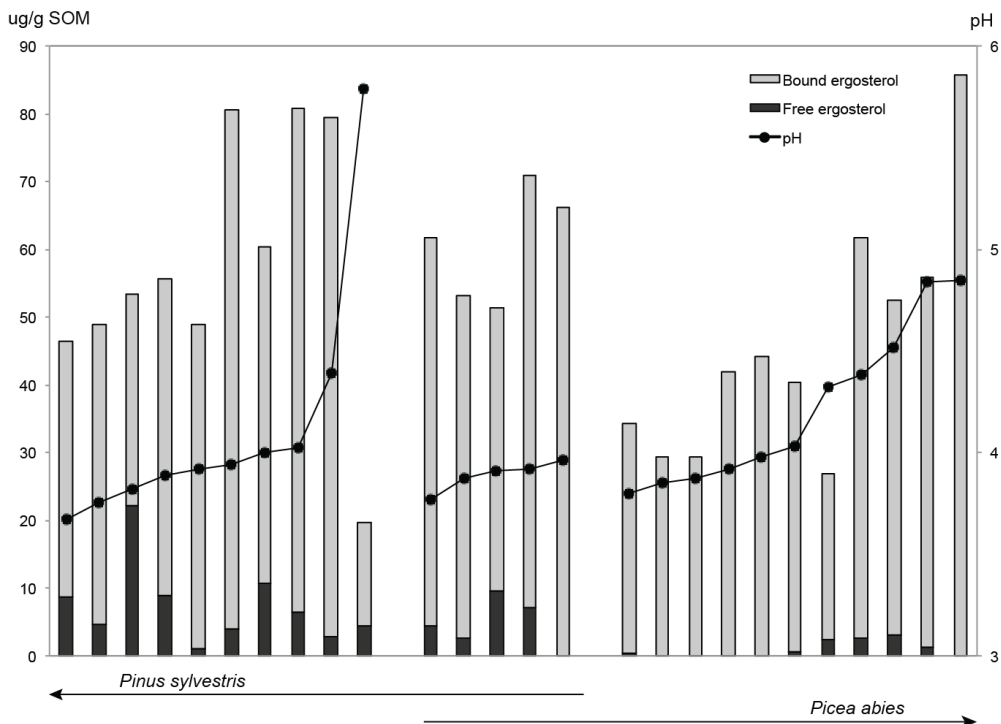


Figure 11: Bound ergosterol levels (grey part of bars) and free ergosterol levels (black part of bars) in the humus. Samples are sorted after dominant tree species of the forests, pine forests in the left part of the graph, spruce forests in the right part and codominance of the two species in the middle. For each tree species, the samples are ordered after humus pH.

NITROGEN RETENTION BY ECTOMYCORRHIZAL FUNGI

It has been hypothesised that EMM activity counteracts leaching of N (Aber et al., 1998; Nilsson et al., 2007; Högberg et al., 2011), and indications of this have been observed in a few studies (e.g. Nilsson et al., 2007). According to the SWETHRO survey (**Paper II**) elevated N losses seemed to occur at relatively low EMM production (Fig. 12). The lack of high N losses at abundant EMM production indicates a counteracting effect of EMM on N leaching. It was however not possible to draw any firm conclusions regarding the capacity of EMM to retain N in the soil, since N leaching increased with N deposition at the same time as N deposition had a negative effect on EMM production. The effects of these mechanisms on N leakage could not be separated with the approach used in the SWETHRO survey.

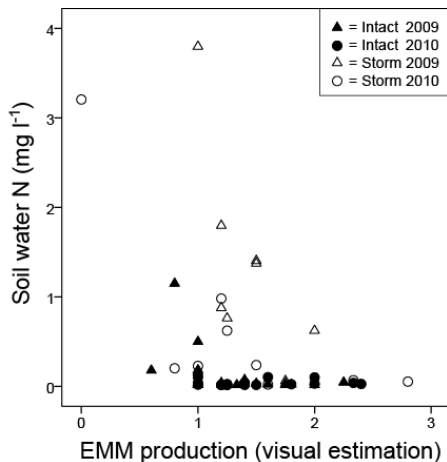


Figure 12: SWETHRO survey (**Paper II**). A tendency was found between nitrogen (N) leaching (soil water N) and visual estimation of ectomycorrhizal extramatrical mycelium (EMM) growth at intact sites (i.e. not storm damaged) during 2009 ($r_s = -0.45$, $P = 0.073$) and at storm damaged sites during 2010 ($r_s = -0.34$, $P = 0.060$). No correlations were found between N leaching and the estimates of EMM based on ergosterol (data not shown).

In order to determine the capacity of EMM to reduce N losses we applied a more intense temporal sampling strategy for both EMM production (in mesh-bags) and N leaching in the fertilization experiment at Tönnersjöheden (**Paper V**). The temporal division of sampling was made to account for the large seasonal variation in both N leaching (Stevens et al., 1993; Piirainen et al., 1998; Wright et al., 2001) and EMM growth (Wallander et al., 2001). Production of EMM, which has been suggested to increase soil N retention (Aber et al., 1998; Nilsson et al., 2007; Högberg et al., 2011), usually peaks at late summer to early fall, while it almost ceases during the winter (Wallander et al., 2001). In contrast, large temporal N flushes in the spring are typically explained by snow melting (Aber et al., 1998; Piirainen et al., 1998), intense periods of precipitation and low plant assimilation (Wright et al., 2001). In comparison to N treated plots, growth of EMM, as well as N leaching (sampled monthly in lysimeters), tended to be lower when N was combined with P application, which does not suggest that EMM had any crucial potential to reduce the N leaching. It rather seems like an alleviation of an N induced P limitation led to elevated assimilation of the tree roots directly or perhaps through EMF types not colonizing the bags. Similarly, EMM growth declined during winter but no subsequent increase in N leaching was found. However, tracking of the stable N isotope ^{15}N (that was injected into ingrowth mesh-bags two days before harvest) in EMM and ion exchange resin beads at the bottom of the mesh-bags showed that EMM take up more N and reduce leaching to a larger extent in control plots than in N fertilized plots. The ^{15}N assimilation capacity of the EMM in the mesh bags corresponded to $6 \text{ kg ha}^{-1} \text{ month}^{-1}$ during the most active EMF growth period. This is however only by the EMM produced

during the 4 month period of incubation. If a standing EMM biomass of five tons ha^{-1} is estimated (Wallander et al., 2004) an N assimilation rate by EMM of $0.31 \text{ mg g}^{-1} \text{ day}^{-1}$ would result in a monthly assimilation capacity of 46 kg ha^{-1} . Which potentially could be sufficient to retain a large part of the N solubilized from the NH_4NO_3 fertilization pellets, since previous analyses have shown that only 5 – 10 % of fertilizations with about 150 kg ha^{-1} is leached within the first years after fertilization (Nohrstedt, 2001). However, that could not be verified according to the seasonal and treatment variation in EMM production and N leaching in the present study. We show that EMF play an important role in N retention but to explain N leaching, especially after fertilization with large doses of N, many other environmental variables need to be taken into account. These may be direct assimilation by tree roots, climate variables such as precipitation and snowmelt, growth of saprophytic fungi and bacteria and chemical reactions between N and humus.

CARBON SEQUESTRATION BY ECTOMYCORRHIZAL FUNGI

EMF play an important role in the boreal forest C cycle (Smith and Read, 2008) and a reduction in EMM production may have substantial consequences for C sequestration (Godbold et al., 2006). In the fertilization experiment at Tönnersjöheden (**Paper V**), production of EMM at control plots was calculated to 583 kg ha^{-1} during four months in late summer and early autumn, and an average EMF C sequestration in mesh-bags was calculated to $320 \text{ kg ha}^{-1} \text{ y}^{-1}$ in the SWETHRO survey (**Paper II**).

The belowground contribution to SOC buildup was analyzed in northern Sweden forests at different successional stages (**Paper**

IV). They were located at islands largely unaffected by anthropogenic activities, where the main disturbance has been forest fires. Due to a larger area, large islands experience lightning ignited fires more often than small islands, resulting in a restart of the succession. The mean age of succession ranged from a few hundred years at the large islands to thousands of years at the small islands (Wardle et al., 1997). In late successional stages the organic soil layer was about 1m deep, while the younger successions had a more typical boreal forest soil profile with an organic layer of about 10 cm. We analyzed organic soil profiles from 30 islands of different sizes. With a parameterized model based on ^{14}C dating (Fig. 13) we analyzed the contribution of aboveground (e.g. litter) and belowground (e.g. mycorrhiza) C inputs to the humus built up during the last 100 years. Root-derived C constituted 70 % of SOC at small islands (late succession) and 47 % at the large islands (early succession). Differences in organic matter accumulation between islands were primarily determined by processes at the interface between the fragmented litter (F) and humus (H) layers, which corresponded to the zone of highest root density. Thus, root-mediated C input to the upper part of the profile represents a major contribution to the long-term buildup of humus, especially in late successional ecosystems.

The increase in root-derived C sequestration as succession proceeds was matched by a shift in the balance between the production and decomposition of fungal mycelium. We measured the fungal-specific cell membrane lipid ergosterol as a marker for fungal biomass throughout each soil profile. Free ergosterol, characteristic of newly formed mycelia (**Paper I**), was about 20 times more abundant on large than on small islands, indicating greater mycelial production. In

contrast, bound ergosterol, the proportion of which increases during mycelial senescence (**Paper I**), was more abundant on smaller islands, indicating older mycelium with slower biomass turnover (Fig. 14). Furthermore, the fungal cell-wall polysaccharide chitin peaked in the F layer and declined in lower horizons of large islands, but remained at high concentrations at greater depths on the small islands (Fig. 14). Chitin persists longer than ergosterol in fungal tissues after death (Ekblad et al., 1998), and the high level of chitin on small islands suggests retarded decomposition of fungal cell wall residues. Thus, in spite of apparently greater mycelial production on the large islands, less mycelial necromass accumulated there than on small islands, suggesting that the large production was counterbalanced by faster decomposition of mycelial remains.

The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures in the uppermost organic layers were similar to those of leaves (Hyodo and Wardle, 2009), whereas signatures in humus layers were closer to those of mycorrhizal mycelium (Fig. 14) and sporocarps (Taylor et al., 2003). The incorporation of isotopically enriched root and fungal remains in the SOM is likely an important mechanism behind the progressive enrichment of heavier stable isotopes with soil depth in this system, indicating that mycorrhizal fungi are a large contributor to the SOC buildup. This is consistent with the observation that isotopic signatures remain relatively constant in the initial litter decomposition phase (Fig. 14) and only increase when root-associated fungi dominate C and N dynamics (**Paper IV**).

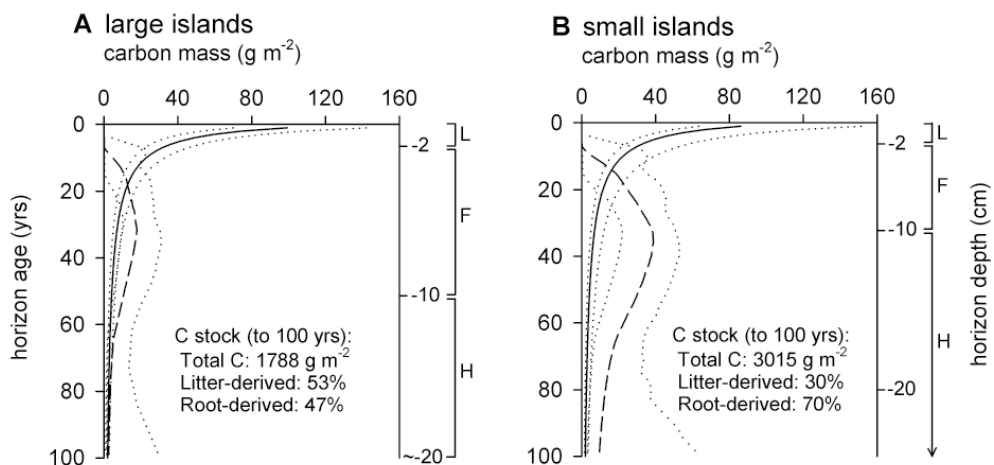


Figure 13: Northern Sweden island chronosequence (**Paper IV**). Carbon (C) dynamics in vertically stratified organic horizons of forested islands. Model estimates of C from aboveground litter (solid lines) and C introduced belowground via root transport (broken lines). Carbon mass was modeled to a horizon age of 100 years based on C mass and ^{14}C measurements in profiles from three large (A, representing early succession) and three small (B representing late succession) islands. Solid lines show means and dotted lines show the 95 % central credibility intervals. The posterior probability that the root-derived fraction is larger in small islands than in large islands is 0.97. Approximate depths are indicated for transitions between the main categories of horizons sampled; L: litter; F: fragmented litter; H: humus.

Our results elucidate the mechanisms underpinning C sequestration in boreal forests and highlight the importance of roots and root-associated fungi for ecosystem C balance and, ultimately, the global C cycle. We challenge the general view that humus accumulation is regulated primarily by saprotrophic decomposition of aboveground litter, and suggest that SOC is primarily controlled by an alternative process in which organic layers grow from below through inputs from roots and root-associated fungi.

Environmental changes, such as N fertilization and deposition, forest management, and elevated atmospheric CO₂ concentrations, are therefore likely to greatly affect soil C sequestration through their alteration of rhizosphere processes. These processes are not well described in current models of ecosystem and global C dynamics, and their more explicit inclusion is likely to improve both the mechanistic realism and future predictive power of models.

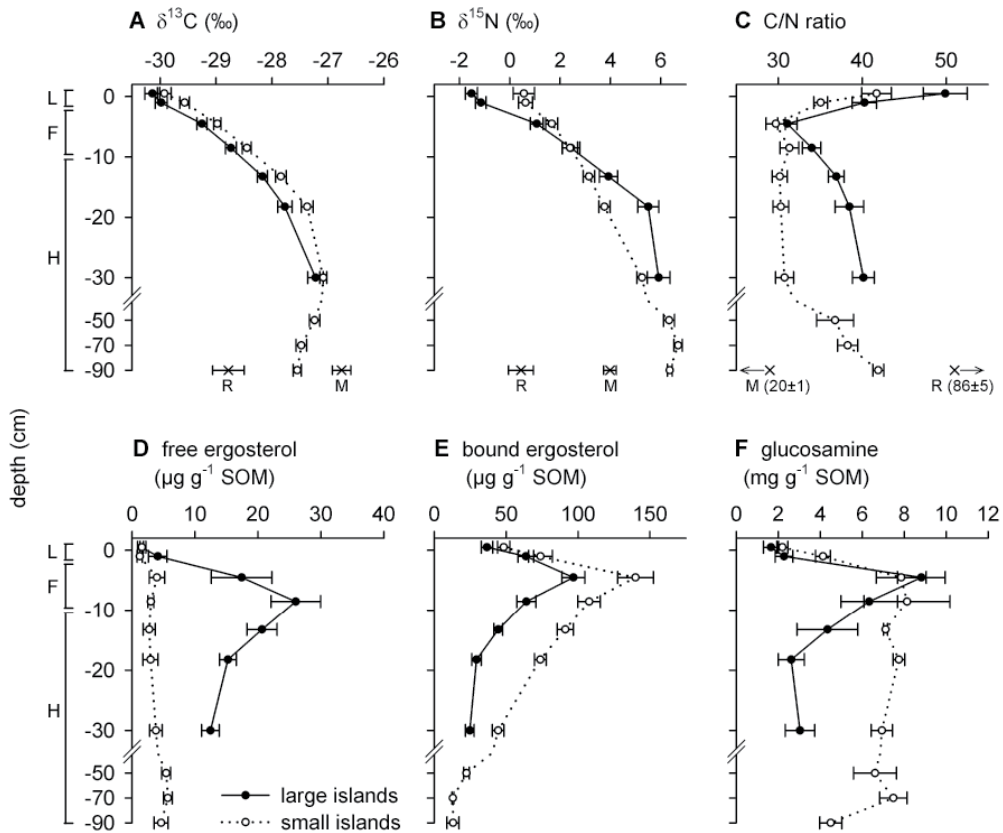


Figure 14: Northern Sweden island chronosequence (Paper IV). Depth profiles of $\delta^{13}\text{C}$ (A), $\delta^{15}\text{N}$ (B), C/N ratio (C) and fungal biochemical markers (D-F) in organic soil profiles of large (solid lines, representing early succession) and small (broken lines, representing late succession) forested islands. All data are means and error bars represent standard error. In the upper panel, levels measured in 1-5 mm diameter roots (R) and mycorrhizal mycelium (M) sampled at 10 cm depth are given for reference.

CONCLUSIONS

Moderate deposition of nitrogen (N) was sufficient to repress production of ectomycorrhizal extramatrical mycelium (EMM).

Elevated N leaching was detected after moderate N deposition and coincided with low EMM productivity.

Abundant EMM could not stop an immediate flush of N, to the soil water at 50 cm depth, from the added fertilizer, but it was calculated that recently produced mycelium could assimilate 6 kg N ha⁻¹ month⁻¹, which may be sufficient to retain moderate additions of N.

The average annual C sequestration by EMM in one hectare was estimated to more than 300 kg C, and the production of EMM was up to more than 500 kg during four months.

Roots and root associated fungi were found important for C sequestration in boreal forest soils, especially in late successional stages where they contributed to 70 % of the soil organic C.

THIS THESIS IN A LARGER CONTEXT

How does inorganic nitrogen affect carbon sequestration?

The general consensus is that the C sequestration of boreal and temperate forests is enhanced by addition of N (e.g. Magnani et al., 2007; Reay et al., 2008; Sutton et al., 2008; Janssens and Luyssaert, 2009). But additions of N typically repress the production of EMM that is potentially important for C sequestration. The close connection between N and C cycles of boreal forests is obvious from simple C to N

stoichiometry since the C:N ratio within various ecosystem components such as soil and microorganisms is relatively stable (Brady and Weil, 2008). Thus, to enable a major enhancement in C storage more N should be needed. The vast majority of reports point out a positive effect of N addition on C sequestration (e.g. Magnani et al., 2007; Reay et al., 2008; Sutton et al., 2008; Janssens and Luyssaert, 2009). Frequently reported underlying mechanisms include that N addition: (1) increases primary production (Magnani et al., 2007; Sutton et al., 2008) and thus litter fall (Franklin et al., 2003); (2) slows down degradation of SOM (Magnani et al., 2007; Sutton et al., 2008) due to (2a) reduced microbial production of enzymes that decay recalcitrant soil substrates (e.g. ligninases) (Janssens et al., 2010), (2b) and relatively less belowground C allocation that will prime the degradation of SOM by microorganisms (Janssens et al., 2010), and finally; (3) addition of N may result in larger C sequestration per N unit since relatively more N is allocated to tissues with higher C:N ratios (e.g. stem wood) (rev. by Janssens and Luyssaert, 2009).

On the other hand, the majority of these mechanisms relate to changes in tree/plant growth, but it is well known that most of the added N ends up in the soil (Högberg, 2012), and some is lost to ground water (Nadelhoffer et al., 1999). Leaching of N would likely be aggravated in forests that become limited by environmental variables other than inorganic N after elevated N input (rev. by Janssens and Luyssaert, 2009). Additionally, in ecosystems with severe N deficiency, addition of N may alleviate microorganism from N limitation, leading to enhanced SOM degradation (Janssens et al., 2010). Most of the studies on the effect of N on C sequestration focus on the change in aboveground plant production, litter fall and

SOM degradation processes (Hyvönen et al., 2007). Less attention has been put on the quantity and fate of the C allocated belowground by the trees, and still less to the C allocated to mycorrhizal fungi, which as showed in the work of this thesis (**Paper II, IV and V**) and other studies (Högberg and Högberg, 2002; Godbold et al., 2006; Wallander et al., 2011) can be both substantial and significant for the formation of stable SOM.

Even though it might be exaggerated (Sutton et al., 2008), Magnani et al. (2007) showed a positive correlation between N deposition and C sequestration based on the total fluxes of C in temperate and boreal forest ecosystems. Thus, it integrated all possible processes involved in the C sequestration (e.g. primary production, belowground allocation, litter fall and SOM degradation), including production and degradation of EMM. However, below a N deposition of 5 kg ha⁻¹ y⁻¹, Magnani (2007) could not demonstrate any enhanced C sequestration due to N deposition, and most other studies on the effect of N on C sequestration are based on large N additions (Hyvönen et al., 2007). The majority of the boreal forests are exposed to lower N deposition rates than 5 kg ha⁻¹ y⁻¹, and often they only receive the natural background deposition of less than 2 kg N ha⁻¹ y⁻¹ (Reay et al., 2008). Even though, in the SWETHRO survey (**Paper II**), we could not find a significant repressive effect of N deposition on EMM production below a N deposition rate of 5 kg ha⁻¹ y⁻¹, the major decrease of EMM production (visual estimation) occurred below N deposition of 10 kg ha⁻¹ y⁻¹ (Fig. 9). Further, N additions may cause a shift towards EMF species that have less recalcitrant tissues (rev. by Ekblad et al., 2013). In the Northern Sweden forest chronosequence (**Paper IV**) we found that more than half of the SOC stock originated from belowground inputs

from roots and their associated microorganisms (Fig. 13). The isotopic signal of ¹⁵N and ¹³C approached that of pure EMM and EMF sporocarps with depth, indicating that EMF was a major contributor (Fig. 14). In late successional stages the belowground contribution to SOC was further enhanced (**Paper IV**).

Nitrogen retention in northern forests

Apart from posing a threat of toxicity and eutrophication to aquatic environments, N leaching may also cause soil acidification as well as depletion of other nutrients that are leached as counter ions together with NO₃⁻ (rev. by Gundersen et al., 2006). Productivity in most northern forests is considered to be N limited and additional N is typically well retained. Nitrogen losses from boreal forests are small (about 0.5 – 5 kg ha⁻¹ y⁻¹) (Stendahl and Hjerpe, 2007) in comparison to what is leached from agricultural lands (about 6 - 50 kg ha⁻¹ y⁻¹) (Johnsson et al., 1997) in the same region. However, N leaching from boreal forests still poses a threat to the environment due to the vast areas they cover. In Sweden the total N load into the Baltic Sea that originates from forests is at level with that from agriculture land (Stendahl and Hjerpe, 2007). Most of the N leaching from forests has however, in contrast to agricultural leaching, been ascribed to natural causes. Still, previous findings (Akselsson et al., 2010) together with results from this thesis (**Paper II**) show that in some Swedish coniferous forests a moderate deposition is sufficient for the soil water N to exceed an annual average of 0.5 mg l⁻¹, which has been suggested to reflect progression towards N saturation (Stoddard, 1994). If the N retention capacity of forest soils is exceeded, increased N leaching may occur (Aber et al., 1998), and the flushes of soil water N that typically follows after

storm damage (**Paper II**), fertilization (Berden et al., 1998, Paper V) and clear cutting (Akselsson et al., 2004) will likely be further enhanced. The leaching is caused as a direct effect of an increased pool of inorganic N in the soil, but it is likely further elevated as a consequence of reduced production and assimilation by EMM. I suggest based upon results in this thesis (**Paper II** and **V**) that EMM is relatively more important for the total N retention capacity in forests that receive no or only moderate anthropogenic additions of N. Given the large area of these forests, reduced EMM production, which occur already at slight elevation of N deposition, could result in increased N leaching with substantial consequences for northern forest ecosystems.

FUTURE ASPECTS

Given the large area and C stock of boreal forests, it is important to put more emphasis on resolving the missing links in the C cycle as well as the N cycle. An important question that still remains to be answered is how moderate levels of N deposition affect the sequestration of carbon in boreal areas. To answer that question and to increase the general knowledge of the role EMM play in the C sequestration of boreal forests, field

surveys like the one in the analysis of the Northern Swedish chronosequence (**Paper IV**) should be repeated in a broader range of forests also including managed and fertilized forests.

While large N inputs lead to elevated aboveground inputs to SOC, belowground inputs may decrease. In order to predict future changes in the boreal C stocks it is necessary to develop models where both these two opposing processes are included, particularly given the evidence that belowground inputs can make a larger contribution to stable SOM pool than aboveground inputs.

Even though growth of EMF is typically reduced by elevated N deposition or N fertilization, severe nutrient limitation also results in less EMF production due to very limited tree growth. Further analysis is needed to identify the optimal fertility for EMM production.

Nitrogen leakage may result in depletion of other nutrients and eutrophication of aquatic systems. EMF has the potential to reduce N losses but further research is needed to estimate their N retention capacity in relation to assimilation by other microorganisms or directly by the tree roots.

REFERENCES

- Aber, J., McDowell, W., Nadelhoffer, K., Alison, M., Berntson, G., Kamakea, M., McNulty, S., Currie, W., Rustad, L., Fernandez, L., 1998. Nitrogen saturation in temperate forest ecosystems. *Bioscience* 48, 921-934.
- Agerer, R., 2001. Exploration types of ectomycorrhizae - A proposal to classify ectomycorrhizal mycelial systems according to their patterns of differentiation and putative ecological importance. *Mycorrhiza* 11, 107-114.
- Akselsson, C., Belyazid, S., Hellsten, S., Klarqvist, M., Pihl-Karlsson, G., Karlsson, P.E., Lundin, L., 2010. Assessing the risk of N leaching from forest soils across a steep N deposition gradient in Sweden. *Environmental Pollution* 158, 3588-3595.
- Akselsson, C., Westling, O., Orlander, G., 2004. Regional mapping of nitrogen leaching from clearcuts in southern Sweden. *Forest Ecology and Management* 202, 235-243.
- Andersson, S., Söderström, B., 1995. Effects of lime (CaCO₃) on ectomycorrhizal colonization of *picea abies* (L.) karst. seedlings planted in a spruce forest. *Scandinavian Journal of Forest Research* 10, 149-154.
- Arnebrant, K., 1994. Nitrogen amendments reduce the growth of extramatrical ectomycorrhizal mycelium. *Mycorrhiza* 5, 7-15.
- Arnebrant, K., Söderström, B., 1992. Effects of different fertilizer treatments on ectomycorrhizal colonization potential in two Scots pine forests in Sweden. *Forest Ecology and Management* 53, 77-89.
- Bakker, M.R., Garbaye, J., Nys, C., 2000. Effect of liming on the ectomycorrhizal status of oak. *Forest Ecology and Management* 126, 121-131.
- Beckjord, P.R., Melhuish, J.H., McIntosh, M.S., 1985. Effects of nitrogen and phosphorus fertilization on growth and formation of ectomycorrhizae of *Quercus alba* and *Q. rubra* seedlings by *Pisolithus tinctorius* and *Scleroderma auranteum*. *Canadian Journal of Botany* 63, 1677-1680.
- Berden, M., Nilsson, S.I., Nyman, P., 1998. Ion leaching before and after clear-cutting in a Norway spruce stand. Effects of long-term application of ammonium nitrate and superphosphate. (vol 93, pg 1, 1997). *Water Air and Soil Pollution* 101, 445-445.
- Bergh, J., Nilsson, U., Grip, H., Hedwall, P.O., Lundmark, T., 2008. Effects of frequency of fertilisation on production, foliar chemistry and nutrient leaching in young Norway spruce stands in Sweden. *Silva Fennica* 42, 721-733.
- Bermingham, S., Maltby, L., Cooke, R.C., 1995. A critical assessment of the validity of ergosterol as an indicator of fungal biomass. *Mycological Research* 99, 479-484.
- Berner, C., 2013. The effect of forest nutrients status on ectomycorrhizal growth and community structure in response to minerals PhD thesis, Lund University Dept. of Biology, Lund.
- Berner, C., Johansson, T., Wallander, H., 2012. Long-term effect of apatite on ectomycorrhizal growth and community structure. *Mycorrhiza* 22, 615-621.
- Bernstein, L., Pachauri, R.K., Change, I.P.o.C., Reisinger, A., 2008. Climate change 2007: Synthesis report. IPCC, Intergovernmental Panel on Climate Change c/o World Meteorological Organization (WMO).
- Bertills, U., Fölster, J., Lager, H., Lindstedt, U., Andersson, P., 2007. Bara naturlig försurning - Underlagsrapport till nytt delmål för utsläpp av svavel och kväve ifrån sjöfart. 2 October 2007 http://www.naturvardsverket.se/upload/01_sveriges_miljomal/eet/bara_naturlig_forsurning_071001.pdf, Stockholm.
- Bidartondo, M.I., Ek, H., Wallander, H., Söderström, B., 2001. Do nutrient additions alter carbon sink strength of ectomycorrhizal fungi? *New Phytologist* 151, 543-550.
- Bonan, G.B., Shugart, H.H., 1989. Environmental factors and ecological processes in boreal forests. *Annual Review of Ecology and Systematics* 20, 1-28.
- Brady, N.C., Weil, R.R., 2008. The nature and properties of soils, 13 ed. Prentice Hall, New Jersey, USA.
- Brockley, R.P., 2010. Effects of repeated fertilization in a young spruce stand in central British Columbia. *Canadian Journal of Forest Research* 40, 1687-1697.
- Bååth, E., Arnebrant, K., 1994. Growth rate and response of bacterial communities to pH in limed and ash treated forest soils. *Soil Biology and Biochemistry* 26, 995-1001.
- Clemmensen, K.E., Sorensen, P.L., Michelsen, A., Jonasson, S., Ström, L., 2008. Site-dependent N uptake from N-form mixtures by arctic plants, soil microbes and ectomycorrhizal fungi. *Oecologia* 155, 771-783.
- Deluca, T.H., Boisvenue, C., 2012. Boreal forest soil carbon: distribution, function and modelling. *Forestry* 85, 161-184.
- Dixon, R.K., Solomon, A.M., Brown, S., Houghton, R.A., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. *Science* 263, 185-190.

- Ekblad, A., Näsholm, T., 1996. Determination of chitin in fungi and mycorrhizal roots by an improved HPLC analysis of glucosamine. *Plant and Soil* 178, 29-35.
- Ekblad, A., Wallander, H., Carlsson, R., Huss-Danell, K., 1995. Fungal biomass in roots and extramatrical mycelium in relation to macronutrients and plant biomass of ectomycorrhizal *Pinus sylvestris* and *Alnus incana*. *New Phytologist* 131, 443-451.
- Ekblad, A., Wallander, H., Godbold, D.L., Cruz, C., Johnson, D., Baldrian, P., Björk, R.G., Epron, D., Kieliszewska-Rokicka, B., Kjoller, R., Kraigher, H., Matzner, E., Neumann, J., Plassard, C., 2013. The production and turnover of extramatrical mycelium of ectomycorrhizal fungi in forest soils: role in carbon cycling. *Plant and Soil* 366, 1-27.
- Ekblad, A., Wallander, H., Näsholm, T., 1998. Chitin and ergosterol combined to measure total and living fungal biomass in ectomycorrhizas. *New Phytologist* 138, 143-149.
- Ericsson, T., 1995. Growth and shoot: root ratio of seedlings in relation to nutrient availability. *Plant and Soil* 168-169, 205-214.
- Erland, S., Söderström, B., 1991. Effects of lime and ash treatments on ectomycorrhizal infection of *Pinus sylvestris* L. seedlings planted in a pine forest. *Scandinavian Journal of Forest Research* 6, 519-525.
- Fang, C., Moncrieff, J., 2005. The variation of soil microbial respiration with depth in relation to soil carbon composition. *Plant and Soil* 268, 243-253.
- Fernandez, C.W., Koide, R.T., 2011. The role of chitin in the decomposition of ectomycorrhizal fungal litter. *Ecology* 93, 24-28.
- Formánek, P., Vranová, V., 2003. A contribution to the effect of liming on forest soils: Review of literature. *Journal of Forest Science (Prague)* 49, 182-190.
- Franklin, O., Höglberg, P., Ekblad, A., Ågren, G.I., 2003. Pine forest floor carbon accumulation in response to N and PK additions: Bomb ¹⁴C modelling and respiration studies. *Ecosystems* 6, 644-658.
- Gimeno, L., Marin, E., Del Teso, T., Bourhim, S., 2001. How effective has been the reduction of SO₂ emissions on the effect of acid rain on ecosystems? *Science of the Total Environment* 275, 63-70.
- Godbold, D.L., Fritz, H.-W., Jentschke, G., Meessenburg, H., Rademacher, P., 2003. Root turnover and root necromass accumulation of Norway spruce (*Picea abies*) are affected by soil acidity. *Tree Physiology* 23, 915-921.
- Godbold, D.L., Hoosbeek, M.R., Lukac, M., Cotrufo, M.F., Janssens, I.A., Ceulemans, R., Polle, A., Velthorst, E.J., Scarascia-Mugnozza, G., De Angelis, P., Miglietta, F., Peressotti, A., 2006. Mycorrhizal hyphal turnover as a dominant process for carbon input into soil organic matter. *Plant and Soil* 281, 15-24.
- Gostinčar, C., Grube, M., De Hoog, S., Zalar, P., Gunde-Cimerman, N., 2010. Extremotolerance in fungi: evolution on the edge. *FEMS Microbiology Ecology* 71, 2-11.
- Gundersen, P., Rasmussen, L., 1995. Nitrogen mobility in a nitrogen limited forest at Klosterhede, Denmark, examined by NH₄NO₃ addition. *Forest Ecology and Management* 71, 75-88.
- Gundersen, P., Schmidt, I.K., Raulund-Rasmussen, K., 2006. Leaching of nitrate from temperate forests - effects of air pollution and forest management. *Environmental Reviews* 14, 1-57.
- Hedh, J., Wallander, H., Erland, S., 2008. Ectomycorrhizal mycelial species composition in apatite amended and non-amended mesh bags buried in a phosphorus-poor spruce forest. *Mycological Research* 112, 681-688.
- Hendricks, J.J., Mitchell, R.J., Kuehn, K.A., Pecot, S.D., Sims, S.E., 2006. Measuring external mycelia production of ectomycorrhizal fungi in the field: the soil matrix matters. *New Phytologist* 171, 179-186.
- Hibbett, D.S., Gilbert, L.B., Donoghue, M.J., 2000. Evolutionary instability of ectomycorrhizal symbioses in basidiomycetes. *Nature* 407, 506-508.
- Hobbie, E., Agerer, R., 2010. Nitrogen isotopes in ectomycorrhizal sporocarps correspond to belowground exploration types. *Plant and Soil* 327, 71-83.
- Hobbie, E.A., 2006. Carbon allocation to ectomycorrhizal fungi correlates with belowground allocation in culture studies. *Ecology* 87, 563-569.
- Hobbie, E.A., Werner, R.A., 2004. Intramolecular, compound-specific, and bulk carbon isotope patterns in C₃ and C₄ plants: a review and synthesis. [Erratum: 2004 Apr., v. 162, no. 1, p. 240.]. *The New phytologist* 161, 371-385.
- Hyodo, F., Wardle, D.A., 2009. Effect of ecosystem retrogression on stable nitrogen and carbon isotopes of plants, soils and consumer organisms in boreal forest islands. *Rapid Communications in Mass Spectrometry* 23, 1892-1898.
- Hyvönen, R., Ågren, G.I., Linder, S., Persson, T., Cotrufo, M.F., Ekblad, A., Freeman, M., Grelle, A., Janssens, I.A., Jarvis, P.G., Kellomäki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R.J., Oren, R.,

- Pilegaard, K., Ryan, M.G., Sigurdsson, B.D., Strömberg, M., Oijen, M.v., Wallin, G., 2007. The likely impact of elevated CO₂, nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: A literature review. *New Phytologist* 173, 463-480.
- Högberg, M.N., 2006. Discrepancies between ergosterol and the phospholipid fatty acid 18 : 2 omega 6,9 as biomarkers for fungi in boreal forest soils. *Soil Biology and Biochemistry* 38, 3431-3435.
- Högberg, M.N., Briones, M.J.I., Keel, S.G., Metcalfe, D.B., Campbell, C., Midwood, A.J., Thornton, B., Hurry, V., Linder, S., Näsholm, T., Högberg, P., 2010. Quantification of effects of season and nitrogen supply on tree below-ground carbon transfer to ectomycorrhizal fungi and other soil organisms in a boreal pine forest. *New Phytologist* 187, 485-493.
- Högberg, M.N., Högberg, P., 2002. Extramatrical ectomycorrhizal mycelium contributes one-third of microbial biomass and produces, together with associated roots, half the dissolved organic carbon in a forest soil. *New Phytologist* 154, 791-795.
- Högberg, P., 1997. Tansley review No. 95. ¹⁵N natural abundance in soil-plant systems. *New Phytologist* 137, 179-203.
- Högberg, P., 2012. What is the quantitative relation between nitrogen deposition and forest carbon sequestration? *Global Change Biology* 18, 1-2.
- Högberg, P., Johannisson, C., Yarwood, S., Callesen, I., Näsholm, T., Myrold, D.D., Högberg, M.N., 2011. Recovery of ectomycorrhiza after 'nitrogen saturation' of a conifer forest. *New Phytologist* 189, 515-525.
- Högberg, P., Plamboeck, A.H., Taylor, A.F.S., Fransson, P.M.A., 1999. Natural ¹³C abundance reveals trophic status of fungi and host-origin of carbon in mycorrhizal fungi in mixed forests. *Proceedings of the National Academy of Sciences of the United States of America* 96, 8534-8539.
- Jacobson, M.Z., 2009. Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science* 2, 148-173.
- Jacobson, S., Pettersson, F., 2010. An assessment of different fertilization regimes in three boreal coniferous stands. *Silva Fennica* 44, 815-827.
- Janssens, I.A., Dieleman, W., Luyssaert, S., Subke, J.A., Reichstein, M., Ceulemans, R., Ciais, P., Dolman, A.J., Grace, J., Matteucci, G., Papale, D., Piao, S.L., Schulze, E.D., Tang, J., Law, B.E., 2010. Reduction of forest soil respiration in response to nitrogen deposition. *Nature Geosci* 3, 315-322.
- Janssens, I.A., Luyssaert, S., 2009. Nitrogen's carbon bonus. *Nature Geoscience* 2, 318-319.
- Johansson, H., Mårtensson, K., Naturvårdsverket, 1997. Kväveläckage från svensk åkermark: Beräkningar av normalutlakning för 1995 och 1999. *NATURVÅRDSVERKET rapport* 5248
- Karst, J., Marczak, L., Jones, M.D., Turkington, R., 2008. The mutualism-parasitism continuum in ectomycorrhizas: A quantitative assessment using meta-analysis. *Ecology* 89, 1032-1042.
- Kjøller, R., 2006. Disproportionate abundance between ectomycorrhizal root tips and their associated mycelia. *Fems Microbiology Ecology* 58, 214-224.
- Kjøller, R., Clemmensen, K.E., 2009. Belowground ectomycorrhizal fungal communities respond to liming in three southern Swedish coniferous forest stands. *Forest Ecology and Management* 257, 2217-2225.
- Kjøller, R., Nilsson, L.-O., Hansen, K., Schmidt, I.K., Vesterdal, L., Gundersen, P., 2012. Dramatic changes in ectomycorrhizal community composition, root tip abundance and mycelial production along a stand-scale nitrogen deposition gradient. *New Phytologist* 194, 278-286.
- Koide, R.T., Malcolm, G.M., 2009. N concentration controls decomposition rates of different strains of ectomycorrhizal fungi. *Fungal Ecology* 2, 197-202.
- Korkama, T., Fritze, H., Pakkanen, A., Pennanen, T., 2007. Interactions between extraradical ectomycorrhizal mycelia, microbes associated with the mycelia and growth rate of Norway spruce (*Picea abies*) clones. *New Phytologist* 173, 798-807.
- Leake, J., Johnson, D., Donnelly, D., Muckle, G., Boddy, L., Read, D., 2004. Networks of power and influence: the role of mycorrhizal mycelium in controlling plant communities and agroecosystem functioning. *Canadian Journal of Botany* 82, 1016-1045.
- LeBauer, D.S., Treseder, K.K., 2008. Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. *Ecology* 89, 371-379.
- Lehto, T., 1994. Effects of soil pH and calcium on mycorrhizas of *Picea abies*. *Plant and Soil* 163, 69-75.
- Lilleskov, E.A., Hobbie, E.A., Fahey, T.J., 2002. Ectomycorrhizal fungal taxa differing in response to nitrogen deposition also differ in pure culture organic nitrogen use and natural abundance of nitrogen isotopes. *New Phytologist* 154, 219-231.

- Lindahl, B.D., Ihrmark, K., Boberg, J., Trumbore, S.E., Högberg, P., Stenlid, J., Finlay, R.D., 2007. Spatial separation of litter decomposition and mycorrhizal nitrogen uptake in a boreal forest. *New Phytologist* 173, 611-620.
- Litton, C.M., Raich, J.W., Ryan, M.G., 2007. Carbon allocation in forest ecosystems. *Global Change Biology* 13, 2089-2109.
- Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis, P.G., Kolari, P., Kowalski, A.S., Lankreijer, H., Law, B.E., Lindroth, A., Loustau, D., Manca, G., Moncrieff, J.B., Rayment, M., Tedeschi, V., Valentini, R., Grace, J., 2007. The human footprint in the carbon cycle of temperate and boreal forests. *Nature* 447, 848-850.
- Meier, S., Robarge, W.P., Bruck, R.I., Grand, L.F., 1989. Effects of simulated rain acidity on ectomycorrhizae of red spruce seedlings potted in natural soil. *Environmental Pollution* 59, 315-324.
- Nadelhoffer, K.J., Emmett, B.A., Gundersen, P., Kjonaas, O.J., Koopmans, C.J., Schleppi, P., Tietema, A., Wright, R.F., 1999. Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. *Nature* 398, 145-148.
- Nilsson, L.O., Bååth, E., Falkengren-Grerup, U., Wallander, H., 2007. Growth of ectomycorrhizal mycelia and composition of soil microbial communities in oak forest soils along a nitrogen deposition gradient. *Oecologia* 153, 375-384.
- Nilsson, L.O., Wallander, H., 2003. Production of external mycelium by ectomycorrhizal fungi in a Norway spruce forest was reduced in response to nitrogen fertilization. *New Phytologist* 158, 409-416.
- Nilsson, L.O., Wallander, H., Gundersen, P., 2012. Changes in microbial activities and biomasses over a forest floor gradient in C-to-N ratio. *Plant and Soil* 355, 75-86.
- Nöhrstedt, H.-Ö., 2001. Response of coniferous forest ecosystems on mineral soils to nutrient additions: A review of Swedish experiences. *Scandinavian Journal of Forest Research* 16, 555-573.
- Nowotny, I., Dähne, J., Klingelhöfer, D., Rothe, G.M., 1998. Effect of artificial soil acidification and liming on growth and nutrient status of mycorrhizal roots of Norway spruce (*Picea abies* [L.] Karst.). *Plant and Soil* 199, 29-40.
- Nylund, J.E., Wallander, H., 1992. Ergosterol analysis as a means of quantifying mycorrhizal biomass. *Methods in Microbiology* 24, 77-88.
- Näsholm, T., Högberg, P., Franklin, O., Metcalfe, D., Keel, S.G., Campbell, C., Hurry, V., Linder, S., Högberg, M.N., 2013. Are ectomycorrhizal fungi alleviating or aggravating nitrogen limitation of tree growth in boreal forests? *198*, 214-221.
- Parrent, J.L., Vilgalys, R., 2007. Biomass and compositional responses of ectomycorrhizal fungal hyphae to elevated CO₂ and nitrogen fertilization. *New Phytologist* 176, 164-174.
- Persson, O., Eriksson, H., Johansson, U., 1995. An attempt to predict long-term effects of atmospheric nitrogen deposition on the yield of Norway spruce stands (*Picea abies* (L.) Karst.) in southwestern Sweden. *Plant and Soil* 168-169, 249-254.
- Piirainen, S., Finér, L., Starr, M., 1998. Canopy and soil retention of nitrogen deposition in a mixed boreal forest in eastern Finland. *Water, Air, and Soil Pollution* 105, 165-174.
- Read, D.J., Perez-Moreno, J., 2003. Mycorrhizas and nutrient cycling in ecosystems – a journey towards relevance? *New Phytologist* 157, 475-492.
- Reay, D.S., Dentener, F., Smith, P., Grace, J., Feely, R.A., 2008. Global nitrogen deposition and carbon sinks. *Nature Geosci* 1, 430-437.
- Rineau, F., Maurice, J.-P., Nys, C., Voiry, H., Garbaye, J., 2010. Forest liming durably impact the communities of ectomycorrhizas and fungal epigeous fruiting bodies. *Annals of Forest Science* 67:110.
- Rineau, F., Roth, D., Shah, F., Smits, M., Johansson, T., Canbäck, B., Olsen, P.B., Persson, P., Grell, M.N., Lindquist, E., Grigoriev, I.V., Lange, L., Tunlid, A., 2012. The ectomycorrhizal fungus *Paxillus involutus* converts organic matter in plant litter using a trimmed brown-rot mechanism involving Fenton chemistry. *Environmental Microbiology* 14, 1477-1487.
- Rineau, F., Shah, F., Smits, M.M., Persson, P., Johansson, T., Carleer, R., Troein, C., Tunlid, A., 2013. Carbon availability triggers the decomposition of plant litter and assimilation of nitrogen by an ectomycorrhizal fungus. *ISME J.*
- Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen,

- J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. *Nature* 461, 472-475.
- Rousk, J., Brookes, P.C., Bååth, E., 2011. Fungal and bacterial growth responses to N fertilization and pH in the 150-year 'Park Grass' UK grassland experiment. *FEMS Microbiology Ecology* 76, 89-99.
- Rousk, J., Bååth, E., 2011. Growth of saprotrophic fungi and bacteria in soil. *FEMS Microbiology Ecology* 78, 17-30.
- Runion, G.B., Mitchell, R.J., Rogers, H.H., Prior, S.A., Counts, T.K., 1997. Effects of nitrogen and water limitation and elevated atmospheric CO₂ on ectomycorrhiza of longleaf pine. *New Phytologist* 137, 681-689.
- Schulze, E.D., 2000. Carbon and nitrogen cycling in european forest ecosystems. Springer-Verlag GmbH.
- Setälä, H., Kulmala, P., Mikola, J., Markkola, A.M., 1999. Influence of ectomycorrhiza on the structure of detrital food webs in pine rhizosphere. *Oikos* 87, 113-122.
- Simard, S.W., Jones, M.D., Durall, D.M., 2002. Carbon and nutrient fluxes within and between mycorrhizal plants, In: van der Heijden, M.G.A.S.I.R. (Ed.), *Ecological Studies. Mycorrhizal ecology*, pp. 33-74.
- Smith, S.E., Read, D.J., 2008. *Mycorrhizal symbiosis*, third edition. Academic Press, London.
- Stendahl, J., Hjerpe, K., 2007. Utgör kvävegödning av skog en risk för Östersjön? Slutsatser från ett seminarium anordnat av Baltic Sea 2020 i samarbete med Skogsstyrelsen. SKOGSSTYRELSEN Rapport 10.
- Stevens, P.A., Harrison, A.F., Jones, H.E., Williams, T.G., Hughes, S., 1993. Nitrate leaching from a Sitka spruce plantation and the effect of fertilisation with phosphorus and potassium. *Forest Ecology and Management* 58, 233-247.
- Stoddard, J.L., 1994. Long-term changes in watershed retention of nitrogen - its causes and aquatic consequences, In: Baker, L.A. (Ed.), *Environmental Chemistry of Lakes and Reservoirs*, pp. 223-284.
- Sutton, M.A., Simpson, D., Levy, P.E., Smith, R.I., Reis, S., Van Oijen, M., De Vries, W.I.M., 2008. Uncertainties in the relationship between atmospheric nitrogen deposition and forest carbon sequestration. *Global Change Biology* 14, 2057-2063.
- Söderstrom, B., 1992. The ecological potential of the ectomycorrhizal mycelium, In: Read, D.J., Lewis, D.H., Fitter, A.H., Alexander, I.J. (Eds.), *Mycorrhizas in Ecosystems*, pp. 77-83.
- Tarasova, O.A., Koide, H., Dlugokencky, E., Hall, B., Montzka, S.A., Krummel, P., Brunke, E., Scheel, H.-E., 2012. The state of greenhouse gases in the atmosphere using global observations through 2010. *Geophysical Research Abstracts* 14.
- Taylor, A.F.S., Fransson, P.M., Höglberg, P., Höglberg, M.N., Plamboeck, A.H., 2003. Species level patterns in ¹³C and ¹⁵N abundance of ectomycorrhizal and saprotrophic fungal sporocarps. *New Phytologist* 159, 757-774.
- Taylor, A.F.S., Martin, F., Read, D.J., 2000. Fungal diversity in ectomycorrhizal communities of Norway spruce (*Picea abies* [L.] Karst.) and Beech (*Fagus sylvatica* L.) along north-south transects in Europe., In: Schulze, E.-D. (Ed.), *Ecol. Stud.* Springer-Verlag, Heidelberg, pp. 343-365.
- Tedersoo, L., May, T.W., Smith, M.E., 2010. Ectomycorrhizal lifestyle in fungi: global diversity, distribution, and evolution of phylogenetic lineages. *Mycorrhiza* 20, 217-263.
- Thelin, G., Rosengren, U., Nihlgård, B., 2002. Barrkemi på skånska gran- och tallprovdytor - Förändringar mellan 1985 och 2000. Länsstyrelsen (Ed.). Länsstyrelsen i Skåne län, Kristianstad.
- Underwood, A.J., 2009. Components of design in ecological field experiments. *Annales Zoologici Fennici* 46, 93-111.
- Wallander, H., 1995. A new hypothesis to explain allocation of dry matter between mycorrhizal fungi and pine seedlings in relation to nutrient supply. *Plant and Soil* 168-169, 243-248.
- Wallander, H., Arnebrant, K., Östrand, F., Kårén, O., 1997. Uptake of ¹⁵N-labelled alanine, ammonium and nitrate in *Pinus sylvestris* L. ectomycorrhiza growing in forest soil treated with nitrogen, sulphur or lime. *Plant and Soil* 195, 329-338.
- Wallander, H., Ekblad, A., Bergh, J., 2011. Growth and carbon sequestration by ectomycorrhizal fungi in intensively fertilized Norway spruce forests. *Forest Ecology and Management* 262, 999-1007.
- Wallander, H., Göransson, H., Rosengren, U., 2004. Production, standing biomass and natural abundance of ¹⁵N and ¹³C in ectomycorrhizal mycelia collected at different soil depths in two forest types. *Oecologia* 139, 89-97.
- Wallander, H., Johansson, U., Sterkenburg, E., Brandström Durling, M., Lindahl, B.D., 2010. Production of ectomycorrhizal mycelium peaks during canopy closure in Norway spruce forests. *New Phytologist* 187, 1124-1134.
- Wallander, H., Nilsson, L.O., Hagerberg, D., Baath, E., 2001. Estimation of the biomass and seasonal growth of external mycelium of ectomycorrhizal fungi in the field. *New Phytologist* 151, 753-760.

- Wallander, H., Nylund, J.-E., 1992. Effects of excess nitrogen and phosphorus starvation on the extramatrical mycelium of ectomycorrhizas of *Pinus sylvestris* L. *New Phytologist* 120, 495-503.
- Wallander, H., Thelin, G., 2008. The stimulating effect of apatite on ectomycorrhizal growth diminishes after PK fertilization. *Soil Biology and Biochemistry* 40, 2517-2522.
- van Hees, P.A.W., Jones, D.L., Finlay, R., Godbold, D.L., Lundström, U.S., 2005. The carbon we do not see - the impact of low molecular weight compounds on carbon dynamics and respiration in forest soils: a review. *Soil Biology & Biochemistry* 37, 1-13.
- Wardle, D.A., Zackrisson, O., Hörnberg, G., Gallet, C., 1997. The influence of island area on ecosystem properties. *Science* 277, 1296-1299.
- Watson, R.T., Change, I.P.o.C., 2000. Land use, land-use change, and forestry: A special report of the intergovernmental panel on climate change. Cambridge University Press.
- Weigt, R., Raidl, S., Verma, R., Agerer, R., 2012. Exploration type-specific standard values of extramatrical mycelium – a step towards quantifying ectomycorrhizal space occupation and biomass in natural soil. *Mycological Progress* 11, 287-297.
- Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H., Tilman, D.G., 1997. Human alteration of the global nitrogen cycle: Sources and consequences. *Ecological Applications* 7, 737-750.
- Vitousek, P.M., Howarth, R.W., 1991. Nitrogen limitation on land and in the sea - how can it occur. *Biogeochemistry* 13, 87-115.
- Wright, I.J., Reich, P.B., Westoby, M., Ackerly, D.D., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Cornelissen, J.H.C., Diemer, M., Flexas, J., Garnier, E., Groom, P.K., Gulias, J., Hikosaka, K., Lamont, B.B., Lee, T., Lee, W., Lusk, C., Midgley, J.J., 2004. The worldwide leaf economics spectrum. *Nature* 428, 821-827.
- Wright, R.F., Alewell, C., Cullen, J.M., Evans, C.D., Marchetto, A., Moldan, F., Prechtel, A., Rogora, M., 2001. Trends in nitrogen deposition and leaching in acid-sensitive streams in Europe. *Hydrology and Earth System Sciences* 5, 299-310.
- Yuan, J.P., Kuang, H.C., Wang, J.H., Liu, X., 2008. Evaluation of ergosterol and its esters in the pileus, gill, and stipe tissues of agaric fungi and their relative changes in the comminuted fungal tissues. *Applied Microbiology and Biotechnology* 80, 459-465.
- Zhao, X.R., Lin, Q., Brookes, P.C., 2005. Does soil ergosterol concentration provide a reliable estimate of soil fungal biomass? *Soil Biology and Biochemistry* 37, 311-317.

POPULÄRVETENSKAPLIG SAMMANFATTNING:

Vanliga skogssvampar är viktiga för kretsloppen av kol och kväve

Ektomykorrhiza

I alla skogar växande i ett klimat liknande Sveriges, lever nästan samtliga trädarter i ett nära samspel (symbios) med svampar. Till skillnad från nedbrytarsvampar (som kan leva enbart på dött organiskt material) är flera av de kända skogssvamparna såsom kantareller, soppar, flugsvampar, kremlor och riskor beroende av denna symbios med träd för att överleva. Symbiosen mellan träd och svamp kallas för ektomykorrhiza. Svamparna som vi ofta plockar i skogen utgör bara fruktkropparna av svampen som lever som ett nätverk av svamphyfer i marken, kallat mycel. Som liknelse kan man tänka sig att svampfruktkropparna är som äpplen på ett äppelträd. Ektomykorrhiza-svamparnas mycel ansluter till trädets rotspetsar och omsluter i regel över 90 % av dem, likt en handske. Ektomykorrhiza-svampar levererar näringsämnen och vatten ifrån marken till trädet, i utbyte mot kol som nyligen fångats in ifrån atmosfären genom trädens fotosyntes. Ektomykorrhiza-svamparna utgör en potentiellt viktig kolsänka då 10-50 % av allt det kol som binds in i trädens fotosyntes transporteras via rötterna direkt till svamparnas mycel i marken. I ett enda gram skogsjord kan det finnas upp till en kilometer svampmycel och svamparna ökar i regel trädrötternas kontaktyta med jorden över 100 gånger. Dessutom kan svamparna frigöra näringsämnen som är inbundna i organiskt material, som annars är otillgängliga för trädrötterna. Detta gör att nästan allt näringsutbyte trädet har går igenom ektomykorrhizasvampar.

Kvävebegränsning i skogen

Träden i barrskogsbältet är oftast begränsade av tillgången på kväve. Om kväve tillsätts via gödsling blir det mer lättillgängligt för trädrötterna och träden behöver därför inte skicka ner lika mycket kol för att utveckla rötter eller ektomykorrhiza-svampar. Större mängder av kol binds istället in i trädets biomassa ovan mark. Mänskliga utsläpp (från bland annat trafik och industrier) har gjort att kvävet som tillsätts från atmosfären ökat från mindre än 2 kg per hektar och år till hela 50 kg per hektar och år i vissa områden i exempelvis Centraleuropa. Även om kvävenedfallet i Sverige är betydligt mindre är det ändå upp till 10 gånger högre än det naturliga nedfallet. Det har flera gånger visats att gödsling med stora mängder kväve (ofta 100 kg per hektar och år) i nordliga skogar leder till minskad tillväxt av ektomykorrhiza-mycel, men det saknas fortfarande studier på effekten av den låga kontinuerliga tillsatsen av kväve som sker via nedfall. Detta är viktigt att reda ut då det kan få stora konsekvenser gällande upplagringen av kol och kväve i skogsmarken. Resultat ifrån denna avhandling visar att kvävenedfallet i Sverige är tillräckligt för att minska tillväxten av ektomykorrhizasvampar, och att en kraftig minskning sker redan vid kvävenedfall under 10 kg per hektar och år.

Då ektomykorrhizamycel effektivt tar upp kväve i marken är det sannolikt att det bidrar till att motverka kväveläckage. Man har tidigare hittat samband med ökat kväveläckage vid låg tillväxt av ektomykorrhizasvampar efter kvävegödsling. Det har dock inte varit möjligt att särskilja betydelsen av minskat mycel från den direkta effekt som kvävegödsling har på läckaget. För att bättre reda ut svampens kapacitet att ta upp kväve satte vi upp ett gödslingsförsök i granskogar nära Simlångsdalen. Resultaten visade att ektomykorrhizasvampar har en stor kapacitet att ta upp kväve, men att detta inte var tillräckligt för att motverka det läckage som kom direkt efter gödsling.

Skogen som kolsänka

Globalt sett binder barrskogsbältet in enorma mängder kol, och det mesta av detta finns lagrat i marken. Det finns enligt den internationella klimatpanelens (IPCC) rapport, ungefär lika mycket kol lagrat i barrskogsmarken som i både mark och växtlighet i samtliga regnskogar. Detta gör det viktigt att fokusera på de processer som bidrar till kollagringen. En majoritet av de studier som gjorts hittills på effekter av kväveutsläpp och kvävegödsling visar att detta gynnar skogens kolinlagring. Dessa studier visar att kvävetillsats leder till mer kolinbindning genom en ökad tillväxt av träden och större produktion av barr samt minskade nedbrytningsprocesser i marken, men det saknas fortfarande kunskap gällande den kolinlagring som sker under markytan via rötter och ektomykorrhiza-svampar. Då kvävetillsatts minskar mängden kol som transporteras direkt ner i marken kan detta istället leda till en minskad kollagring. För att kunna utveckla en korrekt rådgivning gällande effekten av kvävetillsats på kolinbindningen är det nödvändigt att ta med både dessa motverkande processer i beräkningarna.

Kolinlagring av ektomykorrhiza

I likhet med tidigare studier visar våra analyser av barrskogar i Svealand och Götaland att ektomykorrhiza-svamparna bildar ungefär ett halvt ton mycel per år och hektar. Detta är dock bara den årliga nyproduktionen och den stående svampbiomassan har tidigare uppskattats till ungefär 2 ton per hektar. Delar av ektomykorrhizamyceliet är relativt svårnedbrytbart då det ofta är vattenavstötande och innehåller många motståndskraftiga molekyler, vilket gör att det har en potential att bidra till kolinbindningen. Något vi fann tydliga indikationer på i en undersökning av skogar med olika lång kontinuitet i Norrland. Dessa skogar var belägna på öar av olika storlek i sjöarna Uddjaure och Hornavan, och var i stort sett opåverkade av mänsklig aktivitet. Den största störningen i dessa skogar utgjordes av bränder. Då större öar oftare träffas av blixten resulterar det i mer frekventa skogsbränder som startar om successionen. Kontinuiteten av skog sträckte sig ifrån ett par hundra år (på stora öar) upp till tusentals år på små öar. Det var en enorm upplagring av organiskt material i de riktigt gamla skogarna, då humuslagret kunde vara en hel meter tjockt. I de yngre skogarna var humuslagret ungefär 10 cm tjock, likt de flesta bruksskogar. Över hälften av markkolet som bundits in i jorden de senaste 100 åren visade sig härstamma ifrån rötter och mykorrhizasvampar, och denna mängd ökade ju längre successionen hade fortgått. Tidigare har man ofta ansett att det är vad som produceras ovanför markytan som är viktigast för kolinlagringen. Resultaten i denna avhandling visar att det är viktigt att det kol som matas in i jorden via rötter och mykorrhizasvampar tas med då man beräknar och modellerar kolinbindning i skogsmark.

Slutsats

Kvävenedfall hade en negativ effekt på tillväxten av ektomykorrhizamycel, vilket kan leda till minskad kolinlagring i skogsjordarna. Detta är i direkt kontrast till många studier av andra processer som gör att kolinlagringen istället ökar efter kvävegödsling. Både dessa motverkande system ingår i tidigare studier av det totala kolflödet mellan atmosfären och skogen, som visar på en positiv effekt av högt kvävenedfall. Men denna effekt uppstår inte förrän kvävetillsatsen når minst 5 kg per hektar och år. De flest barrskogarna är utsatta för en ökning i kvävenedfall som är mindre än detta, och våra studier visar att minskad produktion av ektomykorrhiza sker redan efter låga öknings i kvävedeposition. Det är av stor vikt att vidare undersöka hur dessa två

motverkande system påverkas av olika mängder kväve för att bättre kunna modellera och förutsäga effekten av människoskapade kväveutsläpp. Jag visar också att ektomykorrhizasvamparna har en stor potential att motverka kväveläckage men för att ställa deras kväveupptag i relation till vad trädrötterna och övriga mikroorganismer i marken tar upp behövs fler undersökningar.

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I





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Review

Evaluation of methods to estimate production, biomass and turnover of ectomycorrhizal mycelium in forests soils – A review

H. Wallander^{a,*}, A. Ekblad^b, D.L. Godbold^c, D. Johnson^d, A. Bahr^a, P. Baldrian^e, R.G. Björk^f, B. Kieliszewska-Rokicka^g, R. Kjeller^h, H. Kraigherⁱ, C. Plassard^j, M. Rudawska^k

^a Department of Biology, Microbial Ecology Group, Ecology Building, Lund University, SE-223 62 Lund, Sweden

^b School of Science & Technology, Örebro University, SE-701 82 Örebro, Sweden

^c Institute of Forest Ecology, Universität für Bodenkultur, 1190 Vienna, Austria

^d Institute of Biological and Environmental Sciences, University of Aberdeen, Cruickshank Building, St. Machar Drive, Aberdeen AB24 3UU, UK

^e Laboratory of Environmental Microbiology, Institute of Microbiology ASCR, CZ-14220 Praha, Czech Republic

^f Department of Biological and Environmental Sciences, University of Gothenburg, P.O. Box 461, SE-405 30 Gothenburg, Sweden

^g Institute of Environmental Biology, Kazimierz Wielki University, Al. Ossolinskich 12, PL-85-093 Bydgoszcz, Poland

^h Terrestrial Ecology, Biological Institute, University of Copenhagen, Øster Farimagsgade 2D, DK-1353 Copenhagen, Denmark

ⁱ Slovenian Forestry Institute, Vecna pot 2, 1000 Ljubljana, Slovenia

^j INRA, UMR Eco & Sols, 34060 Montpellier Cedex 02, France

^k Institute of Dendrology, Polish Academy of Sciences, Parkowa 5, 62-035 Kórnik, Poland

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ABSTRACT

Mycorrhizal fungi constitute a considerable sink for carbon in most ecosystems. This carbon is used for building extensive mycelial networks in the soil as well as for metabolic activity related to nutrient uptake. A number of methods have been developed recently to quantify production, standing biomass and turnover of extramatrix mycorrhizal mycelia (EMM) in the field. These methods include minirhizotrons, in-growth mesh bags and cores, and indirect measurements of EMM based on classification of ectomycorrhizal fungi into exploration types. Here we review the state of the art of this methodology and discuss how it can be developed and applied most effectively in the field. Furthermore, we also discuss different ways to quantify fungal biomass based on biomarkers such as chitin, ergosterol and PLFAs, as well as molecular methods, such as qPCR. The evidence thus far indicates that mycorrhizal fungi are key components of microbial biomass in many ecosystems. We highlight the need to extend the application of current methods to focus on a greater range of habitats and mycorrhizal types enabling incorporation of mycorrhizal fungal biomass and turnover into biogeochemical cycling models.

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1. Introduction

A better understanding of below ground carbon (C) flux is of fundamental importance to predict how changing climate will influence the C balance of forest (and other) ecosystems (Litton and Giardina, 2008). Litton et al. (2007) reported below ground C allocation in forest ecosystems can represent 25–63% of GPP on a global scale, and this C has a large influence on the physical, chemical and biological properties of soils. The below ground allocation of C links

activity in the forest canopy to the activity in the soil, and provides a flow of organic C from shoots to soil via fine roots and mycorrhizal hyphae. The pathways by which this organic C can enter soils are complex, involving both biomass turnover (Godbold et al., 2003), biomass grazing (Setälä et al., 1999) and turnover of low molecular weight exudates from roots and fungal hyphae (van Hees et al., 2005). The fate of C entering soil systems is also complex. Much of this C is lost as respiration (Janssens et al., 2001) and a small but significant fraction enters the soil organic matter (SOM) pool. Determination of the pools and fluxes of biomass inputs in isolation from fine roots and mycorrhiza provides a major scientific challenge. Some studies (e.g. Wallander et al., 2004) suggest that biomass pools and inputs from fine roots and mycorrhizal hyphae are in the same order of magnitude. However, estimates of fungal inputs rely on

* Corresponding author, MEMEG, Department of Biology, Ecology Building, Lund University, SE-223 62 Lund, Sweden. Tel.: +46 46 222 4247; fax: +46 46 222 4158. E-mail address: hakan.wallander@biol.lu.se (H. Wallander).

methods and conversion factors that contain a certain degree of inaccuracy that needs to be considered.

Precise measurements of production, standing biomass and turnover of extramatrical mycelium (EMM) of mycorrhizal fungi are essential in order to accurately describe the C cycle of terrestrial ecosystems. Although several techniques are available for this, they all have limitations that need to be taken into consideration.

Existing biogeochemical models often treat the uptake apparatus as a single organ, meaning that there is no distinction between roots and mycorrhizal hyphae. It is possible, and probably necessary, to amend this by allocating carbon and nutrients specifically for the fine roots and mycorrhizal hyphae respectively. This would require the development of dynamic allocation routines responsive to carbon, nutrients and water availability (Jönsson, 2006), and would allow the models to simulate nutrient uptake and carbon flux dynamically. In this review, we will discuss and compare available methods to estimate production, standing biomass and turnover of mycorrhizal mycelia (summarized in Tables 1–3). We focus on temperate and boreal forests, in which the dominant plants associate with ectomycorrhizal (ECM) fungi. From a methodological perspective, greatest progress has been made in quantification of production, biomass and turnover of ECM fungi compared to the other main mycorrhizal types (arbuscular and ericoid mycorrhizas). This progress has been driven partly by technical reasons but more importantly because of the recognition of the key roles boreal and temperate forests play in the global C cycle. However, we emphasise from the outset that greater effort must be applied to other ecosystems in which plants are primarily colonised by arbuscular and ericoid mycorrhizal fungi, which also have important roles in regulating biogeochemical cycles. We will also highlight knowledge gaps that need to be filled in order to incorporate mycorrhizal mycelia in models of biogeochemical cycles, which will enable us to better describe the C cycle in forests. Firstly methods to estimate EMM production are described and discussed, since the methodology in this field has developed rapidly over the last decades. We then discuss the advantages and disadvantages of different methods to estimate fungal biomass. Finally we discuss how we can

assess the turnover of fungal hyphae. This area needs clearly to be developed in future research as it is a key process in C sequestration of forest soils. We also include aspects of sampling strategies and indirect estimates of EMM production that have great potential for the future. The mechanisms through which EMM regulate C cycling in terrestrial ecosystems have been considered recently in another review (Cairney, 2012).

2. Measurements of mycorrhizal hyphal production

A key problem in the determination of mycorrhizal hyphal production is lack of methods to distinguish growth of mycorrhizal hyphae from that of saprotrophic fungi. As ECM fungi do not form a monophyletic clade (Hibbett et al., 2000; Tedersoo et al., 2010) no single biochemical or DNA based marker can be found to quantify this group from the complex soil environment. Therefore various methods are needed to distinguish the biomass of EMM from that of other fungal mycelia. Mycelial growth can be estimated by direct observation in minirhizotrons (Treseder et al., 2005; Pritchard et al., 2008; Vargas and Allen, 2008a) and by the use of root free in-growth bags or cores, which is the most commonly applied method to measure EMM production in forests (Wallander et al., 2001; Godbold et al., 2006; Hendricks et al., 2006; Kjoller, 2006; Korkama et al., 2007; Parrent and Vilgalys, 2007; Hedh et al., 2008; Majdi et al., 2008).

2.1. Observational methods

The first observational studies used plastic sheets placed at the litter/soil interface above root clusters where individual ECM tips were observed by pulling back and replacing the litter at different times (Orlov, 1957, 1960). Lussenhop and Fogel (1999) used a method developed by Waid and Woodman (1957) to estimate hyphal production of the ECM fungus *Cenococcum geophilum* by burying nylon mesh in the soil and harvesting them at two week intervals. Rygielwicz et al. (1997) introduced the minirhizotron technique, commonly used to study fine roots, to measure temporal occurrence and lifetime of mycorrhizal root tips. However, the use

Table 1
Strengths and weaknesses of currently used methods to estimate production of ECM extramatrical mycelium (EMM).

Methods	Strengths	Weaknesses	Comments
Production of ECM mycelium	<ul style="list-style-type: none"> • Repeated non-destructive sampling possible. • Not dependent on conversion factors. 	<ul style="list-style-type: none"> • Cannot differentiate between saprotrophic or mycorrhizal hyphae. • High resolution needed to observe individual hyphae. • Growth might be different in observation chamber compared to soil. • Difficult to transfer to biomass per land area. 	<ul style="list-style-type: none"> • Changes in rhizomorph production, which are easier to observe, does not automatically imply similar changes in total EMM production.
Root free in-growth mesh-bags or cores	<ul style="list-style-type: none"> • Easy and relatively cheap method that can be applied in large scales. • Substrates that have no background of old mycelium, chemical markers, DNA etc. can be used. • Substrates can be 'spiked' with isotopic labelled materials, minerals etc. • Relative comparisons may be more reliable than estimates of absolute amounts. 	<ul style="list-style-type: none"> • Growth, standing biomass and turnover may be different in mesh bags compared to soil, and this needs to be further studied. • May select for early colonizers of fungus free space. • Disturbance at installation & harvest. • Interactions with soil animals are restricted. • The way the mycelial biomass is assessed may give different results. 	<ul style="list-style-type: none"> • When bags are left in the soil over years or more, the mycelial mass is possibly a reflection of the standing biomass rather than production? • Disturbance is probably larger for larger bags or cores. • Mycelial biomass can be assessed with: dry weight, loss on ignition or with chemical markers.
Assessment of exploration types	<ul style="list-style-type: none"> • Definition of exploration types is based on EMM production. • ECM communities have been studied in a number of forest ecosystems. • Possible to combine with molecular methods to indirectly non-destructively estimate EMM production. 	<ul style="list-style-type: none"> • Estimation of EMM production is based on observations from (simplified) laboratory conditions – growth might be different in soil due to nutrient conditions and season etc. 	<ul style="list-style-type: none"> • Only 5–10% of all ECM fungi have been characterized and are assigned into exploration types.

Table 2

Strengths and weaknesses of currently used methods to estimate the biomass of ECM extramatrical mycelium (EMM).

Methods	Strengths	Weaknesses	Comments
Biomass of ECM mycelium	<ul style="list-style-type: none"> • Not dependent on chemical conversion factors. 	<ul style="list-style-type: none"> • Difficult to separate mycelium of mycorrhizal and decomposing fungi and living biomass from necromass. 	<ul style="list-style-type: none"> • Dependent on correct conversion factors from length to biomass.
Root free in-growth mesh-bags or cores	<ul style="list-style-type: none"> • See above for mycelium production using bags. 	<ul style="list-style-type: none"> • See above for mycelium production using bags. 	<ul style="list-style-type: none"> • See comments on production estimates using in-growth bags above.
Chemical markers (chitin, ergosterol, PLFAs) combined with incubation	<ul style="list-style-type: none"> • Highly sensitive, small amounts can be estimated. 	<ul style="list-style-type: none"> • Dependent on conversion factors which can vary between species and growth conditions. 	<ul style="list-style-type: none"> • Field studies on variation in conversion factors are lacking.
Molecular DNA and RNA methods	<ul style="list-style-type: none"> • Possible to estimate biomass of individual species. • Targeted especially to dominant species in ECM communities. • Techniques under fast development. 	<ul style="list-style-type: none"> • Suitable primers depend on fungal species, a number yet to be developed. • High costs of next generation sequencing. 	<ul style="list-style-type: none"> • Techniques are under development
Assessment of exploration types	<ul style="list-style-type: none"> • Data from ECM Communities on root tips can be extrapolated to EMM. • Non-destructive estimation of EMM production possible based on ECM community composition. 	<ul style="list-style-type: none"> • EMM biomass of individual exploration types is based on a combination of previously defined estimations. • Few ECM types have been grown in cultures, therefore species-specific fungal diameter and conversion of volume into biomass needs further studies. 	

of observational methods to estimate production, biomass and turnover of EMM in the field has been limited. It has mostly been used to study mycorrhizal roots tips (e.g. Rygiewicz et al., 1997; Majdi et al., 2001; Tingey et al., 2005), but few attempts have been made to estimate the length and longevity of rhizomorphs and hyphae (Treseder et al., 2005; Pritchard et al., 2008; Vargas and Allen, 2008a,b). Similar observations may also be possible using root observation windows (Stober et al., 2000). However, none of the direct techniques can distinguish between the mycelium of ECM and saprotroph mycelia. Two types of minirhizotron cameras are commonly used, which also give different image sizes; BTC 100× microvideo camera (Bartz Technologies, Santa Barbara, CA, USA) that provides image sizes of 1.9×1.3 cm, and a CI-600 (CID Bio-Science Inc., Camas, WA, USA) that provides a 360-degree image (21.59×19.56 cm). The advantage of the minirhizotron techniques, unlike other methods that rely on excavation which can

disrupt extraradical hyphae, is the potential to make repeated, non-destructive observations *in situ* of the same specimen. This allows the specimen to be followed from its emergence (birth) to its disappearance (death). Although the technique has been found useful to monitor the formation and death of mycorrhizal root tips as well as rhizomorphs, several shortcomings exist. For instance, the minirhizotron technique is limited by the resolution and quality of the images (although the technology in this area is progressing rapidly, see for instance Rundel et al., 2009) and the time required for processing (which also restricts sampling intensity, depth and the number of tubes used). Since the technique cannot yet capture the production and turnover of diffuse mycelium it does not enable calculation of overall mycelium production and turnover rates. Furthermore, there is uncertainty in determining when a rhizomorph is dead, leading to the use of different criteria. For instance, Treseder et al. (2005) classified the time of death as the first visual

Table 3

Strengths and weaknesses of currently used methods to estimate the turnover of ECM extramatrical mycelium (EMM).

Methods	Strengths	Weaknesses	Comments
Turnover of ECM mycelium	<ul style="list-style-type: none"> • Birth and death of individual hyphae can be followed. 	<ul style="list-style-type: none"> • Risk of missing the exact birth or death of the hyphae (recording frequency dependent). • May target the fast turnover pool since the length of the study period is limited. 	<ul style="list-style-type: none"> • The problem with lag-time can possibly be solved if small vertically installed bags are used. But this needs to be evaluated.
Direct measurements in growth mesh-bags	<ul style="list-style-type: none"> • In areas with rapid EMM growth and insignificant lag times for mesh bag colonization, sequential harvests at different incubation times could be a way to estimate turnover times. 	<ul style="list-style-type: none"> • Lag-times to colonize the mesh bags may be too high for this method to give reliable results (see Fig. 1). • Turnover may be different in sand than in soil. 	<ul style="list-style-type: none"> • The problem with lag-time can possibly be solved if small vertically installed bags are used. But this needs to be evaluated.
Isotopic techniques	<ul style="list-style-type: none"> • Pulse labelling via the plant is possible. • Mesh bags amended with C_4 substrates can be used to continuously measure C input. 	<ul style="list-style-type: none"> • Analyses of bulk mycelial materials may give false impression of a fast turnover. Analyses of isotopes in structural components would solve that problem. • The method to use C_4 materials is not very sensitive, large fluxes are needed for reliable results. 	

appearance of fragmentation of the rhizomorph, whereas some authors also used the disappearance from the image for determining the death of a rhizomorph (e.g. Pritchard et al., 2008). If a rhizomorph disappears, a judgment had to be made as to whether the rhizomorph has truly died or has become obscured from view due to soil or tube movement. Both criteria are often used for estimating turnover, but may give highly variable results when compared (Borja et al., unpublished). Furthermore, it is not possible to know exactly when a rhizomorph may form or disappear from the camera's visual field between any two subsequent recording events (typically a month, but new automated minirhizotrons for recording images at multiple times per day are in progress (Rundel et al., 2009)). The long lifetime of some rhizomorphs makes it difficult to estimate turnover rate since most minirhizotron studies are conducted over a one (or two) year period. Thus, when using minirhizotrons to estimate production and turnover of rhizomorphs, it is important to consider the recording frequency and study length because both of these affect the accuracy of the estimations.

One method, which was not applied in a forest, but is worthy of mentioning is the 'root box' method of Coutts and Nicoll (1990), as it allows detailed investigation of the growth and survival of diffuse mycelium as well as of rhizomorphs over the year. These authors planted pine seedlings in peat in 2 m tall transparent acrylic tubes, placed the tubes outside and followed the growth of mycelia and rhizomorphs in detail daily from March 1987 to April 1988. This technique may be ideal for detailed studies of various ECM symbioses, for example studies of the different exploration types as defined by Agerer (see below Section 6). Although observational methods have limitations, they also have many advantages, which can substantially increase our understanding of mycelia production and turnover.

2.2. In-growth mesh bags and cores

Mesh bags (e.g. Wallander et al., 2001) are typically made from nylon mesh fine enough to prevent in-growth of roots, but large enough to allow in-growth of fungal hyphae. The fungal communities that colonize the mesh bags are usually dominated by mycorrhizal hyphae as has been verified by trenching experiments (Wallander et al., 2001) and with DNA analyses (Kjøller, 2006; Korkama et al., 2007; Parrent and Vilgalys, 2007; Hedh et al., 2008; Wallander et al., 2010). Mesh sizes between 25 and 50 μm are commonly used. In forest soils with little understorey vegetation, 50 μm prevents in-growth of tree roots, but if understorey Ericaceae or herbs are present, care should be taken so that the fine roots of these do not penetrate the mesh. For example, the fine "hair roots" of ericaceous plants can have diameters of just 20 μm (Bonfante-Fasolo and Gianinazzi-Pearson, 1979). The bags can have different forms and the sides of the nylon mesh can be sealed by sewing, heating and gluing.

The mesh bags are usually placed at the interface between mineral and organic horizons. This will maximize fungal in-growth since mycorrhizal fungi are most abundant in this region (Lindahl et al., 2007). However, when the main aim is to estimate EMM production on an area basis, tubular bags that are placed vertically to a desired soil depth have been used (e.g. Kjøller, 2006). This design also allows the comparison of adjacent soil and root samples taken with the same volume, and it is suitable for sequential harvests since the mesh bags can be replaced with minimal disturbance. In addition to bags, cores can be made of plastic tubes with windows made of mesh to allow fungal in-growth. One advantage with such cores is that they can be rotated regularly to detach fungal in-growth in order to function as controls with similar soil physical conditions but no, or little, fungal in-growth

(Johnson et al., 2001, 2002a,b). This is a considerable advantage when the cores are filled with a natural substrate such as soil (see below). Keeping the volume of the in-growth bags (or cores) as small as possible is important when quantifying EMM production because this helps to ensure that soil physical and chemical conditions inside mesh bags are similar to those outside. In addition, small bags may be colonized more rapidly than larger ones.

Mesh bags are usually incubated in the soil during one growing season because this will give the net production for that year. In some cases a prolonged incubation time (two growing seasons) is necessary in order to detect EMM stimulation by specific substrates such as apatite or other minerals (e.g. Hagerberg et al., 2003; Potila et al., 2009). Berner et al. (2012) suggested that this may be an effect of early colonization by fast-growing ECM species, while species stimulated by minerals are more slowly growing. It has been shown that the stimulation of EMM by apatite was dependent on the P status of the forest (Wallander and Thelin, 2008), while other studies showed that large differences in EMM growth occurred after 5 months along a nitrogen deposition gradient (Kjøller et al., 2012) and in a nitrogen fertilized forest (Nilsson and Wallander, 2003). These findings show that effects of forest management on EMM growth can sometimes be detected with shorter incubation periods. The length of the incubation period thus depends on the purpose of the study. If the main goal is to test for differences between treatments (e.g. forest management or effects of substrates amended to the mesh bags), a longer incubation time can be used. But if the main goal is to estimate net annual production from a specific site, one growing season should be used. On the other hand, if quantifying temporal variation in fungal production is the goal, shorter incubation times than one growing season are used (e.g. Nilsson et al., 2005). Regardless of the approach, it should be noted that a lag time exists before EMM enter bags after they have been inserted into the soil. As an illustration of this, twice as much fungal biomass was found in mesh

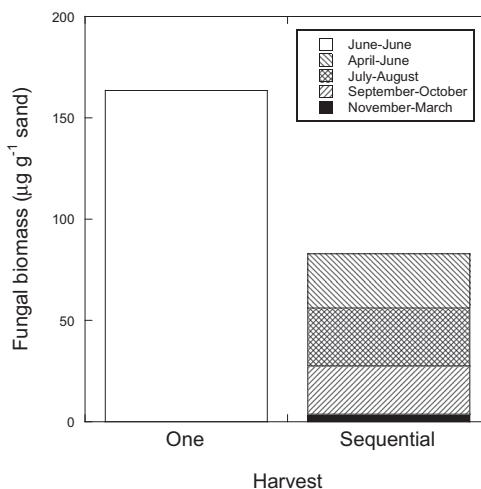


Fig. 1. Fungal in-growth into mesh bags buried in young (10–20 years) Norway spruce forests at Tönnersjöhedens experimental park. Bags were either incubated for 12 months (one harvest) or for 2 (July–August, September–October), 3 (April–June) or 5 (November–March) months periods (sequential harvests). SE for the mean EMM production after one harvest was 37.5, and the SE for the added sequential harvests was 9.3.

bags that were incubated for 12 months, compared to the added amounts in mesh bags that were incubated for 2–5 month periods in 10 young Norway spruce sites in southern Sweden (Fig. 1). Another aspect that complicates the estimate of production is the turnover of the fungal biomass in the mesh bags. A longer incubation period allows more necromass to form and decompose, which results in underestimation of the total production.

There has been concerns raised that the use of pure quartz sand in mesh bags may affect growth of EMM, which can lead to inaccuracies in production rates and biomass estimates (Hendricks et al., 2006). Hendricks et al. (2006) used 10 cm wide cores placed *in situ* for 1 month to demonstrate that mycelial in-growth was greater when natural soil was used as the in-growth substrate rather than pure sand. Whilst for many habitats the use of natural soils as a substrate is desirable, subsequent measurements can be confounded because of the large and variable amounts of background fungal biomass. If more specific methods to quantify ECM fungal biomass are developed (see below Section 3.6), natural soil could be used more reliably. Indeed, growth of arbuscular mycorrhizal fungi has been quantified in mesh bags amended with natural SOM using fatty acids (Labidi et al., 2007; Hammer et al., 2011), which are available for this mycorrhizal group (NLFA 16.1ω5, Section 3.5). Another uncertainty with the mesh bag method is that some ECM fungi appear to show preferences towards certain types of resource. In addition, some species avoid growing in mineral substrates (*Cortinarius*) probably because they are adapted to an environment where they utilize organic nutrients from SOM (Read and Perez-Moreno, 2003). Therefore, despite being abundant on root tips, species within the genera *Cortinarius* may avoid sand filled mesh bags even when they are common on the root tips while the opposite situation is the case for other species (e.g. *Xerocomus*; Kjoller, 2006; Kjoller et al., 2012). The EMM community in mesh bags may thus not represent the community that prevails in the soil, which may be a problem in some studies. An important advantage with the mesh bag method is that the fungi studied are recently formed, while fungi that we can detect in the soil can be old and inactive (see below Section 2.2).

Another important aspect that needs to be considered is that newly placed mesh bags provide a non-exploited area in the soil. Such spaces are probably rare in established forests but may be common in newly planted forests where the EMM from the previous forest can be expected to die back. In a tree age chronosequence, the EMM production was 3 times greater in young forest (10–20 y) compared to older forests (30–130 y) suggesting that young trees are investing more C to establish a mycorrhizal network, while less C is needed to sustain this network in older forests (Wallander et al., 2010). It is possible that mesh bags select for fast-growing species adapted to newly planted forests. For this reason, EMM production may be overestimated when incubating mesh bags over one growing season. As noted previously, such effects may be minimized by reducing as far as possible the volume of mesh bags and cores.

From the discussion above it seems that some factors result in overestimation while other results in underestimation of EMM production using the mesh bag method. As methods to measure fungal biomass and necromass improve (see e.g. Section 3.6), it might be possible to follow the fungal community in mesh bags over several years and quantify the yearly production after the initial empty space has been colonized. A combination of chitin and ergosterol analysis (see below) may give an indication of the ratio between biomass and necromass. Another way to quantify annual production of EMM, including necromass, is to analyse the isotopic change in $^{13}\text{C}/^{12}\text{C}$ in mesh bags that have been amended with organic material from C_4 plants, and follow this change through time (Wallander et al., 2011). A similar approach was used by

Godbold et al. (2006) who filled cores with C_4 soil to estimate the contribution of fungal hyphae to new soil C over a 2.5 year period. Amendment of organic matter in the mesh bags would make the substrate more natural for growth of ECM fungi and probably produce communities more similar to those of the surrounding soil but brings with it greater abundance of saprotrophic fungi. An interesting approach to reduce in-growth by saprotrophic fungi but still use more natural soil was reported by Melanie Jones and co-workers in Canada who used an outer mesh bag with sand, which functioned as a barrier for saprotrophs, and an inner mesh bag with sterilized soil where EMM of ECM fungi proliferated (Lori Phillips and Melanie Jones, pers. comm.).

It is clear that the fungal community colonizing mesh bags may not accurately mirror the mycelial community in natural soil i.e. some species or clades may be over represented and some are underrepresented or even missing in the mesh bags. On the other hand, when working with natural soil it is also difficult to claim that only EMM are in the extracted DNA pool. One needs to be very careful in removing all roots and in reality it will be difficult to state that a soil sample is indeed completely free of ectomycorrhizal root tips or small detached pieces of ectomycorrhizal mantle. Furthermore, extraction of fungal spores in the soil may lead to false positives in the community profile. Extracting DNA or RNA from sand-filled mesh-bags at least ensures that only nucleic acid from actively (or recently active) mycelia is amplified. Another benefit is that the hyphae from the mesh bags are easily extracted from the sand and simple and cheap nucleic acid extraction methods can be applied to produce good quality templates for PCR. Whether extracting nucleic acid from sand-filled mesh bags or directly from soil, primer bias is a confounding factor preventing an accurate description of the fungal community. For each specific primer combination chosen, some groups will be over, and some groups under expressed or even completely missed (Bellemain et al., 2010). As an example of the latter, *Tulasnella* sp. are often completely missed with the standard ITS1-F and ITS4 primer combination (Taylor and McCormick, 2008). In general, careful consideration of primers combinations for the specific study system in question should be made, and the results obtained treated with sound caution.

3. Quantification of fungal biomass in mesh bags and soil

The examination of mycelia in mesh bags should start with a visual classification under a dissecting microscope. This allows a check for the presence of mycelial strands, whether or not they are hydrophilic, and gives insights in exploration types of mycorrhizal fungi (see below Section 5). The amounts of total hyphae can be estimated either by extracting fungal hyphae and converting estimates of hyphal length to biomass, or by using different chemical markers (chitin, ergosterol, phospholipid fatty acid 18:2ω6,9) as proxies for biomass. These methods are described below and the benefits and disadvantages are discussed (Tables 1–3).

3.1. Direct measurements of fungal weight and hyphal length

One approach to estimate fungal biomass that can be used in mesh bags only, is to extract the mycelium from the sand substrate and determine its weight. In this way conversion factors between biomass and a chemical marker can be avoided, but it assumes that all extractable matter is of fungal origin. This is not the case because bacteria and precipitated SOM can be present in the mesh bags, but they probably contribute very little to the weight of putative fungal material extracted. Since it is difficult to remove all sand grains, it is usually necessary to burn the extracted mycelia and use the loss on

ignition as an estimate of the biomass (Hagerberg et al., 2003; Korkama et al., 2007). The C concentration of fungal material is approximately constant (around 45%; Taylor et al., 2003) and C content can be used as a proxy for biomass in the mesh bags. When analysed on a mass spectrometer, both the content and isotopic signature of C can be obtained, which makes it possible to calculate the proportion of ECM and saprotrophic mycelia in the mesh bags because these two groups have different isotopic signatures (Wallander et al., 2001). The recovery of mycelium using this method can be tested by analysing the ergosterol content of both the sand (before and after extraction) and the extracted mycelia.

Fungal hyphae can be extracted from the mesh bags and separated from sand particles by centrifugation and collected on a filter paper for estimates of hyphal length. This approach produced similar results as direct estimates of EMM weight as described above (Wallander et al., 2004). Estimates of hyphal lengths can be converted to biomass using conversion factors from Fogel and Hunt (1979). However, a possible problem with this method is to fully account for rhizomorphs, which are multi-hyphal organs produced by many ECM fungi during growth through soil. The rhizomorphs facilitate efficient transport of carbon towards the mycelia front and mineral nutrients towards to mycorrhizal roots (Cairney, 1992). Separate counts must be carried out for rhizomorphs and hyphae, as they differ greatly in weight per unit length.

3.2. Chemical markers; chitin

Among the three possible fungal biomarkers, chitin seems the most stable parameter to assess the total fungal contribution to microbial tissue in soil (Joergensen and Wichern, 2008). Recent results (Drigo et al., 2012; Koide et al., 2011) from additions of laboratory cultivated mycelial necromass suggest rapid decomposition of chitin in soil. Indeed, fungal cell walls of all true fungi contain chitin, a structural compound with a similar role as cellulose in higher plants. In soil, other organisms may contribute to chitin contents such as microarthropods that contain chitin in their exoskeleton. However, this contribution is probably minimal as their biomass is typically below 0.5% of the fungal biomass (Beare et al., 1997; Simpson et al., 2004). An average chitin concentration of 5% of dry matter was found in a review of various species of fungi mainly grown *in vitro* and belonging mainly to Basidiomycetes, Ascomycetes and Zygomycetes (Appuhn and Joergensen, 2006). No statistically significant difference between the mean values from the three fungal orders was found, and a conversion factor from glucosamine to fungal C of 9 was proposed (Appuhn and Joergensen, 2006).

Using data from Joergensen and Wichern (2008), we estimate that \pm one standard deviation around the mean gives a span of around 6–50 of the glucosamine to C conversion factor, which suggests a rather low precision in the conversion. However, it is unknown if the variation in glucosamine content is smaller or larger when in symbiosis. In the one published study known to us, extramatrical mycelium of *Paxillus involutus* in symbiosis with *Pinus sylvestris* had a glucosamine content of 4.5% (Ekblad et al., 1998). A similar value was found in mycelium extracted from mycelial in-growth bags that were installed in the upper-most soil horizon at the tree line in a *Larix decidua* and *Pinus uncinata* stand near Davos. These two values are close to the average for the pure cultures of the Joergensen and Wichern (2008) review.

It is also possible to measure the chitin content from the pellet left after protein, lipid or DNA extraction (Kjoller and Rosendahl, 1996; Kjoller et al., 2012). This then allows measurements of enzyme activities or molecular identity in the exact same samples that are quantified for chitin. Further studies are needed on chitin concentrations in EMM of mycorrhizal fungi when in association

with roots in forest soil. However, this fungal biomarker does not enable us to distinguish between saprotrophic and ECM fungi in soil samples or to separate living and dead mycelium, although this may be possible by combining ergosterol and chitin analysis (see below).

Chitin assay is easily performed using one of two steps; (i) hydrolysis either with KOH (e.g. Frey et al., 1994) that produces deacetylated chitin (chitosan), or with HCl (Appuhn et al., 2004), H₂SO₄ (e.g. Zamani et al., 2008) or methanesulfonic acid (Olk et al., 2008) that produces glucosamine, and (ii) measurement of the concentrations of hydrolysis products. Chitosan and glucosamine contents can be measured with colorimetric procedures specifically assaying amino sugars (Plassard et al., 1982). Free glucosamine can also be measured with chromatographic techniques (Ekblad et al., 1998).

3.3. Chemical markers; ergosterol

The second chemical marker that has been used to estimate fungal biomass is ergosterol (22E)-Ergosta-5,7,22-trien-3 β -ol (C₂₈H₄₄O). This compound is a membrane lipid, found almost exclusively in membranes of living fungal cells, and is the commonest sterol of Ascomycota and Basidiomycota. As ergosterol is generally not synthesized by plants and animals, and only present in low amounts in some microalgae (Grant and West, 1986; Newell et al., 1987; Weete, 1989), it has been frequently used as fungal biomarker in soils (Djakirana et al., 1996; Möttönen et al., 1999; Bååth, 2001; Wallander et al., 2001; Hagerberg et al., 2003; Zhao et al., 2005; Högborg, 2006; Karliński et al., 2010) and correlations with other methods are usually good (Bermingham et al., 1995; Stahl and Parkin, 1996; Montgomery et al., 2000; Ruzicka et al., 2000; Högborg, 2006). Assay of ergosterol was first employed by Seitz et al. (1977) to quantify fungal infections in stored grain. In mycorrhizal fungi, the analysis of ergosterol was first applied by Salmanowicz and Nylund (1988), but has been used frequently since then (e.g. Nylund and Wallander, 1992; Ekblad et al., 1995, 1998; Laczko et al., 2004; Olsrud et al., 2007). Total ergosterol contents in mycorrhizal roots of *P. sylvestris* plants was correlated to visual estimates of root colonization (Ekblad et al., 1995) as well as to the chitin contents (Ekblad et al., 1998). In contrast, total ergosterol concentration of ericoid hair roots of dwarf shrubs from northern subarctic mires did not correlate with visual estimates of colonization but was instead positively correlated with the colonization of dark septate endophytes, which makes it questionable as a marker for ericoid mycorrhizal fungal colonization (Olsrud et al., 2007). Some studies suggest that ergosterol is a good proxy for active fungal biomass because it was found to degrade shortly after the cells death (Nylund and Wallander, 1992), and ageing mycorrhizal root tips contain low ergosterol concentrations (Ekblad et al., 1998). However, other studies suggest a slow metabolism of ergosterol under certain circumstances, such as disruption of below ground C allocation, increased N loads, addition of toxic compounds like pesticides, or existence of substantial amounts of free ergosterol in soil for considerable periods with little mineralization (Zhao et al., 2005). Soil perturbations, that may negatively influence vitality and growth of soil fungi, resulted in disruption of the proportion between soil ergosterol concentration and soil fungal biomass C (Zhao et al., 2005) and between ergosterol and phospholipid fatty acid (PLFA) 18:2 ω 6,9 (Högborg, 2006). These contradictory results were further criticized and discussed by Young et al. (2006) and Zhao et al. (2006). Mille-Lindblom et al. (2004) reported very slow degradation of free ergosterol in environmental samples without living mycelium when protected from sunlight and suggested that ergosterol may be stable when connected to dead fungal mycelium.

However, significant degradation of ergosterol was observed by the authors under influence of light.

Calculations of conversion factors from ergosterol to fungal biomass have been derived from various fungi and considerable variations in ergosterol concentration in fungal mycelium were reported (Lösel, 1988; Weete, 1989; Nylund and Wallander, 1992; Djajakirana et al., 1996; Montgomery et al., 2000). The average concentration of ergosterol reported thus far for different soil, aquatic and plant inhabiting fungi is $4.5 \mu\text{g mg}^{-1}$ dry mass of mycelia, and this is used to determine fungal biomass in soil. However, the ergosterol concentration in fungal mycelium extracted from mesh bags is less ($1.2 \mu\text{g mg}^{-1}$; Hagerberg et al., 2003). This may indicate that laboratory-grown mycelia contain more ergosterol than field grown mycelia, or that mycelia from mesh bags are contaminated with non-fungal material. The average relative recovery of ergosterol from soil samples was 62%, ranging from 58 to 88% (Montgomery et al., 2000), and the recovery factor value was 1.61 (1/0.62). The authors concluded that determination of fungal biomass (FB) on the basis of ergosterol analysis requires correcting ergosterol concentrations by the proportion of unextracted mycelial ergosterol according to the following calculation:

$$FB(\mu\text{g g}^{-1} \text{ soil}) = \text{Ergosterol}(\mu\text{g g}^{-1} \text{ soil}) \times f \times Rf,$$

where $f = 250$ ($1/4 \times 1000$, mg biomass μg^{-1} ergosterol), and $Rf = 1.61$ (correction factor for average percent recovery, $1/0.62$) (Montgomery et al., 2000).

Separation of ergosterol into free and esterified forms might give some additional information of the vitality of the fungal mycelium. Usually total ergosterol is quantified (Nylund and Wallander, 1992), in other cases the free form is used as a biomass marker (Martin et al., 1990). Free ergosterol is a component of the cell membranes, while the esters are found in cytosolic lipid particles. A ^{14}C -labelling study of *Saccharomyces cerevisiae* indicated that the free sterols and esters are freely inter-changeable and that relatively more esters are formed when the fungus is going into a stationary phase (Taylor and Parks, 1978). Analysis of dried fungal material suggests that the free form can also be converted into the esterified form in this material and that the esterified is more stable than the free form (Yuan et al., 2008). The majority of ergosterol from in-growth bags was found in the free form (90%), while the free ergosterol was below 20% in the mineral soil, supporting the view of increasing proportion of esterified ergosterol in older SOM (Wallander et al., 2010). The relation between free and esterified ergosterol and ergosterol and chitin (Ekblad et al., 1998) could potentially be used as markers for the ratio of active and inactive fungi in soil. This possibility would be very useful but needs to be evaluated further. One problem with analysing free ergosterol in certain soils is to get the extracts clean for chromatographic analysis (Adam Bahr, pers. comm.). Ergosterol can be easily extracted from variable materials and is detectable in low concentrations. The assay comprises of extraction, purification and quantification of the molecule using high-performance liquid chromatography with a UV detector. Young (1995) developed an efficient microwave-assisted method (MAE) to extract ergosterol from a variety of matrices, which has since been applied to soil samples (Montgomery et al., 2000).

3.4. Chemical markers; PLFAs

PLFAs are essential components of cell membranes and they decompose quickly after cell death (White et al., 1979) and are commonly used as chemical markers of soil fungi. As eukaryotes and different groups of prokaryotes contain more or less specific

ester-linked lipid fatty acids (Lechevalier and Lechevalier, 1988; Zelles, 1997, 1999), the analysis of PLFA composition and concentrations are useful as a tool for quantitative and qualitative examination of microbial communities in soil (fungi, bacteria, protozoa; e.g. Tunlid and White, 1992; Cavigelli et al., 1995). However, use of PLFAs for biomass estimation has recently been questioned, because the same PLFAs are stated to indicate very different groups of organism (Frostegård et al., 2011). For instance, the PLFAs cy17:0 and cy19:0 , usually considered to be indicators of Gram-negative bacteria are also found in large amounts in some Gram-positive bacteria (Schouge et al., 2008). The PLFA $16:1\omega5$, common in arbuscular mycorrhizal fungi (Graham et al., 1995; Olsson et al., 1995), and sometimes used as a marker of Glomeromycota fungi in soil, plant roots and external mycelium (e.g. Gryndler et al., 2006), is also found in bacteria (Nichols et al., 1986). Moreover, some environmental conditions, such as temperature or toxic soil contaminants may influence the rate of PLFA degradation, independently with the turnover of soil microorganisms (Frostegård et al., 2011).

The PLFA $18:2\omega6,9$ is the most commonly used PLFA to estimate fungal biomass (Wassef, 1977; Lechevalier and Lechevalier, 1988; Dembitsky et al., 1992). It occurs in all eukaryotes, and is only found in low amounts in bacteria. This PLFA is a dominating fatty acid of fungal fruit bodies (e.g. Dembitsky et al., 1992; Olsson, 1999; Karliński et al., 2007) and spores (Brondz et al., 2004). A strong positive correlation was found between PLFA $18:2\omega6,9$ and the fungal marker ergosterol in soils from cultivated fields, gardens, grasslands and forests (Frostegård and Bååth, 1996; Kaiser et al., 2010). The PLFA $18:2\omega6,9$ has been used as a bioindicator of EMM in soil (Högberg et al., 2010), but it is particularly useful in experiments where other soil fungi can be eliminated or reduced, such as when using in-grow mesh bags where ECM mycelium is preferentially trapped (e.g. Wallander et al., 2001; Hagerberg and Wallander, 2002). To convert PLFA $18:2\omega6,9$ to microbial carbon content, Joergensen and Wichern (2008) reported a weighted conversion factor of $107 \mu\text{g C nmol PLFA}^{-1}$, but values between different species grown in culture could vary 17-fold (Klamer and Bååth, 2004). Another PLFA that is common in fungi, especially Zygomycota, is $18:1\omega9$ (Dembitsky et al., 1992; Ruess et al., 2002; Brondz et al., 2004). The concentration of $18:1\omega9$ is usually closely correlated to $18:2\omega6,9$ (Frostegård et al., 2011). This PLFA is, however, also present in some bacteria (Schouge et al., 2008) and has not proven useful as a fungal indicator in agricultural soils (Frostegård et al., 2011).

A faster way to analyse fatty acids in soil samples is to analyse the whole cell fatty acids (WCFA) without separation of neutral lipid fatty acids (NLFAs) and PLFAs. WCFA reflect both microbial biomass and energy reserves of eukaryotes and are a relatively reliable method of studying fungi (Larsen et al., 2000; Thygesen et al., 2004; Karliński et al., 2007) and mycorrhiza-associated microorganisms in the field (Brondz et al., 2004; Ruess et al., 2005; Karliński et al., 2007). The analysis of WCFA composition requires 10 times less soil material than the PLFA analysis (Drenovsky et al., 2004). Since much of the WCFA is in the form of neutral lipid fatty acids (NLFAs) in triacylglycerols, a storage compound in eukaryotes, a recorded change in WCFA of NLFAs may be a result of changes in the amount of storage C rather than a change in size of the microbial population in a soil. Incorporation of glucose into fatty acids can be used to demonstrate the high microbial activity in soils. Lundberg et al. (2001) used 'solution state' ^{13}C NMR and found that the amount of ^{13}C in fatty acids peaked 3–13 days after glucose addition to a forest soil, and that it had declined by 60% 28 days after the glucose addition. A similar result was found after extraction and analyses of NLFAs and PLFAs at different time intervals after glucose additions to various soils

(Bååth, 2003). Due to the potential for large temporal variation in storage triacylglycerols, NLFAs and WCFAs are probably less suitable than PLFAs as relative measures of the microbial biomass in soils. However, the ratio of neutral lipid fatty acids (NLFAs) and PLFAs was proposed as a method to study the physiological state of the microbial population in the soil (Bååth, 2003).

The analytical procedure for PLFAs and NLFAs comprises four steps: (i) extraction of lipids, (ii) lipid fractionation, (iii) mild alkaline methanolysis, and (iv) GC analyses (White et al., 1979; Frostegård et al., 1991). Recently, the lipid fractionation was modified slightly by Dickson et al. (2009), who reported that the replacement of pure chloroform by the mixture chloroform: acetic acid (100:1, v/v) increased the effectiveness of NLFAs elution from the silica columns and eliminated an interference of NLFAs with glycolipid and phospholipid fractions. Following hydrolysis, their fatty acids (FA) are released and detected using gas chromatography (GC). PLFA analyses should be done as soon as possible after sampling since the composition may change even when stored at low temperatures (Wu et al., 2009). The best strategy is to shock-freeze the samples with liquid nitrogen and further storage at -18°C until analysis. Homogenization of soil samples using a ball mill to a particle size less than $10\text{ }\mu\text{m}$ prior to analysis has been recommended to achieve the most reliable results (Wilkinson et al., 2002).

3.5. Comparison of chemical markers

It is clear that each of the chemical markers described will bring different information about the fungal biomass, whether total or active. Each of them has advantages and limitations (Tables 1–3). Chitin and ergosterol assays are easier to carry-out than fatty acid (PLFAs or WCFAs) extraction, but fatty acid profiles will bring more information about microbial communities than chitin and ergosterol. On the other hand, the PLFA method is more rapid and less expensive than methods based on nucleic acids (Ramsey et al., 2006; Frostegård et al., 2011). However, none of these chemical markers will enable us to distinguish between fungal types (ECM versus non-mycorrhizal fungi) that can be present in forest soil samples. To distinguish between these “functional” types, molecular analysis (see below) should be used. Biomass estimates when using biomarkers, such as ergosterol, chitin and PLFAs, are highly dependent on the use of conversion factors. Different fungal species vary in concentrations of such biomarkers, but the biomarker to biomass ratio is probably more stable in a more complex community. The concentration of ergosterol in pure cultures of ECM fungi ranged between 1.8 and 17.6 mg g^{-1} d.wt. (Nylund and Wallander, 1992; Olsson et al., 1995) and concentration of PLFA $18:2\omega 6,9$ ranged from 0.45 to $12\text{ }\mu\text{mol g}^{-1}$ d.wt. (Olsson et al., 2003). The content of the WCFAs $18:2\omega 6,9$ was reported as 17 – 75% of total WCFAs in fruit bodies and as 53 – 71% of total WCFAs in axenic cultures of ECM fungi (Karliński et al., 2007). Biomarker concentrations may reflect both the biomass and community composition of fungi. In addition, concentrations in a single species can change due to different environmental conditions as were reported for wood-rotting basidiomycete isolates grown in different soils (Törnberg et al., 2003) and ageing, as shown for ergosterol concentrations in the basidiomycete *Hebeloma cylindrosporum* (Plassard et al., 2000), and for ergosterol and fatty acids in pure culture of ECM fungus *Pisolithus tinctorius* (Laczkó et al., 2004).

3.6. Potential of qPCR for the quantification of ECM biomass

In addition to the lipidic or polysaccharidic markers to quantify the biomass of fungi, the developments of quantitative PCR (qPCR) seem to offer a possible taxon-based alternative. The strength of

DNA (or RNA) based methods is that potentially any phylogenetic level from genotypes to large groups or even total (true) fungi can be targeted (Fierer et al., 2005; Šnajdr et al., 2011). Indeed, methods to quantify general fungi or basidiomycetes have been proposed and tested (Fierer et al., 2005; Manter and Vivanco, 2007; Feinstein et al., 2009). A single species laboratory study comparing quantification of *Trametes versicolor* in wood based on chitin content, ergosterol, wood mass loss, and qPCR, showed reasonable correlations with more discrepancies occurring only with older cultures (Eikenes et al., 2005). There are currently two main limitations of the methodology: nucleic acid extraction bias and the differences in target occurrences per unit DNA or biomass. Different methods of nucleic acid extraction yield not only different quality of DNA and RNA but also different proportions of microbial taxa in the extracts (Feinstein et al., 2009). The success of qPCR rapidly decreases with fragmentation of nucleic acids, resulting in lower counts of target sequences per unit DNA. If a treatment is imposed that alters the extractability of nucleic acid or if different soil types are to be compared, this may influence the qPCR success. For the most frequently used target sequence of fungi-specific qPCR – the rDNA cassette – significant differences in copy number per genome were recorded, ranging from 10 to 200 in different species (Garber et al., 1988; Maleszka and Clark-Walker, 1990; Corradi et al., 2007; Amend et al., 2010), which adds another important source of bias. With the advance of fungal population genomics (five ECM species sequenced to date; see the website of JGI (<http://genome.jgi-psf.org/>) and Martin et al., 2008, 2010) in the future it may be possible to identify a universal single copy gene with adequate sequence variation for counting fungal genomes rather than rDNA copies or for delimitation of certain fungal taxa. Population genomics also brings even greater potential to test hypotheses concerning the contribution of particular genotypes to ECM fungal biomass and turnover (Johnson et al., 2012).

When qPCR specifically targets individual species of fungi, PCR-based abundance estimates represent a plausible proxy of fungal biomass content because the numbers of rDNA copies do not show high variation within a species (Amend et al., 2010). Analyses of individual fungi including *Suillus bovinus*, *P. involutus* and *Hypholoma fasciculare* in the DNA from complex samples showed that it is possible to use qPCR to specifically quantify the biomass of fungi at the species level within a community. Such data are comparable to the much more laborious or expensive approaches like cloning, pyrosequencing or DGGE approaches (Landeweert et al., 2003; Parladé et al., 2007; Šnajdr et al., 2011). Competitive PCR (a variant of qPCR) was used to demonstrate that *Hebeloma cylindrosporum* biomass in bulk soil is greatest near fruit bodies (Guidot et al., 2002). A conversion factor between qPCR-based copy number and fungal biomass and hyphal length was obtained for laboratory cultures of the ECM fungus *Piloderma croceum* showing its potential to quantify the biomass of particular species (Raidl et al., 2005). Unfortunately, due to the appearance of ECM fungi in multiple phylogenetic lineages, the finding of suitable primers to specifically amplify ECM fungal DNA and to distinguish it from non-ECM fungi is highly improbable. However, if combined with the cloning approaches or next generation sequencing, qPCR may provide estimates of ECM fungal biomass in soils. Contemporary next generation sequencing results showed that, at least in certain forest soils, fungal communities are dominated by relatively few species (Buée et al., 2009; Baldrian et al., 2012). These findings suggest that qPCR can be used to target specifically the identified dominant members of the community as an estimate of ECM fungal biomass. Recently, qPCR used for analysis of environmental samples has been expanded from the quantification of DNA towards the quantification of RNA, typically the rRNA, representing microbial ribosomes or ITS sequences in unspliced transcripts of the rDNA

operon. Although it is unknown whether the DNA or the RNA content better corresponds with the quantity of fungal biomass, it is clear that the analysis of ITS sequences in the non-spliced rDNA transcripts (indicating fungal taxa synthesizing their ribosomes) is more suitable to quantify the active part of the fungal community (Anderson and Parkin, 2007). Indeed, decomposers in spruce logs or fungi active in soil in winter with limited photosynthate allocation have been specifically identified by combining DNA and RNA analysis (Rajala et al., 2011; Baldrian et al., 2012).

4. Indirect estimation of length, space occupation and biomass of extramatrical mycelium of ectomycorrhizal fungi

Agerer (2001) proposed a classification of ECM mycelial systems into five exploration types. Accurate determination of EMM production and abundance of different exploration types within ECM communities may be used to estimate the overall production of EMM. The exploration types are described according to their pattern of differentiation, indicating their different ecology: contact type (CT), short distance (SD), medium distance (MD), long distance (LD) and pick-a-back (PB) exploration type. The exploration types have been differentiated based on about 400 different morphotypes of ectomycorrhiza, which have been identified as belonging to different fungal species on several host plant roots based on their morphological and anatomical characteristics (Agerer and Rambold, 2004–2011). The characterized ECM morphotypes represent about 5% of known fungi that can form ectomycorrhiza (Taylor and Alexander, 2005), the number of which is estimated to be 5000–6000 fungal species (Agerer, 2006). From this limited database, it appears that in many genera all known species produce only one exploration type (Agerer, 2001; Hobbie and Agerer, 2010), although some genera (i.e. *Russula* spp.) need species-based classification into an exploration type (Table 4).

An estimation of EMM of ECM fungi in natural soils could be deduced from semi-quantitative estimations of the EMM formed by SD and MD exploration types grown in rhizotrons in symbiosis with

Norway spruce (Agerer and Raidl, 2004). The observations in rhizotrons have lately included other MD subtypes and LD exploration types (Weigt et al., 2011), and indices of specific space occupation, mycelial length and biomass were proposed for each exploration type. Mycelial biomass was estimated based on length measurements using calculations described in Weigt et al. (2011); the standard values for the selected exploration types are presented in Table 5. These standards for the most frequent exploration types, expressed as biomass and occupied space of EMM per unit of ECM system, are suggested as basic factors for characterizing mycelial production costs and space occupation in ecological field studies without any extraction of mycelium and for fungal communities in the soils. Since different exploration types show not only differences in distance of EMM from the root tip, space occupation, biomass and energy (C) inputs, but also in other functional relationships within the ecosystem, the ECM fungal community structure and function can be extrapolated. The differentiation into exploration types can be extrapolated from morphotype characterization based on outer morphology of ectomycorrhiza, rhizotron photographs, and fungal species identifications, using molecular based methods of fungal community composition (Grebenc and Kraigher, 2009), in which fungal species identity is linked to growth characteristics and assigned to a certain exploration type.

Indices, such as specific potential mycelial space occupation ($\text{mm}^2 \text{cm}^{-1} \text{ECM tip}^{-1}$), specific EMM length ($\text{m cm}^{-1} \text{ECM tip}^{-1}$), specific EMM biomass ($\mu\text{g cm}^{-1} \text{ECM tip}^{-1}$) can be developed for each exploration type. The specific contribution to EMM by exploration types can be achieved for cultivable and non-cultivable species, and up-scaling of cost–benefit relations is possible (Weigt et al., 2011). The method provides an estimation based on ECM fungi synthesized in experimental laboratory conditions, i.e. on prepared soil substrates, which can influence EMM growth in different exploration types. Therefore, for the calculations presented in Table 5 a number of assumptions had to be made, including i) that growth conditions concerning mycelial growth and space occupation in experimental substrates was similar to

Table 4
Representative fungal genera belonging to different exploration types (summarized from Agerer, 2001; Agerer and Rambold, 2004–2011; Agerer, 2006).

Exploration type	Morphology/anatomy	Fungal genus ^a
Contact	Smooth mantle, only few emanating hyphae, ECM tips in close contact with substrates	<i>Arcangelietia</i> , <i>Balsamia</i> , <i>Chroogomphus</i> , <i>Craterellus</i> , ^b <i>Lactarius</i> , ^c <i>Leucangium</i> , <i>Russula</i> , <i>Tomentella</i>
Short distance	Voluminous envelope of emanating hyphae, no rhizomorphs	<i>Acephala</i> , <i>Byssocorticium</i> , <i>Cenococcum</i> , <i>Coltricia</i> , <i>Coltriciella</i> , <i>Craterellus</i> , ^b <i>Descolea</i> , <i>Descomycetes</i> , <i>Elaphomyces</i> , <i>Genea</i> , <i>Hebeloma</i> , <i>Humaria</i> , <i>Hygrophorus</i> , <i>Inocybe</i> , <i>Pseudotomentella</i> , <i>Rhodocollybia</i> , <i>Rozites</i> , <i>Russula</i> , <i>Sebacina</i> , <i>Sphaerospora</i> , <i>Sphaerozona</i> , <i>Tomentella</i> , <i>Tricharina</i> , <i>Tuber</i> , <i>Tylospora</i>
Medium distance: fringe subtype	Fans of emanating hyphae and rhizomorphs, frequent ramifications and anastomoses, rhizomorph surfaces hairy, extended contact to the soil; rhizomorphs type A, ^c exceptionally C, ^c D ^c	<i>Amphinema</i> , <i>Cortinarius</i> , <i>Dermocybe</i> , <i>Hydnum</i> , <i>Lyophyllum</i> , <i>Piloderma</i> , <i>Sistotrema</i> , <i>Stephanopus</i> , <i>Thaxterogaster</i> , <i>Tricholoma</i>
Medium distance: mat subtype	Limited range, rhizomorphs undifferentiated or slightly differentiated type A, ^c C, ^c exceptionally D ^c	<i>Bankera</i> , <i>Boletopsis</i> , <i>Clavariadelphus</i> , <i>Cortinarius</i> , <i>Gautieria</i> , <i>Gastrum</i> , <i>Gomphus</i> , <i>Hydnellum</i> , <i>Hysterangium</i> , <i>Phellodon</i> , <i>Ramaria</i> , <i>Sarcodon</i>
Medium distance: smooth subtype	Rhizomorphs internally undifferentiated, slightly differentiated or with a central core of thick hyphae. Mantles smooth with no or only a few emanating hyphae. Rhizomorphs type B, ^c C, ^c and D, ^c exceptionally E ^c	<i>Albatrellus</i> , <i>Amanita</i> , ^d <i>Byssospora</i> , <i>Cantharellus</i> , <i>Entoloma</i> , <i>Gomphidius</i> , <i>Hygrophorus</i> , <i>Laccaria</i> , <i>Lactarius</i> , <i>Naucoria</i> , <i>Polyporoletus</i> , <i>Pseudotomentella</i> , <i>Russula</i> , <i>Thelephora</i> , <i>Tomentella</i> , <i>Tomentellopsis</i>
Long distance	Smooth mantle with few but highly differentiated rhizomorphs type F, ^c ECM sparsely monopodially branched, coralloid and tuberculate.	<i>Alpova</i> , <i>Amanita</i> , ^d <i>Austropaxillus</i> , <i>Boletinus</i> , <i>Boletus</i> , <i>Chamonixia</i> , <i>Gyrodon</i> , <i>Gyroporus</i> , <i>Lecinum</i> , <i>Melanogaster</i> , <i>Paxillus</i> , <i>Pisolithus</i> , <i>Porphyrellus</i> , <i>Rhizopogon</i> , <i>Scleroderma</i> , <i>Suillus</i> , <i>Truncocolumella</i> , <i>Tricholoma</i> , <i>Tylophilus</i> , <i>Xerocomus</i>
Pick-a-back	Grow within F ^c -type rhizomorphs or mantles, can produce haustoria, can become ectendomycorrhizal. Can form contact, or smooth medium distance type.	<i>Gomphidiaceae</i> (<i>Gomphidius</i> , <i>Chroogomphus</i>) growing within <i>Suillus</i> or <i>Rhizopogon</i> ; <i>Boletopsis leucomelaena</i> within unknown ECM; <i>Xerocomus parasiticus</i> within <i>Scleroderma citrinum</i>

^a In case of controversial issues genus was categorized to exploration types according to Agerer and Rambold (2004–2011).

^b *Craterellus tubaeformis* forms contact exploration types on *Quercus* but short distance exploration types on *Pinus*.

^c Underlined genera have representatives in more than one exploration types.

^d *Amanita citrina* on *Pinus* can form medium distance and long distance exploration types.

^e The type of rhizomorphs according to Agerer (1987–1998).

Table 5

Characteristics of EMM length, space occupation and biomass for different exploration types (modified after Weigt et al., 2012a,b).

Exploration type	No. of analysed mycelia	Max. distance from root tip (cm)	Projected area per mycelial system (mm ²)	Mycelial coverage per occupied space (mm ² mm ⁻²)	Specific EMM length (m cm ⁻¹ ECM tip ⁻¹)	Specific EMM biomass ^a (μg cm ⁻¹ ECM tip ⁻¹)
Short distance	7	1.2	33 ± 9	0.39 ± 0.07	3.72 ± 1.19	3.24 ± 1.03
Medium distance	14	1.9	84 ± 5	0.58 ± 0.05	6.91 ± 0.54	6.02 ± 0.47
Long distance	3	9.6	630 ± 181	0.28 ± 0.03	55.91 ± 20.25	48.67 ± 17.62

^a Mycelial biomass was estimated based on length measurements using calculations described in Weigt et al. (2011) combining the formula $B = r^2 \pi L D^* M$ (Frankland et al., 1978), where B = fungal biomass, r = hyphal radius, L = hyphal length, D = relative hyphal density, M = % dry mass = $(100 - \text{mycelial moisture content as \% of fresh weight}) / 100$. $r^2 \pi L$ = hyphal biovolume (assuming hyphae to be perfect cylinders) with r based on the species-specific hyphal diameter (in their study it was 2.2 μm for *Piloderma croceum*, deduced from Brand, 1991; Raidl, 1997). L was measured using WinRhizo. $D = 1.09 \text{ g/cm}^3$ and $M = 21\%$ following (Bakken and Olsen, 1983) conversion of hyphal volume into biomass with $D^* M = 0.2289 \text{ g dry mass cm}^{-3}$.

natural soils, ii) no competition or facilitation among mycelia of different fungi has been included, and iii) no site-related growth conditions have been addressed, and several calculation-based assumptions had to be defined (see the explanation at Table 5). However, the proposed exploration type specific standard values may provide a suitable tool for quantification of space occupation, biomass and energy trade-offs of EMM in natural soils. A combination of a further development of the database with descriptions of ECM fungi (Agerer and Rambold, 2004–2011) and functional relationships of different exploration types, grown, observed and assessed in different growth conditions, will contribute to an increasing understanding of the complex belowground mycelial interactions, cost–benefit relations and trade-offs in belowground competition or facilitation.

5. Assessment of turnover rates

Accurate estimates of the turnover of EMM are essential in order to evaluate the role of mycorrhizal fungi in the C cycle. This requires understanding of both the rate of production and decomposition of mycorrhizal mycelium. Sequential harvesting of EMM in mesh bags may be one way to estimate turnover rates, but there seems to be a lag-phase before EMM enter the mesh bags (Fig. 1). However, the lag-phase is probably dependent on the level of disturbance caused by the installation and further tests with bags of different sizes and sampling frequency are needed to evaluate the applicability of this method. Pulse labelling with ¹³C or ¹⁴C has been applied to estimate turnover in arbuscular mycorrhizal mycelium (Staddon et al., 2003; Olsson and Johnson, 2005) but not for estimates of ECM mycelium. One of the problems with isotope techniques is the risk of differences in labelling of different chemical components of the fungal biomass, some of them having a high turnover rate (respiratory substrates), while the heavy isotope will have longer residence time in structural cell materials (Dawson et al., 2002). Analyses of the turnover rate of specific components, such as chitin, may be a way to overcome this. Another issue concerns the collection of sufficient and representative amounts of ECM mycelium for isotopic analysis.

The difference in natural abundance $\delta^{13}\text{C}$ between C_3 and C_4 organic matter has been used in studies of the turnover of plant and microbial substances in soils. In these analyses a combination of pyrolysis–gas chromatography and isotope ratio mass spectrometry was used (Gleixner et al., 1999, 2002). The combination of in-growth cores with a mesh allowing only hyphae or allowing both roots and hyphae filled with C_4 dominated soils have been used to estimate the contribution of mycelia and roots to the formation of stable SOM (Godbold et al., 2006; Wallander et al., 2011). A critical factor when using differences in natural abundance of ¹³C is to have reliable $\delta^{13}\text{C}$ values of the end-members, e.g. mycelial and plant residues. Similar to pulse labelling techniques, differences in isotopic signature between various components within the plant and fungal materials may be a potential problem that should be

considered. For example, chitin is depleted in both ¹³C and ¹⁵N compared to the total fungal biomass (Dijkstra et al., 2006). The EMM in the top soil was depleted in ¹⁵N with around 5‰ compared to mycorrhizal fruit bodies in a Norway spruce site (Wallander et al., 2004), possibly reflecting lower chitin and higher protein contents in fruit bodies compared to mycelia.

We are not aware of any study that has exploited the possibility to estimate the production and turnover of mycelium in FACE-experiments (Free Air Carbon dioxide Enrichment). Sequential installation and harvest of in-growth bags in connection with the initiation or termination of CO₂ treatments should offer ideal periods to estimate the production and turnover of mycelia biomass. During these periods there are drastic shifts in the ¹³C signal of the photosynthates (given that the CO₂ that is used to treat the plants has a different $\delta^{13}\text{C}$ than the atmosphere, which is the case if fossil C has been used to produce the CO₂). However, these experiments do not have corresponding plots that are isotopically-enriched at ambient CO₂ concentrations, and so exploiting FACE facilities would only be useful to estimate turnover under elevated CO₂ conditions.

In contrast to other types of organic inputs to soils, surprisingly little is known about the decay rate of mycorrhizal mycelium. Mesh bags of the type normally used to assess leaf litter decomposition have been used recently to demonstrate that the N concentration of hyphae explained a large part of the mass loss during the initial 4 weeks of decay (Koide and Malcolm, 2009). An alternative method is to capture and quantify CO₂ produced when hyphae are added to micro-respirometers. This approach was used to show that ECM fungal hyphae rapidly stimulated CO₂ efflux but that the effect was dependent on the species richness of the hyphae entering soil (Wilkinson et al., 2011a). Thus species richness of ECM fungi can be important both for maintaining productivity (Wilkinson et al., 2011b) and in regulating their own decomposition. These findings indicate that decomposition of ECM hyphae may be a key pathway by which C rapidly enters the saprotrophic microbial biomass in soil. The application of stable isotope probing (Radajewski et al., 2000) in which ECM fungal hyphae is enriched in ¹³C has recently been used to demonstrate the rapidity of C incorporation into free-living soil fungi via this pathway (Drigo et al., 2012). Despite these recent advances, there is scope for considerably more research quantifying the rate of decay of different genotypes, species and morphologies of ECM fungal hyphae under a range of environmental conditions.

6. Importance of sampling design

Regardless of the effort placed in developing reliable methods to quantify production, biomass and turnover of ECM fungi, the utility of the resulting data is often dependent on the sampling design used to obtain the data in the first place. Moreover, it is often desirable to obtain similar datasets from a wide-range of different

ecosystems and habitats, particularly from a modelling perspective. This requires sampling approaches that have similar ability to quantify spatial variation in EMM abundance and biomass. Yet very few investigations employ spatially-explicit sampling strategies designed to deal with the often vast heterogeneity of EMM production in forest systems. This is in part because variation is likely to occur at a wide range of spatial scales; recent work in Douglas fir stands have demonstrated that genets of *Rhizopogon* spp. could form common mycelial networks connecting individual trees within a 30×30 m area (Beiler et al., 2010). In contrast, there is also clear evidence that ectomycorrhizas and their associated mycelium can form patchy clusters at scales of just a few cm (Guidot et al., 2002), perhaps due to their plasticity in responding to inputs of nutrient-rich substrates (Bending and Read, 1995). Moreover, spatial variation occurs in three dimensions. Only rarely is quantification of abundance and biomass of either ectomycorrhizal roots or EMM undertaken at multiple depths. Among surface soil horizons in a Swedish boreal forest, ECM fungi tended to be associated with slightly older partially-decomposed organic matter (Lindahl et al., 2007). In the UK, detailed analyses of the vertical distribution of 7 species of ectomycorrhizas and their EMM in a Scots pine stand showed contrasting vertical distribution patterns from 0 to 20 cm (Genney et al., 2006). The EMM of some species like *Cadophora finlandia* was distributed quite evenly with depth while the EMM of *Cortinarius* spp. was concentrated in the upper 10 cm (Genney et al., 2006). This study also demonstrated unequal distribution of the EMM of many species at 2 cm intervals. Geostatistical techniques (Legendre and Legendre, 1998) have recently been applied to provide rigorous analysis of the temporal and spatial patterns of ectomycorrhizas (Lilleskov et al., 2004; Pickles, 2007). For example, Pickles (2007) sampled 48 cores at increasing distances in a 20×20 m area to determine when the abundance of key common species showed spatial autocorrelation. Subsequent more intense sampling events (217 cores) in the same location exploited this information and used regular distances of either 1 or 2 m as the primary separation distance to avoid issues with spatial autocorrelation, and to provide detailed interpolated maps of species' abundance (Pickles et al., 2010). The use of geostatistical tools therefore requires an initial high investment in sampling units, but can reap benefits later once optimum sampling distances are identified. Moreover, obtaining data on spatial autocorrelation enables more meaningful inter-site comparisons and so this is an approach we advocate in future studies.

7. Conclusions

Although significant progress has been made over the last ten years in our understanding of the importance of the ECM fungal mycelium in C cycling in ecosystems, our understanding is still highly fragmented. In this paper we have summarized the state of the art in this subject as well as the strengths and weaknesses in the methods and techniques applied. Our aim is that this information will ultimately enable researchers to obtain valuable data on the production, biomass and turnover of mycorrhizal mycelium in all biomes, and modify the approaches outlined here for arbuscular and ericoid mycorrhizal systems. Such data are likely to be essential for improving process-based models of terrestrial biogeochemical cycles that currently ignore the distinct role played by mycorrhizal fungi. This may improve their potential to predict nutrient leaching and carbon sequestration. Moreover, these data could also be incorporated into spatially-explicit modelling frameworks of population dynamics.

All of the applied methods and techniques have their own sets of limitations which the users of these methods should consider before applying them (Tables 1–3). To combine several techniques

in the same study, e.g. chemical markers and isotope labelling, may be a way to overcome some of these limitations. An issue that needs more attention is the turnover of EMM, especially the turnover of diffuse mycelium versus rhizomorphs. The ratio between free and total ergosterol, and the ratio between chitin and ergosterol as an indicator of the necromass/biomass ratio may be useful in such experiments and deserves further studies. Also, it could be useful to develop methods enabling us to quantify specifically the level of ^{13}C enrichment of C in glucosamine residues. Combined to environmental variation of carbon sources available to the ECM fungi (e.g. in FACE experiment using enriched or depleted ^{13}C – CO_2 sources), such a method could fill the gap regarding the actual rate the turnover of ECM fungi in forest soils.

Indices, such as specific EMM length or specific EMM biomass, developed for different exploration types, can be used for indirect estimations of the C costs of growth and storage in ECM fungal mycelium. The utility of such indirect measures are greatest providing the ECM fungal community structure is known, that the identified species belong to different exploration types, and these show different space occupation, mycelial length and biomass.

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References

- Agerer, R., 1987–1998. Colour Atlas of Ectomycorrhizae, 1–11 ed. Einhorn Verlag, Schwäbisch Gmünd, Germany.
- Agerer, R., 2001. Exploration types of ectomycorrhizae – a proposal to classify ectomycorrhizal mycelial systems according to their patterns of differentiation and putative ecological importance. *Mycorrhiza* 11, 107–114.
- Agerer, R., 2006. Fungal relationships and structural identity of their ectomycorrhizae. *Mycological Progress* 5, 67–107.
- Agerer, R., Raidl, S., 2004. Distance-related semi-quantitative estimation of the extramatrical ectomycorrhizal mycelia of *Cortinarius obtusus* and *Tylospora asterophora*. *Mycological Progress* 3, 57–64.
- Agerer, R., Rambold, G., 2004–2011. An Information System for Characterization and Determination of Ectomycorrhizae. First posted on 2004-06-01; most recent update: 2011-01-10. www.deemy.de. München.
- Amend, A.S., Seifert, K.A., Bruns, T.D., 2010. Quantifying microbial communities with 454 pyrosequencing: does read abundance count? *Molecular Ecology* 19, 5555–5565.
- Anderson, I.C., Parkin, P.I., 2007. Detection of active soil fungi by RT-PCR amplification of precursor rRNA molecules. *Journal of Microbiological Methods* 68, 248–253.
- Appuhn, A., Joergensen, R.G., 2006. Microbial colonisation of roots as a function of plant species. *Soil Biology and Biochemistry* 38, 1040–1051.
- Appuhn, A., Joergensen, R.G., Raubuch, M., Scheller, E., Wilke, B., 2004. The automated determination of glucosamine, galactosamine, muramic acid, and mannosamine in soil and root hydrolysates by HPLC. *Journal of Plant Nutrition and Soil Science* 167, 17–21.
- Bååth, E., 2001. Estimation of fungal growth rates in soil using ^{14}C -acetate incorporation into ergosterol. *Soil Biology and Biochemistry* 33, 2011–2018.
- Bååth, E., 2003. The use of neutral lipid fatty acids to indicate the physiological conditions of soil fungi. *Microbial Ecology* 45, 373–383.
- Bakken, L.R., Olsen, R.A., 1983. Buoyant densities and dry-matter contents of microorganisms: conversion of a measured biovolume into biomass. *Applied and Environmental Microbiology* 45, 1188–1195.
- Baldrian, P., Kolařík, M., Štursová, M., Kopecný, J., Valášková, V., Větrovský, T., Žifčáková, L., Snajdr, J., Rídl, J., Vlček, C., Voříšková, J., 2012. Active and total microbial communities in forest soil are largely different and highly stratified during decomposition. *ISME Journal* 6, 248–258.
- Beare, M.H., Hu, S., Coleman, D.C., Hendrix, P.F., 1997. Influences of mycelial fungi on soil aggregation and organic matter storage in conventional and no-tillage soils. *Applied Soil Ecology* 5, 211–219.
- Beiler, K.J., Durall, D.M., Simard, S.W., Maxwell, S.A., Kretzer, A.M., 2010. Architecture of the wood-wide web: *Rhizopogon* spp. genets link multiple Douglas-fir cohorts. *New Phytologist* 185, 543–553.
- Bellemain, E., Carlsen, T., Brochmann, C., Coissac, E., Taberlet, P., Kausarud, H., 2010. ITS as an environmental DNA barcode for fungi: an in silico approach reveals potential PCR biases. *BMC Microbiology* 10, 189.

- Bending, G.D., Read, D.J., 1995. The structure and function of the vegetative mycelium of ectomycorrhizal plants. V. Foraging behaviour and translocation of nutrients from exploited litter. *New Phytologist* 130, 401–409.
- Bermingham, S., Maltby, L., Cooke, R.C., 1995. A critical assessment of the validity of ergosterol as an indicator of fungal biomass. *Mycological Research* 99, 479–484.
- Berner, C., Johansson, T., Wallander, H., 2012. Long-term effect of apatite on ectomycorrhizal growth and community structure. *Mycorrhiza*, 1–7.
- Bonfante-Fasolo, P., Gianinazzi-Pearson, V., 1979. Ultrastructural aspects of endomycorrhiza in the Ericaceae. I. Naturally infected hair roots of *Calluna vulgaris* L. Hull. *New Phytologist* 83, 739–744.
- Brand, F., 1991. EKTOTOMYKORRHIZEN AN FAGUS SYLVATICA: Charakterisierung und identifizierung, ökologische kennzeichnung und unsterile kultivierung. IHW, Eching, 229 pp.
- Brondz, I., Høiland, K., Ekeberg, D., 2004. Multivariate analysis of fatty acids in spores of higher basidiomycetes: a new method for chemotaxonomical classification of fungi. *Journal of Chromatography B* 800, 303–307.
- Buée, M., Reich, M., Murat, C., Morin, E., Nilsson, R.H., Uroz, S., Martin, F., 2009. 454 Pyrosequencing analyses of forest soils reveal an unexpectedly high fungal diversity. *New Phytologist* 184, 449–456.
- Cairney, J.W.G., 1992. Translocation of solutes in ectomycorrhizal and saprotrophic rhizomorphs. *Mycological Research* 96, 135–141.
- Cairney, J.W.G., 2012. Extramatrical mycelia of ectomycorrhizal fungi as moderators of carbon dynamics in forest soil. *Soil Biology and Biochemistry* 47, 198–208.
- Cavigelli, M.A., Robertson, G.P., Klug, M.J., 1995. Fatty acid methyl ester (FAME) profiles as measures of soil microbial community structure. *Plant and Soil* 170, 99–113.
- Corradi, N., Croll, D., Colard, A., Kuhn, G., Ehinger, M., Sanders, I.R., 2007. Gene copy number polymorphisms in an arbuscular mycorrhizal fungal population. *Applied and Environmental Microbiology* 73, 366–369.
- Coutts, M.P., Nicoll, B.C., 1990. Growth and survival of shoots, roots, and mycorrhizal mycelium in clonal Sitka spruce during the first growing season after planting. *Canadian Journal of Forest Research* 20, 861–868.
- Dawson, T.E., Mambelli, S., Plamboeck, A.H., Templer, P.H., Tu, K.P., 2002. Stable isotopes in plant ecology. *Annual Review of Ecology and Systematics* 33, 507–559.
- Dembitsky, V.M., Rezanika, T., Bychek, I.A., Shustov, M.V., 1992. Fatty acid composition of *Paramecia* lichens. *Phytochemistry* 31, 841–843.
- Dickson, L., Bull, I.D., Gates, P.J., Evershed, R.P., 2009. A simple modification of a silicic acid lipid fractionation protocol to eliminate free fatty acids from glycolipid and phospholipid fractions. *Journal of Microbiological Methods* 78, 249–254.
- Dijkstra, P., Ishizu, A., Doucet, R., Hart, S.C., Schwartz, E., Menyailo, O.V., Hungate, B.A., 2006. ¹³C and ¹⁵N natural abundance of the soil microbial biomass. *Soil Biology and Biochemistry* 38, 3257–3266.
- Djakirana, G., Joergensen, R.G., Meyer, B., 1996. Ergosterol and microbial biomass relationship in soil. *Biology and Fertility of Soils* 22, 299–304.
- Drenovsky, R.E., Elliott, G.N., Graham, K.J., Scow, K.M., 2004. Comparison of phospholipid fatty acid (PLFA) and total soil fatty acid methyl esters (TSFAME) for characterizing soil microbial communities. *Soil Biology and Biochemistry* 36, 1793–1800.
- Drigo, B., Anderson, I.C., Kannangara, G.S.K., Cairney, J.W.G., Johnson, D., 2012. Rapid incorporation of carbon from ectomycorrhizal mycelial necromass into soil fungal communities. *Soil Biology and Biochemistry* 49, 4–10.
- Eikenes, M., Hietala, A.M., Alfredsen, G., Fosdal, C.G., Solheim, H., 2005. Comparison of quantitative real-time PCR, chitin and ergosterol assays for monitoring colonization of *Trametes versicolor* in birch wood. *Holzforschung* 59, 568–573.
- Ekblad, A., Wallander, H., Carlsson, R., Huss-Danell, K., 1995. Fungal biomass in roots and extramatrical mycelium in relation to macronutrients and plant biomass of ectomycorrhizal *Pinus sylvestris* and *Alnus incana*. *New Phytologist* 131, 443–451.
- Ekblad, A., Wallander, H., Näsholm, T., 1998. Chitin and ergosterol combined to measure total and living fungal biomass in ectomycorrhizas. *New Phytologist* 138, 143–149.
- Feinstein, L.M., Sul, W.J., Blackwood, C.B., 2009. Assessment of bias associated with incomplete extraction of microbial DNA from soil. *Applied and Environmental Microbiology* 75, 5428–5433.
- Fierer, N., Jackson, J.A., Vilgalys, R., Jackson, R.B., 2005. Assessment of soil microbial community structure by use of taxon-specific quantitative PCR assays. *Applied and Environmental Microbiology* 71, 4117–4120.
- Fogel, R., Hunt, G., 1979. Fungal and arboreal biomass in a western Oregon Douglas-fir ecosystem: distribution patterns and turnover. *Canadian Journal of Forest Research* 9, 245–256.
- Frankland, J.C., Lindley, D.K., Swift, M.J., 1978. A comparison of two methods for the estimation of microbial biomass in leaf litter. *Soil Biology and Biochemistry* 10, 323–333.
- Frey, B., Vilarinho, A., Schüepp, H., Arines, J., 1994. Chitin and ergosterol content of extraradical and intraradical mycelium of the vesicular–arbuscular mycorrhizal fungus *Glomus intraradices*. *Soil Biology and Biochemistry* 26, 711–717.
- Frostegård, Å., Bååth, E., 1996. The use of phospholipid fatty acid analysis to estimate bacterial and fungal biomass in soil. *Biology and Fertility of Soils* 22, 59–65.
- Frostegård, Å., Tunlid, A., Bååth, E., 1991. Microbial biomass measured as total lipid phosphate in soils of different organic content. *Journal of Microbiological Methods* 14, 151–163.
- Frostegård, Å., Tunlid, A., Bååth, E., 2011. Use and misuse of PLFA measurements in soils. *Soil Biology and Biochemistry* 43, 1621–1625.
- Garber, R.C., Turgeon, B.G., Selker, E.U., Yoder, O.C., 1988. Organization of ribosomal RNA genes in the fungus *Cochliobolus heterostrophus*. *Current Genetics* 14, 573–582.
- Genney, D.R., Anderson, I.C., Alexander, I.J., 2006. Fine-scale distribution of pine ectomycorrhizas and their extramatrical mycelium. *New Phytologist* 170, 381–390.
- Gleixner, G., Bol, R., Balesdent, J., 1999. Molecular insight into soil carbon turnover. *Rapid Communications in Mass Spectrometry* 13, 1278–1283.
- Gleixner, G., Poirier, N., Bol, R., Balesdent, J., 2002. Molecular dynamics of organic matter in a cultivated soil. *Organic Geochemistry* 33, 357–366.
- Godbold, D.L., Fritz, H.-W., Jentschke, G., Meessenburg, H., Rademacher, P., 2003. Root turnover and root necromass accumulation of Norway spruce (*Picea abies*) are affected by soil acidity. *Tree Physiology* 23, 915–921.
- Godbold, D.L., Hoosbeek, M.R., Lukac, M., Cotrufo, M.F., Janssens, I.A., Ceulemans, R., Polle, A., Velthorst, E.J., Scarascia-Mugnozza, G., De Angelis, P., Miglietta, F., Peressotti, A., 2006. Mycorrhizal hyphal turnover as a dominant process for carbon input into soil organic matter. *Plant and Soil* 281, 15–24.
- Graham, J.H., Hodge, N.C., Morton, J.B., 1995. Fatty acid methyl ester profiles for characterization of glomalean fungi and their endomycorrhizae. *Applied and Environmental Microbiology* 61, 58–64.
- Grant, W.D., West, A.W., 1986. Measurement of ergosterol, diaminopimelic acid and glucosamine in soil: evaluation as indicators of microbial biomass. *Journal of Microbiological Methods* 6, 47–53.
- Greben, T., Kraigher, H., 2009. Identification and quantification of ectomycorrhiza from field samples – a practical approach. In: Chauhan, A.K., Varma, A. (Eds.), *A Textbook of Molecular Biotechnology*. I. K. International Publishing House, New Delhi, Bangalore, pp. 1087–1104.
- Gryndler, M., Larsen, J., Hřelová, H., Režáčková, V., Gryndlerová, H., Kubát, J., 2006. Organic and mineral fertilization, respectively, increase and decrease the development of external mycelium of arbuscular mycorrhizal fungi in a long-term field experiment. *Mycorrhiza* 16, 159–166.
- Guidor, A., Debaud, J.-C., Marmeisse, R., 2002. Spatial distribution of the below-ground mycelia of an ectomycorrhizal fungus inferred from specific quantification of its DNA in soil samples. *FEMS Microbiology Ecology* 42, 477–486.
- Hagerberg, D., Wallander, H., 2002. The impact of forest residue removal and wood ash amendment on the growth of the ectomycorrhizal external mycelium. *FEMS Microbiology Ecology* 39, 139–146.
- Hagerberg, D., Thelin, G., Wallander, H., 2003. The production of ectomycorrhizal mycelium in forests: relation between forest nutrient status and local mineral sources. *Plant and Soil* 252, 279–290.
- Hammer, E.C., Nasr, H., Wallander, H., 2011. Effects of different organic materials and mineral nutrients on arbuscular mycorrhizal fungal growth in a Mediterranean saline dryland. *Soil Biology and Biochemistry* 43, 2332–2337.
- Hedh, J., Wallander, H., Erland, S., 2008. Ectomycorrhizal mycelial species composition in apatite amended and non-amended mesh bags buried in a phosphorus-poor spruce forest. *Mycological Research* 112, 681–688.
- Hendricks, J.J., Mitchell, R.J., Kuehn, K.A., Pecot, S.D., Sims, S.E., 2006. Measuring external mycelia production of ectomycorrhizal fungi in the field: the soil matrix matters. *New Phytologist* 171, 179–186.
- Hibbert, D.S., Gilbert, L.B., Donoghue, M.J., 2000. Evolutionary instability of ectomycorrhizal symbioses in basidiomycetes. *Nature* 407, 506–508.
- Hobbie, E.A., Agerer, R., 2010. Nitrogen isotopes in ectomycorrhizal sporocarps correspond to belowground exploration types. *Plant and Soil* 327, 71–83.
- Högborg, M.N., 2006. Discrepancies between ergosterol and the phospholipid fatty acid 18:2ω6,9 as biomarkers for fungi in boreal forest soils. *Soil Biology and Biochemistry* 38, 3431–3435.
- Högborg, M.N., Briones, M.J.L., Keel, S.G., Metcalfe, D.B., Campbell, C., Midwood, A.J., Thornton, B., Hurry, V., Linder, S., Näsholm, T., Högborg, P., 2010. Quantification of effects of season and nitrogen supply on tree below-ground carbon transfer to ectomycorrhizal fungi and other soil organisms in a boreal pine forest. *New Phytologist* 187, 485–493.
- Janssens, I.A., Lankreier, H., Matteucci, G., Kowalski, A.S., Buchmann, N., Epron, D., Pilegaard, K., Kutsch, W., Longdoz, B., Grünwald, T., Montagnani, L., Dore, S., Rebmann, C., Moors, E.J., Grelle, A., Rannik, Ü., Morgenstern, K., Oltchev, S., Clement, R., Gudmundsson, J., Minerbi, S., Berbigier, P., Ibrom, A., Moncrieff, J., Aubinet, M., Bernhofer, C., Jensen, N.O., Vesala, T., Granier, A., Schulze, E.-D., Lindroth, A., Dolman, A.J., Jarvis, P.G., Ceulemans, R., Valentini, R., 2001. Productivity overshadows temperature in determining soil and ecosystem respiration across European forests. *Global Change Biology* 7, 269–278.
- Joergensen, R.G., Wichern, F., 2008. Quantitative assessment of the fungal contribution to microbial tissue in soil. *Soil Biology and Biochemistry* 40, 2977–2991.
- Johnson, D., Leake, J.R., Read, D.J., 2001. Novel in-growth core system enables functional studies of grassland mycorrhizal mycelial networks. *New Phytologist* 152, 555–562.
- Johnson, D., Leake, J.R., Ostle, N., Ineson, P., Read, D.J., 2002a. In situ ¹³C₂ pulse-labelling of upland grassland demonstrates a rapid pathway of carbon flux from arbuscular mycorrhizal mycelia to the soil. *New Phytologist* 153, 327–334.
- Johnson, D., Leake, J.R., Read, D.J., 2002b. Transfer of recent photosynthate into mycorrhizal mycelium of an upland grassland: short-term respiratory losses and accumulation of ¹⁴C. *Soil Biology & Biochemistry* 34, 1521–1524.
- Johnson, D., Martin, F., Cairney, J.W.G., Anderson, I.C., 2012. The importance of individuals: intraspecific diversity of mycorrhizal plants and fungi in ecosystems. *New Phytologist* 194, 614–628.

- Jönsson, U., 2006. A conceptual model for the development of Phytophthora disease in *Quercus robur*. New Phytologist 171, 55–68.
- Kaiser, C., Frank, A., Wild, B., Koranda, M., Richter, A., 2010. Negligible contribution from roots to soil-borne phospholipid fatty acid fungal biomarkers 18:2 ω 6,9 and 18:1 ω 9. Soil Biology and Biochemistry 42, 1650–1652.
- Karlinski, L., Ravnkov, S., Kieliszewska-Rokicka, B., Larsen, J., 2007. Fatty acid composition of various ectomycorrhizal fungi and ectomycorrhizas of Norway spruce. Soil Biology and Biochemistry 39, 854–866.
- Karlinski, L., Rudawska, M., Kieliszewska-Rokicka, B., Leski, T., 2010. Relationship between genotype and soil environment during colonization of poplar roots by mycorrhizal and endophytic fungi. Mycorrhiza 20, 315–324.
- Kjeller, R., 2006. Disproportionate abundance between ectomycorrhizal root tips and their associated mycelia. FEMS Microbiology Ecology 58, 214–224.
- Kjeller, R., Rosendahl, S., 1996. The presence of the arbuscular mycorrhizal fungus *Glomus intraradices* influences enzymatic activities of the root pathogen *Aphanomyces euteiches* in pea roots. Mycorrhiza 6, 487–491.
- Kjeller, R., Nilsson, L.-O., Hansen, K., Schmidt, I.K., Vesterdal, L., Gundersen, P., 2012. Dramatic changes in ectomycorrhizal community composition, root tip abundance and mycelial production along a stand-scale nitrogen deposition gradient. New Phytologist 194, 278–286.
- Klamer, M., Bååth, E., 2004. Estimation of conversion factors for fungal biomass determination in compost using ergosterol and PLFA 18:2 ω 6,9. Soil Biology and Biochemistry 36, 57–65.
- Koide, R.T., Malcolm, G.M., 2009. N concentration controls decomposition rates of different strains of ectomycorrhizal fungi. Fungal Ecology 2, 197–202.
- Koide, R.T., Fernandez, C.W., Peoples, M.S., 2011. Can ectomycorrhizal colonization of *Pinus resinosa* roots affect their decomposition? New Phytologist 191, 508–514.
- Korkama, T., Fritze, H., Pakkanen, A., Pennanen, T., 2007. Interactions between extraradical ectomycorrhizal mycelia, microbes associated with the mycelia and growth rate of Norway spruce (*Picea abies*) clones. New Phytologist 173, 798–807.
- Labidi, S., Nasr, H., Zouaghi, M., Wallander, H., 2007. Effects of compost addition on extra-radical growth of arbuscular mycorrhizal fungi in *Acacia tortilis* ssp. *radfiana* savanna in a pre-Saharan area. Applied Soil Ecology 35, 184–192.
- Laczko, E., Boller, T., Wiemken, V., 2004. Lipids in roots of *Pinus sylvestris* seedlings and in mycelia of *Psilocybe tinctorius* during ectomycorrhiza formation: changes in fatty acid and sterol composition. Plant, Cell and Environment 27, 27–40.
- Landeweert, R., Veenman, C., Kuypers, T.W., Fritze, H., Wernars, K., Smit, E., 2003. Quantification of ectomycorrhizal mycelium in soil by real-time PCR compared to conventional quantification techniques. FEMS Microbiology Ecology 45, 283–292.
- Larsen, J., Mansfeld-Giese, K., Bødker, L., 2000. Quantification of *Aphanomyces euteiches* in pea roots using specific fatty acids. Mycological Research 104, 858–864.
- Lechevalier, H., Lechevalier, M.P., 1988. Chemotaxonomic use of lipids – an overview. In: Ratledge, C., Wilkinson, S.G. (Eds.), Microbial Lipids. Academic Press, New York, pp. 869–902.
- Legendre, P., Legendre, L., 1998. Numerical Ecology, second ed. Elsevier, Amsterdam.
- Lilleskov, E.A., Bruns, T.D., Horton, T.R., Taylor, D.L., Grogan, P., 2004. Detection of forest stand-level spatial structure in ectomycorrhizal fungal communities. FEMS Microbiology Ecology 49, 319–332.
- Lindahl, B.D., Ihrmark, K., Boberg, J., Trumbore, S.E., Högborg, P., Stenlid, J., Finlay, R.D., 2007. Spatial separation of litter decomposition and mycorrhizal nitrogen uptake in a boreal forest. New Phytologist 173, 611–620.
- Litton, C.M., Giardina, C.P., 2008. Below-ground carbon flux and partitioning: global patterns and response to temperature. Functional Ecology 22, 941–954.
- Litton, C.M., Raich, J.W., Ryan, M.G., 2007. Carbon allocation in forest ecosystems. Global Change Biology 13, 2089–2109.
- Lösel, D.M., 1988. Fungal lipids. In: Ratledge, C., Wilkinson, S.G. (Eds.), Microbial Lipids. Academic Press, London, pp. 699–806.
- Lundberg, P., Ekblad, A., Nilsson, M., 2001. ¹³C NMR spectroscopy studies of forest soil microbial activity: glucose uptake and fatty acid biosynthesis. Soil Biology and Biochemistry 33, 621–632.
- Lussenhop, J., Fogel, R., 1999. Seasonal change in phosphorus content of *Pinus strobus*–*Cenococcum geophilum* ectomycorrhizae. Mycologia 91, 742–746.
- Majdi, H., Damm, E., Nylund, J.E., 2001. Longevity of mycorrhizal roots depends on branching order and nutrient availability. New Phytologist 150, 195–202.
- Majdi, H., Truus, L., Johansson, U., Nylund, J.-E., Wallander, H., 2008. Effects of slash retention and wood ash addition on fine root biomass and production and fungal mycelium in a Norway spruce stand in SW Sweden. Forest Ecology and Management 255, 2109–2117.
- Maleszka, R., Clark-Walker, G.D., 1990. Magnification of the rDNA cluster in *Glomeromycetes lactis*. Molecular & General Genetics 223, 342–344.
- Manter, D.K., Vivanco, J.M., 2007. Use of the ITS primers, ITS1F and ITS4, to characterize fungal abundance and diversity in mixed-template samples by qPCR and length heterogeneity analysis. Journal of Microbiological Methods 71, 7–14.
- Martin, F., Delaruelle, C., Hilbert, J.-L., 1990. An improved ergosterol assay to estimate fungal biomass in ectomycorrhizas. Mycological Research 94, 1059–1064.
- Martin, F., Aerts, A., Åhrén, D., Brun, A., Danchin, E.G.J., Duchaussoy, F., Gibon, J., Kohler, A., Lindquist, E., Pereda, V., et al., 2008. The genome of *Laccaria bicolor* provides insights into mycorrhizal symbiosis. Nature 452, 88–92.
- Martin, F., Kohler, A., Murat, C., Balestrini, R., Coutinho, P.M., Jaillon, O., Montanini, B., Morin, E., Noel, B., Percudani, R., et al., 2010. Périgord Black Truffle genome uncovers evolutionary origins and mechanisms of symbiosis. Nature 464, 1033–1038.
- Mille-Lindblom, C., von Wachenfeldt, E., Tranvik, L.J., 2004. Ergosterol as a measure of living fungal biomass: persistence in environmental samples after fungal death. Journal of Microbiological Methods 59, 253–262.
- Montgomery, H.J., Monreal, C.M., Young, J.C., Seifert, K.A., 2000. Determination of soil fungal biomass from soil ergosterol analyses. Soil Biology and Biochemistry 32, 1207–1217.
- Möttönen, M., Järvinen, E., Hokkanen, T.J., Kuuluvainen, T., Ohtonen, R., 1999. Spatial distribution of soil ergosterol in the organic layer of a mature Scots pine (*Pinus sylvestris* L.) forest. Soil Biology and Biochemistry 31, 503–516.
- Newell, S.Y., Miller, J.D., Fallon, R.D., 1987. Ergosterol content of salt-marsh fungi: effect of growth conditions and mycelial age. Mycologia 79, 688–695.
- Nichols, P., Stulp, B.K., Jones, J.G., White, D.C., 1986. Comparison of fatty acid content and DNA homology of the filamentous gliding bacteria *Vitreoscilla*, *Flexibacter*, *Filibacter*. Archives of Microbiology 146, 1–6.
- Nilsson, L.O., Wallander, H., 2003. Production of external mycelium by ectomycorrhizal fungi in a Norway spruce forest was reduced in response to nitrogen fertilization. New Phytologist 158, 409–416.
- Nilsson, L.O., Giesler, R., Bååth, E., Wallander, H., 2005. Growth and biomass of mycorrhizal mycelia in coniferous forests along short natural nutrient gradients. New Phytologist 165, 613–622.
- Nylund, J.-E., Wallander, H., 1992. Ergosterol analysis as a means of quantifying mycorrhizal biomass. Methods in Microbiology 24, 77–88.
- Olk, D.C., Fortuna, A., Honeycutt, C.W., 2008. Using anion chromatography-pulsed amperometry to measure amino compounds in dairy manure-amended soils. Soil Science Society of America Journal 72, 1711–1720.
- Olsson, P., Michelsen, A., Wallander, H., 2007. Ergosterol content in ericaceous hair roots correlates with dark seepage endophytes but not with ericoid mycorrhizal colonization. Soil Biology and Biochemistry 39, 1218–1221.
- Olsson, P.A., 1999. Signature fatty acids provide tools for determination of the distribution and interactions of mycorrhizal fungi in soil. FEMS Microbiology Ecology 29, 303–310.
- Olsson, P.A., Johnson, N.C., 2005. Tracking carbon from the atmosphere to the rhizosphere. Ecology Letters 8, 1264–1270.
- Olsson, P.A., Bååth, E., Jakobsen, I., Söderström, B., 1995. The use of phospholipid and neutral lipid fatty acids to estimate biomass of arbuscular mycorrhizal fungi in soil. Mycological Research 99, 623–629.
- Olsson, P.A., Larsson, L., Bago, B., Wallander, H., van Aarle, I.M., 2003. Ergosterol and fatty acids for biomass estimation of mycorrhizal fungi. New Phytologist 159, 7–10.
- Orlov, A.Y., 1957. Observations on absorbing roots of spruce (*Picea excelsa* Link) in natural conditions (translated title). Botanicheskii Zhurnal SSSR 42, 1072–1081.
- Orlov, A.Y., 1960. Growth and growth dependent changes in absorbing roots of *Picea excelsa* Link (translated title). Botanicheskii Zhurnal SSSR 45, 888–896.
- Parladé, J., Hortal, S., Pera, J., Galipienso, L., 2007. Quantitative detection of *Lactarius deliciosus* extraradical soil mycelium by real-time PCR and its application in the study of fungal persistence and interspecific competition. Journal of Biotechnology 128, 14–23.
- Parrent, J.L., Vigalys, R., 2007. Biomass and compositional responses of ectomycorrhizal fungal hyphae to elevated CO₂ and nitrogen fertilization. New Phytologist 176, 164–174.
- Pickles, B.J., 2007. Spatial Ecology of Scots Pine Ectomycorrhizas. PhD thesis, University of Aberdeen, Aberdeen.
- Pickles, B.J., Genney, D.R., Potts, J.M., Lennon, J.J., Anderson, I.C., Alexander, I.J., 2010. Spatial and temporal ecology of Scots pine ectomycorrhizas. New Phytologist 186, 755–768.
- Plassard, C.S., Mousain, D.G., Salsac, L.E., 1982. Estimation of mycelial growth of basidiomycetes by means of chitin determination. Phytochemistry 21, 345–348.
- Plassard, C., Bonafos, B., Touraine, B., 2000. Differential effects of mineral and organic N sources, and of ectomycorrhizal infection by *Hebeloma cylindrosporum*, on growth and N utilization in *Pinus pinaster*. Plant, Cell and Environment 23, 1195–1205.
- Potila, H., Wallander, H., Sarjala, T., 2009. Growth of ectomycorrhizal fungi in drained peatland forests with variable P and K availability. Plant and Soil 316, 139–150.
- Pritchard, S.G., Strand, A.E., McCormack, M.L., Davis, M.A., Oren, R., 2008. Mycorrhizal and rhizomorph dynamics in a loblolly pine forest during 5 years of free-air-CO₂-enrichment. Global Change Biology 14, 1252–1264.
- Radajewski, S., Ineson, P., Parekh, N.R., Murrell, J.C., 2000. Stable-isotope probing as a tool in microbial ecology. Nature 403, 646–649.
- Raidl, S., 1997. Studies on the ontogeny of ectomycorrhizal rhizomorphs. Bibliotheca Mycologica 169.
- Raidl, S., Bonfigli, R., Agerer, R., 2005. Calibration of quantitative real-time TaqMan PCR by correlation with hyphal biomass and ITS copies in mycelia of *Piloderma croceum*. Plant Biology 7, 713–717.
- Rajala, T., Peltoniemi, M., Hantula, J., Mäkipää, R., Pennanen, T., 2011. RNA reveals a succession of active fungi during the decay of Norway spruce logs. Fungal Ecology 4, 437–448.
- Ramsey, P.W., Rillig, M.C., Feris, K.P., Holben, W.E., Gannon, J.E., 2006. Choice of methods for soil microbial community analysis: PLFA maximizes power compared to CLPP and PCR-based approaches. Pedobiologia 50, 275–280.
- Read, D.J., Perez-Moreno, J., 2003. Mycorrhizas and nutrient cycling in ecosystems – a journey towards relevance? New Phytologist 157, 475–492.

- Ruess, L., Häggblom, M.M., Zapata, E.J.G., Dighton, J., 2002. Fatty acids of fungi and nematodes – possible biomarkers in the soil food chain? *Soil Biology and Biochemistry* 34, 745–756.
- Ruess, L., Schütz, K., Haubert, D., Häggblom, M.M., Kandeler, E., Scheu, S., 2005. Application of lipid analysis to understand trophic interactions in soil. *Ecology* 86, 2075–2082.
- Rundel, P.W., Graham, E.A., Allen, M.F., Fisher, J.C., Harmon, T.C., 2009. Environmental sensor networks in ecological research. *New Phytologist* 182, 589–607.
- Ruzicka, S., Edgerton, D., Norman, M., Hill, T., 2000. The utility of ergosterol as a bioindicator of fungi in temperate soils. *Soil Biology and Biochemistry* 32, 989–1005.
- Rygiel, P.T., Johnson, M.G., Ganio, L.M., Tingey, D.T., Storm, M.J., 1997. Lifetime and temporal occurrence of ectomycorrhizae on ponderosa pine (*Pinus ponderosa* Laws.) seedlings grown under varied atmospheric CO₂ and nitrogen levels. *Plant and Soil* 189, 275–287.
- Salmanowicz, B., Nylund, J.-E., 1988. High performance liquid chromatography determination of ergosterol as a measure of ectomycorrhiza infection in Scots pine. *European Journal of Forest Pathology* 18, 291–298.
- Schoug, A., Fischer, J., Heipieper, H.J., Schnürer, J., Håkansson, S., 2008. Impact of fermentation pH and temperature on freeze-drying survival and membrane lipid composition of *Lactobacillus coryniformis* S13. *Journal of Industrial Microbiology & Biotechnology* 35, 175–181.
- Seitz, L.M., Mohr, H.E., Burroughs, R., Sauer, D.B., 1977. Ergosterol as an indicator of fungal invasion in grains. *Cereal Chemistry* 54, 1207–1217.
- Setälä, H., Kulmala, P., Mikola, J., Markkola, A.M., 1999. Influence of ectomycorrhiza on the structure of detrital food webs in pine rhizosphere. *Oikos* 87, 113–122.
- Simpson, R.T., Frey, S.D., Six, J., Thiet, R.K., 2004. Preferential accumulation of microbial carbon in aggregate structures of no-tillage soils. *Soil Science Society of America Journal* 68, 1249–1255.
- Šnajdr, J., Dobíášová, P., Větrovský, T., Valášková, V., Alawi, A., Boddy, L., Baldrian, P., 2011. Saprotrophic basidiomycete mycelia and their interspecific interactions affect the spatial distribution of extracellular enzymes in soil. *FEMS Microbiology Ecology* 78, 80–90.
- Staddon, P.L., Ramsey, C.B., Ostle, N., Ineson, P., Fitter, A.H., 2003. Rapid turnover of hyphae of mycorrhizal fungi determined by AMS microanalysis of ¹⁴C. *Science* 300, 1138–1140.
- Stahl, P.D., Parkin, T.B., 1996. Relationship of soil ergosterol concentration and fungal biomass. *Soil Biology and Biochemistry* 28, 847–855.
- Stober, C., George, E., Persson, H., 2000. Root growth and response to nitrogen. *Ecological Studies* 142, 99–121.
- Taylor, A.F.S., Alexander, I., 2005. The ectomycorrhizal symbiosis: life in the real world. *Mycologist* 19, 102–112.
- Taylor, A.F.S., Fransson, P.M., Högborg, P., Högborg, M.N., Plamboeck, A.H., 2003. Species level patterns in ¹³C and ¹⁵N abundance of ectomycorrhizal and saprotrophic fungal sporocarps. *New Phytologist* 159, 757–774.
- Taylor, D.L., McCormick, M.K., 2008. Internal transcribed spacer primers and sequences for improved characterization of basidiomycetous orchid mycorrhizas. *New Phytologist* 177, 1020–1033.
- Taylor, F.R., Parks, L.W., 1978. Metabolic interconversion of free sterols and steryl esters in *Saccharomyces cerevisiae*. *Journal of Bacteriology* 136, 531–537.
- Tedersoo, L., May, T.W., Smith, M.E., 2010. Ectomycorrhizal lifestyle in fungi: global diversity, distribution, and evolution of phylogenetic lineages. *Mycorrhiza* 20, 217–263.
- Thygesen, K., Larsen, J., Bødker, L., 2004. Arbuscular mycorrhizal fungi reduce development of pea root-rot caused by *Aphanomyces euteiches* using oospores as pathogen inoculum. *European Journal of Plant Pathology* 110, 411–419.
- Tingey, D.T., Phillips, D.L., Johnson, M.G., Rygiel, P.T., Beedlow, P.A., Hogsett, W.E., 2005. Estimates of Douglas-fir fine root production and mortality from minirhizotrons. *Forest Ecology and Management* 204, 359–370.
- Tornberg, K., Bååth, E., Olsson, S., 2003. Fungal growth and effects of different wood decomposing fungi on the indigenous bacterial community of polluted and unpolluted soils. *Biology and Fertility of Soils* 37, 190–197.
- Treseder, K.K., Allen, M.F., Ruess, R.W., Pregitzer, K.S., Hendrick, R.L., 2005. Lifespans of fungal rhizomorphs under nitrogen fertilization in a pinyon-juniper woodland. *Plant and Soil* 270, 249–255.
- Tunlid, A., White, D.C., 1992. Biochemical analysis of biomass, community structure, nutritional status, and metabolic activity of microbial communities in soil. *7*, 229–262.
- van Hees, P.A.W., Jones, D.L., Finlay, R., Godbold, D.L., Lundström, U.S., 2005. The carbon we do not see – the impact of low molecular weight compounds on carbon dynamics and respiration in forest soils: a review. *Soil Biology and Biochemistry* 37, 1–13.
- Vargas, R., Allen, M.F., 2008a. Dynamics of fine root, fungal rhizomorphs, and soil respiration in a mixed temperate forest: integrating sensors and observations. *Vadose Zone Journal* 7, 1055–1064.
- Vargas, R., Allen, M.F., 2008b. Environmental controls and the influence of vegetation type, fine roots and rhizomorphs on diel and seasonal variation in soil respiration. *New Phytologist* 179, 460–471.
- Waid, J.S., Woodman, M.J., 1957. A method of estimating hyphal activity in soil. *Pedologie* 7, 155–158.
- Wallander, H., Thelin, G., 2008. The stimulating effect of apatite on ectomycorrhizal growth diminishes after PK fertilization. *Soil Biology and Biochemistry* 40, 2517–2522.
- Wallander, H., Nilsson, L.O., Hagerberg, D., Bååth, E., 2001. Estimation of the biomass and seasonal growth of external mycelium of ectomycorrhizal fungi in the field. *New Phytologist* 151, 753–760.
- Wallander, H., Göransson, H., Rosengren, U., 2004. Production, standing biomass and natural abundance of ¹⁵N and ¹³C in ectomycorrhizal mycelia collected at different soil depths in two forest types. *Oecologia* 139, 89–97.
- Wallander, H., Johansson, U., Sterkenburg, E., Brandström Durling, M., Lindahl, B.D., 2010. Production of ectomycorrhizal mycelium peaks during canopy closure in Norway spruce forests. *New Phytologist* 187, 1124–1134.
- Wallander, H., Ekblad, A., Bergh, J., 2011. Growth and carbon sequestration by ectomycorrhizal fungi in intensively fertilized Norway spruce forests. *Forest Ecology and Management* 262, 999–1007.
- Wassaf, M.K., 1977. Fungal lipids. In: Paoletti, R., Kritichevsky, L. (Eds.), *Advances in Lipid Research*. Academic Press, New York, pp. 159–232.
- Weete, J.D., 1989. Structure and function of sterols in fungi. *Advances in Lipid Research* 23, 115–167.
- Weigt, R.B., Raidl, S., Verma, R., Rodenkirchen, H., Götting, A., Agerer, R., 2011. Effects of twice-ambient carbon dioxide and nitrogen amendment on biomass, nutrient contents and carbon costs of Norway spruce seedlings as influenced by mycorrhization with *Pirola crocea* and *Tomentolopsis submolis*. *Mycorrhiza* 21, 375–391.
- Weigt, R., Raidl, S., Verma, R., Agerer, R., 2012a. Erratum to: exploration type-specific standard values of extramatrical mycelium – a step towards quantifying ectomycorrhizal space occupation and biomass in natural soil. *Mycological Progress* 11, 349–350.
- Weigt, R., Raidl, S., Verma, R., Agerer, R., 2012b. Exploration type-specific standard values of extramatrical mycelium – a step towards quantifying ectomycorrhizal space occupation and biomass in natural soil. *Mycological Progress* 11, 287–297.
- White, D.C., Davis, W.M., Nickels, J.S., King, J.D., Bobbie, R.J., 1979. Determination of the sedimentary microbial biomass by extractable lipid phosphate. *Oecologia* 40, 51–62.
- Wilkinson, S.C., Anderson, J.M., Scardelli, S.P., Tisiafouli, M., Taylor, A., Wolters, V., 2002. PLFA profiles of microbial communities in decomposing conifer litter subject to moisture stress. *Soil Biology and Biochemistry* 34, 189–200.
- Wilkinson, A., Alexander, I.J., Johnson, D., 2011a. Species richness of ectomycorrhizal hyphal necromass increases soil CO₂ efflux under laboratory conditions. *Soil Biology and Biochemistry* 43, 1350–1355.
- Wilkinson, A., Solan, M., Alexander, I.J., Johnson, D., 2011b. Species diversity regulates the productivity of ectomycorrhizal fungi with increasing nitrogen supply. *Fungal Ecology* 5, 211–222.
- Wu, Y., Ding, N., Wang, G., Xu, J., Wu, J., Brookes, P.C., 2009. Effects of different soil weights, storage times and extraction methods on soil phospholipid fatty acid analyses. *Geoderma* 150, 171–178.
- Young, J.C., 1995. Microwave-assisted extraction of the fungal metabolite ergosterol and total fatty acids. *Journal of Agricultural and Food Chemistry* 43, 2904–2910.
- Young, I.M., Illian, J., Harris, J.A., Ritz, K., 2006. Comment on Zhao et al. (2005) “Does ergosterol concentration provide a reliable estimate of soil fungal biomass?”. *Soil Biology and Biochemistry* 38, 1500–1501.
- Yuan, J.-P., Kuang, H.-C., Wang, J.-H., Liu, X., 2008. Evaluation of ergosterol and its esters in the pileus, gill, and stipe tissues of agaric fungi and their relative changes in the comminuted fungal tissues. *Applied Microbiology and Biotechnology* 80, 459–465.
- Zamani, A., Jethanipour, A., Edebo, L., Niklasson, C., Taherzadeh, M.J., 2008. Determination of glucosamine and N-acetyl glucosamine in fungal cell walls. *Journal of Agricultural and Food Chemistry* 56, 8314–8318.
- Zelles, L., 1997. Phospholipid fatty acid profiles in selected members of soil microbial communities. *Chemosphere* 35, 275–294.
- Zelles, L., 1999. Fatty acid patterns of phospholipids and lipopolysaccharides in the characterisation of microbial communities in soil: a review. *Biology and Fertility of Soils* 29, 111–129.
- Zhao, X.R., Lin, Q., Brookes, P.C., 2005. Does soil ergosterol concentration provide a reliable estimate of soil fungal biomass? *Soil Biology and Biochemistry* 37, 311–317.
- Zhao, X.R., Lin, Q., Brookes, P.C., 2006. Reply to Young et al. (2006) on the paper of Zhao et al. (2005) “Does ergosterol concentration provide a reliable estimate of soil fungal biomass?”. *Soil Biology and Biochemistry* 38, 1502–1503.

II





Growth of ectomycorrhizal fungal mycelium along a Norway spruce forest nitrogen deposition gradient and its effect on nitrogen leakage

Adam Bahr^{a,*}, Magnus Ellström^a, Cecilia Akselsson^b, Alf Ekblad^c, Anna Mikusinska^c, Håkan Wallander^a

^a Lund University, Microbial Ecology, Dept. of Biology, SE-223 62 Lund, Sweden

^b Lund University, Dept. of Physical Geography & Ecosystems Science, SE-223 62 Lund, Sweden

^c Örebro University, School of Science & Technology, SE-701 82 Örebro, Sweden

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ABSTRACT

Almost all boreal and temperate forest tree species live in symbiosis with ectomycorrhizal fungi (EMF); the trees transfer carbon (C) to the fungi in exchange for nutrients and water. Several studies have shown that experimental application of inorganic nitrogen (N) represses production of EMF extramatrical mycelia (EMM), but studies along N deposition gradients are underrepresented. Other environmental variables than N may influence EMM production and in this study we included 29 thoroughly monitored Norway spruce stands from a large geographical region in Sweden in order to evaluate the importance of N deposition on EMM growth and N leaching in a broader context. It was concluded that N deposition was the most important factor controlling EMM production and that the amounts typically deposited in boreal and boreo-nemoral regions can be sufficient to reduce EMM growth. Other factors, such as phosphorus status and pH, were also correlated with EMM production and should be considered when predicting EMM growth and N leaching. We also showed that EMM production substantially contributed to the C sequestration ($320 \text{ kg ha}^{-1} \text{ yr}^{-1}$), suggesting that it should be included in C cycle modelling. Furthermore, EMF are probably important for the N retention capacity since high N leaching coincided with low EMM growth. However, it was not possible to differentiate between the effects of EMF and the direct effect of N deposition on N leaching in the present study.

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1. Introduction

Almost all boreal and northern temperate forest tree species live in symbiosis with ectomycorrhizal fungi (EMF). The EMF are dependent on photoassimilated carbon (C) allocated by the trees. In exchange, the EMF provide the trees with nutrients and water that are efficiently assimilated from the soil solution by extensive hyphal networks of EMF (Smith and Read, 2008), often referred to as extramatrical mycorrhizal mycelia (EMM). Nitrogen (N) is one of the most important nutrients for primary production and has a substantial impact on forest growth globally (LeBauer and Treseder, 2008), and is generally the limiting nutrient in temperate and boreal forests (Vitousek and Howarth, 1991). Several studies have shown that the net primary production of boreal forests was enhanced by N deposition or N fertilization (Bergh et al., 2008; Brockley, 2010; Jacobson and Pettersson, 2010), while excess N has been observed to have a negative influence on EMF biomass, growth

and colonization in pot/microcosm studies (e.g. Beckjord et al., 1985; Wallander and Nylund, 1992; Arnebrant, 1994; Runion et al., 1997) as well as in field studies (e.g. Arnebrant and Söderström, 1992; Nilsson and Wallander, 2003; Nilsson et al., 2007; Högborg et al., 2011; Kjeller et al., 2012). Only a few studies have reported no effects, or even a positive effect, of N addition on EMM (reviewed by Wallenda and Kottke, 1998). Most of the field experiments on the effect of N addition on EMM production have been designed to examine the consequences of fertilization, with additions of about 50–100 $\text{kg ha}^{-1} \text{ yr}^{-1}$ (e.g. Nilsson and Wallander, 2003; Wallander et al., 2011), while only a few have investigated the effect of the N added by atmospheric deposition (Nilsson et al., 2007; Kjeller et al., 2012). Even though deposition of N can reach such high levels as 50–100 $\text{kg ha}^{-1} \text{ yr}^{-1}$ in some Central European areas, remote forests at higher latitudes receive considerably less (reviewed by Hyvönen et al., 2007). The mean regional deposition of inorganic N in Swedish forests during the period 2003–2007 ranged from about 2 to 16 $\text{kg ha}^{-1} \text{ yr}^{-1}$ (Karlsson et al., 2012), with a declining gradient extending from the south-west to the seemingly unaffected northern part (Akselsson et al., 2010). Nilsson et al. (2007) found tendencies of reduced EMM growth due to N deposition

* Corresponding author.

E-mail address: adam.bahr@biol.lu.se (A. Bahr).

(10–20 kg ha⁻¹ y⁻¹, according to MATCH model) in oak forests in south west Sweden, but the effect was only tested in two different N deposition categories without any direct measurements of deposited N. To make accurate estimations of the effects of N deposition it is necessary with continuous direct measurements of the canopy throughfall, since it can be highly variable in both space and time in wooded ecosystems (Levia and Frost, 2006). An example of the spatial variation is seen in a recent study by Kjeller et al. (2012), who found a dramatic reduction in EMM and EMF colonised root tips with increasing N along a short distance (90 m) N deposition gradient in a Norway spruce (*Picea abies*) forest. However, the N deposition was intense (27–43 kg ha⁻¹ y⁻¹) since the gradient was stretching from a forest edge facing a poultry farm and a mink farm. Moderate N deposition (0.27–2.44 kg ha⁻¹ 60 d⁻¹) has been found to affect the composition of the EMF community (Lilleskov et al., 2002), but there is still a lack of studies of how moderate N deposition affects EMM production. In this study we approached that gap of knowledge by analysing production of EMM in Norway spruce forests exposed to a moderate N deposition gradient (1–25 kg ha⁻¹ y⁻¹), typical for most boreal and boreo-nemoral forests regions. The study area had a large geographical distribution and included continuous sampling of the canopy throughfall at all sites. Further, the sites were thoroughly monitored for other variables than N, allowing us to test if inclusion of some of these would improve the prediction of EMF growth.

Enhanced N leaching has been observed regularly after anthropogenic disturbances (e.g. clear-cuttings, reviewed by Gundersen et al., 2006) or natural disturbances, such as storm felling (Legout et al., 2009; Akselsson et al., 2010). N mineralization rates increase due to degradation of residues and higher soil temperature, which together with reduced root assimilation leads to accumulation of NH₄⁺ and increased nitrification (Fisk and Fahey, 1990; Gundersen et al., 2006). Nitrate (NO₃⁻) leaching from clear-cut areas in southern Sweden has been found to be positively correlated with N deposition (Löfgren and Westling, 2002; Akselsson et al., 2004, 2010) and to remain at elevated levels for up to five years after the disturbance (Westling et al., 2004). Although most boreal forests are N limited, enhanced N losses could occur even in undisturbed stands if the N addition rate exceeds the N retention capacity of the ecosystem (Aber et al., 1998). Increased N leaching has been found to occur when the canopy N throughfall is above 10–15 kg ha⁻¹ y⁻¹ (Dise and Wright, 1995; Kristensen et al., 2004; Gundersen et al., 2006). Leaching of N in forest ecosystems is most often correlated with the soil C:N ratio (Högbom et al., 2001; Nohrstedt, 2001; Kristensen et al., 2004). However, N leaching is highly variable within a broad range of soil humus C:N ratios (of about 20–30; Gundersen et al., 1998) and Högbom et al. (2011) suggested that the activity of EMF might be a better indicator of N retention in forest soil than the C:N ratio, since the growth of EMM recovered concurrently with more efficient N retention after the termination of N fertilization, while the C:N ratio did not. A reduction in EMM, resulting from a change in C allocation by the host plant, would hypothetically enhance N leaching due to a reduction in the efficiency of assimilation (Aber et al., 1998). Coincidence between abundant EMM and low N leaching has been found in an oak forest deposition gradient by Nilsson et al. (2007) but further studies are needed to interpret the specific effect and role of EMM on N leaching (Nilsson et al., 2007; Kjeller et al., 2012).

Since as much as 10–50% of the belowground allocated C can be transferred to EMF (Simard et al., 2002), it constitutes a potentially important C sink. The different isotopic composition of C4 and C3 plants have been used to quantify the carbon flux in soil (Kuzakov and Domanski, 2000; Wallander et al. (2011) used this approach to estimate an annual C sequestration of 300–1000 kg C ha⁻¹ by EMM in young Norway spruce forests. There is, however, still a lack of

knowledge regarding the turnover of EMM and the role of EMF necromass in the formation of soil organic matter. Further research within this area is of importance to improve our understanding of the role of EMF in the C cycle and enable us to make better predictions of the consequences of fertilization and anthropogenic emissions in boreal forests. Belowground C allocation is dependent on many other factors than N availability, such as a deficiency of mineral nutrients closely associated with photosynthesis. Deficiencies of potassium (K), magnesium (Mg) and manganese (Mn) typically lead to a reduction in belowground C allocation, while the opposite is seen with nutrients such as N, phosphorus (P) and sulphur (S), which are more involved in the production of new plant tissue (Ericsson, 1995). Such changes in C allocation patterns will have influences on EMM production, which may also be affected by other environmental variables, such as precipitation levels (Sims et al., 2007). It is, therefore, important to include other variables apart from N when making predictions of EMM growth and its consequences for C sequestration and nitrogen leaching.

The aim of this study was to predict EMM production and N leaching in Norway spruce forests in the south part of Sweden, by including more than 50 environmental variables, as well as detailed measurements of N deposition. The hypotheses investigated were: (1) N deposition is the most important variable affecting EMM production and N leaching; and (2) improved prediction of EMM growth and N leaching will be obtained by including needle and soil chemistry in the model, in such a way that low P levels are positively related to EMM growth while low K, Mg and Mn levels are negatively related to EMM growth, and that N leaching is negatively correlated with EMM production.

2. Material and methods

2.1. Study sites

The project took place from May 2009 until October 2010 at 29 Norway spruce forest locations in southern Sweden, stretching from the county of Skåne in the south to the northernmost site in the county of Värmland (Fig. 1). The sites belong to the Swedish

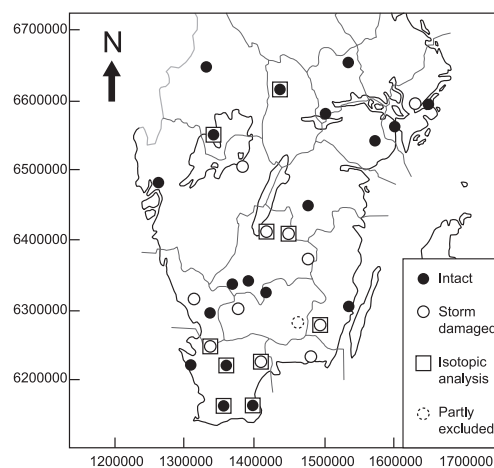


Fig. 1. Location of the field sites in the southern part of Sweden. RT90 coordinates are given.

Throughfall Monitoring Network (SWETHRO, Pihl-Karlsson et al., 2011), which is a subset of the ICP Forests (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests), run by the IVL Swedish Environmental Research Institute and the Swedish Forest Agency. The survey covered all of the SWETHRO Norway spruce forest sites located south of the Dal River. The sites in this region represent most of the national variation in soil water N, N deposition and N accumulation (Hallgren Larsson et al., 1995; Akselsson et al., 2010). The stand age varied from 50 to 109 years (mean value = 68 years, SE = 3.1) and the soil types were sandy podzol at different stages of development, with a bedrock consisting mainly of igneous rock (Akselsson et al., 2010). Twelve of the sites had been damaged by the hurricane Gudrun that hit southern Sweden in 2005 (denoted 'Storm damaged' in Fig. 1). Eleven of those sites were classified as storm damaged by Hellsten et al. (2009) and one additional site was classified as storm damaged due to the presence of uprooted trees and cleared areas within the plot. One of the sites was excluded from soil water analyses since three of the lysimeters were positioned in an open, recently wind thrown area bordering the plot. The SWETHRO monitoring was terminated at two of the sites at the end of 2009 and thus no data were available for the 2010 analysis. Totally, in 2009, 29 sites were included in throughfall correlations and 28 in soil water correlations, and in 2010 these numbers were reduced to 27 and 26 sites (Fig. 1).

2.2. Environmental variables

At each forest site, canopy throughfall and soil water were monitored continuously (Pihl-Karlsson et al., 2011) together with analyses of soil and needle chemistry (descriptive statistics are given in Table 1). The environmental variables included in this study are listed in Table 2. Monitoring took place along two borders or the diagonals of a 30 × 30 m plot positioned within a homogeneous forest stand (Pihl-Karlsson et al., 2011). Monthly throughfall was collected in 10 aluminium foil covered polyethylene bottles with funnels (Ø = 15.5 cm) amended with a mesh filter or, during winter, in buckets (Ø = 15.5 cm). Soil water samples were collected at 50 cm depth three times a year (before, after and during the growing season) using 5 ceramic cup suction lysimeters after two days of soil water suction. The 10 throughfall samples and the 5 soil water samples from each site on each occasion were pooled before analysis. Further details regarding sampling and chemical analyses

Table 1

Overview of the values of the explanatory environmental variables analysed. Values of canopy throughfall and soil water are based on mean annual values during the two years, while humus and needle chemistry are based on the most recent analyses.

	Variable	Range	Mean	SD
Throughfall	NO ₃ -N (kg ha ⁻¹)	0.46–11.0	3.09	0.53
	NH ₄ -N (kg ha ⁻¹)	0.50–13.5	3.11	0.60
	Tot. N (kg ha ⁻¹)	0.95–24.6	6.20	1.12
	SO ₄ -S (kg ha ⁻¹)	1.27–11.9	3.93	0.45
Soil water	NO ₃ -N (mg l ⁻¹)	<0.005–3.48	0.34	0.14
	NH ₄ -N (mg l ⁻¹)	<0.001–0.11	0.04	0.01
	pH _{H₂O}	3.91–5.89	4.93	0.09
Humus	C:N ratio	21.5–32.6	27.4	0.76
	K (mg g ⁻¹)	3.14–25.8	11.51	1.30
	pH _{H₂O}	3.35–4.80	4.04	0.10
Needles	P (mg g ⁻¹)	1.18–1.92	1.51	0.06
	K (mg g ⁻¹)	3.20–6.09	4.65	0.20
	δ ¹⁵ N	–6.93 to –2.08	–4.19	0.31

Abbreviations are given for chemical compounds.

Table 2

Environmental variables included in the multivariate analyses (PLS regressions).

Throughfall	Acid neutralizing capacity (ANC), H ⁺ , alkalinity, SO ₄ -S, Cl, NO ₃ -N, NH ₄ -N, Ca, Mg, Na, K, Mn
Soil water	pH _{H₂O} , TOC ^a , ANC, H ⁺ , SO ₄ -S, Cl, NO ₃ -N, NH ₄ -N, Ca, Mg, Na, K, Mn, Fe, i.o. Al, o. Al
Humus	Water content, CEC ^b , base saturation, org. C:N ratio, pH _{H₂O} , H ⁺ , Na, K, Mg, Ca, Mn, Fe, Al
Needles	Weight, N, S, P, Ca, Mg, K, Fe, Mn, arginine, C, δ ¹³ C, δ ¹⁵ N
Other	Precipitation, stand age, stand index, elevation, humus depth, RT90 coord., storm damage

Abbreviations are given for chemical compounds.

^a Total organic carbon.

^b Cation exchange capacity.

are described by Hallgren Larsson et al. (1995) and Pihl-Karlsson et al. (2011).

Two composite humus samples of about one litre each were compiled from 15 to 20 soil cores taken at each site, and the mean values obtained from the analysis of the two composite samples were used in the calculations. The number of variables monitored differed depending on whether the site was maintained by the IVL Swedish Environmental Research Institute or the Swedish Forest Agency. There were also some regional deviations leading to fewer variables being monitored at some sites. Soil samples had been taken at 21 of the sites during the autumn of 2005, 2006 or 2007, and 10 shoots were collected from the upper canopy of at least 5 representative trees for needle analysis at 20 of the sites during January 2006. Previous year needles (<1 year old) were used for the analyses since they have been shown to generally represent the current nutrient status better than other plant tissue (reviewed by Driessche and Rieche, 1974). Composite soil and needle samples from each site were analysed to determine values of the variables listed in Table 2. Detailed descriptions of the methods of sampling and chemical analysis is given by Ladanai et al. (2010), and are thoroughly described on the web page for ICP Forests (www.icp-forests.org/manual.htm).

2.3. Growth of ectomycorrhizal fungi

Sand-filled mesh-bags were used to determine the production of EMM (Wallander et al., 2001). A square sheet of nylon mesh (7 × 7 cm) with a pore size of 50 µm was folded diagonally and then welded to give a triangular bag, which was then filled with 10 g acid-washed and burned quartz sand (0.36–2.00 mm, 99.6% SiO₂, Ahlsell AB, Sweden). The mesh-bags were buried in the soil during two separate growing seasons, the first (May 2009–October 2009) is referred to as 2009 and the second (October 2009–October 2010) referred to as 2010. To analyse EMM production, sand filled mesh-bags were buried about two metres from each of the five suction lysimeters at each site. They were placed at the interface between the organic and mineral horizons, where the production of EMM has been found to be greatest (Lindahl et al., 2007).

To investigate possible P deficiency five additional mesh-bags, amended with 0.5% of the phosphorus-containing mineral apatite and 1% maize leaf compost, were installed at each site. Enhanced EMM production in apatite-amended bags indicates P deficiency of the trees (Wallander and Thelin, 2008). It has been shown that the addition of organic material enhances EMM production (Hendricks et al., 2006; Wallander et al., 2011), and therefore compost made from maize leaves was added to the apatite amended bags and their controls to improve the detection of any possible differences in EMM growth due to P deficiency. Since it has been reported that the increase in EMM production is only observable after two growing seasons (Hagerberg et al., 2003; Potila et al., 2009), the apatite and

maize amended bags together with controls (only maize) were left in the soil during the whole study period (2009–2010). Further, additional maize compost amended bags were buried at 10 of the sites during the first period to study the contribution of EMM production to C sequestration in the bags (see Chapter 2.4). In total, 20 or 28 mesh-bags were installed at each site during the period of the study (Table 3). Directly after harvest, the mesh-bags were stored at 4 °C for up to 4 days, until they were transferred to a freezer where they were kept at –18 °C. Each of the mesh-bags was coded at harvest with a randomised identification number to avoid subjectivity in further analysis.

We used two different approaches to analyse the ingrowth of EMM into the mesh-bags, visual estimation with stereo microscope and analysis of the chemical biomarker ergosterol. Ergosterol is a cell membrane component specific to fungi that can be used as a quantitative indicator of fungal biomass (Nylund and Wallander, 1992). Each mesh-bag was wiped clean and carefully opened before visual estimation of the EMM ingrowth. The EMM ingrowth was graded according to a 6 level scale (similar to Wallander et al., 2001): (0) no mycelia, (1) few hyphae present, (2) mycelia present but no aggregation of sand particles, (3) mycelia present and some aggregation of sand particles, (4) mycelia abundant and aggregation of sand particles, and (5) mycelia abundant with aggregation of almost all sand particles. After visual determination of the fungal ingrowth, the content of each mesh-bag was transferred to a plastic zip bag and homogenised by hand before being returned to the freezer and stored at –18 °C.

The contents of the mesh-bags from each time interval were pooled site-wise and 5 g from each of the pooled samples were used for ergosterol analysis. After adding 5 ml KOH solution (10% KOH in methanol) the samples were extracted by sonication for 15 min followed by heating for 1 h in a 70 °C water bath. One ml H₂O was added to increase the polarity and 2 ml cyclohexane to serve as the lipophilic phase. After shaking the tubes for 1 min in a multivortex (Multi Reax, Heidolph, Germany), they were centrifuged for 5 min at 1000 × g before the lipophilic phase was separated from the methanol based phase. Phase separation was repeated once more after the addition of another 2 ml cyclohexane. The supernatants were evaporated on a 40 °C heating block under nitrogen gas flow, to prevent oxidation, and then dissolved in 200 µl methanol. The solution was filtered through a 0.45 µm filter (SUN SRI, 44504-NPC, titan syringe filter, PTFE, 0, Rockwood, TN, USA) before analysis in a reversed-phase column (Chromolith C18 column, Merck and an Elite LaChrome C18 pre-column, Hitachi, Japan) high pressure liquid chromatograph (auto sampler L2130 with UV-detector L2400 by Hitachi, Japan). The ergosterol peak was detected at 280 nm with a flow rate of 1 ml min⁻¹.

2.4. Isotopic analysis

To estimate the contribution of EMM to sequestration of C we used mesh-bags filled with sand mixed with 1% of composted

maize leaves (a C4 plant) in a similar way as Wallander et al. (2011). Ten of the sites (Fig. 1), representing the total experimental range of N deposition, were selected for this study. Maize-amended mesh-bags were installed inside and outside trenched subplots (within a 30 cm deep, 16 cm diameter PVC-tube), the former acting as controls with no EMF ingrowth. This part of the experiment was restricted to the first period (2009), since longer periods can result in ingrowth of EMM into the trenching tubes from below (Wallander et al., 2011). Prior to isotopic analyses the content of the five pooled mesh-bags was freeze dried and milled with a ball mill to a fine powder. The amount of C as well as natural abundance of ¹³C were analysed with an elemental analyser (model EuroEA3024, Eurovector, Milan, Italy) and an isotope ratio mass spectrometer (Isoprime, Manchester, UK). The ¹³C abundance was calculated in per mille (‰) deviation from the international standard (Vienna Pee Dee Belemnite):

$$\delta^{13}\text{C} = \left(\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \right) \times 1000,$$

where R is the ratio of ¹³C/¹²C. The proportion of new C was calculated according to Wallander et al. (2011) with a two component mixing model:

$$\text{C}_4\text{-carbon} = \left(\frac{\delta^{13}\text{C}_{\text{sample}} - \delta^{13}\text{C}_{\text{new carbon}}}{\delta^{13}\text{C}_{\text{C}_4} - \delta^{13}\text{C}_{\text{new carbon}}} \right),$$

where $\delta^{13}\text{C}_{\text{new carbon}}$ was set as –26.8‰ (Wallander et al., 2011) and $\delta^{13}\text{C}_{\text{C}_4}$ values was determined from mesh-bags from trenched plots at each of the 10 sites.

2.5. Statistics

Partial least square regression (PLS) was used to interpret the multidimensional pattern of the complex dataset. PLS is an appropriate multivariate method when the response variables are few and co-linearity is apparent between x -variables (Wold et al., 2001). Since many ecological studies have a large array of predictor variables which often interact there is a large potential to use PLS, especially in studies with more predictors than response variables (Carrascal et al., 2009). Even though PLS modelling is typically used in other fields, such as analytical chemistry, it has been applied several times as a statistical tool in ecological publications (reviewed by Carrascal et al., 2009), including a few studies of soil microorganisms (e.g. Ekblad et al., 2005; Comstedt et al., 2011). After running a PLS on the whole dataset the number of x -variables was reduced, to analyse their specific contribution to the predictability of the response variables. PLS analyses were performed in Microsoft Excel (Microsoft Office Professional Plus 2010) with the Multibase 2012 plugin (Numerical Dynamics, www.numericaldynamics.com). All variables and sites with less than 20% missing values were included in the analyses and

Table 3

Overview of the mesh-bag experimental set-up. The mesh-bags were filled with 10 g acid-washed, burned quartz sand and buried in the soil to investigate growth of ectomycorrhizal mycelium. Bags amended with 1% maize leaf compost were buried with and without 0.5% apatite at all sites for the analysis of phosphorus deficiency. Additional bags containing 1% maize leaf compost were buried in trenched plots at 10 of the sites to study carbon sequestration.

Mesh-bag content	Analyses	No. Bags site ⁻¹	No. Sites	Period	Trenched
Sand	EMM prod.	5	29	2009 May–2009 Oct.	No
Sand	EMM prod.	5	27	2009 Oct.–2010 Oct.	No
Sand + maize	P limitation	5	29	2009 May–2010 Oct.	No
Sand + maize + apatite	P limitation	5	27	2009 May–2010 Oct.	No
Sand + maize	C allocation	3	10	2009 May–2009 Oct.	Yes
Sand + maize	C allocation	5	10	2009 May–2009 Oct.	No

missing values were replaced by values estimated by the software. No transformation of data was performed prior to analysis. Each X and Y variable was standardised by auto-scaling (divided by the standard deviation and then the mean value was subtracted) prior to analysis. Cross-validation with the minimum predicted residual sum of squares (PRESS) was used to interpret significant amount of PLS components, basically R^2 values show how much the response-variables can be explained by the model while Q^2 values (from PRESS) provide a measure of the predictability of them (Eriksson et al., 2006). T -tests, Mann Whitney U tests and regression analyses were performed in SPSS (IBM SPSS Statistics, version 19.0.0), Pearson correlations (R^2) were calculated for parametric data, and Spearman rank correlations (r_s) for ordinal data (e.g. the visual estimates of EMM growth). Only two-way analyses were performed and paired tests were used for within-site differences while unpaired tests were used between sites.

3. Results

3.1. Estimation of EMM production

There was agreement between the visual estimation of ingrowth and the ergosterol content in the mesh-bags in 2010 ($r_s = 0.402, P = 0.019$) but not in 2009 ($r_s = 0.165, P = 0.197$). EMM ingrowth during 2009 and 2010 were well correlated according to the visual estimates ($r_s = 0.508, P = 0.008$) but this could not be verified by analysis of the ergosterol content ($R^2 = 0.097, P = 0.134$).

3.2. Environmental variables affecting EMM production

PLS regression using visually estimated EMM growth and ergosterol content during 2009 and 2010 as response variables to 63 environmental variables (mean values of the two years) revealed two significant components, as shown in Fig. 2 ($R^2 = 0.51$, $Q^2 = 0.31$). Performing separate PLS models for visual and chemical EMM estimation from each year resulted in $R^2 = 0.92$ and $Q^2 = 0.54$ (4 significant components) for visual growth estimation for 2009, while the corresponding values for 2010 were $R^2 = 0.57$ and $Q^2 = 0.31$ (1 significant component). Growth estimation using ergosterol gave $R^2 = 0.43$ and $Q^2 = 0.06$ (1 significant component) in year 2009, while the corresponding values for 2010 were $R^2 = 0.60$ and $Q^2 = 0.38$ (1 significant component). As the separate models gave similar results to the combined model regarding the variable importance in projection (VIP) and loadings, only the latter is presented. VIP values (Fig. 3) together with the loading plot (Fig. 2) indicated that N deposition, pH-related variables and geographical position were the most important predictors. The chemical composition of needles seemed to mostly contribute to the pattern along the second component axis. A better model was obtained by removing all environmental variables apart from throughfall N, soil water N, needle nutrient status (N, P, Mg, K and Mn), soil pH and soil water pH, resulting in a higher predictability ($Q^2 = 0.36$) than the full model ($Q^2 = 0.31$). Although N was the most important factor to explain EMM growth, predictability declined ($Q^2 = 0.27$) when throughfall N and soil water N alone were included as x-variables in the model. N deposition was the N

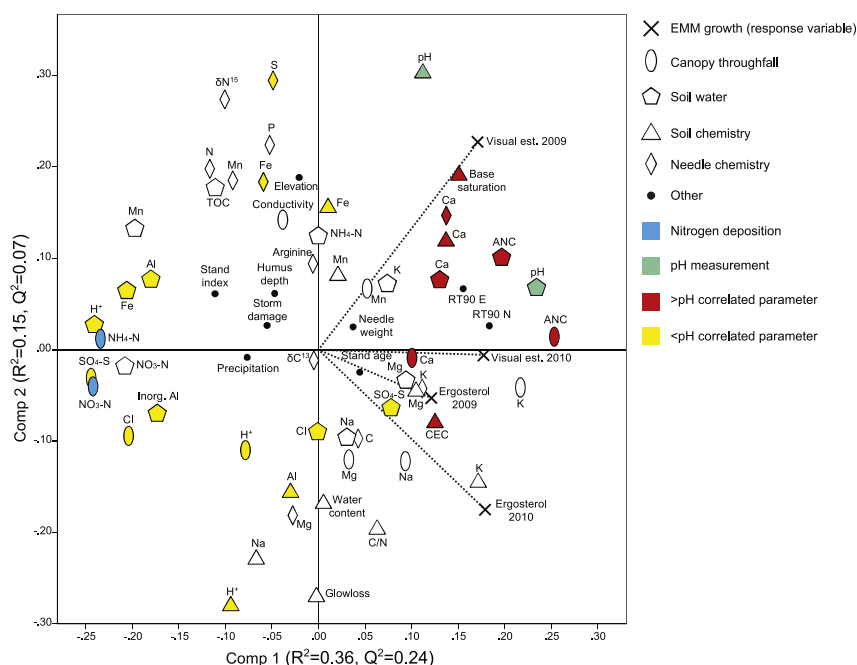


Fig. 2. Loading plot from PLS regression using growth of ectomycorrhizal extramatrical mycelium (EMM) during 2009 and 2010, according to visual and ergosterol-based estimates, as response variables (Y-variables). Canopy throughput and soil water variables are based on mean annual values during the two years. Soil and needle chemistry are based on the most recent measurement (1997 respectively 2006). Cross-validation resulted in two significant components.

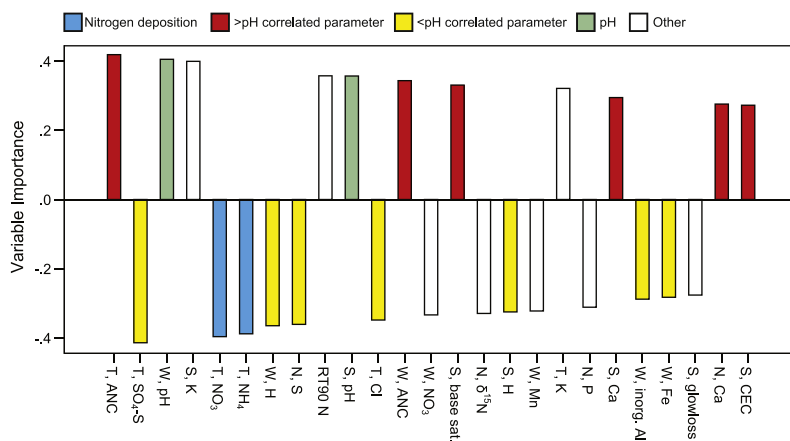


Fig. 3. Variable importance in projection (VIP) from the first PLS regression (Fig. 2), using growth of ectomycorrhizal extramatrical mycelium, according to visual estimation and ergosterol measurements, as response variables (Y-variables). Environmental variables are canopy throughfall (T), soil water (W), soil chemistry (S), needle chemistry (N) and geographic position (RT90). Of the 63 environmental variables used in the PLS, the 25 with highest VIP values are presented. Negative values are given for variables showing a negative trend with the response variable along the first PLS component axis.

factor most negatively correlated with EMM growth (Fig. 4) during 2009 ($r_s = -0.58$, $P = 0.001$) and 2010 ($r_s = -0.61$, $P < 0.001$) respectively according to visual estimation. This could not be verified by ergosterol analyses (2009: $R^2 = 0.234$, $P = 0.221$; 2010: $R^2 = 0.257$, $P = 0.195$). Soil water pH was positively correlated with visual EMM estimation (2009: $r_s = 0.65$, $P < 0.001$; 2010: $r_s = 0.513$, $P = 0.006$), and a trend was also observed with the ergosterol values during 2010 ($R^2 = 0.12$, $P = 0.074$). The growth of EMM increased along the north-eastern gradient (calculated as the sum of the RT90 north and east coordinates) according to visual estimates (2009: $r_s = 0.55$, $P = 0.002$; 2010: $r_s = 0.584$, $P = 0.001$), and

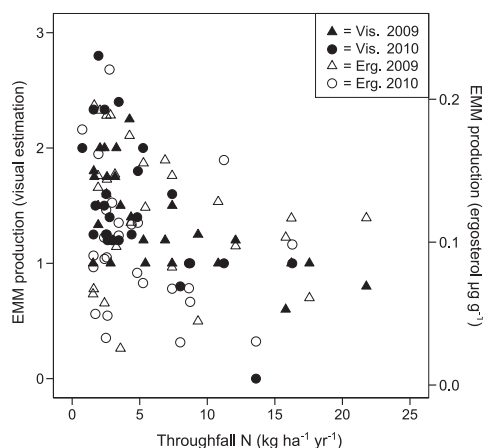


Fig. 4. A negative correlation between nitrogen deposition on ectomycorrhizal extramatrical mycelium growth (EMM) was found during both 2009 ($r_s = -0.58$, $P = 0.001$) and 2010 ($r_s = -0.61$, $P < 0.001$) according to visual estimation, but this could not be verified by ergosterol analyses (2009: $R^2 = 0.234$, $P = 0.221$; 2010: $R^2 = 0.257$, $P = 0.195$).

chemical estimation based on ergosterol showed a tendency towards the same trend (2009: $R^2 = 0.334$, $P = 0.077$; 2010: $R^2 = 0.374$, $P = 0.054$). Along the same gradient there was a decline in N deposition (2009: $R^2 = 0.674$, $P < 0.001$; 2010: $R^2 = 0.606$, $P < 0.001$). N deposition was negatively correlated to soil water pH (2009–2010: $R^2 = 0.75$, $P < 0.001$) and soil pH (2009–2010: $R^2 = 0.44$, $P = 0.051$).

Some significant correlations were observed between elemental concentration in needles and EMM production. Negative correlations were observed with concentrations of P (ergosterol 2009: $R^2 = 0.20$, $P = 0.058$; ergosterol 2010: $R^2 = 0.28$, $P = 0.022$), S (ergosterol 2009: $R^2 = 0.36$, $P = 0.008$) and Fe (ergosterol 2009: $R^2 = 0.21$, $P = 0.048$; Visual estimation 2010: $r_s = -0.602$, $P = 0.008$) while the needle Ca content increased with EMM production (ergosterol 2009: $R^2 = 0.25$, $P = 0.029$; visual estimation 2009: $r_s = 0.507$, $P = 0.027$; visual estimation 2010: $r_s = 0.482$, $P = 0.043$). Of the elements analysed in needles sampled in 2006, only N, K and P were, at least occasionally, observed at levels stated as deficient in *P. abies* foliage (Braekke and Salih, 2002) at any of the sites.

Apatite addition caused enhanced EMM production (Mann–Whitney U test, $P = 0.010$) at one site only. This site had the lowest needle P content of all investigated sites (1.19 mg g^{-1}), which is below the deficiency level 1.2 mg g^{-1} (Thelin et al., 2002). None of the other sites had needle P concentrations below the deficiency level.

3.3. Environmental variables affecting N leakage

When using N leaching during the two periods (the sum of soil water $\text{NO}_3\text{-N}$ and $\text{NO}_4\text{-N}$) as a response variable, PLS gave two significant components ($R^2 = 0.90$, $Q^2 = 0.58$). In this model (Fig. 5) only 53 of the environmental variables were included as predictors since all the soil water variables except the response variable (N leaching) were excluded to avoid overestimation of the model due to directly correlated variables within the same medium. According to the VIP values (Fig. 6) and the PLS output (Fig. 5) the most important variables on the first component axis were pH-related variables, N deposition and growth of EMM, while storm damage

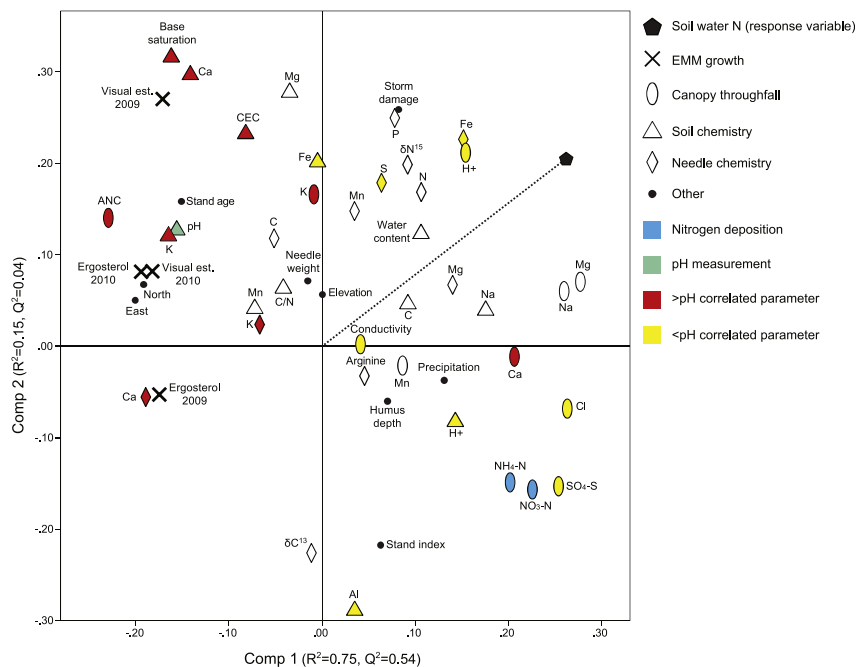


Fig. 5. Loading plot from PLS regression using the nitrogen leaching (soil water N) as response variable (Y-variable). Canopy throughfall and soil water variables are based on mean annual values during the two years, while soil and needle chemistry are based on the most recent measurement (1997 respectively 2006). Growth of ectomycorrhizal extramatrical mycelium (EMM) was estimated visually and chemically (ergosterol). Cross-validation resulted in two significant components.

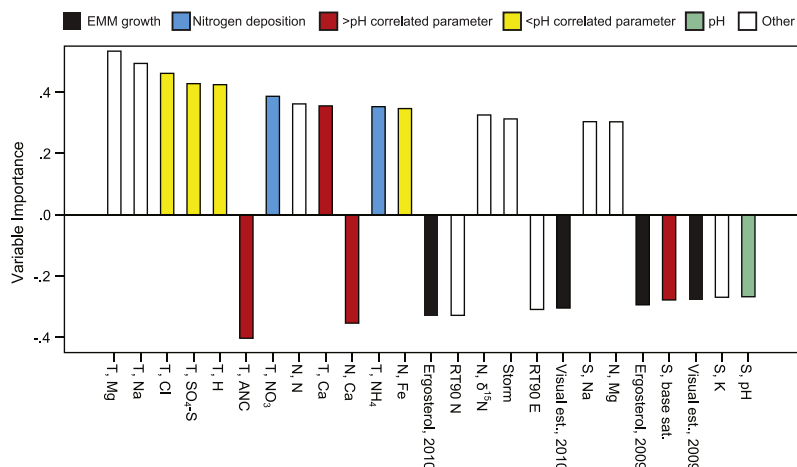


Fig. 6. Variable importance in projection (VIP) from the PLS regression, with soil water nitrogen ($\text{NO}_3^- + \text{NH}_4^+$) as response variable (Y-variable). Environmental variables are growth of ectomycorrhizal extramatrical mycelium (visual estimation and ergosterol), canopy throughfall (T), soil chemistry (S), needle chemistry (N), geographic position (RT90) and storm damage. Of the 51 environmental variables used in the PLS, the 25 with highest VIP values are presented. Negative values are given for variables showing a negative trend with the response variable along the first PLS component axis.

seemed to have a considerable effect on the second component. However, other variables were also important since running the PLS with pH, N deposition and growth of EMM as the only x -variables resulted in a substantial decline of the predictability ($Q^2 = 0.38$). Leaching of N increased with N deposition at intact sites in 2009 ($R^2 = 0.70$, $P < 0.001$) but not in 2010 (when no sites had elevated N leaching), while a positive correlation was observed at storm damaged sites in both years (2009: $R^2 = 0.69$, $P = 0.002$; 2010: $R^2 = 0.44$, $P = 0.025$). During 2009 the mean soil water N content of 0.98 mg l^{-1} (SE = 0.34) at storm damaged sites was larger ($P = 0.007$) than the values (0.15 mg l^{-1} SE = 0.069) observed at the intact sites. In 2010, intact sites (mean = 0.04 mg l^{-1} , SE = 0.01) tended ($P = 0.061$) to have lower N leaching than storm damaged sites (mean = 0.51 mg l^{-1} , SE = 0.28). Leaching of N tended to be negatively correlated with the visual estimates of EMM growth (Fig. 7) at intact sites during 2009 ($r_s = -0.45$, $P = 0.073$) and at storm damaged sites during 2010 ($r_s = -0.34$, $P = 0.060$). This trend could not be found at storm damaged sites 2009, intact sites in 2010, or at any of the above combinations according to ergosterol analysis. However, it should be borne in mind that there were no intact sites with elevated N leakage in 2010, and that observations at the two intact sites showing the greatest N leaching in 2009 was terminated at the end of 2009, and there were thus no detected N leaching to be predicted in 2010.

3.4. Isotopic analysis

The value of $\delta^{13}\text{C}$ was significantly ($P = 0.021$) higher in maize amended mesh-bags from non-trenched plots (mean = -15.3 , SE = 0.29) compared to the trenched (mean = -14.4 , SE = 0.19). Subtraction of the mean value from the trenched bags at each site resulted in a difference of -0.93 (SE = 0.22) regarding $\delta^{13}\text{C}$ in the non-trenched bags. Based on C_4 carbon and the total C content it was calculated that the mean C sequestration was $0.32 \text{ mg C g sand}^{-1}$ (SD: 0.35) from May 2009 until October 2009.

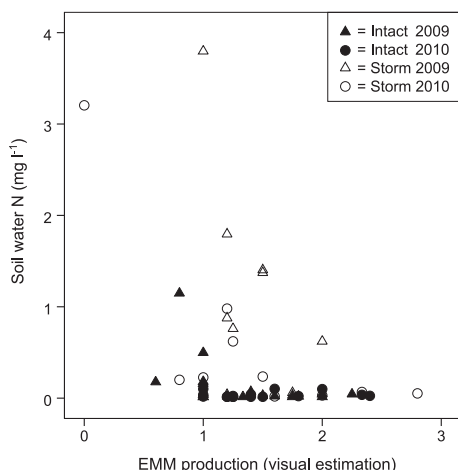


Fig. 7. A tendency was found between N leaching (soil water N) and visual estimation of ectomycorrhizal extramatrical mycelium (EMM) growth at intact sites (not storm damaged) during 2009 ($r_s = -0.45$, $P = 0.073$) and at storm damaged sites during 2010 ($r_s = -0.34$, $P = 0.060$). No correlations were found between N leaching and the estimates of EMM based on ergosterol (data not shown).

By converting this into the 10 cm top soil it was possible to estimate the annual C sequestration by EMF per ha (Wallander et al., 2011) to 320 kg (SD: 351). However, linear regression (data not shown) revealed no clear trends between C sequestration and N deposition.

4. Discussion

Our two methods to quantify fungal biomass in the mesh-bags gave somewhat different results. In separate regressions, only visual estimation revealed a negative correlation between EMM production and N deposition as well as tendencies of a negative pattern with N leakage. At the same time, negative correlations between EMM production and needle P content could only be found with biomarker estimation of the ingrowth in the mesh-bags. A reason for this could be that visual estimation likely is better to detect the proliferation of newly produced mycelia, while biomarker estimation probably reflects the total ingrowth during the whole incubation period, since the analysed chemical biomarker, ergosterol, has been shown more stable than expected during degradation of fungal biomass (Mille-Lindblom et al., 2004). Further, the ergosterol content has been shown to have both intraspecific (Yuan et al., 2008) and interspecific variation (Bermingham et al., 1995), and values may be related to the composition of the EMF community and the abundance of rhizomorphs rather than to hyphal proliferation.

The production of EMM is known to be negatively affected by high N availability (e.g. Beckjord et al., 1985; Wallander and Nylund, 1992; Arnebrant, 1994; Rönning et al., 1997; Nilsson and Wallander, 2003; Nilsson et al., 2007; Kjeller et al., 2012), but this knowledge is mainly based on experimental studies with rather high N addition rates (e.g. Nilsson and Wallander, 2003, $100 \text{ kg N ha}^{-1} \text{ y}^{-1}$). Here we show during two consecutive years that reduction of EMM production also occurs when moderate levels ($<10 \text{ kg N ha}^{-1} \text{ y}^{-1}$) of N are added by atmospheric deposition. The reduction in EMM growth may be due to a greater demand of photoassimilated C for above ground plant production, resulting in relatively less C being allocated belowground to support nutrient assimilation (Hobbie, 2006). In support of this Högborg et al. (2010) found a reduction in belowground C allocation to soil biota of more than half after N fertilization of a pine forest in northern Sweden. In addition, the C that is allocated to EMF will, to a larger extent, be used for energy purposes and as C skeletons for amino acid assimilation during elevated N availability resulting in less C being available for fungal growth (Wallander, 1995). Reduced production of EMM at elevated N input may also be related to changes in the EMF community. Agerer (2001) divided EMF into different exploration types, depending on the structure of the EMM. For example, the contact exploration type have a very limited growth of EMM and is hypothetically less C demanding than distance exploration types (Hobbie and Agerer, 2010), and the difference in biomass and distance between different exploration types can be 15-fold (Weigt et al., 2012). Reduced growth of EMM at high N availability may be an effect of a shift to less carbon demanding exploration types, in support for this Nilsson and Wallander (2003) found reduced growth of EMM in N fertilised plots where the amount of fungal biomass on roots were unchanged, and Kjeller et al. (2012) found that relative abundance of contact exploration types increased with N deposition while distance exploration types decreased.

Although most of the variation in production of EMM could be explained by N availability, inclusion of needle nutrient status and pH increased the predictability further (from $Q^2 = 0.27$ to $Q^2 = 0.36$). Together, these variables seem to be the most important ones since inclusion of additional variables did not contribute to any further increase of the predictability. According to the PLS model, needle N, P and S concentration were negatively, while

needle K concentration was positively related to EMM production. This can be explained by reductions in belowground C allocation when nutrients closely associated with photosynthesis, such as K, Mg and Mn are deficient, while the opposite is seen with nutrients such as N, P and S, which are more involved in the production of new plant tissue (Ericsson, 1995). Furthermore, enhanced production of EMM at P deficiency is commonly found in pot cultures (Wallander and Nylund, 1992; Ekblad et al., 1995) and this has also been found in the field (Bernier et al., 2012). The correlation between EMM production and needle P concentration found in the present study show that it may be important to take P into account in studies of EMM production, even if P is above the deficiency level. The content of Ca in needles, which plays a fundamental role in plant biomass formation as a structural component (Marschner, 1995), was positively correlated with EMM production. In Swedish forests, Ca is however high above optimum levels in plant tissue and it has been suggested that Ca assimilation depends on availability rather than plant requirement (Knecht and Göransson, 2004). This is consistent with the results of the present study since needle Ca was correlated with Ca content in both humus ($R^2 = 0.28$, $P = 0.004$) and soil water Ca (Yr 1: $R^2 = 0.47$, $P = 0.001$), and the positive correlations between Ca and EMM production are probably due to the greater abundance of Ca at higher pH (Brady and Weil, 2008).

Strong positive correlations were found between pH and visual estimation of the amount of EMM in the present study. Only a few field studies have analysed the effects of a reduction in pH on EMF, but it has been observed that simulated acid rain did not affect formation of mycorrhizas (Meier et al., 1989; Nowotny et al., 1998) or EMF morphotypes (Meier et al., 1989). On the other hand, liming to counteract soil acidification has a strong effect on the composition of the EMF community (Erland and Söderström, 1991; Lehto, 1994; Andersson and Söderström, 1995; Wallander et al., 1997; Bakker et al., 2000), while species richness (Kjeller and Clemmensen, 2009) and diversity (Rineau et al., 2010) seem to be rather unaffected by liming. It is often reported that species with well developed EMM increases after liming (Bakker et al., 2000; Kjeller and Clemmensen, 2009) and highly competitive ubiquitous species are more common at higher pH (Rineau et al., 2010). Lehto (1994) found that the reduction of contact exploration type EMF was mainly due to increased pH and ionic strength. Thus the positive relation between pH and EMM production in our study could be related to the composition of the EMF community. Increasing the pH in acidic forest soils has been found to promote microbial activity (Bååth and Arnebrant, 1994) and, in general, to elevate nutrient availability. Nevertheless, the effects of liming on the N cycle in N limited, acidic soils are complex, and reduced N mineralisation after liming have also been reported (reviewed by Formánek and Vranová, 2003). However, the positive correlation between pH and EMM growth observed in the present study may also be due to the acidifying effect of N deposition. Nilsson et al. (2007) found lower EMM production in areas with elevated N deposition, but these also had the lowest pH values. Acidification is caused by the atmospheric formation of HNO_3 from NO_x and Swedish air concentrations of NO_2 were about ten times higher than NH_3 around the turn of the millennium (Pihl-Karlsson et al., 2011). The amount of deposited $\text{NO}_3\text{--N}$ in the present study was similar to deposited $\text{NH}_4\text{--N}$ ($\text{NO}_3\text{--N} = -0.28 + 1.10 \times \text{NH}_4\text{--N}$, $R^2 = 0.93$, $P < 0.001$). Kjeller et al. (2012) found no change of pH in an N deposition gradient where the pollution consisted mainly of NH_3 . The acidifying effect of HNO_3 deposition together with a narrow pH gradient and a dispersed pattern of pH-related variables (according to PLS regression, Fig. 2) in the present study, indicates that canopy throughfall of N was the most important variable affecting EMM growth, and probably the cause of the pH trend.

4.1. C sequestration by EMF

EMF play an important role in the boreal forest C cycle (Smith and Read, 2008) and a reduction in EMM production may have substantial consequences for C sequestration (Godbold et al., 2006). In this study, an average C sequestration of $320 \text{ kg ha}^{-1} \text{ y}^{-1}$ was calculated by extrapolating the amount of fungal C accumulating in the mesh-bags to an areal basis. However, this data has low precision since it is based on small differences in $\delta^{13}\text{C}$ (0.93 , $\text{SE} = 0.34$). From the ten sites included in this part of the study, we could not find any relation between N deposition and C sequestration.

4.2. Environmental variables affecting N leakage

Since the surface area for plant nutrient assimilation can be increased in the order of two magnitudes through formation of ectomycorrhiza (Smith and Read, 2008), it is likely that high abundance of EMM increase the N retention capacity of the soil. It has been hypothesised that EMM growth counteracts leaching of N (Aber et al., 1998; Nilsson et al., 2007; Högborg et al., 2011), and indications of this has been observed in a few studies (e.g. Nilsson et al., 2007). The effect of EMM on nitrogen retention may be affected by the composition of the EMF community and the abundance of specific exploration types. Kjeller et al. (2012) found that the relative abundance of contact exploration types (e.g. *Lactarius* spp.), with potentially less capacity to retain N, increased in areas with higher N leaching. According to the visual estimation of EMM production (Fig. 7) elevated N losses seemed to occur at relatively low EMM production, while low N leaching was detected at all levels of EMM production. The lack of high N losses at abundant EMM production indicates a counteracting effect of EMM on N leaching. It was however not possible to draw any firm conclusions regarding the capacity of EMM to retain N in the soil, since N leaching increased with N deposition at the same time as N deposition had a negative effect on EMM production. The effects of these mechanisms on N leakage couldn't be separated with the approach used in the present study. In order to determine the capacity of EMM to reduce N losses it might be better to apply more intense temporal sampling strategies for both EMM production and N leaching. EMM production in the boreal and boreo-nemoral regions generally peaks during the autumn while N leaching vary more depending on the climate: northern and central areas of Sweden tend to have increased N leaching during snowmelt in spring, while further south N losses usually occur in late autumn due to high precipitation (Gustafson, 1983). Another approach to detect the N retention capacity of the soil could be to add isotopically labelled nutrients, which would enable the detection of assimilation (Harrison et al., 1995). In an ongoing experiment, we are exposing plots differing in EMM proliferation to ^{15}N -labelled $\text{NO}_3\text{--}$ to investigate the N retention capacity of EMM.

4.3. Conclusions

By including a comprehensive dataset of environmental variables regarding canopy throughfall, soil water, soil chemistry and needle chemistry we here conclude that N deposition is the most important abiotic variable controlling EMM production in the surveyed forest type, and that the N deposition of $2\text{--}20 \text{ kg ha}^{-1} \text{ y}^{-1}$, typical for the boreal and boreo-nemoral region, is sufficient to repress EMM production. Other important abiotic factors found to be negatively related to EMM growth were low pH and high needle P concentration. Further, we also conclude that the most important variables explaining the N leakage were N deposition, low pH, storm damage and low EMM production, but a more experimental approach to investigate mechanisms, and more intense seasonal

sampling efforts are needed to improve our understanding of the N retention capacity of EMM.

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References

- Aber, J., McDowell, W., Nadelhoffer, K., Alison, M., Berntson, G., Kamakea, M., McNulty, S., Currie, W., Rustad, L., Fernandez, I., 1998. Nitrogen saturation in temperate forest ecosystems. *Bioscience* 48, 921–934.
- Agerer, R., 2001. Exploration types of ectomycorrhizae – a proposal to classify ectomycorrhizal mycelial systems according to their patterns of differentiation and putative ecological importance. *Mycorrhiza* 11, 107–114.
- Akesson, C., Westling, O., Orlander, G., 2004. Regional mapping of nitrogen leaching from clearcuts in southern Sweden. *Forest Ecology and Management* 202, 235–243.
- Akesson, C., Belyazid, S., Hellsten, S., Klarqvist, M., Pihl-Karlsson, G., Karlsson, P.E., Lundin, L., 2010. Assessing the risk of N leaching from forest soils across a steep N deposition gradient in Sweden. *Environmental Pollution* 158, 3588–3595.
- Andersson, S., Söderström, B., 1995. Effects of lime (CaCO₃) on ectomycorrhizal colonization of *Picea abies* (L.) karst. seedlings planted in a spruce forest. *Scandinavian Journal of Forest Research* 10, 149–154.
- Arnebrant, K., 1994. Nitrogen amendments reduce the growth of extramatrical ectomycorrhizal mycelium. *Mycorrhiza* 5, 7–15.
- Arnebrant, K., Söderström, B., 1992. Effects of different fertilizer treatments on ectomycorrhizal colonization potential in two Scots pine forests in Sweden. *Forest Ecology and Management* 53, 77–89.
- Bååth, E., Arnebrant, K., 1994. Growth rate and response of bacterial communities to pH in limed and ash treated forest soils. *Soil Biology and Biochemistry* 26, 995–1001.
- Bakker, M.R., Garbaye, J., Nys, C., 2000. Effect of liming on the ectomycorrhizal status of oak. *Forest Ecology and Management* 126, 121–131.
- Beckjord, P.R., Melhuish, J.H., McIntosh, M.S., 1985. Effects of nitrogen and phosphorus fertilization on growth and formation of ectomycorrhizae of *Quercus alba* and *Q. rubra* seedlings by *Pisolithus tinctorius* and *Scleroderma aurantenum*. *Canadian Journal of Botany* 63, 1677–1680.
- Bergh, J., Nilsson, U., Grip, H., Hedwall, P.O., Lundmark, T., 2008. Effects of frequency of fertilisation on production, foliar chemistry and nutrient leaching in young Norway spruce stands in Sweden. *Silva Fennica* 42, 721–733.
- Bermingham, S., Malby, L., Cooke, R.C., 1995. A critical assessment of the validity of ergosterol as an indicator of fungal biomass. *Mycological Research* 99, 479–484.
- Berner, C., Johansson, T., Wallander, H., 2012. Long-term effect of apatite on ectomycorrhizal growth and community structure. *Mycorrhiza* 22, 615–621.
- Brady, N.C., Weil, R.R., 2008. *The Nature and Properties of Soils*, thirteenth ed. Prentice Hall, New Jersey, USA.
- Braekke, F.H., Salih, N., 2002. Reliability of foliar analyses of Norway spruce stands in a Nordic gradient. *Silva Fennica* 36, 489–504.
- Brockley, R.P., 2010. Effects of repeated fertilization in a young spruce stand in central British Columbia. *Canadian Journal of Forest Research* 40, 1687–1697.
- Carrascal, L.M., Galván, I., Gordo, O., 2009. Partial least squares regression as an alternative to current regression methods used in ecology. *Oikos* 118, 681–690.
- Comstedt, D., Boström, B., Ekblad, A., 2011. Autotrophic and heterotrophic soil respiration in a Norway spruce forest: estimating the root decomposition and soil moisture effects in a trenching experiment. *Biogeochemistry* 104, 121–132.
- Dise, N.B., Wright, R.F., 1995. Nitrogen leaching from European forests in relation to nitrogen deposition. *Forest Ecology and Management* 71, 153–161.
- Driessche, R.v.d., Rieche, K., 1974. Prediction of mineral nutrient status of trees by foliar analysis. *Botanical Review* 40, 347–394.
- Ekblad, A., Wallander, H., Carlsson, R., Huss-Danell, K., 1995. Fungal biomass in roots and extramatrical mycelium in relation to macronutrients and plant biomass of ectomycorrhizal *Pinus sylvestris* and *Alnus incana*. *New Phytologist* 131, 443–451.
- Ekblad, A., Bostrom, B., Holm, A., Comstedt, D., 2005. Forest soil respiration rate and delta ¹³C is regulated by recent above ground weather conditions. *Oecologia* 143, 136–142.
- Ericsson, T., 1995. Growth and shoot: root ratio of seedlings in relation to nutrient availability. *Plant and Soil* 168–169, 205–214.
- Eriksson, L., Johansson, N., Kettanah-Wold, J., Trygg, J., Wikström, C., Wold, S., 2006. *Multi- and Megavariable Data Analysis, Part 1, Basic Principles and Applications*, second ed. Umetrics AB, Umeå.
- Erland, S., Söderström, B., 1991. Effects of lime and ash treatments on ectomycorrhizal infection of *Pinus sylvestris* L. seedlings planted in a pine forest. *Scandinavian Journal of Forest Research* 6, 519–525.
- Fisk, M., Fahey, T.J., 1990. Nitrification potential in the organic horizons following clearfelling of northern hardwood forests. *Soil Biology and Biochemistry* 22, 277–279.
- Formánek, P., Vranová, V., 2003. A contribution to the effect of liming on forest soils: review of literature. *Journal of Forest Science (Prague)* 49, 182–190.
- Godbold, D.L., Hoosbeek, M.R., Lukac, M., Cotrufo, M.F., Janssens, I.A., Ceulemans, R., Polle, A., Velthorst, E.J., Scarascia-Mugnozza, G., De Angelis, P., Miglietta, F., Peressotti, A., 2006. Mycorrhizal hyphal turnover as a dominant process for carbon input into soil organic matter. *Plant and Soil* 281, 15–24.
- Gundersen, P., Callesen, I., De Vreis, W., 1998. Nitrate leaching in forest ecosystems is related to forest floor C/N ratios. *Environmental Pollution* 102, 403–407.
- Gundersen, P., Schmidt, I.K., Raulund-Rasmussen, K., 2006. Leaching of nitrate from temperate forests – effects of air pollution and forest management. *Environmental Reviews* 14, 1–57.
- Gustafson, A., 1983. Leaching of nitrate from arable land into groundwater in Sweden. *Environmental Geology* 5, 65–71.
- Hagerberg, D., Thelin, G., Wallander, H., 2003. The production of ectomycorrhizal mycelium in forests: relation between forest nutrient status and local mineral sources. *Plant and Soil* 252, 279–290.
- Hallgren Larsson, E., Knulst, J., Malm, G., Westling, O., 1995. Deposition of acidifying compounds in Sweden. *Water Air and Soil Pollution* 85, 2271–2276.
- Harrison, A.F., Stevens, P.A., Dighton, J., Quarmby, C., Dickinson, A.L., Jones, H.E., Howard, D.M., 1995. The critical load of nitrogen for Sitka spruce forests on stagnopodsols in Wales: role of nutrient limitations. *Forest Ecology and Management* 76, 139–148.
- Hellsten, S., Stadmark, J., Akesson, C., Pihl-Karlsson, G., Karlsson, P.E., 2009. Effekter av stormen Gudrun på kvävetillstånd från skogsmark. IVL Report B 1926. IVL Swedish Environmental Research Institute, Göteborg, Sweden.
- Hendricks, J.J., Mitchell, R.J., Kuehn, K.A., Pecot, S.D., Sims, S.E., 2006. Measuring external mycelia production of ectomycorrhizal fungi in the field: the soil matrix matters. *New Phytologist* 171, 179–186.
- Hobbie, E.A., 2006. Carbon allocation to ectomycorrhizal fungi correlates with belowground allocation in culture studies. *Ecology* 87, 563–569.
- Hobbie, E., Agerer, R., 2010. Nitrogen isotopes in ectomycorrhizal sporocarps correspond to belowground exploration types. *Plant and Soil* 327, 71–83.
- Högborg, M.N., Briones, M.J.L., Keel, S.C., Metcalfe, D.B., Campbell, C., Midwood, A.J., Thornton, B., Hurry, V., Linder, S., Näsholm, T., Högborg, P., 2010. Quantification of effects of season and nitrogen supply on tree below-ground carbon transfer to ectomycorrhizal fungi and other soil organisms in a boreal pine forest. *New Phytologist* 187, 485–493.
- Högborg, P., Johansson, C., Yarrowood, S., Callesen, I., Näsholm, T., Myröld, D.D., Högborg, M.N., 2011. Recovery of ectomycorrhiza after 'nitrogen saturation' of a conifer forest. *New Phytologist* 189, 515–525.
- Högborg, L., Nohrstedt, H.O., Nordlund, S., 2001. Nitrogen fertilization effects on stream water cadmium concentration. *Journal of Environmental Quality* 30, 189–193.
- Hyvönen, R., Ågren, G.J., Linder, S., Persson, T., Cotrufo, M.F., Ekblad, A., Freeman, M., Grelle, A., Janssens, I.A., Jarvis, P.G., Kellomäki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R.J., Oren, R., Pilegaard, K., Ryan, M.G., Sigurdsson, B.D., Strömberg, M., Ojien, M.v., Wallin, G., 2007. The likely impact of elevated CO₂, nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. *New Phytologist* 173, 463–480.
- Jacobson, S., Pettersson, F., 2010. An assessment of different fertilization regimes in three boreal coniferous stands. *Silva Fennica* 44, 815–827.
- Karlsson, G.P., Karlsson, P.E., Akesson, C., Kronnäs, V., Hellsten, S., 2012. Kron-droppsnätets övervakning av luftföroreningar i Götaland. County Administration of Västra Götaland Report 2012:14. Environmental protection unit, County administration of Västra Götaland, Sweden.
- Kjeller, R., Clemmensen, K.E., 2009. Belowground ectomycorrhizal fungal communities respond to liming in three southern Swedish coniferous forest stands. *Forest Ecology and Management* 257, 2217–2225.
- Kjeller, R., Nilsson, L.-O., Hansen, K., Schmidt, I.K., Vesterdal, L., Gundersen, P., 2012. Dramatic changes in ectomycorrhizal community composition, root tip abundance and mycelial production along a stand-scale nitrogen deposition gradient. *New Phytologist* 194, 278–286.
- Knecht, M.F., Göransson, A., 2004. Terrestrial plants require nutrients in similar proportions. *Tree Physiology* 24, 447–460.
- Kristensen, H.L., Gundersen, P., Callesen, I., Reinds, G.J., 2004. Throughfall nitrogen deposition has different impacts on soil solution nitrate concentration in European coniferous and deciduous forests. *Ecosystems* 7, 180–192.
- Kuz'yakov, Y., Domanski, G., 2000. Carbon input by plants into the soil. Review. *Journal of Plant Nutrition and Soil Science* 163, 421–431.
- Ladanai, S., Ågren, G.J., Olsson, B.A., 2010. Relationships between tree and soil properties in *Picea abies* and *Pinus sylvestris* forests in Sweden. *Ecosystems* 13, 302–316.
- LeBauer, D.S., Treseder, K.K., 2008. Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. *Ecology* 89, 371–379.
- Legout, A., Nys, C., Picard, J.F., Turpault, M.P., Dambrine, E., 2009. Effects of storm Lothar (1999) on the chemical composition of soil solutions and on herbaceous cover, humus and soils (Fougères, France). *Forest Ecology and Management* 257, 800–811.
- Lehto, T., 1994. Effects of soil pH and calcium on mycorrhizas of *Picea abies*. *Plant and Soil* 163, 69–75.

- Levia, D.F., Frost, E.E., 2006. Variability of throughfall volume and solute inputs in wooded ecosystems. *Progress in Physical Geography* 30, 605–632.
- Lilleskov, E.A., Hobbie, E.A., Fahey, T.J., 2002. Ectomycorrhizal fungal taxa differing in response to nitrogen deposition also differ in pure culture organic nitrogen use and natural abundance of nitrogen isotopes. *New Phytologist* 154, 219–231.
- Lindahl, B.D., Ihrmark, K., Boberg, J., Trumbore, S.E., Högberg, P., Stenlid, J., Finlay, R.D., 2007. Spatial separation of litter decomposition and mycorrhizal nitrogen uptake in a boreal forest. *New Phytologist* 173, 611–620.
- Löfgren, S., Westling, O., 2002. Modell för att beräkna kväveförlust från växande skog och hyggen i Sydsvrige. Swedish University of Agricultural Sciences, Dept of Environmental Assessment Report 2002:1.
- Marschner, H., 1995. Mineral Nutrition of Higher Plants, second ed. Academic Press, London.
- Meier, S., Robarge, W.P., Bruck, R.L., Grand, L.F., 1989. Effects of simulated rain acidity on ectomycorrhizae of red spruce seedlings potted in natural soil. *Environmental Pollution* 59, 315–324.
- Mille-Lindblom, C., von Wachenfeldt, E., Tranvik, L.J., 2004. Ergosterol as a measure of living fungal biomass: persistence in environmental samples after fungal death. *Journal of Microbiological Methods* 59, 253–262.
- Nilsson, L.O., Wallander, H., 2003. Production of external mycelium by ectomycorrhizal fungi in a Norway spruce forest was reduced in response to nitrogen fertilization. *New Phytologist* 158, 409–416.
- Nilsson, L.O., Bååth, E., Falkengren-Grerup, U., Wallander, H., 2007. Growth of ectomycorrhizal mycelia and composition of soil microbial communities in oak forest soils along a nitrogen deposition gradient. *Oecologia* 153, 375–384.
- Nohrstedt, H.O., 2001. Response of coniferous forest ecosystems on mineral soils to nutrient additions: a review of Swedish experiences. *Scandinavian Journal of Forest Research* 16, 555–573.
- Nowotny, I., Dähne, J., Klingelhöfer, D., Rothe, G.M., 1998. Effect of artificial soil acidification and liming on growth and nutrient status of mycorrhizal roots of Norway spruce (*Picea abies* [L.] Karst.). *Plant and Soil* 199, 29–40.
- Nylund, J.E., Wallander, H., 1992. Ergosterol analysis as a means of quantifying mycorrhizal biomass. *Methods in Microbiology* 24, 77–88.
- Pihl-Karlsson, G., Akseleson, C., Hellsten, S., Karlsson, P.E., 2011. Reduced European emissions of S and N – effects on air concentrations deposition and soil water chemistry in Swedish forests. *Environmental Pollution* 159, 3571–3582.
- Potila, H., Wallander, H., Sarjala, T., 2009. Growth of ectomycorrhizal fungi in drained peatland forests with variable P and K availability. *Plant and Soil* 316, 139–150.
- Rineau, F., Maurice, J.-P., Nys, C., Voiry, H., Garbaye, J., 2010. Forest liming durably impact the communities of ectomycorrhizas and fungal epigeous fruiting bodies. *Annals of Forest Science* 67, 110.
- Runion, G.B., Mitchell, R.J., Rogers, H.H., Prior, S.A., Counts, T.K., 1997. Effects of nitrogen and water limitation and elevated atmospheric CO₂ on ectomycorrhiza of longleaf pine. *New Phytologist* 137, 681–689.
- Simard, S.W., Jones, M.D., Durall, D.M., 2002. Carbon and nutrient fluxes within and between mycorrhizal plants. In: van der Heijden, M.G.A., Sanders, I.R. (Eds.), *Ecological Studies. Mycorrhizal Ecology*, pp. 33–74.
- Sims, S., Hendricks, J., Mitchell, R., Kuehn, K., Pecot, S., 2007. Nitrogen decreases and precipitation increases ectomycorrhizal extramatrical mycelia production in a longleaf pine forest. *Mycorrhiza* 17, 299–309.
- Smith, S.E., Read, D.J., 2008. *Mycorrhizal Symbiosis*, third ed. Academic Press, London.
- Thelin, G., Rosengren, U., Nihlgård, B., 2002. In: Länsstyrelsen (Ed.), *Barrkemi på Skånska gran- och tallprovdytor – förändringar mellan 1985 och 2000. Länsstyrelsen i Skåne län, Kristianstad*.
- Vitousek, P.M., Howarth, R.W., 1991. Nitrogen limitation on land and in the sea – how can it occur. *Biogeochemistry* 13, 87–115.
- Wallander, H., 1995. A new hypothesis to explain allocation of dry matter between mycorrhizal fungi and pine seedlings in relation to nutrient supply. *Plant and Soil* 168–169, 243–248.
- Wallander, H., Nylund, J.-E., 1992. Effects of excess nitrogen and phosphorus starvation on the extramatrical mycelium of ectomycorrhizas of *Pinus sylvestris* L. *New Phytologist* 120, 495–503.
- Wallander, H., Thelin, G., 2008. The stimulating effect of apatite on ectomycorrhizal growth diminishes after PK fertilization. *Soil Biology and Biochemistry* 40, 2517–2522.
- Wallander, H., Arnebrant, K., Östrand, F., Kärén, O., 1997. Uptake of ¹⁵N-labelled alanine, ammonium and nitrate in *Pinus sylvestris* L. ectomycorrhiza growing in forest soil treated with nitrogen, sulphur or lime. *Plant and Soil* 195, 329–338.
- Wallander, H., Nilsson, L.O., Hagerberg, D., Baath, E., 2001. Estimation of the biomass and seasonal growth of external mycelium of ectomycorrhizal fungi in the field. *New Phytologist* 151, 753–760.
- Wallander, H., Ekblad, A., Bergh, J., 2011. Growth and carbon sequestration by ectomycorrhizal fungi in intensively fertilized Norway spruce forests. *Forest Ecology and Management* 262, 999–1007.
- Wallenda, T., Kottke, I., 1998. Nitrogen deposition and ectomycorrhizas. *New Phytologist* 139, 169–187.
- Weigt, R., Raidl, S., Verma, R., Agerer, R., 2012. Exploration type-specific standard values of extramatrical mycelium – a step towards quantifying ectomycorrhizal space occupation and biomass in natural soil. *Mycological Progress* 11, 287–297.
- Westling, O., Örlander, G., Andersson, I., 2004. Effekter på askåterföring till granplanteringar med riståkt. IVL Report B1552. IVL, Göteborg, Sweden.
- Wold, S., Sjöström, M., Eriksson, L., 2001. PLS-regression: a basic tool of chemometrics. *Chemometrics and Intelligent Laboratory Systems* 58, 109–130.
- Yuan, J.P., Kuang, H.C., Wang, J.H., Liu, X., 2008. Evaluation of ergosterol and its esters in the pileus, gill, and stipe tissues of agaric fungi and their relative changes in the comminuted fungal tissues. *Applied Microbiology and Biotechnology* 80, 459–465.

III



Shift in composition and functioning of the fungal community along a natural boreal forest nutrient gradient

Erica Sterkenburg^a, Adam Bahr^b, Mikael Brandström-Durling^a, Karina E. Clemmensen^a and Björn D. Lindahl^a

^a Swedish University of Agricultural Sciences, Dept. of Forest Mycology and Plant Pathology, Uppsala BioCenter, Box 7026, SE-750 07 Uppsala, Sweden.

^b Lund University, Microbial Ecology, Dept. of Biology, SE-223 62 Lund, Sweden

Abstract

In the boreal forest ecosystem, fungi are the principal decomposers of organic matter and pivotal symbionts of trees. Yet, compared to plants and animals, large knowledge gaps remain concerning fungal niche differentiation. Here we investigate if fungal communities reflect patterns of ecosystem productivity, aiming for a better understanding of the functional ecology of fungi and their interplay with the plant community and environmental factors.

We used high throughput 454-sequencing of ITS2 amplicons to analyse the fungal community in humus and needle litter in 26 pristine boreal forests in central Sweden. Ergosterol was used as a fungal biomass-marker. The forests were selected to represent a gradient in nitrogen availability and pH as well as different vegetation types with respect to dominant tree species (*Pinus sylvestris*, *Picea abies*) and understory vegetation.

We found a significant relationship between the fungal community composition and soil acidity as well as C:N-ratio. Moving from the low-productive to the high-productive end of the gradient, there was a shift from a community dominated by ascomycetes to a community with increased contribution of basidiomycetes, both in humus and litter. The levels of ergosterol decreased at low pH, indicating environmental stress, but superimposed on this general pattern, the presence of *Pinus sylvestris* had a positive influence on fungal biomass in the humus layer. Against our expectations, the relative abundance of ectomycorrhizal fungi in the humus layer did not decline in the most fertile forests, but remained at 50-70% of the amplicons.

With this study, we show that it is possible to make statistical predictions about the composition and biomass of fungal communities within the range of forest types that we covered. This implies that it is possible to establish general relationships that are of potential use in theoretical and quantitative ecosystem modelling.

Introduction

Fungi are the principal decomposers of organic matter in forest ecosystems and pivotal symbionts of trees (Smith and Read, 2008). Yet, compared to plants and animals, large knowledge gaps remain concerning fungal diversity and ecology. Like plants, fungi are immobile and, thus, bound to their habitats, potentially forming habitat-specific communities. Variation of plant communities along habitat gradients, in e.g. productivity, mineralogy and hydrology (e.g. Lahti and Väisänen, 1987), is well described. In contrast, niche differentiation of fungal species and prevalence of functional groups along such gradients are yet not well described and understood. Until recently, microbial soil ecology has been driven by methods with no or low phylogenetic

resolution, such as microscopic observation, total biomass/activity measurements or phospholipid analysis. Since closely related taxa may have very different ecology (Hibbett et al., 2000), it is necessary to analyse the fungal community at levels of orders, genera or even species, to separate and quantify functional groups. Only recently, methodological advances in molecular biology, for example high-throughput sequencing of molecular markers (Lindahl et al., 2013), enable detailed and at least semi-quantitative analysis of fungal communities, and subsequent testing for correlation with stand properties and potential environmental drivers.

Boreal forests are, in general, nitrogen (N) limited (Vitousek and Howarth, 1991), and dominated by coniferous trees producing recalcitrant litter with a high content of lignin and phenolic compounds (Aerts, 1995). In these forests both mycorrhizal and saprotrophic fungi play a fundamental role in the cycling of nutrients and carbon (Lindahl et al., 2007). Saprotrophic fungi are the main decomposers of litter, woody debris and soil organic matter (Rayner and Boddy, 1998; Baldrian, 2009; Fontaine et al., 2011), recycling carbon (C) to the atmosphere. Furthermore, symbiotic mycorrhizal fungi provide their host plants with soil-derived N and other nutrients in return for recently photosynthesised C (Smith and Read, 2008; Högberg et al., 2010), which they route into the soil, making a major contribution to long term C sequestration (Clemmensen et al., 2013). In the boreal forest, nutrient availability, hydrology and soil acidity are the principal, and usually co-varying environmental determinants of plant communities. Since mycorrhizal fungi depend on allocation of recently photoassimilated C and saprotrophic fungi are dependent on plant litter production, it seems likely that fungal communities vary along similar gradients.

In the most low-productive habitats, low N-availability may directly constrain fungal growth of both saprotrophs (Boberg et al., 2008) and mycorrhizal fungi (Clemmensen et al., 2008). In addition, low-productive plant communities provide less C to fungi, in terms of litter to saprotrophs and, in absolute terms, also with respect to root sugars to mycorrhizal fungi. Furthermore, plants produce more recalcitrant litter (Aerts, 1995). Acidic soils, typical for boreal forests (Brady and Weil, 2008), may also constitute a stressful environment for fungi. Even though, in a broader perspective, fungal abundance usually increase with low pH while bacterial abundance decrease (Rousk and Bååth, 2011), reduced fungal growth was observed at pH less than 4.5 (Rousk et al., 2011). Furthermore, in a large-scale boreal forest field survey (Bahr et al., 2013) it was found that the production of mycorrhizal fungi increased with increasing pH (although acidifying N-deposition is a confounding factor here). Among bacteria, resource availability is the principal determinant of community composition, with oligotrophic (as opposed to copiotrophic) groups being characterized by low resource utilization rates (Fierer et al., 2007). Similarly, in fungi, scarce resource availability and stressful conditions are likely to favour species with slow mycelial growth (Cooke and Rayner, 1984). In plant leaves, low productivity is generally associated with robust and long-lived tissues (Wright et al., 2004), traits being favoured under stressful conditions (Grime, 1977). Correspondingly, in fungi, long-lived mycelial structures may enable more economic resource utilization. To retain mycelium for a long time, it needs to be protected against fungivores and harsh abiotic conditions, e.g. by impregnation of cell walls with melanin and hydrophobic compounds (rev. by Ekblad et al., 2013). Fungi associated with stressful environments are often ascomycetes adapted to e.g. drought and acidity (Gostinčar et al., 2010).

Alleviation of severe environmental stress leads to elevated plant productivity, with more C potentially becoming available to fungi via increased plant litter production and root-mediated fluxes, concomitant with increased N availability and decomposability of organic matter (Peltzer et al., 2010). Improved conditions probably enable higher mycelial production and open up for colonisation by fungal species without prominent stress tolerant traits, and thus results in enhanced competition. Assuming a trade-off between stress tolerance and combative strength, the incidence of species with high capacity of interference and competitive antagonism should increase with decreasing environmental stress (Cooke and Rayner, 1984), and basidiomycetes are thought to be particularly successful in this respect (Boddy, 1999, 2000). Many basidiomycetes have highly differentiated mycelia, with rapidly advancing mycelial fronts, which degrades and regress into a sparse network of aggregated cords, as the mycelium senesce. This strategy has been proposed to provide an advantage with respect to colonisation of heterogeneously distributed resources, as well as combative interactions (Boddy, 1999, 2000). By redistribution of acquired nutrients, cord-forming basidiomycetes may optimize the efficiency by which they exploit colonised resources. Many basidiomycetes are also known for their ability to produce a potent repertoire of degrading enzymes (Rayner et al., 1987; Floudas et al., 2012). Combining high combative strength with efficient substrate degradation, translocation capacity and, for some groups, efficient ectomycorrhizal symbiosis, cord-forming basidiomycetes maximize the efficiency by which they exploit available resources in stable environments (Cooke and Rayner, 1984). They display many traits that are associated with K-selection, resulting in a competitive advantage at high mycelial densities with strong competition for space.

As abiotic stress is replaced by biotic stress (antagonism) along the gradient of increasing productivity, competition does not only intensify between fungal species, but also between entire functional groups. Interactions between mycorrhizal fungi and saprotrophic fungi in soil microcosm (Lindahl et al., 2001), as well as field experiments (Gadgil and Gadgil, 1971), have indicated antagonism and competition for nutrients between the two functional groups. The relative competitive strength of the two different groups has been hypothesised to change along a gradient in plant productivity, due to changed allocation of photosynthesis products (Högberg et al., 2003). At low nutrient availability, mycorrhizal fungi may exchange plant C for soil nutrients, and any surplus of photosynthetic sugars should preferably be allocated to them. Mycorrhizal fungi have, thus, been proposed to out-compete saprotrophs from the humus layers in low productive boreal forests, restricting their niche to the uppermost litter layer (Lindahl et al., 2007; Clemmensen et al., 2013). Sufficient availability of nutrients shifts tree production above ground (Janssens et al., 2010), resulting in less relative allocation of carbon to roots (Högberg et al., 2010). For example, anthropogenic N addition usually results in repressed mycorrhizal production (Nilsson et al., 2007; Kjoller et al., 2012; Bahr et al., 2013). This altered resource partitioning may, supposedly, shift the dominance from mycorrhizal fungi to saprotrophic fungi as fertility increases and relax the strict vertical partitioning of these functional groups that occurs in low-productivity forests.

At high fertility, trees and undergrowth species composition shifts to a higher inclusion of deciduous species that shed litter seasonally, resulting in flushes of easily available resources into the soil. With higher nutrient availability and better quality of litter, mineralization results in a

mobile, inorganic N-pool, whereby competition for nutrients decreases, reducing the benefit of differentiated mycelia with cords. Further, fertile soils usually constitutes a better environment for many soil animals, which may disturb the soil by mixing and grazing, preventing establishment of large and long-lived mycelial networks (Crowther et al., 2012). Thus, in such disturbed and fluctuating environments, r-selected fungi such as yeasts and moulds should be favoured, since they grow rapidly, are short-lived and reproduce fast, predominantly by asexual conidia or budding.

By using DNA extractions from soil and organic matter, the entire fungal community in the sample can be characterized at species level by using sequencing of the ITS region of the ribosomal RNA genes. Identification of species subsequently enables assembling of taxa into functional guilds. We can, thus, now begin to elucidate niche differentiation and specific ecosystem functions of fungal community components, in order to formulate hypotheses about the prevalence of different functional guilds in contrasting environments (Moorhead and Sinsabaugh, 2006; Koide et al., 2011). Such information is pivotal, since different functional guilds transform organic matter in strikingly different, often opposite ways, and play contrasting roles in C- and N-cycling (Lindahl et al., 2007; Clemmensen et al., 2013).

We analysed fungal communities in litter and humus layers from 26 pristine boreal forests in central Sweden by 454-pyrosequencing of PCR amplified molecular markers (Ihrmark et al., 2012; Lindahl et al., 2013). The fungal specific membrane lipid ergosterol was used as a marker of fungal biomass (Nylund and Wallander, 1992). Both free and total ergosterol was analysed; the free form has been shown to decline during senescence of fungal tissues (Yuan et al., 2008) and may be used to indicate the contribution of freshly formed mycelium (rev. by Wallander et al., 2013). Fungal biomass and community composition was related to the plant community and soil parameters. The forests were selected to represent a gradient of increasing fertility, as indicated by increasing soil NH_4 concentration and pH and decreasing C:N-ratio of litter and soil organic matter.

We hypothesize that:

1. In the most low-productive habitats, fungal biomass is low and stress tolerant ascomycetes dominate
2. In habitats with intermediate productivity, fungal biomass is high and cord-forming basidiomycetes dominate
3. In the most high-productive habitats, fungal biomass is low, and opportunistic moulds and yeasts dominate
4. Mycorrhizal fungi are progressively replaced by saprotrophs with increasing productivity and that the strict vertical separation of these functional groups between litter and humus is relaxed at high nutrient availability

Materials and Methods

Site description and sampling procedure

Twenty-six forests, located in central Sweden were selected to represent a gradient in fertility with contrasting levels of pH and N availability of soils, in addition to the relative composition of Norway spruce (*Picea abies* (L.) H.Karst.) and Scots pine (*Pinus sylvestris* L.) as well as understory plants (supplementary material). To reduce variation due to anthropogenic disturbance, areas outside the range of elevated N deposition were chosen based on national inventories of forests with high conservation values. The forest stands are all old (>100 years) and have never been subjected to intense forestry. Dominant type species of trees and ground vegetation were noted.

In September of 2008, ten soil cores ($\varnothing = 2$ cm) were randomly collected at an approximate minimum distance of 10 m between samples from each forest. The humus part from each soil core was pooled within sites, resulting in one humus sample per forest. In addition, 10 needles were picked from the ground at each spot where a soil core was collected, and then pooled within sites. When both dominant tree species were co-occurring, needles from each species were collected and kept as separate samples. The samples were stored in a cold container and frozen within 6h after collection at -20°C .

Soil chemical analyses

The samples were thawed and homogenized before further analyses. A part of each homogenized sample was freeze dried and analysed for C:N ratio using an elemental analyser. Humus samples were analysed for the following parameters: Extractable NH_4 was determined by shaking 5 g of soil in 25 ml 0.5 M K_2SO_4 for one hour. The extracts were filtered (Munktell OOH S1-80-40) and measured with a Flow Injection Analyser (FIAstar TM, Foss Tecator, Höganäs, Sweden). Water content was determined by oven drying subsamples at 60°C for 12h. Organic matter content was analysed by burning subsamples at 550°C for 6h. Soil pH was measured in deionized water in a 1:3, soil:water ratio (744 pH meter, Metrohm, Herisau, Switzerland).

Ergosterol analysis

Free and total ergosterol content was analyzed according to Clemmensen *et al.* (2013) with minor adjustments (free ergosterol was analysed in humus samples only). Total ergosterol in 75 mg humus or 150 mg mineral soil was extracted with 5 ml 10 % KOH in methanol, while free ergosterol in 200 mg humus or 400 mg mineral soil was extracted with 5 ml methanol. After 15 min sonication and 60 min 70°C water bath, 1 ml H_2O was added to increase the polarity of the methanol phase. After adding 2 ml cyclohexane the tubes were shaken 1 min on a multivortex (Multi Reax, Heidolph, Germany) followed by 5 min centrifugation at 1 000 g, and the non-polar phase was then transferred into new tubes. The phase separation was repeated once more after addition of another 2 ml cyclohexane to the original tubes. The cyclohexane was evaporated on a 40°C heating block under N_2 gas flow. The ergosterol was then extracted in 200 μl methanol in a 40°C water bath. The samples were transferred into 2 ml microcentrifuge tubes and centrifuged at 13 000 g before the supernatants were filtrated (0.45 μm titan syringe filter, 44504-NPC by Sun sri, USA) into high-performance liquid chromatograph (HPLC) vials with inserts. The samples were analyzed in a reversed-phase column (C18 column: Chromolith model by Merck, C18 pre-column: Elite LaChrome model by Hitachi, Japan) HPLC (auto sampler L2130 with UV-detector L2400 by Hitachi, Japan) with a flow rate of 1 ml min^{-1} , and the ergosterol peak was detected at 280 nm.

DNA analysis

Prior to DNA analysis, the freeze-dried soil was cleared from roots larger than 2 mm in diameter and carefully homogenised in a mortar. Freeze-dried needles were homogenised in a ball mill (Retsch GmbH, Haan, Germany). Approximately 50 mg of humus or needles or 400 mg of mineral soil were used for DNA extraction with 1 ml extraction buffer (3 % cetyl trimethylammonium bromide (CTAB), 2mM EDTA, 150 mM tris-HCl and 2.6 M NaCl, pH8) at 65 °C for 1 h. After extraction with chloroform, DNA was precipitated with 1.5 volumes of isopropanol. Following centrifugation, the pellet was cleaned with ethanol and re-suspended in 50 µl water. The DNA extracts were further purified with the Wizard purification systems kit (Promega, Madison, USA). DNA samples were subjected to PCR, using the two primer combinations ITS4-gITS7 and ITS4-fITS9 (Ihrmark et al., 2012). In both combinations, the ITS4 primer was elongated by a unique sample tag of eight bases, designed using the BARCRAWL software (Frank, 2009). An annealing temperature of 56 °C and 55 °C was used respectively. By using qPCR, the number of cycles in the PCR was optimized for each sample and ranged between 25 and 35 cycles. Three PCR reactions from each sample and primer pair were pooled and purified with the AMPure kit (Beckman Coulter Inc., Brea, CA, USA). The concentration of the purified PCR products was established with a Qubit fluorometer (Life Technologies, Carlsbad, CA, USA) and equal amounts of DNA from each sample were pooled to provide one sample per primer combination for the entire study. Adaptor ligation and sequencing were performed by LGC Genomics, Berlin, Germany, on a 454-Genomic Sequencer (Roche, Basel, Switzerland), using titanium chemistry.

Sequence analysis

Sequences were analysed using the SCATA pipeline (scata.mykopat.slu.se). Sequences were filtered for quality, removing sequences with an average quality score below 20 or with score below 10 at any position, using the high quality region (HQR) extraction option. Sequences were then screened for primers and sample identifying tag and complementary reversed when necessary. For sequences obtained with the ITS4-fITS9 primer combination, 44 bp of the 5.8 region were removed, resulting in equal lengths of sequences from both primer combinations. The sequences were then compared for similarity, using BLAST as the search engine, requiring a minimum match length of 85 %. Pairwise alignments were scored using a scoring function with 1 in penalty for mismatch, 0 for gap open and 1 for gap extension. Homopolymers were collapsed to 2 bp before clustering. Sequences were clustered into operational taxonomic units (OTU) by single linkage clustering, with the maximum distance allowed for sequences to enter clusters set to 1.5 %.

The two datasets resulting from different primer combinations were merged. If a cluster differed more than three fold in relative abundance between the datasets, the highest relative abundance was used. Otherwise, the average relative abundance was recorded. Relative abundances were then adjusted to sum up to one.

Taxonomic and functional identification

From each sample, OTU:s were taxonomically identified in decreasing order of abundance until at least 80 % of all sequences were identified in each sample. The most abundant sequence in each operational taxonomic unit (OTU) was used as a representative. For each OTU, the most

closely related reference sequences were retrieved from the UNITE database or GenBank (NCBI) by BLASTn massblaster in PlutoF (Abarenkov et al., 2010). OTU representatives were aligned together with reference sequences in MegAlign (DNASStar) and taxonomic identities were assigned based on neighbour joining trees. Plant sequences were removed from the dataset and relative abundances were adjusted accordingly.

When an OTU, according to the neighbour joining tree was closely related to a reference sequence from an identified species with a known ecological function, it was assigned to that species and that specific function. However, when an OTU was closely related to a reference sequence from unidentified material (*i.e.* from community sequencing) with unknown function, it was assigned to a putative function depending on the substrate from which closely related reference sequences were derived.

When possible, the identified fungal taxa were ordered into groups according to their ecological function. Six groups were defined:

- *ECM*; fungi known to be ectomycorrhizal, both basidiomycetes and ascomycetes. This group was further divided into two subgroups.
 - *ECM with differentiated mycelium*; ectomycorrhizal fungi with medium distance fringe exploration type and long distance exploration type (Agerer, 2001)
 - *ECM with undifferentiated mycelium*; ectomycorrhizal fungi with contact, short-distance, medium distance (mat and smooth subtype) exploration types (Agerer, 2001).
- *Root associated ascomycetes*; ascomycetes associated with living plant roots, but not known ECM (e.g. ericoid mycorrhiza). The following two groups were used.
 - *Known root associated ascomycetes*; OTUs within the Ascomycota known to be associated with roots.
 - *Known and putative root associated ascomycetes*; OTUs within the Ascomycota known to be associated with roots and OTUs within the Ascomycota with close match to reference sequences from living root material.
- *Yeasts and molds*; Species in the orders Eurotiales, Hypocreales, Mortieriales, Mucorales, Saccharomycetales, Tremellales and Sporidiales.
- *Litter associated ascomycetes*; ascomycetes related to litter, saprotrophic fungi as well as endophytic. The following two groups were used.
 - *Known litter associated ascomycetes*; OTUs known to be associated with litter.
 - *Known and putative litter associated ascomycetes*; OTUs known to be associated with litter and OTUs with close match to reference sequences from intact, living or dead leaves or needles.

- *Litter associated basidiomycetes*; basidiomycetes related to litter, mainly saprotrophic. The following two groups were used.
 - *Known litter associated basidiomycetes*; OTUs known to be associated with litter.
 - *Known and putative litter associated basidiomycetes*; OTUs known to be associated with litter and OTUs with close match to reference sequences from intact, living or dead leaves or needles.
- *Unknown function*; fungi with unknown ecological role or fungi unclassified down to a sufficient taxonomical level.

Statistics

Ordination analyses were performed in Canoco for Windows v. 4.55 (Microcomputer Power, Ithaca, NY, USA). A detrended correspondence analysis (DCA) was carried out in order to obtain a graphical representation of fungal community similarity in the different forests and substrates. Correlation between environmental parameters and fungal community composition was established by canonical correspondence analysis (CCA), both on species level and on the level of genera and orders. Genera were used when possible, but in orders with many less clearly defined genera (e.g. *Helotiales*) the order was used instead. The CCA:s were followed by Monte Carlo permutation test with forward selection of explaining variables, in order to establish the level of significance for the tested variables.

To test how the different functional groups of fungi were related to the environmental parameters, a multiple regression analyses were performed using General Regression Model, Multiple regression, Forward stepwise selection, in the Statistica software (Statsoft inc., Tulsa, OK, USA). Multiple regression was also used to test how the levels of ergosterol in the samples were related to environmental parameters as well as the functional groups of fungi.

Results

Correlation between environmental parameters

In the litter, litter C:N-ratio, pine litter, lingonberry and heather were significantly and positively correlated, while all of these were negatively correlated with humus NH_4 , spruce litter, blueberry and herbs.

In the humus, pH, NH_4 and mineral content were significantly and positively correlated, while all of these were negatively correlated with C:N, together forming a set of fertility indicators. Scots pine was negatively correlated with these fertility indicators whereas Norway spruce was predominantly found in forests with low C:N-ratio. Lingonberry and heather were predominantly found in forests with low NH_4 -levels, while herbs were more common in forests with high NH_4 -levels.

Ergosterol

In the litter, there was a significant negative correlation ($p=0.0001$) between total ergosterol and litter C:N-ratio (Table 1; Fig. 1a). With C:N ratio in the model, the plant species origin of the litter did not significantly contribute additional explanatory power, and the interaction term between C/N-ratio and litter species was not significant. Total ergosterol levels in the humus were

significantly correlated with, pH, presence of Scots pine, mineral content, and relative abundance of yeasts and moulds, in order of decreasing additional explanatory power (Table 1). Ergosterol levels were higher in the presence of Scots pine, and within tree species the levels increased with higher pH. In combination with the fact that Scots pine forests commonly grow on more acidic soils, these additive effects result in a complex overall relationship between soil acidity and fungal biomass across the entire range of pH variation (Fig. 1b). Higher abundance of yeasts and moulds correlated with lower amounts of total ergosterol. There were no significant between-effects between tree species or any of the other significant parameters. The levels of free ergosterol in the humus were significantly and positively correlated with C:N-ratio and the presence of herbs (Table 1).

Community composition

In the litter, the DCA showed that a large portion of the variation in fungal species composition could be explained by host tree species (Fig. 2). In a CCA analysis with fungal species, the first axis explained a significant part of the variation in fungal community composition ($F=4.1$ and $p=0.0001$), and was positively correlated with C:N, pine litter, heather and lingonberry but negatively correlated with spruce litter and blueberry. Humus NH_4 and herbs correlated with the second CCA axis. Forward selection picked out litter type ($p=0.0001$), humus NH_4 ($p=0.0008$), presence of blueberry ($p=0.034$) and litter C:N ($p=0.034$) in order of decreasing additional explanatory power, as the best explanatory variables. The additional explanatory power contributed by other variables was not significant. The CCA axes (representing variation explained by environmental variables) together accounted for 39 % of inertia in the data. In a CCA analysis with species merged into genera or orders, the first CCA axis was positively correlated with C:N-ratio and pine litter but negatively correlated with spruce litter, and explained a significant part of the variation in fungal community composition ($F=7.2$ and $P=0.0001$) (Fig. 4). Forward selection picked out C:N-ratio ($p=0.0001$), presence of herbs ($p=0.004$) and litter type ($p=0.03$) in order of decreasing additional explanatory power, were the best explanatory variables for the fungal community composition in the litter. The additional explanatory power contributed by other variables was not significant. The CCA axes together accounted for 44 % of inertia in the data.

Multiple regression of the relative abundances of functional groups in relation to environmental parameters showed that the relative abundance of litter-associated ascomycetes was positively and significantly correlated with C:N-ratio, but negatively with the presence of herbs. When only taxonomically identified species were included in the analysis, the relative abundance of litter ascomycetes correlated positively with pine litter. Litter-associated basidiomycetes decreased with higher C:N-ratio. Ectomycorrhizal fungi in the litter decreased in the presence of *Calluna*, while root-associated ascomycetes were not affected by any of the environmental parameters. Root associated fungi together never exceeded 12 % of the amplicons in the litter. The relative abundance of yeasts and moulds was positively correlated with pine litter, but never exceeded 7 % of the amplicons (Fig. 6).

As shown by the DCA, the fungal species composition in the humus could, to a large extent, be predicted by the environmental parameters (Fig. 3). In a CCA analysis with fungal species, the first axis was positively correlated with pH, NH_4 , mineral content, Norway spruce, blueberry and

herbs but negatively correlated with C:N, Scots pine, heather and lingonberry, and explained a significant part of the variation in fungal community composition ($F=1.3$ and $p=0.025$). Forward selection indicated that pH ($p=0.0001$), mineral content ($p=0.003$) and *Calluna* ($p=0.003$) in order of decreasing additional explanatory power, were the best explanatory variables. The additional explanatory power contributed by other variables was not significant. The CCA axis accounted for 48 % of inertia in the data. In a CCA analysis with species merged into genera or orders, the first CCA axis was positively correlated with pH, NH_4 , herbs, mineral content and Norway spruce but negatively correlated with C:N-ratio, Scots pine and heather and explained a significant part of the variation in fungal community composition ($F=3.056$ and $p=0.007$) (Fig. 5). Forward selection indicated that pH ($p=0.0001$), C:N-ratio ($p=0.02$) and presence of *Calluna* ($p=0.04$) in order of decreasing additional explanatory power, were the best explanatory variables. The additional explanatory power contributed by other variables was not significant. The CCA axis accounted for 53 % of inertia in the data.

Multiple regression analysis showed that, in the humus, the relative abundance of root associated ascomycetes was positively and significantly correlated with C:N-ratio and with the presence of *Calluna*. In contrast, the total relative abundance of ectomycorrhizal fungi as well as ectomycorrhizal fungi with undifferentiated mycelium was significantly lower in forests where *Calluna* was present. When all forests were included in the analysis, yeasts and moulds did not correlate significantly with any environmental parameters. However, when the analysis was separated into mono-specific Norway spruce and Scots pine forests, yeasts and moulds correlated negatively with C:N-ratio in the spruce forests. The relative abundance of litter-associated fungi in the humus was higher in forests with higher N-availability, but never exceeded 5 % of the amplicons (Fig. 6).

Discussion

The fungal community composition varied strongly along the studied gradient. In each set of pooled subsamples from each site, there were a few highly frequent species that dominated the fungal community, and forests with similar characteristics shared dominant fungal species. Just as plant communities vary in predictive ways along gradients (Lahti and Väisänen, 1987), variation in the dominant components of the fungal communities could, to a large extent, be explained by pH, C:N and NH_4 content in the humus. In the litter, the fungal community depended strongly on the host tree species (Fig. 1 and 2), whereas in the more degraded humus layer the fungal community rather correlated with the understory plant community and less so with tree species (Fig. 3). Ergosterol concentrations also varied with environmental parameters in a predictable way. Thus, we here show that it is possible, with some statistical certainty, to predict the composition and biomass of fungal communities from environmental variables, within the range of forest types that we covered. Predictions are valid at the level of species, but also on higher taxonomic levels, as well as broad functional groups. This implies that it is possible to generate general relationships, which are useful in theoretical and quantitative ecosystem modelling.

There was a clear shift from a community dominated by ascomycetes in the low-productive end of the gradient to a community with increased contribution of basidiomycetes in the rich end. This observation was consistent both in the litter samples and the humus samples, although ascomycetes generally were more abundant in the litter than in the humus (Fig. 6). The dominant ascomycetes in the poor forests could largely be assigned to species in the

Leotiomycetes and Chaetothyriales. This is consistent with our hypothesis (hypothesis 1) that there would be an increase in more stress tolerant ascomycetes in poor environments, since fungi in Leotiomycetes and Chaetothyriales commonly display traits associated with stress tolerance, such as melanised cell walls (Gostinčar et al., 2010).

After manipulating soil acidity in a field experiment in arable soils, Rousk *et al.* (2010) also observed increasing dominance of Leotiomycete 18S markers at a pH below 4.5 (in a range from pH 8.3 to pH 4.1). Furthermore, within both Scots pine and Norway spruce forests, there was a negative correlation between ergosterol and acidity in humus, and for litter there was a negative correlation between ergosterol and C:N ratio (Fig. 1). This lends further support to the negative influence of environmental stress on the ascomycetes found in acidic forests with low N-availability. We hypothesise that stress tolerance with respect to acidity and low nutrient availability has been a major driver during early evolution of these sections of Ascomycota, underlying their generally high abundance in low-productive, acidic ecosystems globally. Within these sections, functional differentiation into saprotrophic litter fungi, endophytes and root-associated symbionts seem to have evolved much later in smaller clades roughly corresponding to the genus level.

The identified OTUs with the highest abundance, among the root associated ascomycetes, in the humus were *Rhizoscyphus ericae*, *Meliniomyces variabilis* and *Oidiodendron pilocola*. These Leotiomycetes are all mycorrhizal on ericaceous plants, and it could be argued that their distribution is regulated by the presence of their plant hosts. However, from a more ‘mycocentric’ perspective, the success of these plants under stressful conditions could just as well depend on their capacity to form symbiosis with fungi that facilitate survival in a stressful environment. A more balanced view would be that the two partners have co-evolved into a symbiosis that is highly successive in harsh environments (Read and Perez-Moreno, 2003).

In high C:N ratio litter, *Lophodermium pinastri* and *Lophodermium picea* dominated. These fungi are endophytes/pathogens and their persistence in litter after abscission seems to be favoured by high C:N ratios.

At intermediate N-availability and pH, the need for traits associated with stress-tolerance should be smaller, and fungi with competitive traits would increase. Moving towards more high-productive forests, we found an increase in the abundance of basidiomycetes relative to ascomycetes, both in litter and humus (in agreement with hypothesis 2). The higher combative strength of the basidiomycetes seems to have evolved on the expense of acidity/nutrient tolerance. Among the root-associated fungi in the humus, the apparent competitive balance between stress-tolerant ascomycetes and combative basidiomycetes also implied a shifting proportion of ericoid mycorrhizal fungi (mainly ascomycetes) and ectomycorrhizal symbionts (mainly basidiomycetes; Fig. 5), which most likely paralleled the relative abundance of their host plants (Read and Perez-Moreno, 2003).

In parallel with the increase in relative abundance of basidiomycetous fungi, the level of total ergosterol in low C:N needle litter was three times higher than in high C:N litter (Fig. 1). Boberg et al (2008) showed that NH_4 addition resulted in increased mycelial production of saprotrophic basidiomycetous fungi (in the genus *Mycena*), elevated respiration rates and increased needle mass loss in single species laboratory systems. In our study a similar increased fungal biomass in

response to higher N-content of the litter was observed in a range of forests and within complex fungal communities.

We further hypothesised that with increasing N-availability the mycorrhizal community would be replaced by saprotrophs, primarily opportunistic yeasts and moulds (hypothesis 3 & 4). The established view is that when nutrient availability increases, plant C allocation to roots would decline with negative effect on the presumably C-limited mycorrhizal community, leaving saprotrophic fungi with a competitive advantage (Högberg et al., 2003; Högberg et al., 2010). Additionally, a higher disturbance of mixing soil fauna (Butenschoen et al., 2007) in combination with temporal fluctuations in substrate availability should favour opportunistic saprotrophs. Previous studies have shown a decline in fungal biomass (relative to prokaryotes) with increasing nitrogen availability by quantifying PLFA's (Pennanen et al., 1999; Nilsson and Wallander, 2003).

In contrast to our hypothesis, the relative abundance of ectomycorrhizal fungi did not decline even under the most nutrient rich conditions, but remained high at 50-70 % of the amplicons (Fig. 6). Neither did the total fungal biomass decrease (Hypothesis 3), as shown by the high ergosterol levels in the more fertile forests with higher pH (Fig. 1). Positive responses of ectomycorrhizal fungi to N-additions, both in terms of mycelial growth and abundance, have been observed previously in low-productive arctic heathland (Clemmensen et al., 2008). We postulate that negative effects of high N-availability on mycorrhizal fungi are primarily found at the higher inorganic N-levels associated with fertilizer addition or atmospheric deposition, but that this relationship is not valid within the range of variation commonly found in undisturbed boreal forests not exposed to artificial or anthropogenic N-deposition. In fact, a single Scots pine forest, with much higher pH and inorganic N levels than commonly found in Scandinavian boreal forests, had the lowest ergosterol content of the entire study (and was therefore excluded from data analysis). This single observation may be due to a decrease in fungal biomass further along the fertility gradient, but such conditions are found only rarely in boreal forest not exposed to deposition or fertilization of N.

Dividing ectomycorrhizal fungi into subgroups based on the level of mycelial differentiation, we found that species with undifferentiated mycelium (e.g. *Tylospora*) were relatively more common towards the richer end of the gradient, whereas cord-forming species with differentiated mycelium (e.g. *Suillus* and *Cortinarius*) were more common in the low-productive forests, at least in relation to other ectomycorrhizal taxa (Fig. 5). This finding is in agreement with previous studies of colonised root tips (Lilleskov et al., 2002; Toljander et al., 2006; Cox et al., 2010; Kjoller et al., 2012), and here we corroborate this relationship based on total soil DNA, across wide geographical distances, and within a natural range in N-availability.

The shift in ectomycorrhizal morphology may imply that a larger proportion of the fungal biomass was found in ectomycorrhizal mantle tissues, closely associated with the roots at higher levels of nutrient availability. Thereby, removal of roots prior to analysis (e.g. by sieving) could contribute to previous observations of declining fungal biomass with increasing ecosystem productivity, explaining discrepancies between studies.

Even though litter-associated basidiomycetes increased in the humus layer in the most fertile forests, they still contributed a minor part (<5 %) of the amplicons only (Fig. 6). This small

increase may be explained by mixing of litter components into the more decomposed humus by soil fauna (in line with findings of larger mineral content mixed into the humus), possibly in combination with decreased competition from the ectomycorrhizal fungal community. However, we did not find significant amounts of DNA from terricolous, non-litter saprotrophs, such as members of the family Agaricaceae. A small increase in the abundance of yeasts and moulds with increasing N-availability was observed, but only in Norway spruce forests where Scots pine was absent. Here some groups (tremellales) increased in abundance with decreasing C:N-ratio (Fig. 5), and there were also some indications of a small increase in free ergosterol in these herb rich spruce forests (Fig. 1). However, including Scots pine forests in the analysis, the general pattern was completely opposite to our expectations; yeasts within Saccharomycetes, as well as moulds in the genera *Mortierella* and *Penicillium* were most abundant in acidic, high C:N ratio pine forests (Fig. 5), and free ergosterol was also positively correlated with the C:N ratio (Table 1). Thus, the expected major shift to a community dominated by saprotrophs, yeasts and moulds towards the richest part of the gradient was not observed. It is possible that the saprotrophic niche in humus is occupied primarily by bacteria, as proposed by (Högberg et al., 2003), but among fungi the vertical separation of a litter-associated, saprotrophic community above and a humus-associated mycorrhizal community below (Lindahl et al., 2007; Clemmensen et al., 2013) was maintained across the full range of ecosystem fertility.

The Scots pine forests deviated from our hypotheses with high levels of both free and total ergosterol in spite of their stressful growth conditions with low pH and severe nutrient limitation (Fig. 1). This is partly contradictory to our hypothesis (hypothesis 1) that fungal abundance generally would increase towards intermediate fertility. In addition, the abundance of free ergosterol was higher in the low-productive end of the gradient (Fig. 1), suggesting a higher proportion of recently formed fungal biomass (rev. by. Wallander et al., 2013) and a higher turn-over rate of the mycelium. Presumably, by allocating a higher proportion of photoassimilates to their mycorrhizal symbionts, Scots pines are better able than Norway spruces to support a high mycelial biomass of competitive ectomycorrhizal fungi, in spite of high levels of environmental stress. We postulate that Scots pines, by investing more C in cord-forming ectomycorrhizal symbionts, such as *Suillus* and *Cortinarius* species, with a high potential to forage recalcitrant organic pools for nutrients (Bending and Read, 1995; Bödeker et al., 2009; Hobbie and Agerer, 2010; Hobbie et al., 2013), are able to efficiently exchange C for scarcely available nutrients and compete successfully with ericoid plants and their associated stress-tolerant ascomycetes (Collier and Bidartondo, 2009).

The capacity of mycorrhizal fungi to support their host with nutrients is largely regulated by their propensity to immobilise nutrients in their own mycelia, particularly under nutrient limiting conditions (Alberton et al., 2007; Corrêa et al., 2012). Näsholm et al. (2013) recently showed that the more C the plants allocate to their mycorrhizal symbionts, the larger fraction of tracer ^{15}N was immobilised in mycelial biomass. The dilemma of the ectomycorrhizal symbiosis is that efficient foraging for nutrients from organic matter is conditional on high mycelial production, but efficient transfer of nutrients to the host plants requires a low degree of N-immobilisation in mycelial biomass. We postulate that under strongly nutrient limiting conditions, some ectomycorrhizal fungi combine high biomass production with rapid mycelial turn-over (here evident as high levels of free ergosterol), thereby enabling efficient substrate colonisation while

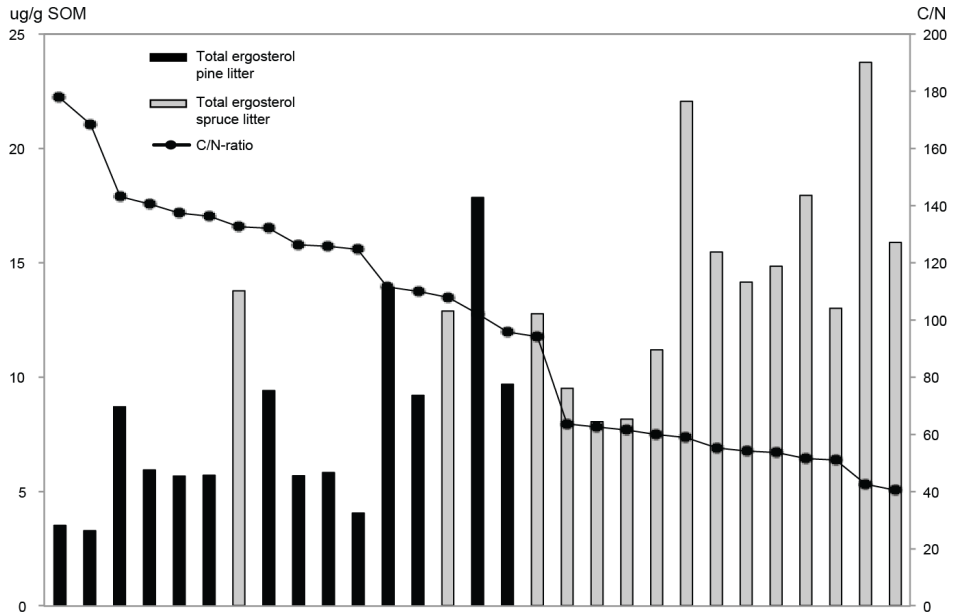
still maintaining a high proportional transfer of acquired nutrients to their hosts. Such properties are well described from cord-forming saprotrophs, which take advantage of their highly differentiated mycelia to efficiently explore heterogeneous environments and redistribute nutrients between resource units of contrasting qualities (Boddy, 1999). Similar strategies with rapidly advancing mycelial fronts, which degrades and regress into a sparse network of aggregated cords as the mycelium senesce, have also been described in ectomycorrhizal fungi, particularly in the genus *Suillus* (Finlay and Read, 1986). We further postulate that this self-induced fast mycelial turn-over support a community of opportunistic saprotrophs. After killing mycorrhizal mycelium by severing root connections, Lindahl et al. (2010) found increased abundance of yeasts and molds (again *Mortierella*, *Saccharomycetes* and *Penicillium*). It, thus, seems as if pines support a fungal community that combines functional groups of stress-tolerant, competitive as well as ruderal fungi, but to a high cost in terms of root derived carbon. Furthermore, the significant negative relationship between yeast and mould abundance and total ergosterol levels in the humus (Table 1) support that that these opportunists take part in rapid degradation of recently dead ectomycorrhizal mycelium. A correlation between high C allocation to roots, rapid production and turn-over of mycorrhizal mycelium, high levels of free ergosterol, and efficient N recycling was recently demonstrated by Clemmensen et al. (2013) in low-productive old-growth boreal forest ecosystems. Similar to the present study, these features were associated with the presence of Scots pine, and primarily connected to ectomycorrhizal fungi in the genera *Suillus* and *Cortinarius* as well as opportunistic molds and yeasts (Clemmensen et al., 2013).

In conclusion, we found a significant relationship between the fungal community composition and soil acidity as well as C:N-ratio. Moving from the low-productive to the high-productive end of the gradient, there was a shift from a community dominated by ascomycetes to a community with increased contribution of basidiomycetes, both in humus and litter. The levels of ergosterol decreased at low pH, indicating environmental stress, but superimposed on this general pattern, the presence of Scots pine had a positive influence on fungal biomass in the humus layer. Against our expectations, the relative abundance of ectomycorrhizal fungi in the humus layer did not decline in the most fertile forests, and we propose that further enhanced N addition by deposition or fertilization, above the levels usually encountered in non-disturbed boreal forests, is needed for a negative effect to occur. With this study, we show that it is possible to make statistical predictions about the composition and biomass of fungal communities within the range of forest types that we covered, which is potentially useful in theoretical and quantitative ecosystem modelling.

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a) Litter



b) Humus

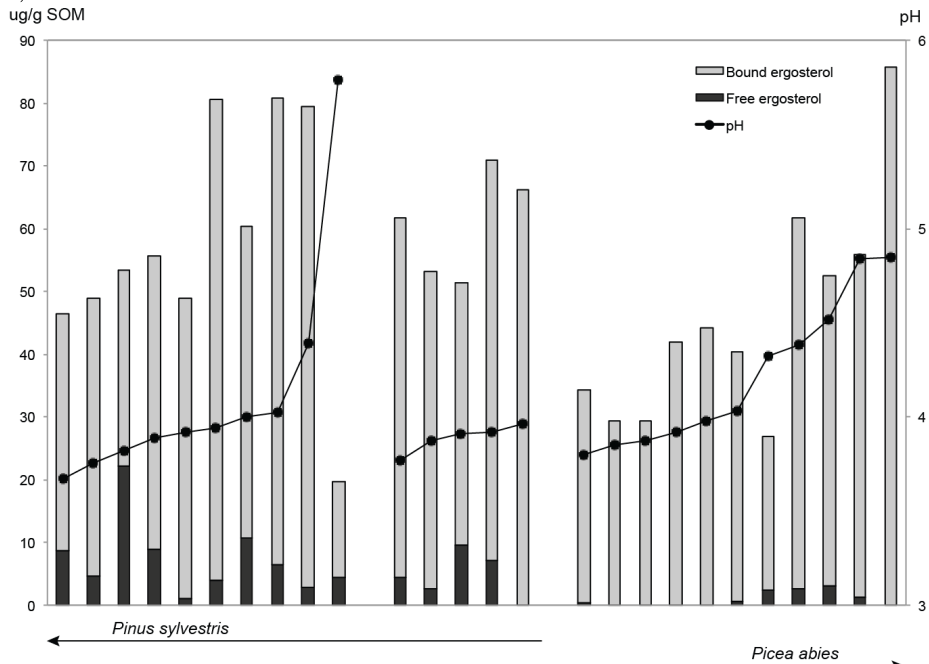


Fig 1. a) Ergosterol levels in the in needle litter of Scots pine (black bars) and Norway spruce (grey bars). Samples are sorted after litter C:N-ratio.

b) Bound ergosterol levels (grey part of bars) and free ergosterol levels (black part of bars) in the humus. Samples are sorted after dominant tree species of the forests, pine forests in the left part of the graph, spruce forests in the right part and codominance of the two species in the middle. For each tree species, the samples are ordered after humus pH.

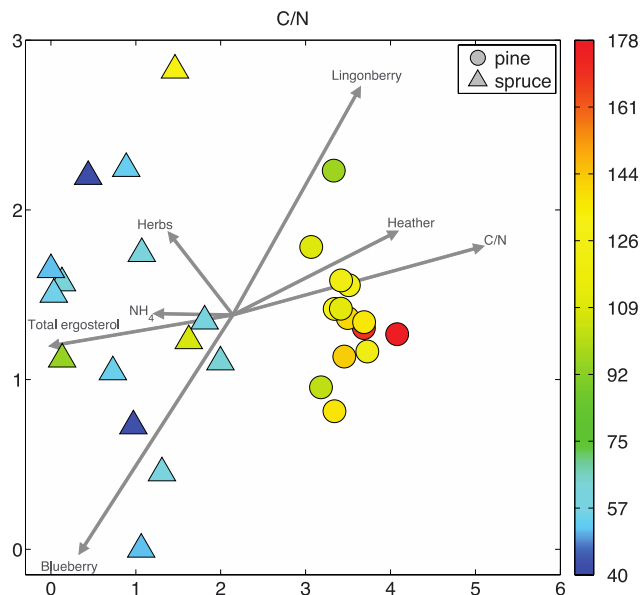
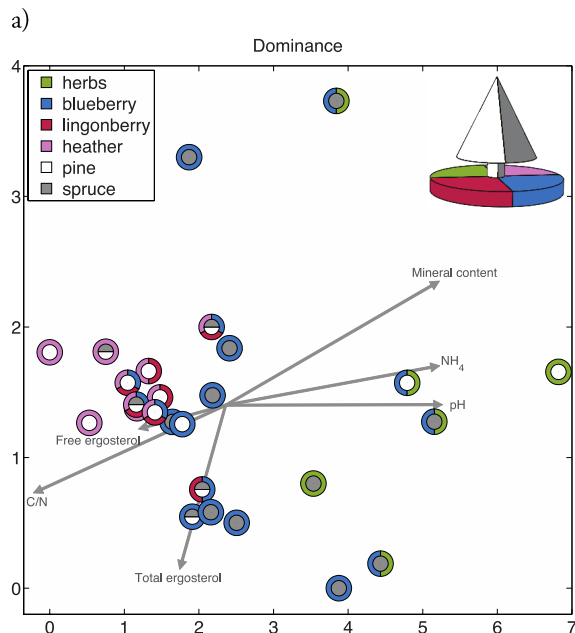


Fig 2. Joint biplot derived from a detrended correspondence analysis (DCA) of fungal communities in the litter layer of 26 Swedish boreal forest. Circles represent fungal communities in pine litter and triangles represents the fungal communities in spruce litter, both colour coded after litter C:N ratio. Vectors indicate the direction and degree (arrow length) of the correlation between quantitative soil parameters and the two first DCA axes.



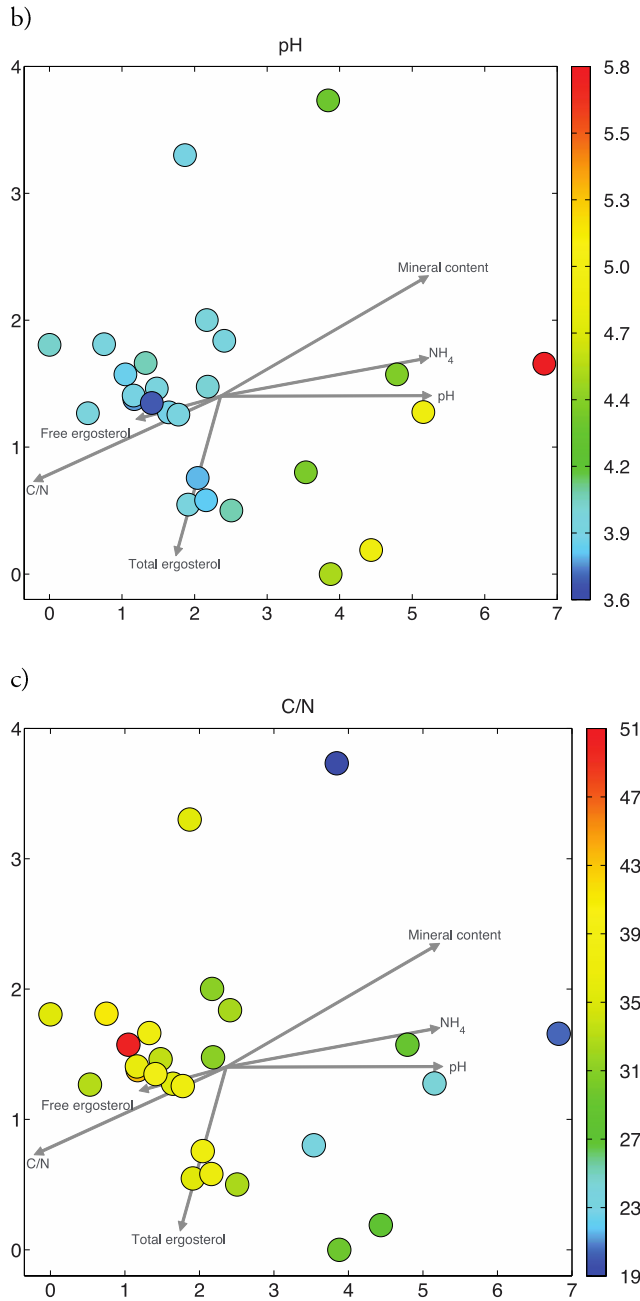


Fig. 3. Joint biplot derived from a detrended correspondence analysis (DCA) of data from the humus fungal communities in humus of 26 Swedish boreal forests. Each circle represents the fungal community in one forest where a) the outer part is colour-coded after understory vegetation and the inner part represents dominant tree species of the forest b) circles are colour-coded after humus pH and c) circles are colour-coded after humus C:N-ratio. Vectors indicate the direction and degree (arrow length) of the correlation between quantitative soil parameters and the two first DCA axes.

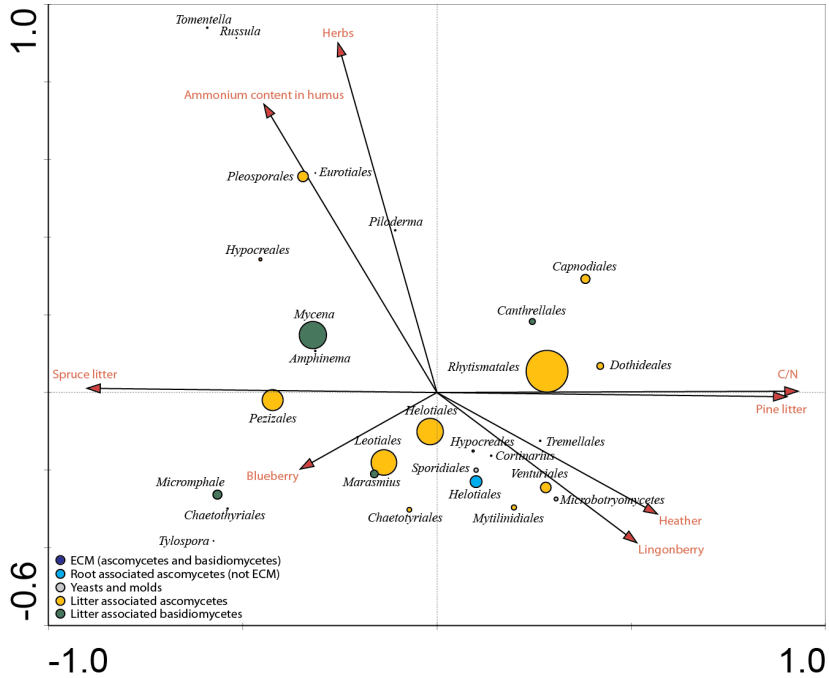


Fig 4. Joint biplot derived from a canonical correspondence analysis (CCA) of fungal communities in litter layers of 26 Swedish boreal forests, where species have been merged into genera or orders. Circles are colour coded depending on function of the genus or order. Vectors represent the constraining environmental variables in the CCA.

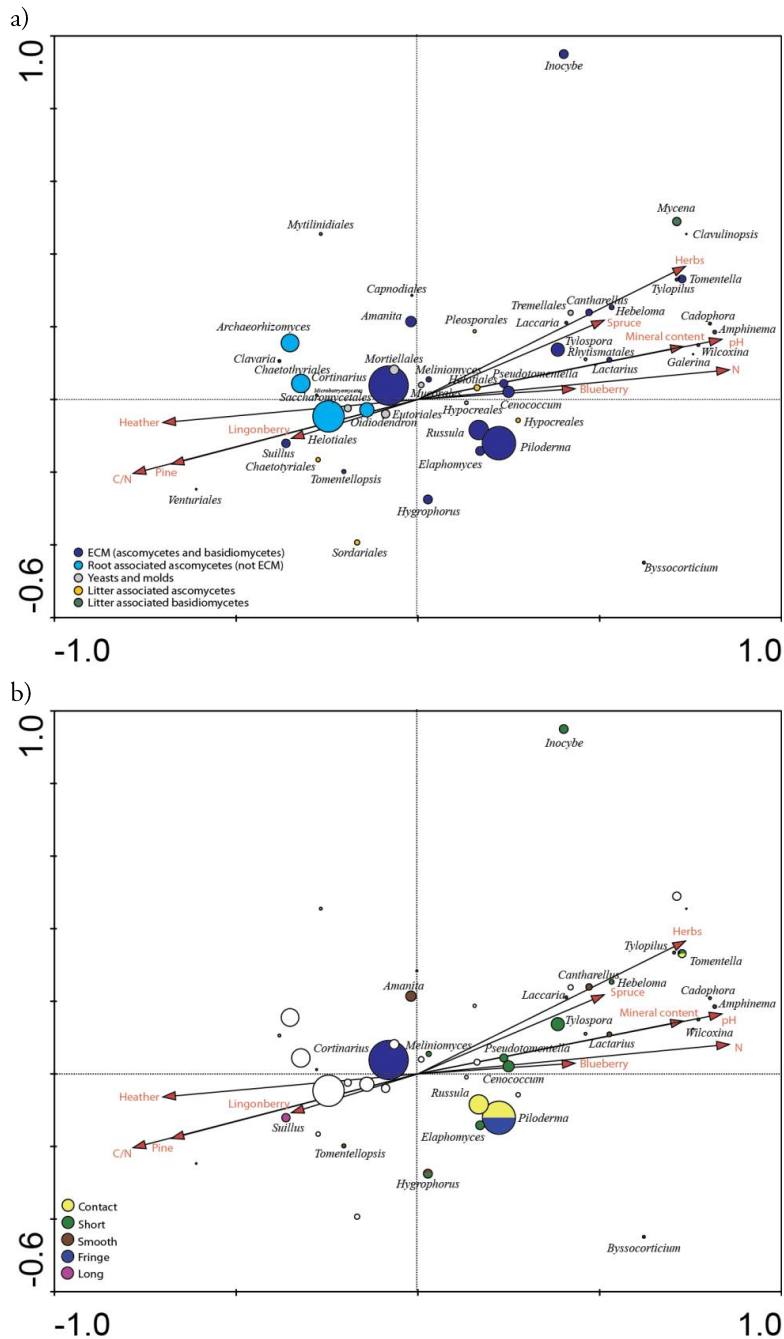


Fig 5. Joint biplot derived from a canonical correspondence analysis (CCA) of fungal communities in humus of 26 Swedish boreal forests, where species have been merged into genera or orders a) Circles are colour coded depending on function of the genus or order and b) Ectomycorrhizal genera are colour coded depending on exploration type of the genus according to Agerer (2001). Vectors represent the constraining environmental variables in the CCA.

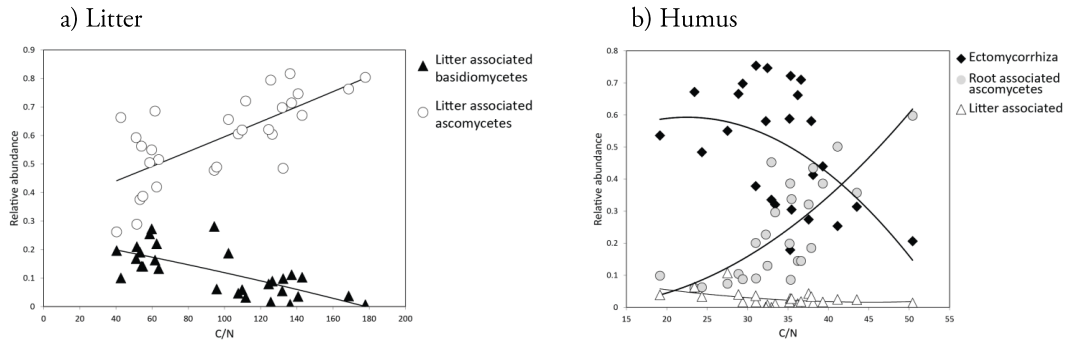


Fig 6 . Relative abundance of the ITS2 amplicons categorized as species being ectomycorrhizal (diamonds), root associated ascomycetes (dots) or litter associated (triangles), with increasing soil C:N-ratio in the a) litter and b) humus.

Table 1. Result from a general regression model, multiple regression of how free and total ergosterol levels in humus and litter was related to environmental parameters. P-value specified when significant, and direction of coefficient between brackets.

	Humus Total ergosterol	Humus Free ergosterol	Litter Total ergosterol
pH	p<0.0001 (+)		
NH ₄ in humus			
C:N-ratio		p=0.0001 (+)	p<0.0001 (-)
Mineral content	p=0.004 (-)		
Pine	p<0.0001 (+)		
Spruce			
Herbs		p=0.038 (+)	
Blueberry			
Lingonberry			
Heather			
ECM diff			
ECM undiff			
Root ass asco			
Yeasts and moulds	p=0.01 (-)		
Litter ass asco			
Litter ass basidio			
Whole model	p<0.0001, R ² =0.47	p=0.0003, R ² =0.47	p<0.0001, R ² =0.46

References

- Abarenkov, K., Tedersoo, L., Nilsson, R.H., Vellak, K., Saar, I., Veldre, V., Parmasto, E., Prous, M., Aan, A., Ots, M., Kurina, O., Ostonen, I., Jõgeva, J., Halapuu, S., Põldmaa, K., Toots, M., Truu, J., Larsson, K.-H., Kõljalg, U., 2010. PlutoF-a web based workbench for ecological and taxonomic research, with an online implementation for fungal ITS sequences. *Evolutionary Bioinformatics* 6, 189-196.
- Aerts, R., 1995. The advantages of being evergreen. *Trends in Ecology & Evolution* 10, 402-407.
- Agerer, R., 2001. Exploration types of ectomycorrhizae - A proposal to classify ectomycorrhizal mycelial systems according to their patterns of differentiation and putative ecological importance. *Mycorrhiza* 11, 107-114.
- Alberton, O., Kuyper, T.W., Gorissen, A., 2007. Competition for nitrogen between *Pinus sylvestris* and ectomycorrhizal fungi generates potential for negative feedback under elevated CO₂. *Plant and Soil* 296, 159-172.
- Bahr, A., Ellström, M., Akselsson, C., Ekblad, A., Mikusinska, A., Wallander, H., 2013. Growth of ectomycorrhizal fungal mycelium along a Norway spruce forest nitrogen deposition gradient and its effect on nitrogen leakage. *Soil Biology and Biochemistry* 59, 38-48.
- Baldrian, P., 2009. Ectomycorrhizal fungi and their enzymes in soils: is there enough evidence for their role as facultative soil saprotrophs? *Oecologia* 161, 657-660.
- Bending, G.D., Read, D.J., 1995. The structure and function of the vegetative mycelium of ectomycorrhizal plants. VI. Activities of nutrient mobilizing enzymes in birch litter colonized by *Paxillus involutus* (Fr.) Fr. *New Phytologist* 130, 411-417.
- Boberg, J., Finlay, R.D., Stenlid, J., Näsholm, T., Lindahl, B.D., 2008. Glucose and ammonium additions affect needle decomposition and carbon allocation by the litter degrading fungus *Mycena epipterygia*. *Soil Biology and Biochemistry* 40, 995-999.
- Boddy, L., 1999. Saprotrophic cord-forming fungi: Meeting the challenge of heterogeneous environments. *Mycologia* 91, 13-32.
- Boddy, L., 2000. Interspecific combative interactions between wood-decaying basidiomycetes. *FEMS Microbiology Ecology* 31, 185-194.
- Brady, N.C., Weil, R.R., 2008. The nature and properties of soils, 13 ed. Prentice Hall, New Jersey, USA.
- Butenschoen, O., Poll, C., Langel, R., Kandeler, E., Marhan, S., Scheu, S., 2007. Endogeic earthworms alter carbon translocation by fungi at the soil-litter interface. *Soil Biology and Biochemistry* 39, 2854-2864.
- Bödeker, I.T.M., Nygren, C.M.R., Taylor, A.F.S., Olson, A., Lindahl, B.D., 2009. ClassII peroxidase-encoding genes are present in a phylogenetically wide range of ectomycorrhizal fungi. *ISME J* 3, 1387-1395.
- Clemmensen, K.E., Bahr, A., Ovaskainen, O., Dahlberg, A., Ekblad, A., Wallander, H., Stenlid, J., Finlay, R.D., Wardle, D.A., Lindahl, B.D., 2013. Roots and associated fungi drive long-term carbon sequestration in boreal forest. *Science* 339, 1615-1618.
- Clemmensen, K.E., Sorensen, P.L., Michelsen, A., Jonasson, S., Ström, L., 2008. Site-dependent N uptake from N-form mixtures by arctic plants, soil microbes and ectomycorrhizal fungi. *Oecologia* 155, 771-783.
- Collier, F.A., Bidartondo, M.I., 2009. Waiting for fungi: the ectomycorrhizal invasion of lowland heathlands. *Journal of Ecology* 97, 950-963.

- Cooke, R.C., Rayner, A.D.M., 1984. Ecology of saprotrophic fungi. Longman.
- Corrêa, A., Gurevitch, J., Martins-Loução, M.A., Cruz, C., 2012. C allocation to the fungus is not a cost to the plant in ectomycorrhizae. *Oikos* 121, 449-463.
- Cox, F., Barsoum, N., Lilleskov, E.A., Bidartondo, M.I., 2010. Nitrogen availability is a primary determinant of conifer mycorrhizas across complex environmental gradients. *Ecology Letters* 13, 1103-1113.
- Crowther, T.W., Boddy, L., Hefin Jones, T., 2012. Functional and ecological consequences of saprotrophic fungus-grazer interactions. *ISME J* 6, 1992-2001.
- Eklblad, A., Wallander, H., Godbold, D.L., Cruz, C., Johnson, D., Baldrian, P., Björk, R.G., Epron, D., Kieliszewska-Rokicka, B., Kjoller, R., Kraigher, H., Matzner, E., Neumann, J., Plassard, C., 2013. The production and turnover of extramatrical mycelium of ectomycorrhizal fungi in forest soils: role in carbon cycling. *Plant and Soil* 366, 1-27.
- Fierer, N., Bradford, M.A., Jackson, R.B., 2007. Toward an ecological classification of soil bacteria. *Ecology* 88, 1354-1364.
- Floudas, D., Binder, M., Riley, R., Barry, K., Blanchette, R.A., Henrissat, B., Martínez, A.T., Otilar, R., Spatafora, J.W., Yadav, J.S., Aerts, A., Benoit, I., Boyd, A., Carlson, A., Copeland, A., Coutinho, P.M., de Vries, R.P., Ferreira, P., Findley, K., Foster, B., Gaskell, J., Glotzer, D., Górecki, P., Heitman, J., Hesse, C., Hori, C., Igarashi, K., Jurgens, J.A., Kallen, N., Kersten, P., Kohler, A., Kües, U., Kumar, T.K.A., Kuo, A., LaButti, K., Larrondo, L.F., Lindquist, E., Ling, A., Lombard, V., Lucas, S., Lundell, T., Martin, R., McLaughlin, D.J., Morgenstern, I., Morin, E., Murat, C., Nagy, L.G., Nolan, M., Ohm, R.A., Patyshakuliyeva, A., Rokas, A., Ruiz-Dueñas, F.J., Sabat, G., Salamov, A., Samejima, M., Schmutz, J., Slot, J.C., St. John, F., Stenlid, J., Sun, H., Sun, S., Syed, K., Tsang, A., Wiebenga, A., Young, D., Pisabarro, A., Eastwood, D.C., Martin, F., Cullen, D., Grigoriev, I.V., Hibbett, D.S., 2012. The paleozoic origin of enzymatic lignin decomposition reconstructed from 31 fungal genomes. *Science* 336, 1715-1719.
- Fontaine, S., Henault, C., Aamor, A., Bdioui, N., Bloor, J.M.G., Maire, V., Mary, B., Revallot, S., Maron, P.A., 2011. Fungi mediate long term sequestration of carbon and nitrogen in soil through their priming effect. *Soil Biology and Biochemistry* 43, 86-96.
- Frank, D.N., 2009. BARCRAWL and BARTAB: software tools for the design and implementation of barcoded primers for highly multiplexed DNA sequencing. *Bmc Bioinformatics* 10.
- Gadgil, R.L., Gadgil, P.D., 1971. Mycorrhiza and litter decomposition. *Nature* 233, 133-133.
- Gostinčar, C., Grube, M., De Hoog, S., Zalar, P., Gunde-Cimerman, N., 2010. Extremotolerance in fungi: evolution on the edge. *FEMS Microbiology Ecology* 71, 2-11.
- Grime, J.P., 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. *The American Naturalist* 111, 1169-1194.
- Hibbett, D.S., Gilbert, L.-B., Donoghue, M.J., 2000. Evolutionary instability of ectomycorrhizal symbioses in basidiomycetes. *Nature* 407, 506-508.
- Hobbie, E., Agerer, R., 2010. Nitrogen isotopes in ectomycorrhizal sporocarps correspond to belowground exploration types. *Plant and Soil* 327, 71-83.
- Hobbie, E., Ouimette, A., Schuur, E.G., Kierstead, D., Trappe, J., Bendiksen, K., Ohenoja, E., 2013. Radiocarbon evidence for the mining of organic nitrogen from soil by mycorrhizal fungi. *Biogeochemistry* 114, 381-389.

- Högberg, M.N., Briones, M.J.I., Keel, S.G., Metcalfe, D.B., Campbell, C., Midwood, A.J., Thornton, B., Hurry, V., Linder, S., Näsholm, T., Högberg, P., 2010. Quantification of effects of season and nitrogen supply on tree below-ground carbon transfer to ectomycorrhizal fungi and other soil organisms in a boreal pine forest. *New Phytologist* 187, 485-493.
- Högberg, M.N., Bååth, E., Nordgren, A., Arnebrant, K., Högberg, P., 2003. Contrasting effects of nitrogen availability on plant carbon supply to mycorrhizal fungi and saprotrophs - a hypothesis based on field observations in boreal forest. *New Phytologist* 160, 225-238.
- Ihrmark, K., Bödeker, I.T.M., Cruz-Martinez, K., Friberg, H., Kubartova, A., Schenck, J., Strid, Y., Stenlid, J., Brandström-Durling, M., Clemmensen, K.E., Lindahl, B.D., 2012. New primers to amplify the fungal ITS2 region – evaluation by 454-sequencing of artificial and natural communities. *FEMS Microbiology Ecology* 82, 666-677.
- Janssens, I.A., Dieleman, W., Luyssaert, S., Subke, J.A., Reichstein, M., Ceulemans, R., Ciais, P., Dolman, A.J., Grace, J., Matteucci, G., Papale, D., Piao, S.L., Schulze, E.D., Tang, J., Law, B.E., 2010. Reduction of forest soil respiration in response to nitrogen deposition. *Nature Geosci* 3, 315-322.
- Kjøller, R., Nilsson, L.-O., Hansen, K., Schmidt, I.K., Vesterdal, L., Gundersen, P., 2012. Dramatic changes in ectomycorrhizal community composition, root tip abundance and mycelial production along a stand-scale nitrogen deposition gradient. *New Phytologist* 194, 278-286.
- Koide, R., Fernandez, C., Petprakob, K., 2011. General principles in the community ecology of ectomycorrhizal fungi. *Annals of Forest Science* 68, 45-55.
- Lahti, T., Väisänen, R., 1987. Ecological gradients of boreal forests in South Finland: an ordination test of Cajander's forest site type theory. *Vegetatio* 68, 145-156.
- Lilleskov, E.A., Hobbie, E.A., Fahey, T.J., 2002. Ectomycorrhizal fungal taxa differing in response to nitrogen deposition also differ in pure culture organic nitrogen use and natural abundance of nitrogen isotopes. *New Phytologist* 154, 219-231.
- Lindahl, B., Stenlid, J., Finlay, R., 2001. Effects of resource availability on mycelial interactions and ³²P transfer between a saprotrophic and an ectomycorrhizal fungus in soil microcosms. *FEMS Microbiology Ecology* 38, 43-52.
- Lindahl, B.D., de Boer, W., Finlay, R.D., 2010. Disruption of root carbon transport into forest humus stimulates fungal opportunists at the expense of mycorrhizal fungi. *ISME J* 4, 872-881.
- Lindahl, B.D., Ihrmark, K., Boberg, J., Trumbore, S.E., Högberg, P., Stenlid, J., Finlay, R.D., 2007. Spatial separation of litter decomposition and mycorrhizal nitrogen uptake in a boreal forest. *New Phytologist* 173, 611-620.
- Lindahl, B.D., Nilsson, R.H., Tedersoo, L., Abarenkov, K., Carlsen, T., Kjøller, R., Kõljalg, U., Pennanen, T., Rosendahl, S., Stenlid, J., Kauserud, H., 2013. Fungal community analysis by high-throughput sequencing of amplified markers – a user's guide. *New Phytologist* 199, 288-299.
- Moorhead, D.L., Sinsabaugh, R.L., 2006. A Theoretical Model of Litter Decay and Microbial Interaction. *Ecological Monographs* 76, 151-174.
- Nilsson, L.O., Bååth, E., Falkengren-Grerup, U., Wallander, H., 2007. Growth of ectomycorrhizal mycelia and composition of soil microbial communities in oak forest soils along a nitrogen deposition gradient. *Oecologia* 153, 375-384.

- Nilsson, L.O., Wallander, H., 2003. Production of external mycelium by ectomycorrhizal fungi in a Norway spruce forest was reduced in response to nitrogen fertilization. *New Phytologist* 158, 409-416.
- Nylund, J.E., Wallander, H., 1992. Ergosterol analysis as a means of quantifying mycorrhizal biomass. *Methods in Microbiology* 24, 77-88.
- Näsholm, T., Högberg, P., Franklin, O., Metcalfe, D., Keel, S.G., Campbell, C., Hurry, V., Linder, S., Högberg, M.N., 2013. Are ectomycorrhizal fungi alleviating or aggravating nitrogen limitation of tree growth in boreal forests? *New Phytologist* 198, 214-221.
- Peltzer, D.A., Wardle, D.A., Allison, V.J., Baisden, W.T., Bardgett, R.D., Chadwick, O.A., Condron, L.M., Parfitt, R.L., Porder, S., Richardson, S.J., Turner, B.L., Vitousek, P.M., Walker, J., Walker, L.R., 2010. Understanding ecosystem retrogression. *Ecological Monographs* 80, 509-529.
- Pennanen, T., Liski, J., Bååth, E., Kitunen, V., Uotila, J., Westman, C.J., Fritze, H., 1999. Structure of the microbial communities in coniferous forest soils in relation to site fertility and stand development stage. *Microbial Ecology* 38, 168-179.
- Rayner, A.D.M., Boddy, L., 1998. *Terrestrial fungal communities*. Oxford University Press, Walton Street, Oxford OX2 6DP, England 198 Madison Avenue, New York, New York 10016, USA, 163-202 pp.
- Rayner, A.D.M., Boddy, L., Dowson, C.G., 1987. Genetic interactions and developmental versatility during establishment of decomposer basidiomycetes in wood and tree litter. *Ecology of microbial communities*, 83-123.
- Read, D.J., Perez-Moreno, J., 2003. Mycorrhizas and nutrient cycling in ecosystems – a journey towards relevance? *New Phytologist* 157, 475-492.
- Rousk, J., Baath, E., Brookes, P.C., Lauber, C.L., Lozupone, C., Caporaso, J.G., Knight, R., Fierer, N., 2010. Soil bacterial and fungal communities across a pH gradient in an arable soil. *ISME J* 4, 1340-1351.
- Rousk, J., Brookes, P.C., Bååth, E., 2011. Fungal and bacterial growth responses to N fertilization and pH in the 150-year 'Park Grass' UK grassland experiment. *FEMS Microbiology Ecology* 76, 89-99.
- Rousk, J., Bååth, E., 2011. Growth of saprotrophic fungi and bacteria in soil. *FEMS Microbiology Ecology* 78, 17-30.
- Smith, S.E., Read, D.J., 2008. *Mycorrhizal symbiosis*, third edition. Academic Press, London.
- Toljander, J.F., Eberhardt, U., Toljander, Y.K., Paul, L.R., Taylor, A.F.S., 2006. Species composition of an ectomycorrhizal fungal community along a local nutrient gradient in a boreal forest. *New Phytologist* 170, 873-884.
- Wallander, H., Ekblad, A., Godbold, D.L., Johnson, D., Bahr, A., Baldrian, P., Björk, R.G., Kieliszewska-Rokicka, B., Kjoller, R., Kraigher, H., Plassard, C., Rudawska, M., 2013. Evaluation of methods to estimate production, biomass and turnover of ectomycorrhizal mycelium in forest soils – A review. *Soil Biology and Biochemistry* 57, 1034-1047.
- Vitousek, P.M., Howarth, R.W., 1991. Nitrogen limitation on land and in the sea - how can it occur. *Biogeochemistry* 13, 87-115.

- Wright, I.J., Reich, P.B., Westoby, M., Ackerly, D.D., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Cornelissen, J.H.C., Diemer, M., Flexas, J., Garnier, E., Groom, P.K., Gulias, J., Hikosaka, K., Lamont, B.B., Lee, T., Lee, W., Lusk, C., Midgley, J.J., 2004. The worldwide leaf economics spectrum. *Nature* 428, 821-827.
- Yuan, J.P., Kuang, H.C., Wang, J.H., Liu, X., 2008. Evaluation of ergosterol and its esters in the pileus, gill, and stipe tissues of agaric fungi and their relative changes in the comminuted fungal tissues. *Applied Microbiology and Biotechnology* 80, 459-465.

IV



We have found major changes in a plant-pollinator network over the past 120 years. This is partly explained by the nonrandom extirpation of bee species that are expected to be the most vulnerable to land-use and climate change, such as rare and specialized species, species occupying higher trophic levels, and cavity-nesting species. We found large changes in phenology of both forbs and pollinators and the potential for interaction mismatches, and these phenological changes can explain some of the species and interaction losses observed in this system. Our more optimistic finding was that plant-pollinator interaction networks were quite flexible in the face of strong phenological change and bee species extirpations, with many extant species gaining interactions through time. However, the redundancy in network structure has been reduced, interaction strengths have weakened, and the quantity and quality of pollinator service has declined through time. Further interaction mismatches and reductions in population sizes are likely to have substantial negative consequences for this crucial ecosystem service.

References and Notes

1. A. M. Klein et al., *Proc. Biol. Sci.* **274**, 303 (2007).
2. J. Ollerton, R. Winfree, S. Tarrant, *Oikos* **120**, 321 (2011).
3. J. M. Tylianakis, R. K. Didham, J. Bascompte, D. A. Wardle, *Ecol. Lett.* **11**, 1351 (2008).
4. J. Bascompte, P. Jordano, C. J. Melián, J. M. Olesen, *Proc. Natl. Acad. Sci. U.S.A.* **100**, 9383 (2003).
5. J. C. Biesmeijer et al., *Science* **313**, 351 (2006).
6. A. H. Fitter, R. S. Fitter, *Science* **296**, 1689 (2002).
7. A. J. Miller-Rushing, R. B. Primack, *Ecology* **89**, 332 (2008).
8. I. Bartomeus et al., *Proc. Natl. Acad. Sci. U.S.A.* **108**, 20645 (2011).
9. S. J. Hegland, A. Nielsen, A. Lázaro, A.-L. Bjerknes, O. Totland, *Ecol. Lett.* **12**, 184 (2009).
10. J. Memmott, P. G. Craze, N. M. Waser, M. V. Price, *Ecol. Lett.* **10**, 710 (2007).
11. E. Thébault, C. Fontaine, *Science* **329**, 853 (2010).
12. C. Robertson, *Psyche* **33**, 116 (1926).
13. C. Robertson, *Flowers and Insects: Lists of Visitors to Four Hundred and Fifty-Three Flowers* (Science Press Printing Company, Lancaster, PA, 1929).
14. C. Robertson, *Psyche* **36**, 112 (1929).
15. Materials and methods are available as supplementary material on Science Online.
16. J. C. Marlin, W. E. LaBerge, *Conservation Ecol.* **5**, 9 (2001).
17. R. K. Colwell, J. A. Coddington, *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **345**, 101 (1994).
18. M. A. Aizen, M. Sabatino, J. M. Tylianakis, *Science* **335**, 1486 (2012).
19. N. M. Williams et al., *Biol. Conserv.* **143**, 2280 (2010).
20. K. Henle, K. F. Davies, M. Kleyer, C. Margules, J. Settele, *Biodivers. Conserv.* **13**, 207 (2004).
21. J. Bascompte, R. Sole, *J. Anim. Ecol.* **65**, 465 (1996).
22. L. Cagnolo, G. Valladares, A. Salvo, M. Cabido, M. Zak, *Conserv. Biol.* **23**, 1167 (2009).
23. F. Encinas-Viso, T. A. Revilla, R. S. Etienne, *Ecol. Lett.* **15**, 198 (2012).
24. A. Menzel, P. Fabian, *Nature* **397**, 659 (1999).
25. D. W. Inouye, F. Saavedra, W. Lee-Yang, *Am. J. Bot.* **90**, 905 (2003).
26. D. B. Roy, T. H. Sparks, *Glob. Change Biol.* **6**, 407 (2000).
27. J. Peñuelas, I. Filella, P. Comas, *Glob. Change Biol.* **8**, 531 (2002).
28. A. J. Miller-Rushing, D. W. Inouye, R. B. Primack, *J. Ecol.* **96**, 1289 (2008).
29. E. Toby Kiers, T. M. Palmer, A. R. Ives, J. F. Bruno, J. L. Bronstein, *Ecol. Lett.* **13**, 1459 (2010).
30. T. Petanidou, A. S. Kallimanis, J. Tzanopoulos, S. P. Sgardelis, J. D. Pantis, *Ecol. Lett.* **11**, 564 (2008).
31. S. A. Cameron et al., *Proc. Natl. Acad. Sci. U.S.A.* **108**, 662 (2011).
32. D. W. Inouye, *Ecology* **59**, 672 (1978).

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Supplementary Materials

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Materials and Methods
Supplementary Text
Figs. S1 to S10
Tables S1 to S3
References (33–37)

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Roots and Associated Fungi Drive Long-Term Carbon Sequestration in Boreal Forest

K. E. Clemmensen,^{1*} A. Bahr,² O. Ovaskainen,³ A. Dahlberg,^{1,4} A. Ekblad,⁵ H. Wallander,² J. Stenlid,¹ R. D. Finlay,¹ D. A. Wardle,⁶ B. D. Lindahl¹

Boreal forest soils function as a terrestrial net sink in the global carbon cycle. The prevailing dogma has focused on aboveground plant litter as a principal source of soil organic matter. Using ¹⁴C bomb-carbon modeling, we show that 50 to 70% of stored carbon in a chronosequence of boreal forested islands derives from roots and root-associated microorganisms. Fungal biomarkers indicate impaired degradation and preservation of fungal residues in late successional forests. Furthermore, 454 pyrosequencing of molecular barcodes, in conjunction with stable isotope analyses, highlights root-associated fungi as important regulators of ecosystem carbon dynamics. Our results suggest an alternative mechanism for the accumulation of organic matter in boreal forests during succession in the long-term absence of disturbance.

Globally, the boreal forest biome covers 11% of the land surface (1) and contains 16% of the carbon (C) stock sequestered in soils (2). Aboveground plant litter quality and decomposition rates have been proposed as the fundamental determinants of long-term soil organic matter accumulation (3–6). However, a large proportion of photosynthetically fixed C is directed belowground to roots and associated microorganisms (7, 8), potentially affecting C sequestration either positively or negatively (9–12). A better mechanistic understanding of how the belowground allocation of C affects

long-term sequestration rates is crucial for predictions of how the currently large C stock in boreal forest soils may respond to altered forest management practices, climate change, elevated CO₂ levels, and other environmental shifts.

Here we present evidence from a fire-driven boreal forest chronosequence that enables the study of soil C sequestration over time scales of centuries to millennia. The system consists of forested islands in two adjacent lakes, Lake Hornavan and Lake Uddjaure (65°55′ to 66°09′N; 17°43′ to 17°55′E), in northern Sweden. The islands in these lakes were formed after the most recent

glaciation and have since been subjected to similar extrinsic factors. Larger islands, however, burn more frequently because they have a larger area to intercept lightning strikes (6, 13); several large islands have burned in the past century, whereas some small islands have not burned in the past 5000 years. It has previously been shown that as the time since fire increases, soil and total ecosystem C accumulates unabated and linearly (6, 14), leading to humus layers that can exceed 1 m in depth on the smallest islands. This has been attributed to a decline in the quality of aboveground litter inputs and impaired litter decomposition as the chronosequence proceeds (6, 14, 15). We studied organic soil profiles on 30 islands representing three size classes with increasing belowground C stocks (14): 10 large islands (>1.0 ha; on average, 6.2 kg of C m⁻² accumulated belowground; mean time since fire 585 years), 10 medium islands (0.1 to 1.0 ha, 11.2 kg of C m⁻², 2180 years), and 10 small islands (<0.1 ha, 22.5 kg of C m⁻², 3250 years).

¹Department of Forest Mycology and Plant Pathology, Uppsala BioCenter, Swedish University of Agricultural Sciences, Box 7026, SE-75007 Uppsala, Sweden. ²Department of Biology, Microbial Ecology Group, Lund University, Box 117, SE-221 00 Lund, Sweden. ³Department of Biosciences, University of Helsinki, Box 65, FI-00014 University of Helsinki, Finland. ⁴Swedish Species Information Centre, Swedish University of Agricultural Sciences, Box 7007, SE-750 07 Uppsala, Sweden. ⁵School of Science and Technology, Örebro University, SE-701 82 Örebro, Sweden. ⁶Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, SE-901 83 Umeå, Sweden.

*Corresponding author. E-mail: karina.clemmensen@slu.se

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We explored C dynamics across the chronosequence by analyzing bomb ^{14}C (16) to determine the age since fixation of soil C, and then fitted a mathematical model to measurements of C mass and age distribution across vertical organic matter profiles for six representative islands; three large and three small (Fig. 1) (17). The model assumes two sources of C inputs: (i) a series of consecutively deposited cohorts of aboveground plant litter with negligible vertical mixing, and (ii) belowground inputs through root transport and rhizosphere processes. The dynamics of both C sources were estimated by a Bayesian parameterization of the model. The observed distribution of C mass and age was adequately predicted only when root C input was accounted for (Table 1 and figs. S1 and S2). The parameterized model estimates that the proportion of root-derived C accumulated over the past 100 years is larger on small islands (70%) than on large islands (47%), and the larger total C sequestration on small islands during this period can be explained entirely by root-derived inputs (Fig. 1). Differences in organic matter accumulation between islands were primarily determined by processes at the interface between the fragmented litter (F) and humus (H) layers, which corresponded to the zone of highest root density (Fig. 2B) and where the aboveground litter was 10 to 60 years old. The model was run for 100 years, covering almost the entire humus profile of the large islands, but on small islands a major proportion of C is stored in deeper horizons that are older than this. However, the model indicates that below 20 cm depth, root-derived C inputs are low and the C remaining from the horizons above decomposes slowly, as is also supported by ^{14}C depletion in the deeper layers of small islands (Table 1). Thus, root-mediated C input to the upper part of the profile represents a major contribution to the long-term buildup of humus, especially in late successional ecosystems.

Fungi play central roles in boreal forest ecosystems, both as decomposers of organic matter and as root-associated mediators of belowground C transport and respiration. We profiled the relative abundance of major functional groups of fungi through the depth profile of each island by DNA barcoding based on 454 pyro sequencing of the ITS2 region of ribosomal RNA genes (17, 18). These analyses suggest that fungal communities in the uppermost litter layers were dominated by free-living saprotrophs, whereas mycorrhizal and other root-associated fungi dominated at greater depth (Fig. 2A). Thus, root-associated fungi dominate the part of the soil profile where the model indicates the largest difference in C sequestration between the island size classes. At this depth, free-living saprotrophs (mainly molds and yeasts) make a much reduced contribution, suggesting a correspondingly greater role of root-associated fungi in the regulation of organic matter dynamics.

The increase in root-derived C sequestration as the chronosequence proceeds is matched by a

shift in the balance between the production and decomposition of fungal mycelium in the F-H transition zone of the soil profile. We measured the fungal-specific cell membrane lipid ergosterol as a marker for fungal biomass throughout each soil profile. Even though standing fungal biomass, as indicated by total (free plus bound) ergosterol (Fig. 3, A and B) and ITS copy numbers (table S1), was roughly similar on all islands, free ergosterol (characteristic of newly formed mycelia) (19–21) was about 20 times more abundant on large than on small islands, indicating a larger proportion of freshly produced mycelium and thus greater mycelial production. In contrast, bound ergosterol (the proportion of which increases during mycelial senescence) (19, 20) was more abundant on smaller islands, indicating older mycelium with slower biomass turnover.

Furthermore, the fungal cell-wall polysaccharide chitin (Fig. 3C) peaked in the F layer and declined in lower horizons of large islands, but remained at high concentrations at greater depths on the small islands. Chitin persists longer than ergosterol in fungal tissues after death (21), and the high level of chitin on small islands suggests retarded decomposition of fungal cell wall residues. Thus, in spite of supposedly greater mycelial production on the large islands, less mycelial necromass accumulated there than on small islands, suggesting that the large production was counterbalanced by faster decomposition of mycelial remains. Correspondingly, the ^{14}C model indicated faster decomposition of root-derived C on large islands, despite inputs being conservatively constrained to be equal across all islands. Taken together, our results point to impaired

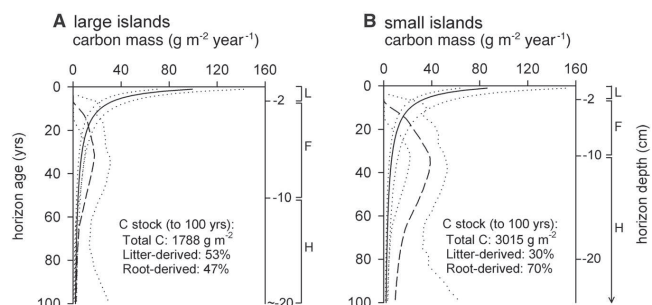


Fig. 1. Carbon dynamics in vertically stratified organic horizons of forested islands. Model estimates of C from aboveground litter (solid lines) and C introduced belowground via root transport (broken lines) are shown. C mass was modeled to a horizon age of 100 years, based on C mass and ^{14}C measurements in profiles from three large (A) and three small (B) islands. Dotted lines show the 95% central credibility intervals around posterior means. The posterior probability that the root-derived fraction is larger on small islands than on large islands is 0.97. Approximate depths are indicated for transitions between the main categories of horizons sampled; L, litter; F, fragmented litter; H, humus.

Table 1. C mass, ^{14}C abundance, and estimated C mean age of sampled organic layers on large and small islands. Means \pm SE, $n = 3$ ($n = 2$ for the deepest layer in both size classes; both values are given).

Layer	Large islands			Small islands		
	C mass (g m ⁻²)	$\Delta^{14}\text{C}$ (‰)	C age (years)	C mass (g m ⁻²)	$\Delta^{14}\text{C}$ (‰)	C age (years)
Litter, on surface	103 \pm 3	70 \pm 3	7 \pm 0	95 \pm 7	62 \pm 1	6 \pm 0
Litter, 0 to 2 cm	185 \pm 17	81 \pm 17	9 \pm 3	180 \pm 11	84 \pm 11	9 \pm 2
Fragmented litter, 2 to 7 cm	454 \pm 91	118 \pm 12	15 \pm 2	539 \pm 63	101 \pm 14	12 \pm 2
Fragmented litter, 7 to 10 cm	493 \pm 76	165 \pm 19	20–39*	494 \pm 77	136 \pm 7	18 \pm 1
Humus, 10 to 16 cm	1170 \pm 90	150 \pm 31	42–51*	1150 \pm 165	191 \pm 14	23–33*
Humus, 16 to 20 cm	1620 \pm 230	21 \pm 16	53 \pm 1	910 \pm 105	195 \pm 17	34–50*
Humus, 20 to 40 cm	3410, 1846	9.4, -14.3	53, 57	6440 \pm 815	14 \pm 15	59 \pm 7
Humus, 40 to 60 cm				7660 \pm 700	-99 \pm 14	780 \pm 120
Humus, 60 to 80 cm				7380 \pm 1760	-194 \pm 9	1670 \pm 90
Humus, 80 to 100 cm				5620, 3650	-285, -267	2628, 2432

*The mean age is within the given interval in samples that include the 1960s peak in bomb ^{14}C .

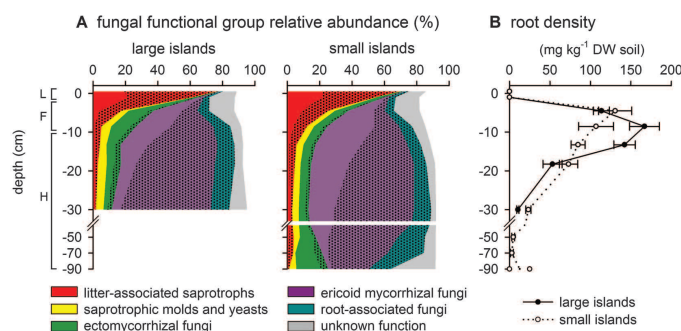


Fig. 2. Depth profiles of the relative abundance of fungal functional groups (percent of amplified ITS sequences) (**A**) and root (1 to 5 mm in diameter) density (**B**) on large and small forested islands. The profile corresponds to the organic layers L, F, and H. Functional groups comprise identified species with known function (unshaded) and species putatively assigned to a function (shaded) (17). The data set contains 650,000 sequence reads, and the globally most abundant 583 clusters are analyzed, covering 82 to 95% of the reads in individual sample types. The total ITS copy number was not affected by island size but decreased with depth (with 3×10^3 , 4×10^3 , and 2×10^4 copies g^{-1} of organic matter in L, F, and H layers, respectively) (table S1). The abundances of different functional groups should be compared with caution because of possible differences in ITS copy numbers per unit of biomass. All values are based on means of $n=10$ islands (except that $n=2$, 5, and 7 for the lowest horizons) (17).

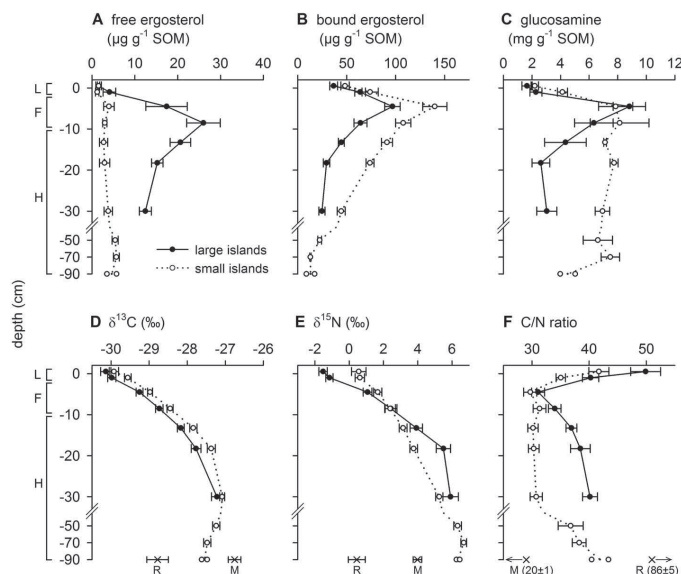


Fig. 3. Depth profiles of fungal biochemical markers (**A** to **C**), $\delta^{13}\text{C}$ (**D**), $\delta^{15}\text{N}$ (**E**), and the C/N ratio (**F**) in organic soil profiles of large (solid lines) and small (broken lines) forested islands. All data are means \pm SE, $n=10$ (except that $n=3$ for glucosamine and $n=2$, 5, and 7 for the lowest horizons) (17). Medium-sized islands are not shown but are included in the statistical analyses presented in table S1. In the lower panel, levels measured in roots (R) 1 to 5 mm in diameter and mycorrhizal mycelium (M) sampled at 10 cm depth are given for reference.

decomposition of fungal residues as an important regulator of C accumulation as the chronosequence proceeds.

The often observed increases in ^{13}C and ^{15}N abundances with soil depth have been interpreted as evidence of increasing contributions of enriched microbial components to residual soil organic matter (22–24). In our system, where the dominant plant species form ecto- or ericoid mycorrhizal associations, the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures in the uppermost organic layers were similar to those of leaves (25), whereas signatures in humus layers were closer to those of rhizosphere mycelium (Fig. 3, D and E, and table S1) and mycorrhizal fungal sporocarps (26). Plant C allocated belowground is relatively enriched in ^{13}C , and this enrichment is further accentuated during C transfer to mycorrhizal fungi (27). However, historic changes in atmospheric $\delta^{13}\text{C}$ (28) may also contribute to the depth gradient (22, 24). Mycorrhizal fungi also have higher $\delta^{15}\text{N}$ signatures than their host plants, because they supply N to their hosts that is ^{15}N -depleted relative to that retained in their own mycelium (29). Thus, the incorporation of isotopically enriched root and fungal remains is likely to be an important mechanism behind the increasing stable isotope signatures with soil depth in this system. This is consistent with the observation that isotopic signatures remain relatively constant in the initial litter decomposition phase and only increase when root-associated fungi dominate C and N dynamics (Figs. 2 and 3) (30, 31).

Previous studies in this (6, 14) and other (3, 4) systems have pointed to the input and quality of aboveground litter as important regulators of C and N sequestration during long-term ecosystem development and succession. Our results show that aboveground plant litter dynamics on its own cannot explain the increasing rate of organic matter accumulation with time since wildfire, and that the dynamics of roots and associated fungi is an important additional factor explaining C accumulation in boreal forests. Although we observe less C accumulation on large islands, it is reasonable to assume that C allocation to roots and associated mycelium is greatest on those islands, especially given their higher root densities (Fig. 2B), free ergosterol levels (Fig. 3A), and net primary productivity (6). This apparent contradiction corroborates recent results (32, 33) showing that increased C input to roots in response to CO_2 enrichment accelerates the turnover of soil organic matter, counteracting C accumulation and enhancing N cycling through the microbial pools. In our system, a similar stimulation of N recycling by large C inputs is supported by the steeper ^{15}N gradient (31) and higher C:N-ratio in the humus of large islands (Fig. 3, E and F) (30). In contrast, the less steep ^{15}N gradient and lower C:N-ratio on smaller islands suggest impaired mycorrhizal N mobilization (31) and accumulation of N in biochemically stabilized fungal remains, consistent with the high levels of bound ergosterol and

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chitin on those islands. The consequential reduced N availability to plants leads to progressive nutrient limitation and compositional changes in the vegetation with increasing time since a major disturbance (14, 34). Changes in plant productivity and community composition may, in turn, influence total belowground C allocation and distribution to fungal associates. Together, these feedbacks result in continuing C and N accumulation in the humus layer and decreasing plant production, and this process is only reset by major disturbances, such as wildfire.

Our results elucidate the mechanisms underpinning C sequestration in boreal forests and highlight the importance of root-associated fungi for ecosystem C balance and, ultimately, the global C cycle. We challenge the previous dogma that humus accumulation is regulated primarily by saprotrophic decomposition of aboveground litter, and envisage an alternative process in which organic layers grow from below through the continuous addition of recently fixed C to the organic matter profile in the form of remains from roots and associated mycelium. Environmental changes, such as N fertilization and deposition, forest management, and elevated atmospheric CO₂ concentrations, are therefore likely to greatly affect soil C sequestration through their alteration of rhizosphere processes. These processes are not well described in current models of ecosystem and global C dynamics, and their more explicit inclusion is likely to improve both the mechanistic realism and future predictive power of models.

References and Notes

- G. B. Bonan, H. H. Shugart, *Annu. Rev. Ecol. Syst.* **20**, 1 (1989).
- W. M. Post, W. R. Emanuel, P. J. Zinke, A. G. Stangenberger, *Nature* **298**, 156 (1982).
- W. K. Cornwell et al., *Ecol. Lett.* **11**, 1065 (2008).
- V. Brovkin et al., *Biogeosciences* **9**, 565 (2012).
- M. Makkonen et al., *Ecol. Lett.* **15**, 1033 (2012).
- D. A. Wardle, G. Hörmberg, O. Zackrisson, M. Kalela-Brundin, D. A. Coomes, *Science* **300**, 972 (2003).
- P. Höggberg et al., *Nature* **411**, 789 (2001).
- A. Heinemeyer, I. P. Hartley, S. P. Evans, J. A. C. De la Fuente, P. Ineson, *Glob. Change Biol.* **13**, 1786 (2007).
- D. Godbold et al., *Plant Soil* **281**, 15 (2006).
- F. A. Dijkstra, W. X. Cheng, *Ecol. Lett.* **10**, 1046 (2007).
- J. E. Drake et al., *Ecol. Lett.* **14**, 349 (2011).
- M. Heimann, M. Reichstein, *Nature* **451**, 289 (2008).
- D. A. Wardle, O. Zackrisson, G. Hörmberg, C. Gallet, *Science* **277**, 1296 (1997).
- D. A. Wardle et al., *J. Ecol.* **100**, 16 (2012).
- M. Jonsson, D. A. Wardle, *Biol. Lett.* **6**, 116 (2010).
- J. B. Gaudinski, S. E. Trumbore, E. A. Davidson, S. H. Zheng, *Biogeochemistry* **51**, 33 (2000).
- Materials and methods are available as supplementary materials on Science Online.
- K. Ihrmark et al., *FEMS Microbiol. Ecol.* **82**, 666 (2012).
- J. P. Yuan, H. C. Kuang, J. H. Wang, X. Liu, *Appl. Microbiol. Biotechnol.* **80**, 459 (2008).
- H. Wallander, U. Johansson, E. Sterkenburg, M. Brandström-Durling, B. D. Lindahl, *New Phytol.* **187**, 1124 (2010).
- A. Ekblad, H. Wallander, T. Näsholm, *New Phytol.* **138**, 143 (1998).
- J. R. Ehrlinger, N. Buchmann, L. B. Flanagan, *Ecol. Appl.* **10**, 412 (2000).
- E. A. Hobbie, A. P. Oumette, *Biogeochemistry* **95**, 355 (2009).
- B. Boström, D. Comstedt, A. Ekblad, *Oecologia* **153**, 89 (2007).
- F. Hyodo, D. A. Wardle, *Rapid Commun. Mass Spectrom.* **23**, 1892 (2009).
- A. F. S. Taylor, P. M. Fransson, P. Höggberg, M. N. Höggberg, A. H. Plamboeck, *New Phytol.* **159**, 757 (2003).
- E. A. Hobbie, R. A. Werner, *New Phytol.* **161**, 371 (2004).
- R. J. Francey et al., *Tellus B Chem. Phys. Meteorol.* **51**, 170 (1999).
- P. Höggberg et al., *Oecologia* **108**, 207 (1996).
- B. D. Lindahl et al., *New Phytol.* **173**, 611 (2007).
- P. Höggberg et al., *New Phytol.* **189**, 515 (2011).
- R. P. Phillips et al., *Ecol. Lett.* **15**, 1042 (2012).
- L. Cheng et al., *Science* **337**, 1084 (2012).
- O. Albertson, T. W. Kuyper, A. Gorissen, *Plant Soil* **296**, 159 (2007).

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Supplementary Materials

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The Biological Underpinnings of Namib Desert Fairy Circles

Norbert Juergens

The sand termite *Pseudotermes allocerus* generates local ecosystems, so-called fairy circles, through removal of short-lived vegetation that appears after rain, leaving circular barren patches. Because of rapid percolation and lack of evapotranspiration, water is retained within the circles. This process results in the formation of rings of perennial vegetation that facilitate termite survival and locally increase biodiversity. This termite-generated ecosystem persists through prolonged droughts lasting many decades.

Fairy circles (FCs) are large, conspicuous, circular patches devoid of vegetation in the center but with perennial grasses at the margin. These patches occur in large numbers in the desert margin grasslands of southern Africa (Fig. 1, A and B). Early observers considered poisonous plants, ants, or termites as causal factors; however, most of these early hypotheses were systematically tested and rejected (1, 2). It has also been proposed that an unknown semivolatile substance in the soil might be respon-

sible for the absence of grass within the FCs (2, 3). In fact, a wide range of volatile organic compounds are found in FCs (4). Measurements of carbon monoxide and hydrocarbons in the soil led to the proposal of a geochemical origin of FCs (5). Carnivorous ants (6) and "self-organizing vegetation dynamics" (7) have also been considered as causes for FCs. Despite the many hypotheses, the origin and the ecosystem function of FCs are still a much-debated mystery. I used a long-term data set describing the environmental and biogeographical characteristics and dynamics of FCs to identify the most likely cause of these unique formations. Additionally, I analyze the function of FCs in terms of

water management, biodiversity, and adaptation to arid conditions.

FCs occur along a narrow belt at the eastern margin of the Namib Desert, running from mid-Angola to northwestern South Africa. The area of distribution is closely associated with the isohyet of 100-mm mean annual precipitation (MAP) (Fig. 1B). The disjunct occurrence of FCs is caused by their pronounced restriction to sandy soils.

High soil humidity within FCs has been observed previously (1, 2). To confirm and quantify this potentially adaptive function, I measured volumetric soil water content ($m^3/m^3 \times 100$) from 2006 to 2012 within and around FCs. At sites with a MAP of 100 mm, more than 53 mm of water were stored in the upper 100 cm of soil, even during the driest time of the year (table S1). At a depth >40 cm, a soil humidity of more than 5% volumetric water content was recorded over 4 years.

Higher temporal resolution of water flux was gained by automatic measurements recorded every hour within the bare patch and the grass matrix at 10-, 30-, 60-, and 90-cm depths using FDR sensors. During the observation period of 4 years, the humidity at 60-cm depth within the FC was either at or well above 5% volumetric water content (Fig. 2A). In the typical sand texture of FC soils with dominant grain sizes around

BioCenter Klein Flottbek, University of Hamburg, Ohnhorststrasse 18, 22609 Hamburg, Germany. E-mail: norbert.juergens@t-online.de



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Supplementary Materials for

Roots and Associated Fungi Drive Long-Term Carbon Sequestration in Boreal Forest

K. E. Clemmensen,* A. Bahr, O. Ovaskainen, A. Dahlberg, A. Ekblad, H. Wallander, J. Stenlid, R. D. Finlay, D. A. Wardle, B. D. Lindahl

*Corresponding author. E-mail: karina.clemmensen@slu.se

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Model Code S1
References (35–48)

1 **Supplementary materials:**

2

3 **Materials and Methods**

4

5 Field sampling

6 The study was conducted in a boreal forest chronosequence situated on a series of forested
7 islands in the two adjacent Swedish lakes, Lake Hornavan and Lake Uddjaure (65°55' N to
8 66°09' N; 17°43' E to 17°55' E) in N Sweden (6, 13). We studied 30 islands that represent three
9 size classes: 10 large islands (>1.0 ha; on average 6.2 kg C m⁻² accumulated belowground; mean
10 time since fire 585 years), 10 medium islands (0.1 to 1.0 ha; 11.2 kg C m⁻²; 2180 years), and 10
11 small islands (<0.1 ha, 22.5 kg C m⁻²; 3250 years).

12

13 In August 2009, ten 3-cm diameter soil cores at least 10 m apart were sampled from each island
14 using a PN425 JMC Sub-Soil Probe PLUS (JMC Soil Samplers, Newton, USA). The full humus
15 depth of up to 1.2 m was sampled directly into separate plastic tubes and the cores were frozen
16 within a few hours after sampling and kept intact until further processing. In the laboratory, the
17 ten cores from each island were sorted according to organic layer thickness represented by the
18 depth of the coring hole measured in the field (mineral parts subtracted if present). The shortest
19 and longest cores out of the ten were discarded. The remaining eight cores were split into 20-cm
20 horizons, accounting for their compression in the sampling tubes, as estimated by sample length
21 in tube divided by depth of coring hole. The uppermost 20 cm was further split into two litter (L)
22 horizons (intact litter on the surface and more degraded intact litter in the upper 0-2 cm of the
23 core), two fragmented litter (F) horizons (2-7 and 7-10 cm depth) and two humus (H) horizons

(10-16 and 16-20 cm depth), representing sequentially more decomposed organic material by depth. Material from the same horizon was pooled within each island; living roots and rhizomes with a diameter of >1 mm were removed, and remaining organic matter homogenized, freeze-dried, weighed and milled to a fine powder before sub-sampling for further analyses. The island system consisted of a continuum of humus depths. From small islands we sampled up to 10 horizons, with the 60-80 cm horizon present on seven islands (i.e. $n=7$ for this depth), and the 80-100 cm horizon present on $n=2$ islands. For medium islands, the three lowest horizons (20-40, 40-60, 60-80 cm) were present on $n=9$, $n=5$ and $n=2$ replicate islands. For large islands, the lowest horizon (20-40 cm) was present on $n=7$ replicate islands. All other horizons were represented by $n=10$ islands. In total the data set consisted of 232 soil samples.

To obtain reference data from potential sources of soil organic matter (apart from roots collected from soil cores), fungal mycelium was sampled with sand-filled (20 g) 50 μ m mesh fungal ingrowth bags (35). The bags (2 per island) were incubated at 10 cm depth from August 2005 to August 2006. The sand was extracted in water and mycelium floating in the water phase collected and freeze-dried. Due to small sample sizes mycelium was pooled within island size classes, yielding 3 composite samples per island size class.

Chemical analyses

All soil samples, roots and mycelium were analyzed for total C and N, as well as ^{13}C : ^{12}C and ^{15}N : ^{14}N ratios on an Isoprime isotope ratio mass spectrometer (Micromass-GV Instruments, Manchester, UK) coupled to an Eurovector CN elemental analyzer (model EuroEA3024; Eurovector, Milan, Italy) using continuous flow. Natural abundance of isotopes is expressed in

47 the δ -notation relative to international standards, Vienna Pee Dee Belemnite for C and
48 atmospheric N₂ for N; $\delta X_{\text{sample}} (\text{‰}) = 1000 \times [(R_{\text{sample}}/R_{\text{standard}}) - 1]$ where R is the molar ratio of
49 heavyX:lightX isotope. The standard deviations of isotopic measurements of the working standards
50 used were $\pm 0.1\text{‰}$ for $\delta^{15}\text{N}$ and $\pm 0.05\text{‰}$ for $\delta^{13}\text{C}$.

51
52 The ^{14}C content was analyzed on profiles from a representative subset of three small and three
53 large islands, totaling 49 samples. The $^{14}\text{C}:^{12}\text{C}$ ratio in the dried and milled bulk organic material
54 was analyzed by accelerator mass spectrometry at the Tandem Laboratory (Uppsala University,
55 Sweden). Radiocarbon data are expressed as $\Delta^{14}\text{C}$, defined as the difference between the $^{14}\text{C}:^{12}\text{C}$
56 ratio in the sample and that of a universal standard (oxalic acid I, decay-corrected to 1950). For
57 calculation of $\Delta^{14}\text{C}$, sample ^{14}C activity was corrected for isotopic discrimination after C fixation
58 by correcting sample ^{13}C content to that of the atmosphere.

59
60 Ergosterol was analyzed in freeze dried and milled soil from each of the pooled samples using
61 the method described by Nylund and Wallander (36) with some adjustments. To analyze free
62 ergosterol, 5 ml methanol was added to 100 mg soil while 5ml 10% KOH in methanol was added
63 to 50 mg soil for analysis of total ergosterol. Apart from those differences both free and total
64 ergosterol was analyzed using the same protocol. The samples were extracted with a 15 min
65 sonication and 1 h incubation at 70°C in a water bath. Distilled water (1 ml) was added to
66 increase the polarity and 2 ml cyclohexane to serve as a lipophilic phase. After shaking for 1 min
67 on a multivortex, samples were centrifuged for 5 min at 1000 g before collection of the lipophilic
68 supernatant. The phase separation was then repeated once more after addition of another 2 ml of
69 cyclohexane. The supernatant samples were evaporated on a 40°C heating block under nitrogen

70 gas flow (to prevent oxidation) and then extracted in 200 µl methanol and filtered through a 0.45
71 µm titan syringe filter (44504-NPC by Sun sri, USA) before they were analysed in a reversed-
72 phase column (C18 column: Chromolith model by Merck, C18 pre-column: Elite LaChrome
73 model by Hitachi, Japan) high-performance liquid chromatograph (auto sampler L2130 with UV-
74 detector L2400 by Hitachi, Japan) with a flow rate of 1 ml min⁻¹. The ergosterol peak was
75 detected at 280 nm.

76

77 The chitin content was measured using HPLC as described by Ekblad and Näsholm (37). In
78 short, 10 mg of freeze dried and milled material was treated with 0.2 N NaOH to remove protein
79 and amino acids. Glucosamine residues were released by acid hydrolysis with 6 N HCl and
80 converted to fluorescent derivatives by treatment with 9-flourenylmethylchloroformate.
81 Separation and detection of FMOC-derivatives was carried out on a Waters liquid
82 chromatograph system consisting of a 600E pump and a WISP 700 autoinjector. Reversed-phase
83 separation was carried out at a flow rate of 1 ml min⁻¹ on a 250 mm x 5 mm (I.D.) ODS-hypersil
84 (5 µm) column. The column effluent was directed to a Waters 740 fluorescence detector
85 (excitation 260 nm, emission 330 nm). Chitin content was corrected for a recovery rate of 81%.

86

87 Fungal communities

88 Freeze-dried organic matter (50 mg) was extracted in 1.5 ml CTAB buffer (3%
89 cetyltrimethylammonium bromide, 2 mM EDTA, 150 mM Tris-HCl and 2.5 M NaCl, pH 8) at
90 65°C for 1½ h interrupted twice for homogenization (Precellys 24, Bertin Technologies,
91 Montigny-le-Bretonneux, France). After centrifugation, the supernatant was extracted once with
92 one volume of chloroform. The DNA was then precipitated from the supernatant with 1.5

93 volumes of 2-propanol at -20°C overnight. After centrifugation, the pellet was washed once with
94 70% cold ethanol and re-suspended in water. The resulting 50 µl DNA extracts were cleaned
95 with the Wizard DNA clean-up system using a vacuum manifold (Promega, Madison, USA) and
96 stored at -20°C.

97

98 The content of extractable fungal DNA was estimated using the ITS region of the ribosome
99 encoding genes as a marker. The forward primer fITS9 (18) and the reverse primer ITS4 (38)
100 were used to target the fungal ITS2 region, using a SYBR green mix (Maxima SYBR
101 Green/Fluorescein qPCR Master Mix, Fermentas, Sweden) in a quantitative PCR cycler (Bio-
102 Rad iQ5, Life Technologies, Carlsbad, CA, USA). The DNA extracts were diluted 40-4000 times
103 in 20 µl PCR reactions, with 1 µM of the fITS9 primer and 0.3 µM of ITS4 primer. The PCR
104 was run under the following conditions: 10 min at 95°C and 40 cycles of 15 s at 95°C, 20 s at
105 55°C, 45 s at 60°C and SYBR green was quantified during the 60°C elongation step. A dilution
106 series of plasmids containing an ITS insert from *Pilidium concavum* (Desm)HoeHN was used as a
107 standard. Samples and standards were run in triplicates, and the analysis was repeated with a
108 known quantity of standard plasmid added to each sample, in order to correct for PCR inhibition.
109

110 For production of fungal ITS2 amplicons for 454-sequencing, the two forward primers fITS9 and
111 gITS7 (18) were used in separate reactions in combination with the ITS4 primer in order to
112 maximize coverage of the fungal community. The ITS4 primer was extended with a sample-
113 specific 8bp long identification tag, which was generated using the Barcrawl software (39).
114 Analysis by PCR was conducted with an initial denaturation phase of 5 min at 95°C and 24 - 35
115 cycles of 30 s at 95°C, 30 s at 55°C (fITS9) or 56°C (gITS7) and 30 s at 72°C, and a final

116 elongation phase of 7 min at 72°C. The PCR mix consisted of 0.2 mM dNTPs, 0.75 mM MgCl₂,
117 0.3 µM of ITS4 primer, 1 µM of fITS9 or 0.5 µM of gITS7 primer and 0.5 U of DNA
118 polymerase (Dream Taq, Fermentas) in 50 µl reactions. The number of cycles (22-35) was
119 optimized to reach the exponential phase of the PCR reaction for each sample as determined by
120 qPCR results. Samples were run in technical triplicates that were inspected on a 1% agarose gel
121 and pooled. Amplicons were then purified with the AMPure PCR purification kit (Agencourt
122 Bioscience Corporation, Beverly, MA, USA) and DNA concentrations were measured by
123 spectrophotometry (NanoDrop 1000, Thermo Scientific, Wilmington, DE, USA). Aliquots of
124 each sample containing equal amounts of PCR product were pooled, concentrated by freeze-
125 drying, re-suspended and further purified by the GeneJET PCR purification columns
126 (Fermentas). Adaptor ligation and 454-sequencing were performed by LGC Genomics GmbH
127 (Berlin, Germany) on a GL FLX Titanium system (Roche, Basel, Switzerland).
128
129 Sequences were processed using the bioinformatic pipeline SCATA
130 (<http://scata.mykopat.slu.se/>). Sequences with an average quality score below 20 or below 10 at
131 any single position were discarded, using the high quality region (HQR) extraction option.
132 Sequences with missing primer sequences or identification tags were also discarded, allowing for
133 one mismatch in each of the primer sequences. Out of the total of 442994 and 456918 sequences
134 obtained for the fITS9 and gITS7 datasets respectively, 316211 and 351122 sequences passed
135 this quality control. After removing primer and tag sequences, an additional 44 bp were removed
136 from sequences obtained with the fITS9 forward primer to equalize sequence lengths in the two
137 data sets. This left 41 bp of the conserved 5.8S region, 105-317 bp (on average 185 bp) of the
138 ITS2 region and 38 bp of the LSU, on which the clustering was based. Sequences were compared

139 for similarity using BLAST as a search engine, with the minimum length of pairwise alignments
140 set to 90% of the longest sequence. Pairwise alignments were scored using a scoring function
141 with 1 in penalty for mismatch, 0 for gap opening and 1 for gap extension. Homopolymers were
142 collapsed to 3bp before clustering. Sequences were assembled into clusters by single-linkage
143 clustering with a 98.5% sequence similarity required to enter clusters.

144

145 For species identifications, the entire UNITE database (40) and a curated selection of sequences
146 from the NCBI nr database were included in the clustering procedure in SCATA providing some
147 species identifications based on the same criteria as the clustering. For identification of clusters
148 with no in-cluster reference, the most abundant genotype was compared to databases using the
149 BLASTn algorithm. Based on this, all clusters were split into major phylogenetic groups of fungi
150 (Basal lineages, Leotiomycetes, Eurotiomycetes, other Ascomycota, Basidiomycota) and most
151 abundant genotype aligned together with selected reference sequences using ClustalW (41) in
152 MegAlign (DNASTAR Lasergene 9). Relatedness of the aligned sequences was investigated by
153 neighbor-joining (NJ) analysis with total character difference using PAUP* 4.0b10 (AltiVec;
154 42). Fungal clusters were then assigned to known or putative functional groups based on their
155 placement in relation to reference sequences in the NJ trees (Fig. S3A-E); i.e. we employed a
156 phylogenetically and taxonomically flexible delimitation level of functional groups guided by
157 external reference sequences downloaded from public databases. Fungi identified to species or
158 genera with a well-known function or life-form (based on published literature) were categorized
159 into the functional groups: “Litter-associated saprotrophs”, “Ectomycorrhizal fungi”, “Ericoid
160 mycorrhizal fungi” or “Molds and yeasts”. Fungi included in supported clades representing
161 either a higher phylogenetic level with common function (*i.e.* Archaeorhizomycetes) or a group

of reference sequences derived from a particular substrate (*i.e.* surface-sterilized roots of ectomycorrhizal- or ericoid hosts or litter) were categorized into putative functional groups: “Putative litter-associated saprotrophs”, “Putative ectomycorrhizal fungi”, “Putative ericoid mycorrhizal fungi” or “Putative root-associated fungi”. “Molds and yeasts” are free-living saprotrophs and this group contained clusters included in the major clades of Mucorales, Mortierellales, Saccharomycetales, Microbotryomycetes, Tremellales as well as *Penicillium* and *Trichoderma* spp.. “Putative litter-associated saprotrophs” included litter degraders, such as unidentified *Mycena* spp., and endophytes and pathogens isolated from litter materials (persisting as saprotrophs in dead litter). “Putative root-associated fungi” included species matching reference sequences isolated from roots or rhizoids (other than ericoid or ectomycorrhizal), such as Archaeorhizomycetes, as well as fungi with uncertain mycorrhizal status. Clusters of low abundance identified as lichens or pathogens on soil animals were left in the group of species with unknown function.

175

For establishment of relative abundance of fungal sequence clusters, all non-fungal sequence reads (on average 2% and 15% of the sequences obtained with primers fITS9 and gITS7, respectively) were removed from the data. Thereafter, each of the 233 samples were represented by on average 1329 (fITS9) plus 1275 (gITS7) reads. Potential differences in specificity of the two forward primers were tested by comparing the relative abundance across all samples of each cluster in amplicons obtained with the two primers. When one of the primers clearly disfavored a cluster (<30% of the other primer), data from the highest yielding primer was used, and the relative abundance of the rest of the clusters in each sample was adjusted accordingly (<0.5% of clusters affected). For all other clusters, relative cluster sizes were calculated as the average

185 between the amplicons obtained with the two different forward primers. In order to limit the
186 identification work load, only the globally most abundant 583 clusters were included in analyses,
187 covering 90% of all reads in the data set and with the smallest clusters represented by 70 reads.

188

189 Carbon sequestration model

190 A mathematical model was designed to estimate aboveground plant litter age in different
191 horizons, as well as the amount of non-decomposed C of above- and belowground origin. We
192 used an elaboration of the approach described by Franklin *et al.* (43). The model input data
193 include mass and ^{14}C abundance of sampled soil horizons, yearly deposition of aboveground
194 litter C (hereafter referred to as “litter C”), and previously acquired short term (2 years)
195 decomposition rates of litter C (6, 44). In contrast to other ^{14}C based soil C models (e.g. 45) an
196 assumption here is that the soil consists of a series of consecutively deposited cohorts of litter C
197 with insignificant vertical mixing, which makes the current model applicable to this soil type that
198 contains little activity of burrowing animals. Litter C is assumed to decompose over time
199 according to the equation of Bosatta and Ågren (46). Additionally, recently photosynthesized C
200 is deposited via roots and associated microorganisms at all depths in the humus layer (hereafter
201 referred to as “root C”).

202

203 *Model description*

204 We define the layer of soil that contains the litter C that was deposited on the ground t years ago
205 as the cohort t . We denote by $l(t)$ the mass of litter C (per square meter) in cohort $t = 0, 1, 2, \dots$
206 The age of the C that is deposited on the ground may not be zero and is thus given a parameter

207 a_0 to be estimated. The degradation of litter C is described according to the equation of Bosatta
 208 and Ågren (46):

$$l(t) = l(0)(1 + c_l t)^{-\gamma_l},$$

209

210 where $c_l > 0$ and $\gamma_l > 0$ are parameters. The above equation assumes stationarity, *i.e.* that the
 211 annual deposition of litter $l(0)$ has remained constant over the years.

212

213 We denote by $r(t, \Delta t)$ the mass of root C in cohort t that was deposited Δt years ago and is thus
 214 currently of age Δt . We denote by $s(t)$ the mass of root C that is added annually to cohort
 215 $t = 1, 2, \dots$. Here we also assume stationarity, *i.e.* that the amount of root C added to the system
 216 (and its distribution over the soil layers) has remained the same over the years. Thus, using the
 217 same decomposition model as for litter C, the root C follows the equation:

218

$$r(t, \Delta t) = s(t - \Delta t)(1 + c_r \Delta t)^{-\gamma_r},$$

219

220 where $c_r > 0$ and $\gamma_r > 0$ are parameters. The total amount of C in cohort t is $c(t) = l(t) +$
 221 $\sum_{\Delta t=0, \dots, t-1} r(t, \Delta t)$.

222

223 The average age of the C in cohort t is

224

$$a(t) = \frac{l(t)(t + a_0) + \sum_{\Delta t=0, \dots, t-1} r(t, \Delta t)\Delta t}{c(t)}.$$

225

226 The data are not directly on the average age of the C, but on the average ΔC_{14} value. We describe
 227 the relationship between ΔC_{14} and C age as $\Delta C_{14} = F(a)$, where the function F was
 228 parameterized according to records of stratospheric ^{14}C content of the Northern hemisphere
 229 during the last 50 years (47).

230

231 The average ΔC_{14} of C in cohort t is

232

$$\Delta C_{14}(t) = \frac{l(t)(F(t + a_0)) + \sum_{\Delta t=0, \dots, t-1} r(t, \Delta t)F(\Delta t)}{c(t)}.$$

233

234

235 *Data*

236 There are three kinds of data used to parameterize the model.

237 Soil samples: A soil sample consists of n_h horizons for which the total mass and the average
 238 ΔC_{14} age of the C have been determined. Each horizon h consists of an unknown number of
 239 sequential cohorts, e.g. first horizon of cohort 1, second of cohorts 2-4, third of cohorts 5-20, etc.

240 We denote the duration (the number of years each cohort stays in the horizon) of horizon h by

241 d_h . We denote the model-predicted amount of C in horizon h by c_h and the model-predicted

242 average ΔC_{14} age content of C in the horizon by z_h (these can be computed from the cohort-

243 based predictions). We denote the measurements of c_h and z_h by C_h and Z_h . We assume that the

244 measurements relate to the model-predicted values through a proportional error, modeled as

245 $C_h = c_h \exp(e_c)$, $Z_h = z_h \exp(e_z)$, where the error terms are distributed as $e_c \sim N(0, \sigma_c^2)$,

246 $e_z \sim N(0, \sigma_z^2)$.

247 Litter C deposition: The yearly amount of C in the litter deposited on the soil surface, i.e. $l(0)$,
 248 has been measured as combined tree litter fall (2000-2008 average), dwarf shrub production
 249 (2000-2008 average) and moss production (2010) (6, 44). We denote the measurement by $L(0)$
 250 and assume that $L(0) = l(0)\exp(e_l)$ with $e_l \sim N(0, \sigma_l^2)$.

251 Litter C decomposition bags: Bags of fresh litter ($t = 0$) were left to decompose on the soil
 252 surface and measured for their C content at times $t = 0$ and $t = 2$ (6). We denote these
 253 measurements as $B(0)$ and $B(2)$. As these measurements are likely to be more accurate (in
 254 relative terms) than the other measurements described above, we simplify the model
 255 parameterization by ignoring the measurement error, thus assuming that

$$B(2) = B(0)(1 + c_l t)^{-\gamma_l},$$

257 *i.e.* that

$$c_l = \frac{\left(\frac{B(2)}{B(0)}\right)^{-1/\gamma_l} - 1}{2}.$$

258

259 *Parameterization*

260 Root C input $s(t)$ is unknown for all values of t . To allow suitable flexibility but avoid over-
 261 parameterization, we assume that $s(t)$ is piecewise linear in the $\log t$ -scale, with values
 262 determined at $t = 1, 2, 4, 8, 16, 32, 64, 128$. For $t > 128$, we assume that $s(t) = s(128)$. This
 263 discretization roughly matches the resolution of the sampled horizons. In Model 1 we assume
 264 that $s(t) = 0$ for all t , *i.e.* that all stored C has its origin in aboveground plant litter. In Model 2
 265 we assume that $s(t) = 0$ for $t = 1, 2, 3, 4$, but otherwise $s(t)$ is a free function. The assumption
 266 that no root C enters the uppermost horizons is based on the absence of roots and DNA from

267 root-associated fungi in these layers (Fig. 2). We fixed the parameters $\gamma_l = \gamma_r = 1.19$ based on
 268 literature (46).

269

270 The parameters to be estimated are the following:

- 271 • Same for all islands: $s(t), \sigma_c, \sigma_z, \sigma_l$
- 272 • Specific to each island: $l(0), a_0, c_r$ and d_h , where $h = 1, 2, \dots$ is an index for the cohort

273 We set to log-transformed standard deviation parameters $\sigma_c, \sigma_z, \sigma_l$ a $N(0, 1^2)$ prior, i.e. normal
 274 distribution with mean zero and standard deviation 1. For a_0 we assume a uniform prior in the
 275 range $3 \leq a_0 \leq 5$. For the remaining parameters, i.e. for $s(t)$ with $t = 1, 2, 4, 8, 16, 32, 64, 128$,
 276 for $l(0)$ for each island, for the d_i parameters for each island, and for c_r , we set the essentially
 277 uninformative $N(0, 10^2)$ prior. Additionally, the horizon durations d_i were constrained to total at
 278 most 100 years.

279

280 We fitted the models to data using a slightly adapted version of the MCMC scheme of
 281 Ovaskainen *et al.* (48). Thus, the proposal distributions needed in the Metropolis-Hastings
 282 algorithm were adjusted adaptively during the burn-in (with 10,000 iterations) to obtain an
 283 optimal acceptance ratio, after which the posterior was sampled with 100,000 iterations thinned
 284 to 1,000 samples. The estimation was performed with Mathematica 8.0.

285

286 Statistical analyses

287 Differences in element, biochemical marker and root (1-5 mm) concentrations in organic profiles
 288 were analyzed by generalized linear mixed models, using the GLIMMIX procedure in the SAS
 289 9.3 package (Statistical Analysis System Institute, 2002-2010). To quantify overall effects of

290 island size and sampling layer (upper six horizons included, $n=180$), island size class ($df = 2$;
291 except $df = 1$ for chitin) and layer ($df = 5$) and their interaction ($df = 10$; $df = 5$ for chitin) were
292 defined as fixed factors. To account for possible dependency between measures at different
293 depths within individual islands, residual covariance structures were specified through
294 RANDOM statements. Layer was treated as a repeated measure with island as the subject and a
295 first-order autocorrelation structure. Satterthwaite-type of degrees of freedom based on the
296 Kenward-Roger adjustment were used to calculate Wald F test statistics of the fixed factors and
297 results were evaluated using Tukey's adjustment for multiple comparisons with $\alpha = 0.05$.
298 Residuals were tested for normality with the Shapiro-Wilk test. A lognormal distribution type
299 was specified for all data.

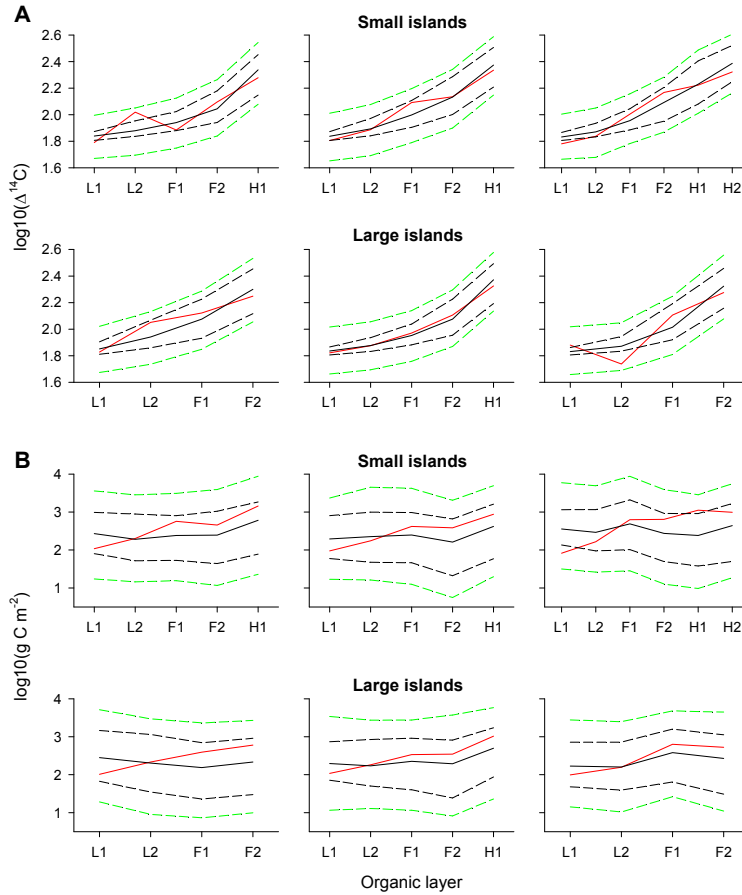


Fig. S1. Predictions of $\Delta^{14}\text{C}$ (A) and C mass (B) in sampled horizons by Model 1 allowing C input from aboveground litter only. Red lines show measured data and black lines show model posterior means. Broken lines represent the 95% central credibility intervals for the mean model predictions (black) and individual measurements (green).

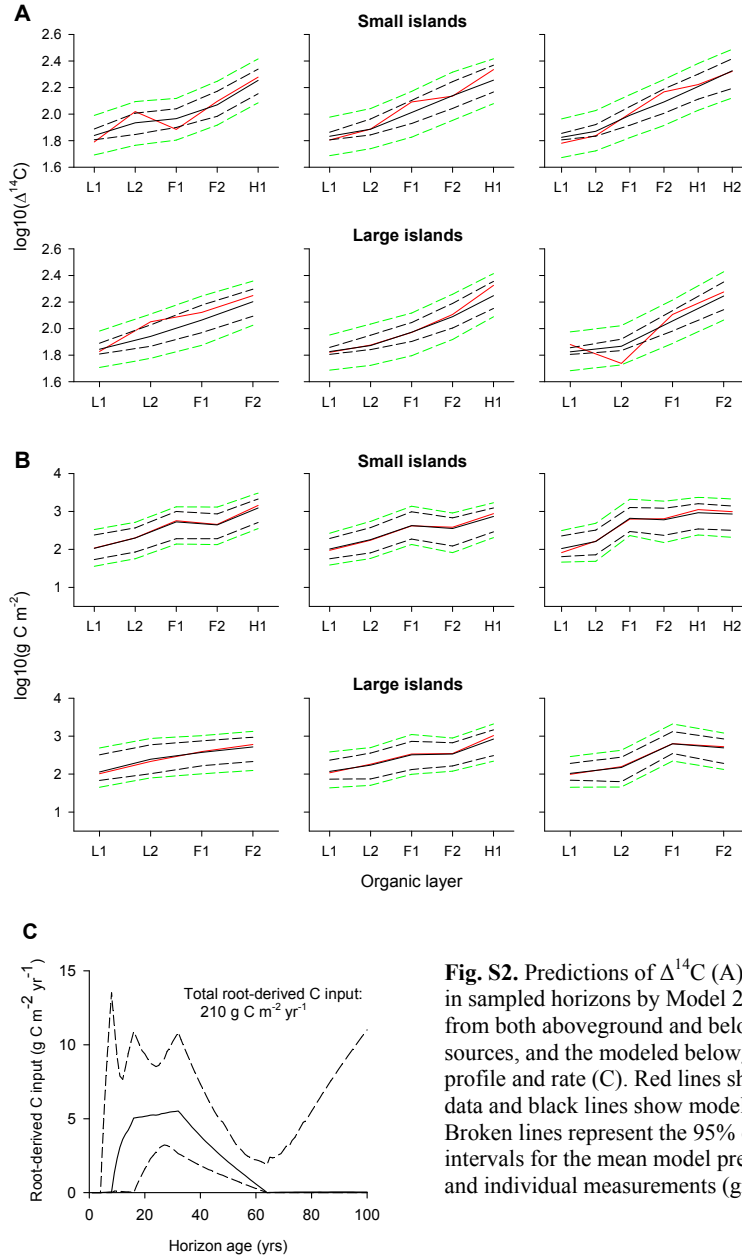


Fig. S2. Predictions of $\Delta^{14}\text{C}$ (A) and C mass (B) in sampled horizons by Model 2 with C input from both aboveground and belowground sources, and the modeled belowground C input profile and rate (C). Red lines show measured data and black lines show model posterior means. Broken lines represent the 95% central credibility intervals for the mean model predictions (black) and individual measurements (green).

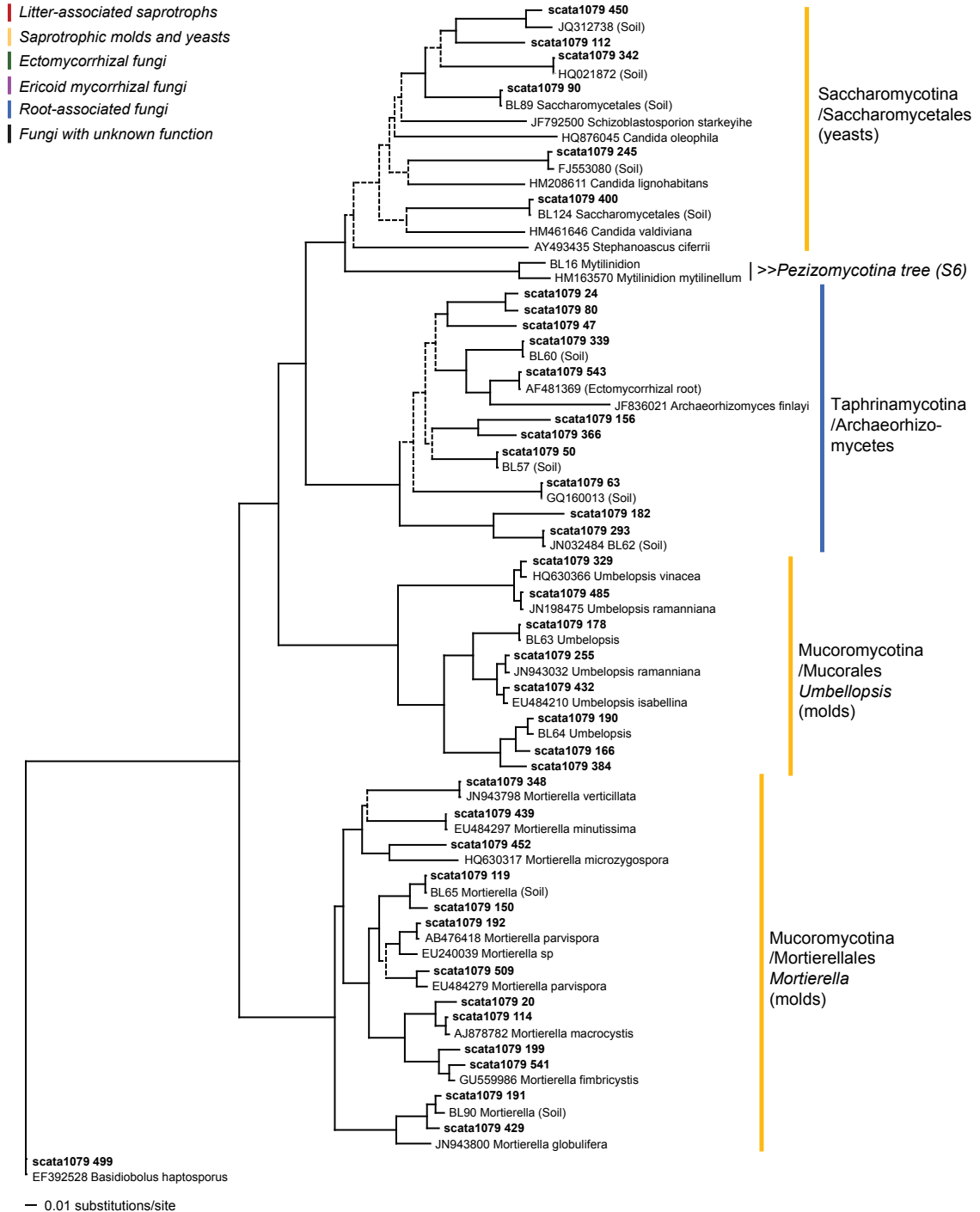
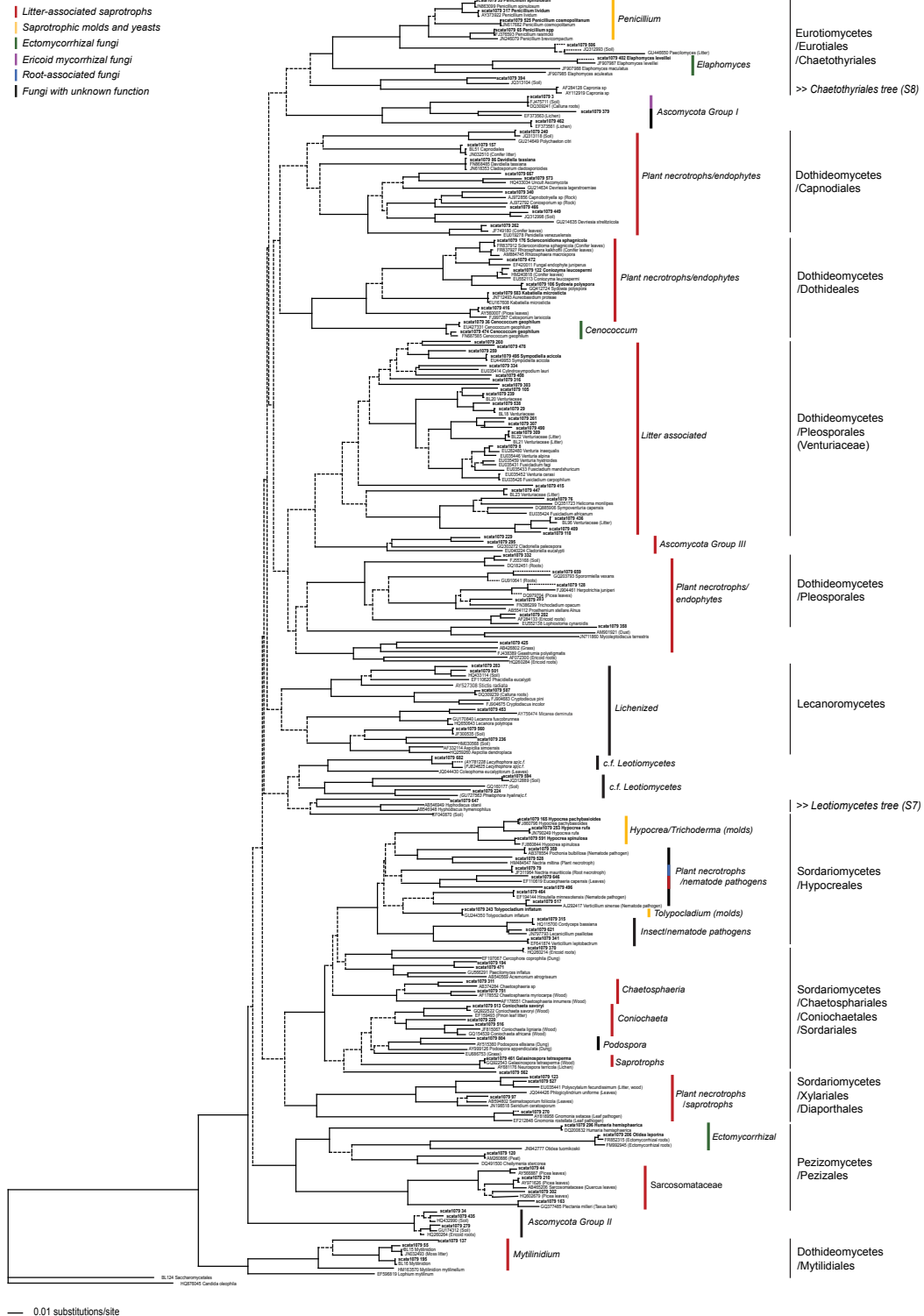


Fig. S3A. Neighbor-joining tree of representative sequences from obtained clusters (name in bold) and reference sequences belonging to Basal fungal lineages and basal clades of Ascomycota. Putative functional assignments are shown by color-coded bars. All branch nodes with boot-strap values of >70 have full lines; broken lines indicate boot-strap values of <70. More abundant clusters have lower identification number.



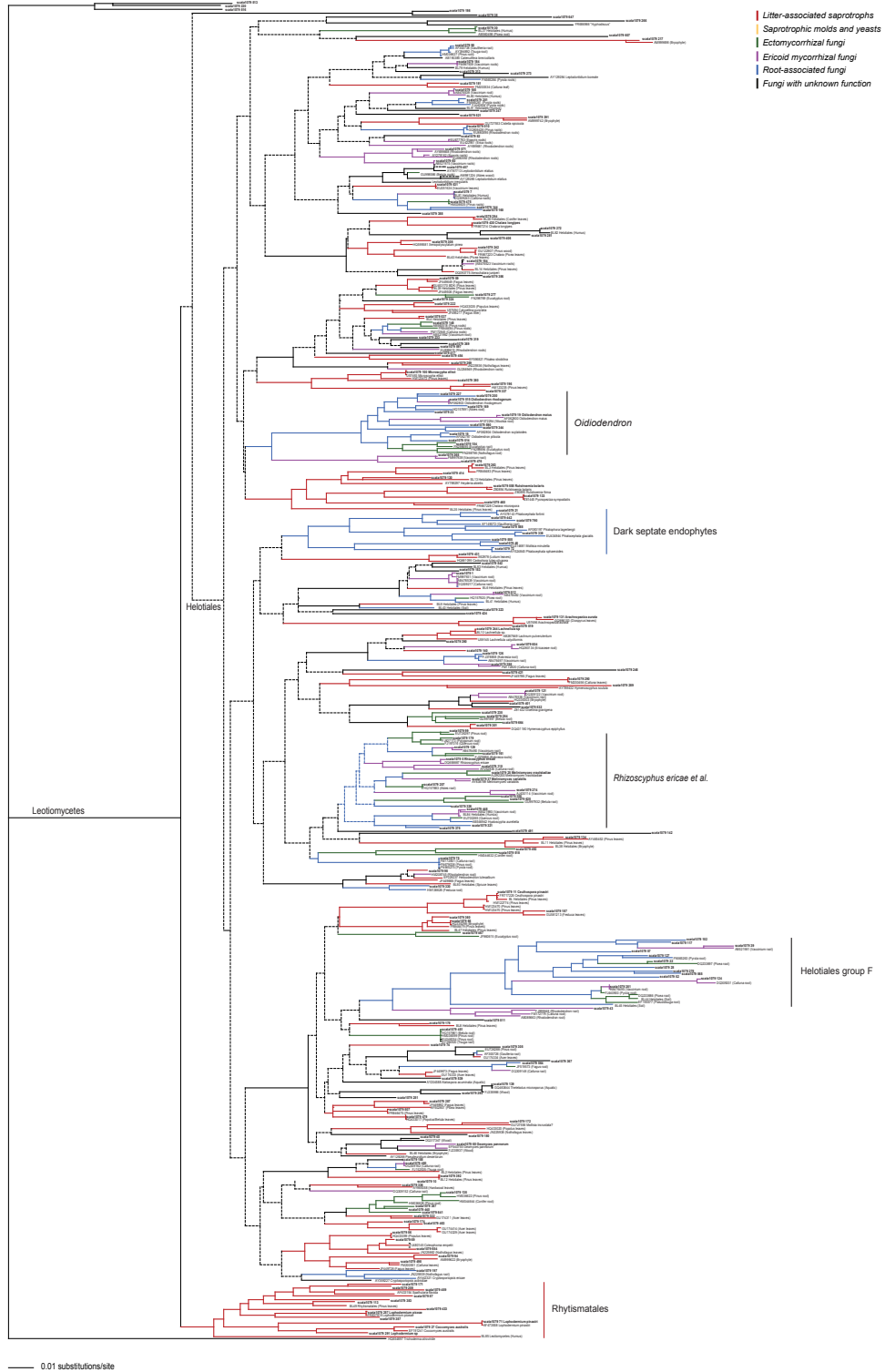


Fig. S3C. Neighbor-joining tree of representative sequences from obtained clusters (name in bold) and reference sequences belonging to Leotiomycetes (Pezizomycotina, Ascomycota). Putative functional assignments are shown by color-coded branches or bars; only identified clusters (with name indicated after sample ID number) are included in known functional groups. The environmental source material of reference sequences is shown in parentheses. Branch nodes with boot-strap values of >70 have solid lines; broken lines indicate boot-strap values of <70. More abundant clusters have lower identification number.

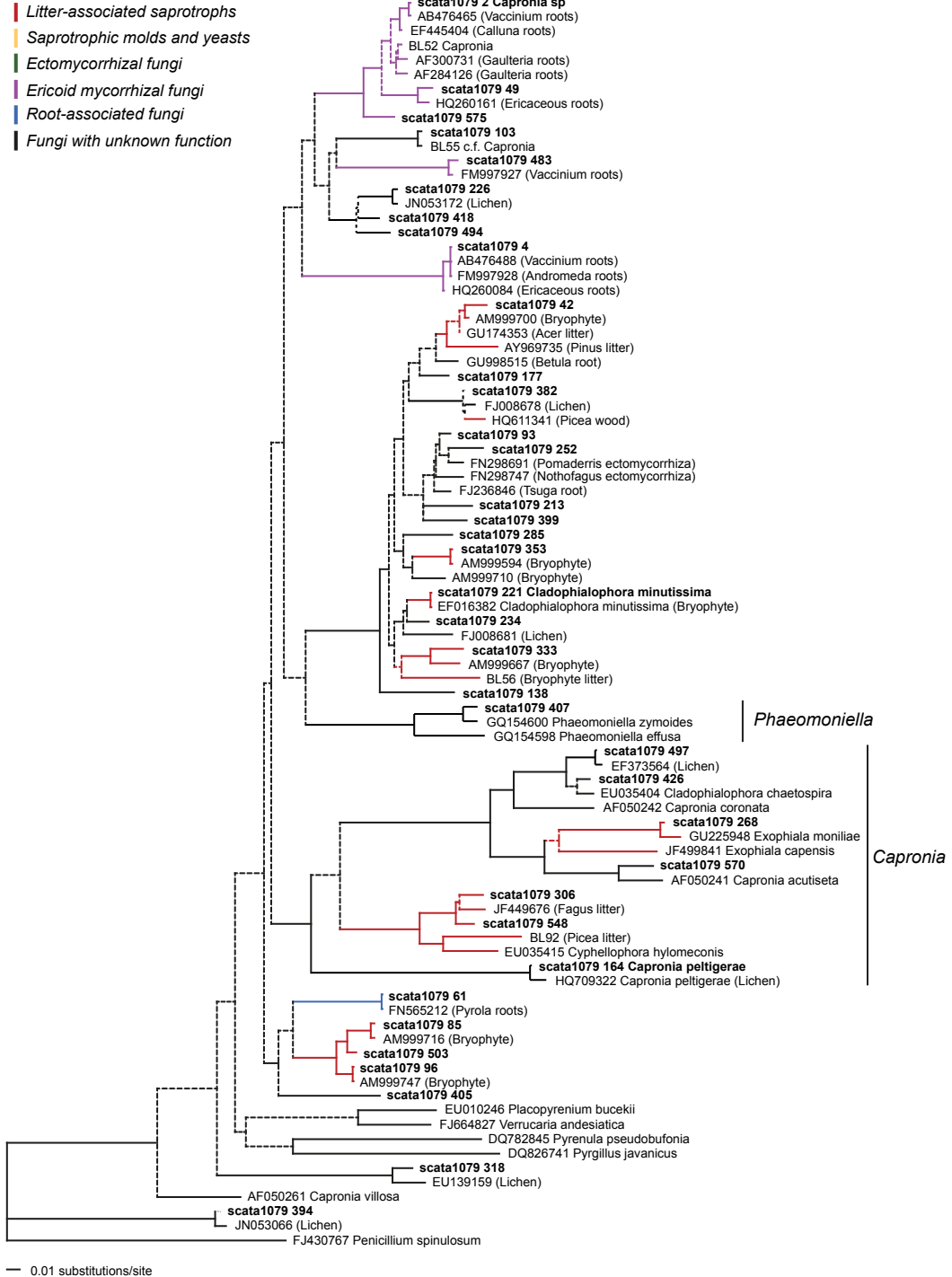


Fig. S3D. Neighbor-joining tree of representative sequences from obtained clusters (name in bold) and reference sequences belonging to Chaetothyriales (Eurotiomycetes, Pezizomycotina, Ascomycota). Putative functional assignments are shown by color-coded branches; only identified clusters (with name indicated after sample ID number) are included in known functional groups. The environmental source material of reference sequences is shown in parentheses. All branch nodes with boot-strap values of >70 have full lines; broken lines indicate boot-strap values of <70. More abundant clusters have lower identification number.

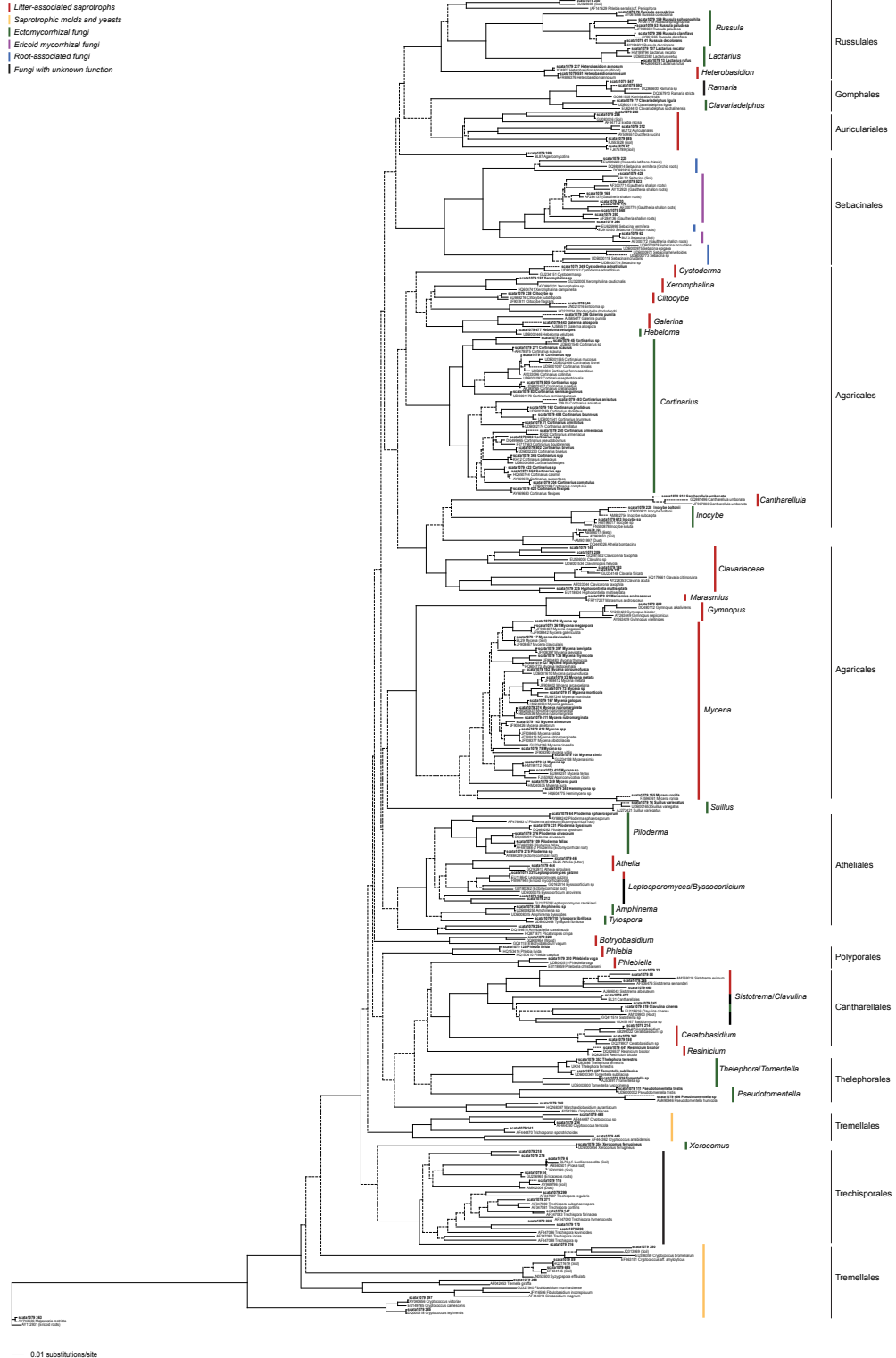


Table S1. *F* and *P* values derived from analyses of variance of results presented in Figs. 2 and 3. Island size class (three levels; two for glucosamine), organic layer (six levels; four for root density) and their interaction were included as fixed factors and layer treated as a repeated measure within each island (30 islands in total) in the random term of a generalized linear mixed model. Degrees of freedom (df) for *F* values (effect, error) were estimated using the Kenward-Roger adjustment.

variable	island size		layer		size x layer interaction	
	<i>F</i> _{df}	<i>P</i>	<i>F</i> _{df}	<i>P</i>	<i>F</i> _{df}	<i>P</i>
C/N ratio	9.64 _{2,37}	0.0004	44.33 _{5,130}	<0.0001	1.05 _{10,133}	0.4041
δ ¹³ C (‰)	5.69 _{2,39}	0.0069	312.65 _{5,131}	<0.0001	0.41 _{10,135}	0.9378
δ ¹⁵ N (‰)	1.80 _{2,38}	0.1798	260.32 _{5,135}	<0.0001	11.6 _{10,137}	<0.0001
Total ergosterol (mg g ⁻¹ SOM)	10.58 _{2,47}	0.0002	46.72 _{5,129}	<0.0001	1.40 _{10,134}	0.1863
Free ergosterol (μg g ⁻¹ SOM)	16.32 _{2,33}	<0.0001	17.40 _{5,126}	<0.0001	4.04 _{10,130}	<0.0001
Bound ergosterol (μg g ⁻¹ SOM)	20.74 _{2,44}	<0.0001	35.56 _{5,130}	<0.0001	2.68 _{10,134}	0.0051
Glucosamine (mg g ⁻¹ SOM)	6.10 _{1,6}	0.0466	13.56 _{5,19}	<0.0001	3.35 _{5,19}	0.0239
ITS copy numbers (g ⁻¹ SOM)	0.65 _{2,42}	0.5265	58.19 _{5,127}	<0.0001	0.20 _{10,132}	0.9958
Root density (mg kg ⁻¹ soil)	0.65 _{2,30}	0.5351	17.01 _{3,74}	<0.0001	2.62 _{6,77}	0.0228

Model code S1. (16 following pages)

The Mathematica 8.0 source code used to estimate the C sequestration model.

```
Needs["ErrorBarPlots`"];

sfunction[t_, st_, ss_] := Module[{res, ns, smaller},
  ns = Length[st];
  res = -1;
  If[t ≤ Min[st], res = ss[[1]]];
  If[t ≥ Max[st], res = ss[[ns]]];
  If[Min[st] < t < Max[st],
    smaller = Position[Sort[Append[st, t]], t][[1, 1]] - 1;
    res = ss[[smaller]] + (ss[[smaller + 1]] - ss[[smaller]]) *
      (Log[t] - Log[st[[smaller]]]) / (Log[st[[smaller + 1]]] - Log[st[[smaller]]]);
  ];
  N[res]];

SplitPars[pars_] := Module[{pars2, res, dh},
  pars2 = pars;
  res = {Take[pars2, 3], Take[pars2, {4, 3 + nt}], Take[pars2,
    {4 + nt, 4 + nt + nsites - 1}], Take[pars2, {4 + nt + nsites, 4 + nt + 2 nsites - 1}],
    Take[pars2, {4 + nt + 2 nsites, 4 + nt + 3 nsites - 1}]}];
  pars2 = Drop[pars2, 4 + nt + 3 nsites - 1];
  dh = {};
  Do[
    dh = Join[dh, {Take[pars2, nh[[i]]]}];
    pars2 = Drop[pars2, nh[[i]]];
    , {i, nsites}];
  res = Join[res, {dh}];
  res];

CarbonModel[pars_, site_, AdditionalOutput_] :=
Module[{c1, sigmac, sigmaz, sigmal, ss, a0, 10, cm, dh, ah, 1, dm, lineage, dmt,
  dmC14, s, m, tm, c, ma, mC14, tma, tmC14, a, C14x, mass, age, C14, res},
  c1 = lcl[[site]];
  {{sigmac, sigmaz, sigmal}, ss, a0, 10, cm, dh} = SplitPars[pars];
  ss = Exp[ss];
  ss = Join[{0, 0, 0}, ss];
  If[! source, ss = Table[0, {i, 3 + nt}]];
  a0 = Exp[a0[[site]]];
  10 = Exp[10[[site]]];
  cm = Exp[cm[[site]]];
  dh = Round[Exp[dh[[site]]]];
  ah = Table[Total[Take[dh, h]], {h, nh[[site]]}];
  If[Max[ah] + a0 ≤ MAXT && Min[dh] ≥ 1,
    l = Table[10 (1 + c1 t) ^ (-gammal), {t, MAXT}];
    dm = Table[(1 + cm dt) ^ (-gammam), {dt, 0, MAXT - 1}];
    lineage = N[Table[t, {t, MAXT}]];
    dmt = dm * (lineage - 1);
    dmC14 = dm * Map[F, lineage - 1];
    s = Table[sfunction[t, st, ss], {t, MAXT}];
    m = Table[Reverse[Take[s, t]] * Take[dm, t], {t, MAXT}];
    tm = Map[Total, m];
    c = 1 + tm;
    ma = Table[Reverse[Take[s, t]] * Take[dmt, t], {t, MAXT}];
    mC14 = Table[Reverse[Take[s, t]] * Take[dmC14, t], {t, MAXT}];
    tma = Map[Total, ma];
    tmC14 = Map[Total, mC14];
```

2 | source code.nb

```

a = (1 * (linage + a0) + tma) / c;
C14x = (1 * (Map[F, linage + a0]) + tmC14) / c;
mass =
  Table[Total[Take[c, {If[h == 1, 1, ah[[h - 1]] + 1], ah[[h]]}], {h, nh[[site]]}];
age = Table[Total[Take[c * a, {If[h == 1, 1, ah[[h - 1]] + 1], ah[[h]]}], {h, nh[[site]]}] / mass;
C14 = Table[Total[Take[c * C14x, {If[h == 1, 1, ah[[h - 1]] + 1], ah[[h]]}], {h, nh[[site]]}] / mass;
If[AdditionalOutput, res = {mass, C14, age, 1, tm}, res = {mass, C14, age}],
res = {-1, -1, -1};
res
];

pri[pars_] := Module[{sigmac, sigmaz, signal, res, ss, a0, l0, cm, dh},
  {{sigmac, sigmaz, signal}, ss, a0, l0, cm, dh} = SplitPars[pars];
  res = Log[PDF[NormalDistribution[0., 1], sigmac]] +
    Log[PDF[NormalDistribution[0., 1], sigmaz]] +
    Log[PDF[NormalDistribution[0., 1], signal]] +
    Total[Log[PDF[NormalDistribution[0., 10], ss]]] +
    Sum[If[3 ≤ Exp[a0[[site]]] ≤ 5, 0., -Infinity] +
      Log[PDF[NormalDistribution[0., 10], l0[[site]]]] +
      Log[PDF[NormalDistribution[0., 1], cm[[site]]]] +
      Total[Log[PDF[NormalDistribution[0., 10], dh[[site]]]]], {site, nsites}];
  res
];

like[pars_] := Module[{sigmac, sigmaz, signal,
  res, ss, a0, l0, cm, dh, mass, C14, age, L0, B2, Dmass, DC14},
  {{sigmac, sigmaz, signal}, ss, a0, l0, cm, dh} = SplitPars[pars];
  {sigmac, sigmaz, signal} = Exp[{sigmac, sigmaz, signal}];
  l0 = Exp[l0];
  res = 0;
  Do[
    {L0, B2, Dmass, DC14} = data[[site]];
    {mass, C14, age} = CarbonModel[pars, site, False];
    If[Length[mass] == 0,
      res = -Infinity,
      res =
        res + Total[Log[PDF[NormalDistribution[0, sigmac], Log[Dmass] - Log[mass]]]] +
        Total[Log[PDF[NormalDistribution[0, sigmaz], Log[DC14] - Log[C14]]]] +
        Log[PDF[NormalDistribution[0, signal], Log[l0[[site]]] - Log[L0]]];
    ],
    {site, nsites}];
  res];

post[pars_] := pri[pars] + like[pars];

trunc[x_] := Min[Max[x, 10.^(-5)], 10.^(5)];

(* update parameter (combination) i *)
update[i_] := Module[{new, nl},
  ac[[i]] += {1, 0};
  new = pars;
  new = new + Re[Random[NormalDistribution[0, kk[[i]] Sqrt[la[[i]]]]] vect[[i]]];

```

```

nli = post[new];
If[Random[] < Exp[nli - li],
  pars = new;
  li = nli;
  ac[[i]] += {0, 1};
];
];

updatelavect := Module[{cov, met},
  cov = ((s2 - Transpose[{s1}].{s1} / nsls2) / (nsls2 - 1));
  met = cov + 10^(-5.) IdentityMatrix[npars];
  {la, vect} = Eigensystem[met];
  la = Abs[la];
];

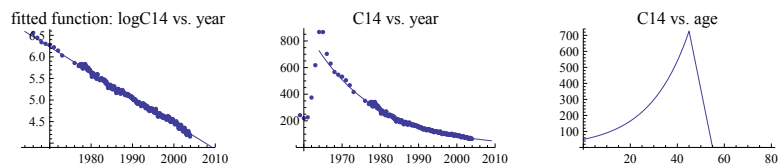
Iterate[repl_] := Module[{q, w, rpars},
  Do[
    If[adapt,
      q = 1. + Exp[-Length[ta] / 500.];
      w = 1. - 0.1 Exp[-Length[ta] / 500.];
      q = w = 1];
    Do[update[j], {j, npars}];
    AppendTo[ta, pars];
    AppendTo[tali, li];
    s1 += w * pars;
    s2 += w * Transpose[{pars}].{pars};
    nsls2 += w;
    If[adapt,
      If[Length[ta] > 50, updatelavect];
      rpars = ac[[All, 2]] / ac[[All, 1]];
      kk = Map[trunc, kk * q^(rpars - 0.44)];
    ];
    ac *= w;
    , {i, repl}];
];

dat = Import["model input data_4.xlsx"];
f1 = ListPlot[dat[[5]], PlotRange -> All];
dax = Drop[dat[[5]], 5];
dax[[All, 2]] = Log[dax[[All, 2]]];
ff[x_] = Fit[dax, {1, x}, x];
f[x_] = Exp[ff[x]];
DataYear = 2009;
MAXT = 100;
f2 = Plot[f[x], {x, 1964, DataYear}];
F[age_] := If[DataYear - age < 1964, If[DataYear - age < 1954, 0,
  f[1964] - (1964 - (DataYear - age)) f[1964] / (10)], f[DataYear - age]];
Print["C14 vs. age:\n", GraphicsGrid[
  {{Show[{Plot[ff[x], {x, 1964, DataYear}], ListPlot[dax]},
    PlotLabel -> "fitted function: logC14 vs. year"],
    Show[f1, f2, PlotLabel -> "C14 vs. year"],
    Plot[F[age], {age, 0, 80}, PlotLabel -> "C14 vs. age", AxesOrigin -> {0, 0}]}],
  ImageSize -> {Automatic, 120}]];

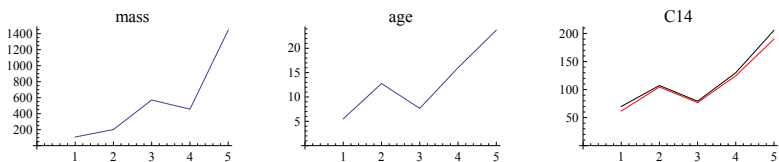
```

4 | source code.nb

C14 vs. age:



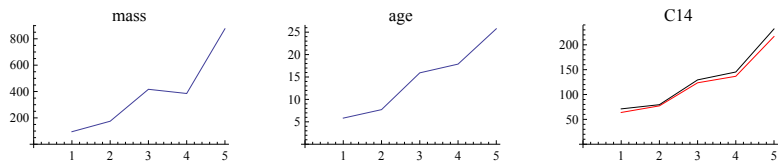
```
sites = Drop[dat[[2, All, 1]], 1];
Print["sites = ", sites];
nsites = Length[sites];
data = Table[{}, {i, nsites}];
nh = Table[0, {i, nsites}];
Print["Red: measurement of C14, Black: value of C14 inferred from age"];
Do[
  da = dat[[1]];
  fsite = sites[[i]];
  take = Flatten[Position[da[[All, 1]], fsite]];
  {site, horizon, Dmass, Dage, DC14} = Transpose[da[[take]]];
  nh[[i]] = Length[horizon];
  da = dat[[2]];
  take = Flatten[Position[da[[All, 1]], fsite]][[1]];
  L0 = da[[take, 2]];
  da = dat[[3]];
  take = Flatten[Position[da[[All, 1]], fsite]][[1]];
  B2 = 1 - da[[take, 2]] / 100;
  data[[i]] = {L0, B2, Dmass, DC14};
  Print["data for site ", i, " = ", fsite];
  Print["L0=", L0];
  Print["B2=", B2]; Print[GraphicsGrid[
    {{ListPlot[Dmass, Joined → True, PlotLabel → "mass", PlotRange → All],
      ListPlot[Dage, Joined → True, PlotLabel → "age", PlotRange → All],
      ListPlot[{DC14, Map[F, Dage]}, Joined → True, PlotStyle → {Red, Black},
        PlotLabel → "C14", PlotRange → All]}}, ImageSize → {Automatic, 120}]]];
  {i,
    nsites}];
sites = {U105, U33, U37, H32, H12, U58}
Red: measurement of C14, Black: value of C14 inferred from age
data for site 1 = U105
L0=79.45
B2=0.5578
```



data for site 2 = U33

L0=79.4

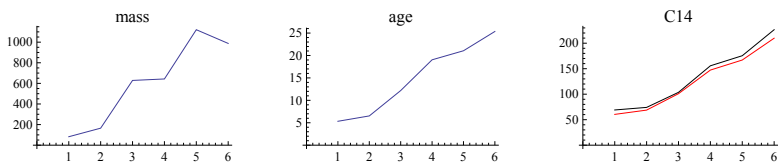
B2=0.6146



data for site 3 = U37

L0=139.25

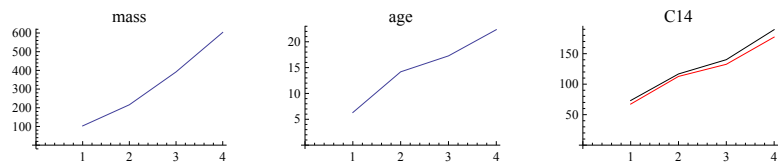
B2=0.524667



data for site 4 = H32

L0=112.55

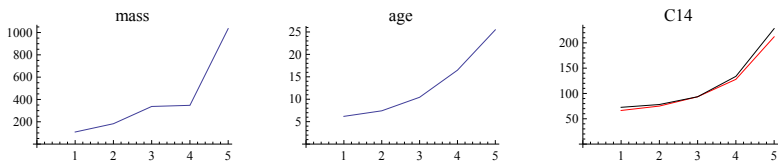
B2=0.456833



data for site 5 = H12

L0=102.8

B2=0.559

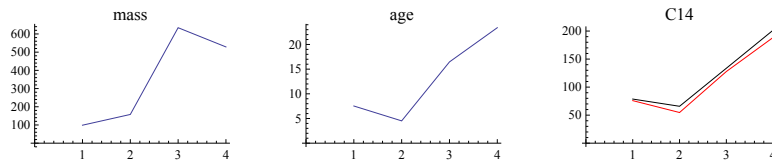


data for site 6 = U58

L0=119.65

B2=0.508

6 | source code.nb



```

gammal = gammam = 1.19;
lcl = ((data[[All, 2]] ^ (-1 / gammal)) - 1) / 2;
source = ! True;
st = {1, 2, 4, 8, 16, 32, 64, 128};
nt = Length[st] - 3; (* values of s for t=8,16,32,64, 128 *)
inpars = Table[3 + nh[[i]], {i, nsites}];
(* island specific parameters to be estimated: a0, l0, cm, and all dh *)
npars = 3 + nt + Total[inpars];
(* global parameters to be estimated: sigmac, sigmaz, sigmal,
and all st *)

estimate = ! True; (* true if to do estimation and scae results,
false if loading estimates from file *)
replicate = 1;

```

```

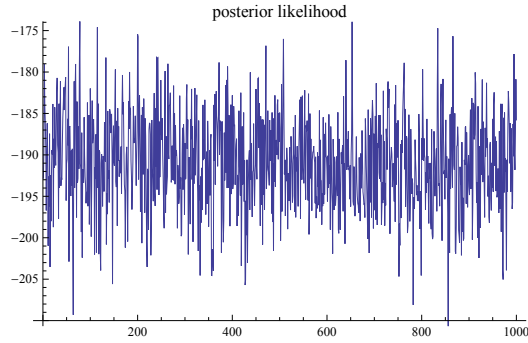
If[estimate,
  trans = 10 000;
  iter = 100 000;
  pars = Table[0, {i, npars}];
  Do[pars[[i]] = Log[4.], {i, 4 + nt, 4 + nt + nsites - 1}];
  Print["initial likelihood = ", li = post[pars]];

  {la, vect} = N[Eigensystem[IdentityMatrix[npars]]];
  nsls2 = 0;
  s1 = Table[0, {i, npars}];
  s2 = Table[0, {i, npars}, {j, npars}];
  kk = Table[1., {i, npars}];
  ac = Table[{0, 0}, {i, npars}];

  Print["INITIAL ITERATION STARTS, NEEDED TO
    GET RID OF THE TRANSIENT AND TO ADJUST THE PROPOSALS"];
  ta = tali = {};
  adapt = True;
  Print[AbsoluteTiming[Iterate[trans]]];
  Print[ListPlot[ac[[All, 2]] / ac[[All, 1]],
    PlotRange → {0, 1}, PlotLabel → "accept ratios"];
  Print[ListPlot[tali, Joined → True, PlotLabel → "posterior likelihood"]];
  Print["MAIN ITERATION STARTS"];
  ac = Table[{0, 0}, {i, npars}];
  ta = tali = {};
  adapt = False;
  Print[AbsoluteTiming[Iterate[iter]]];
  Print[ListPlot[ac[[All, 2]] / ac[[All, 1]],
    PlotRange → {0, 1}, PlotLabel → "accept ratios"];
  Print[ListPlot[tali, Joined → True, PlotLabel → "posterior likelihood"]];
];
file =
  StringJoin["C:\\HY-data\\OVASKAIN\\all stuff\\manuscripts\\InPreparation\\Björn
    Lindahl\\otsos work\\results\\source=",
    ToString[source], " replicate=", ToString[replicate], "_thinned"];
If[estimate,
  Quiet[DeleteFile[file]];
  Save[file, {ta, tali, trans, iter}],
  Get[file];
  Print[ListPlot[tali, PlotRange → {All, {Min[tali], Max[tali]}},
    Joined → True, PlotLabel → "posterior likelihood"]];
];

```

8 | source code.nb



```

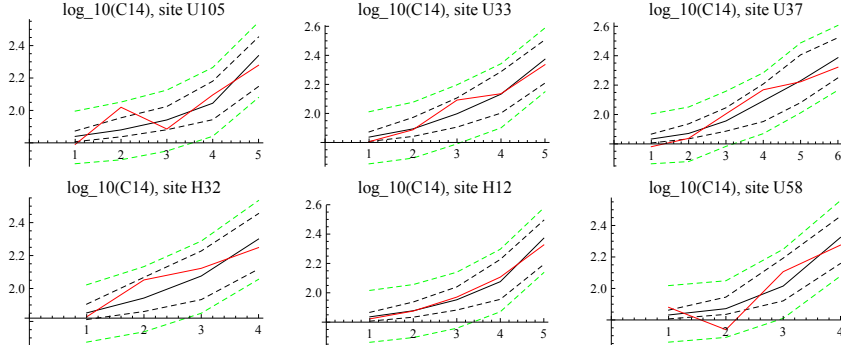
t10 = tc14 = tmass = t10e = tc14e = tmasse = ts = tcm = ta0 = tah = tal = tatm = {};
Do[
  pa = RandomChoice[ta];
  {{sigmac, sigmaz, sigmal}, ss, a0, l0, cm, dh} = SplitPars[pa];
  t10 = Append[t10, Exp[l0]];
  t10e = Append[t10e, Exp[l0] * Exp[Random[NormalDistribution[0, Exp[sigmal]]]]];
  prediction = Table[CarbonModel[pa, site, True], {site, nsites}];
  tc14 = Append[tc14, prediction[[All, 2]]];
  tc14e = Append[tc14e, Table[
    prediction[[site, 2]] * Table[Exp[Random[NormalDistribution[0, Exp[sigmaz]]]],
    {j, nh[[site]]}], {site, nsites}]];
  tmass = Append[tmass, prediction[[All, 1]]];
  tmasse = Append[tmasse, Table[
    prediction[[site, 1]] * Table[Exp[Random[NormalDistribution[0, Exp[sigmac]]]],
    {j, nh[[site]]}], {site, nsites}]];
  tal = Append[tal, prediction[[All, 4]]];
  tatm = Append[tatm, prediction[[All, 5]]];
  ss = Exp[ss];
  ss = Join[{0, 0, 0}, ss];
  If[! source, ss = Table[0, {i, 3 + nt}]];
  s = Table[sfunction[t, st, ss], {t, MAXT}];
  ts = Append[ts, s];
  tcm = Append[tcm, Exp[cm]];
  ta0 = Append[ta0, Exp[a0]];
  ltah = {};
  Do[
    dh2 = Round[Exp[dh[[site]]]];
    ah = Table[Total[Take[dh2, h]], {h, nh[[site]]}];
    ltah = Append[ltah, ah];
    , {site, nsites}];
  tah = Append[tah, ltah];
  , {repl, 1000}];

```

```

Tme = Tlow = Thigh = Tlow2 = Thigh2 = {};
Do[
  me = Median[Log[10, tc14[[All, site]]]];
  low = Quantile[Log[10, tc14[[All, site]]], 0.025];
  high = Quantile[Log[10, tc14[[All, site]]], 0.975];
  low2 = Quantile[Log[10, tc14e[[All, site]]], 0.025];
  high2 = Quantile[Log[10, tc14e[[All, site]]], 0.975];
  AppendTo[Tme, me];
  AppendTo[Tlow, low];
  AppendTo[Thigh, high];
  AppendTo[Tlow2, low2];
  AppendTo[Thigh2, high2];
  f1 = ListPlot[me, PlotStyle → Black, Joined → True];
  f2 = ListPlot[low, Joined → True, PlotStyle → {Black, Dashing[{0.02, 0.02}]}];
  f3 = ListPlot[high, Joined → True, PlotStyle → {Black, Dashing[{0.02, 0.02}]}];
  f2b = ListPlot[low2, Joined → True, PlotStyle → {Green, Dashing[{0.02, 0.02}]}];
  f3b = ListPlot[high2, Joined → True, PlotStyle → {Green, Dashing[{0.02, 0.02}]}];
  f4 = ListPlot[Log[10, data[[site, 4]]], Joined → True, PlotStyle → Red];
  figu[site] = Show[f1, f2, f3, f2b, f3b, f4, PlotRange → All,
    PlotLabel → StringJoin["log10(C14), site ", sites[[site]]],
    , {site, nsites}];
Print["red color = real data; black color = model prediction
      for truth; green color = model prediction for measurement"];
GraphicsGrid[{{figu[1], figu[2], figu[3]}, {figu[4], figu[5], figu[6]}},
  ImageSize → {Automatic, 240}]
red color = real data; black color = model prediction
for truth; green color = model prediction for measurement

```

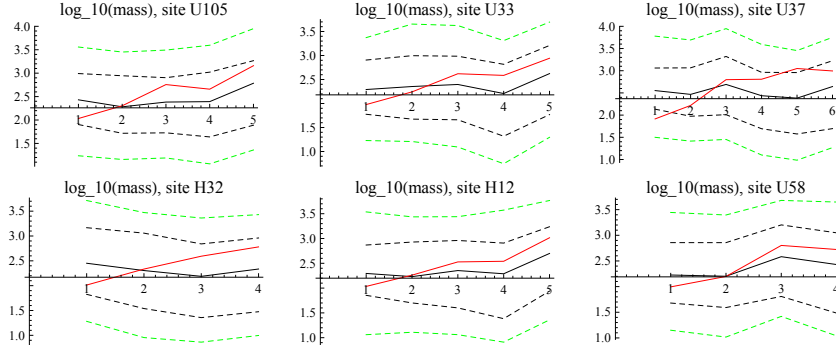


10 | source code.nb

```

Tme = Tlow = Thigh = Tlow2 = Thigh2 = {};
Do[
  me = Median[Log[10, tmass[[All, site]]]];
  low = Quantile[Log[10, tmass[[All, site]]], 0.025];
  high = Quantile[Log[10, tmass[[All, site]]], 0.975];
  low2 = Quantile[Log[10, tmasse[[All, site]]], 0.025];
  high2 = Quantile[Log[10, tmasse[[All, site]]], 0.975];
  AppendTo[Tme, me];
  AppendTo[Tlow, low];
  AppendTo[Thigh, high];
  AppendTo[Tlow2, low2];
  AppendTo[Thigh2, high2];
  f1 = ListPlot[me, PlotStyle → Black, Joined → True];
  f2 = ListPlot[low, Joined → True, PlotStyle → {Black, Dashing[{0.02, 0.02}]}];
  f3 = ListPlot[high, Joined → True, PlotStyle → {Black, Dashing[{0.02, 0.02}]}];
  f2b = ListPlot[low2, Joined → True, PlotStyle → {Green, Dashing[{0.02, 0.02}]}];
  f3b = ListPlot[high2, Joined → True, PlotStyle → {Green, Dashing[{0.02, 0.02}]}];
  f4 = ListPlot[Log[10, data[[site, 3]]], Joined → True, PlotStyle → Red];
  figu[site] = Show[f1, f2, f3, f2b, f3b, f4, PlotRange → All,
    PlotLabel → StringJoin["log_10(mass), site ", sites[[site]]];
    , {site, nsites}];
Print["red color = real data; black color = model prediction
      for truth; green color = model prediction for measurement"];
GraphicsGrid[{{figu[1], figu[2], figu[3]}, {figu[4], figu[5], figu[6]}},
  ImageSize → {Automatic, 240}]
red color = real data; black color = model prediction
for truth; green color = model prediction for measurement

```

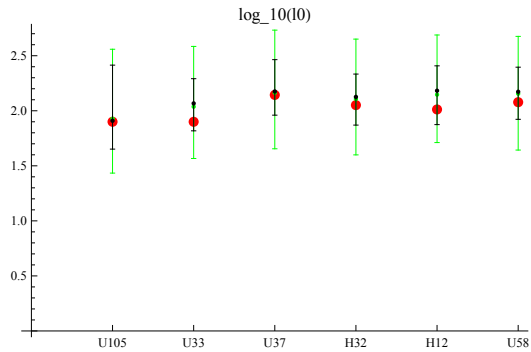


```

tx = Log[10, t10]; f1 = ErrorListPlot[Table[{{site, Median[tx[[All, site]]]},
  ErrorBar[{-Median[tx[[All, site]]] + Quantile[tx[[All, site]], 0.025],
    Quantile[tx[[All, site]], 0.975] - Median[tx[[All, site]]]}],
  {site, nsites}], PlotStyle → Black, PlotRange → All];
tx = Log[10, t10e]; f1b = ErrorListPlot[Table[{{site, Median[tx[[All, site]]]},
  ErrorBar[{-Median[tx[[All, site]]] + Quantile[tx[[All, site]], 0.025],
    Quantile[tx[[All, site]], 0.975] - Median[tx[[All, site]]]}],
  {site, nsites}], PlotStyle → Green, PlotRange → All];
f2 = ListPlot[Log[10, data[[All, 1]]], PlotStyle → {Red, PointSize[Large]}];
Print["red color = real data; black color = model prediction
  for truth; green color = model prediction for measurement"];
Show[f2, f1b, f1, PlotRange → All, AxesOrigin → {0, 0}, PlotLabel → "log_10(10)",
  Ticks → {Table[{site, sites[[site]]}, {site, nsites}], Automatic}]

red color = real data; black color = model prediction
for truth; green color = model prediction for measurement

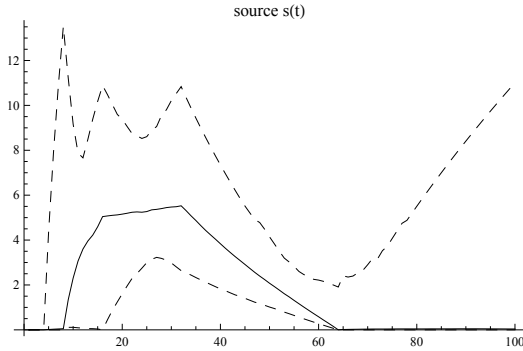
```



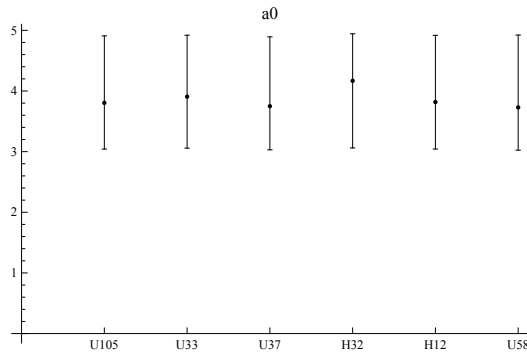
12 | source code.nb

```
me = Median[ts];
low = Quantile[ts, 0.025];
high = Quantile[ts, 0.975];
f1 = ListPlot[me, PlotStyle → Black, Joined → True];
f2 = ListPlot[low, Joined → True, PlotStyle → {Black, Dashing[{0.02, 0.02}]}];
f3 = ListPlot[high, Joined → True, PlotStyle → {Black, Dashing[{0.02, 0.02}]}];
sts = Map[Total, ts];
Print["total source (sum over cohorts) {0.025,0.5,0.975} quantiles: ",
      Quantile[sts, {0.025, 0.5, 0.975}]];
Show[f1, f2, f3, PlotLabel → "source s(t)", PlotRange → {All, All}]

total source (sum over cohorts) {0.025,0.5,0.975} quantiles:
{133.813, 209.099, 460.594}
```



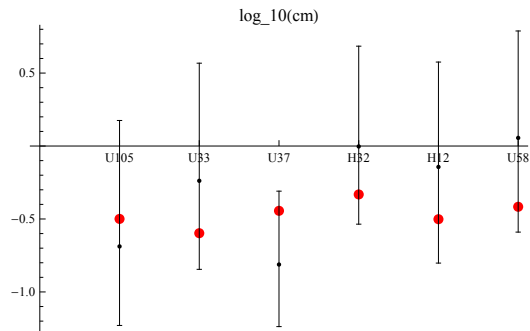
```
tx = ta0; f1 = ErrorListPlot[Table[{{site, Median[tx[[All, site]]]},
  ErrorBar[{-Median[tx[[All, site]]] + Quantile[tx[[All, site]], 0.025],
    Quantile[tx[[All, site]], 0.975] - Median[tx[[All, site]]}]],
  {site, nsites}], PlotStyle → Black, PlotRange → All];
Show[f1, PlotRange → All, AxesOrigin → {0, 0}, PlotLabel → "a0",
  Ticks → {Table[{site, sites[site]]}, {site, nsites}], Automatic}]
```



```

tx = Log[10, tcm];
f1 = ErrorListPlot[Table[{site, Median[tx[[All, site]]],
  ErrorBar[{-Median[tx[[All, site]] + Quantile[tx[[All, site]], 0.025],
    Quantile[tx[[All, site]], 0.975] - Median[tx[[All, site]]}],
  {site, nsites}], PlotStyle -> Black, PlotRange -> All];
f2 = ListPlot[Log[10, lcl], PlotStyle -> {Red, PointSize[Large]};
Print[
  "Probability(average cm for small islands < average cm for large islands) = ",
  N[Count[Sign[Sum[tcm[[All, i]], {i, 3}] / 3 - Sum[tcm[[All, i]] / 3, {i, 4, 6}]], -1] /
  Length[tcm]] ];
Print["red color = cl; blue color = model prediction"];
Show[f2, f1, PlotRange -> All, AxesOrigin -> {0, 0}, PlotLabel -> "log_10(cm)",
  Ticks -> {Table[{site, sites[[site]]}, {site, nsites}], Automatic}]
Probability(average cm for small islands < average cm for large islands) = 0.931
red color = cl; blue color = model prediction

```



14 | source code.nb

```
Do[
  me = Median[tah[[All, site]]];
  low = Quantile[tah[[All, site]], 0.025];
  high = Quantile[tah[[All, site]], 0.975];
  f1 = ListPlot[me, PlotStyle -> Black, Joined -> True];
  f2 = ListPlot[low, Joined -> True, PlotStyle -> {Black, Dashing[{0.02, 0.02}]}];
  f3 = ListPlot[high, Joined -> True, PlotStyle -> {Black, Dashing[{0.02, 0.02}]}];
  figu[site] = Show[f1, f2, f3, PlotRange -> All,
    PlotLabel -> StringJoin["cumulative age for horizon, site ", sites[[site]]],
    , {site, nsites}];
GraphicsGrid[{{figu[1], figu[2], figu[3]}, {figu[4], figu[5], figu[6]}},
  ImageSize -> {Automatic, 240}]
```

cumulative age for horizon, site U105

cumulative age for horizon, site U33

cumulative age for horizon, site U37

cumulative age for horizon, site H32

cumulative age for horizon, site H12

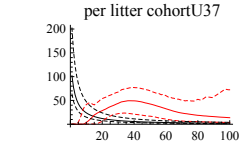
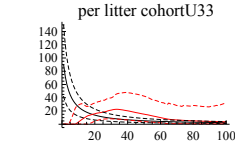
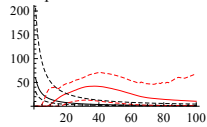
cumulative age for horizon, site U58

```

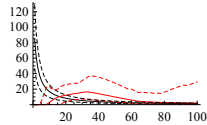
Do[
  me = Table[Median[tal[[All, site, t]]], {t, MAXT}];
  low = Table[Quantile[tal[[All, site, t]], 0.025], {t, MAXT}];
  high = Table[Quantile[tal[[All, site, t]], 0.975], {t, MAXT}];
  f1a = ListPlot[me, Joined → True, PlotStyle → Black, PlotRange → All];
  f2a = ListPlot[low, Joined → True,
    PlotStyle → {Black, Dashing[{0.02, 0.02}]}, PlotRange → All];
  f3a = ListPlot[high, Joined → True, PlotStyle → {Black, Dashing[{0.02, 0.02}]},
    PlotRange → All];
  me = Table[Median[tatm[[All, site, t]]], {t, MAXT}];
  low = Table[Quantile[tatm[[All, site, t]], 0.025], {t, MAXT}];
  high = Table[Quantile[tatm[[All, site, t]], 0.975], {t, MAXT}];
  f1b = ListPlot[me, Joined → True, PlotStyle → Red, PlotRange → All];
  f2b = ListPlot[low, Joined → True,
    PlotStyle → {Red, Dashing[{0.02, 0.02}]}, PlotRange → All];
  f3b = ListPlot[high, Joined → True, PlotStyle → {Red, Dashing[{0.02, 0.02}]},
    PlotRange → All];
  figu[site] = Show[f1a, f1b, f2a, f2b, f3a, f3b, PlotRange → {All, All},
    PlotLabel → StringJoin["amount of litter carbon (black) and\n",
      "source carbon (red)\n per litter cohort", sites[[site]]];
  , {site, nsites}]
GraphicsGrid[{{figu[1], figu[2], figu[3]}, {figu[4], figu[5], figu[6]}},
  ImageSize → {Automatic, 240}]

```

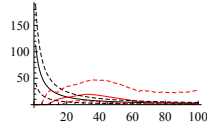
of litter carbon (black) and source carbon (red) per litter cohortU105



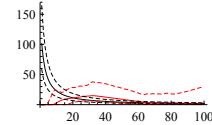
of litter carbon (black) and source carbon (red) per litter cohortH32



of litter carbon (black) and source carbon (red) per litter cohortH12



of litter carbon (black) and source carbon (red) per litter cohortU58



```

lsmall = Sum[Sum[tal[[All, site, t]], {t, MAXT}], {site, 3}] / 3;
llarge = Sum[Sum[tal[[All, site, t]], {t, MAXT}], {site, 4, 6}] / 3;
msmall = Sum[Sum[tatm[[All, site, t]], {t, MAXT}], {site, 3}] / 3;
mlarge = Sum[Sum[tatm[[All, site, t]], {t, MAXT}], {site, 4, 6}] / 3;
Print["Total amount of litter carbon included in cohorts from
      1 to MAXT {0.025 quantile, 0.5 quantile, 0.975 quantile}:"];
Print["average for small islands: ", Quantile[lsmall, {0.025, 0.5, 0.975}]];
Print["average for large islands: ", Quantile[llarge, {0.025, 0.5, 0.975}]];
Print["Total amount of mycelial carbon included in cohorts from
      1 to MAXT {0.025 quantile, 0.5 quantile, 0.975 quantile}:"];
Print["average for small islands: ", Quantile[msmall, {0.025, 0.5, 0.975}]];
Print["average for large islands: ", Quantile[mlarge, {0.025, 0.5, 0.975}]];
Print[
  "Out of all carbon included in cohorts from 1 to MAXT, the fraction F of source
  carbon is {0.025 quantile, 0.5 quantile, 0.975 quantile}:";
Print["small islands: ", Quantile[msmall / (msmall + lsmall), {0.025, 0.5, 0.975}]];
Print["large islands: ", Quantile[mlarge / (mlarge + llarge), {0.025, 0.5, 0.975}]];
Print["Probability that F(large)>F(small): ",
      N[Count[Sign[msmall / (msmall + lsmall) - mlarge / (mlarge + llarge)], -1] /
      Length[msmall]]]

Total amount of litter carbon included in cohorts
  from 1 to MAXT {0.025 quantile, 0.5 quantile, 0.975 quantile}:
average for small islands: {674.209, 923.207, 1627.66}
average for large islands: {659.599, 955.153, 1377.48}

Total amount of mycelial carbon included in cohorts
  from 1 to MAXT {0.025 quantile, 0.5 quantile, 0.975 quantile}:
average for small islands: {1047.8, 2128.44, 3268.19}
average for large islands: {452.199, 836.207, 1722.44}

Out of all carbon included in cohorts from 1 to MAXT, the fraction F
  of source carbon is {0.025 quantile, 0.5 quantile, 0.975 quantile}:
small islands: {0.411271, 0.692914, 0.807554}
large islands: {0.294549, 0.470859, 0.682351}

Probability that F(large)>F(small): 0.055

```

References and Notes

1. G. B. Bonan, H. H. Shugart, Environmental factors and ecological processes in boreal forests. *Annu. Rev. Ecol. Syst.* **20**, 1 (1989). [doi:10.1146/annurev.es.20.110189.000245](https://doi.org/10.1146/annurev.es.20.110189.000245)
2. W. M. Post, W. R. Emanuel, P. J. Zinke, A. G. Stangenberger, Soil carbon pools and world life zones. *Nature* **298**, 156 (1982). [doi:10.1038/298156a0](https://doi.org/10.1038/298156a0)
3. W. K. Cornwell *et al.*, Plant species traits are the predominant control on litter decomposition rates within biomes worldwide. *Ecol. Lett.* **11**, 1065 (2008). [doi:10.1111/j.1461-0248.2008.01219.x](https://doi.org/10.1111/j.1461-0248.2008.01219.x) [Medline](#)
4. V. Brovkin *et al.*, Plant-driven variation in decomposition rates improves projections of global litter stock distribution. *Biogeosciences* **9**, 565 (2012). [doi:10.5194/bg-9-565-2012](https://doi.org/10.5194/bg-9-565-2012)
5. M. Makkonen *et al.*, Highly consistent effects of plant litter identity and functional traits on decomposition across a latitudinal gradient. *Ecol. Lett.* **15**, 1033 (2012). [doi:10.1111/j.1461-0248.2012.01826.x](https://doi.org/10.1111/j.1461-0248.2012.01826.x) [Medline](#)
6. D. A. Wardle, G. Hörnberg, O. Zackrisson, M. Kalela-Brundin, D. A. Coomes, Long-term effects of wildfire on ecosystem properties across an island area gradient. *Science* **300**, 972 (2003). [doi:10.1126/science.1082709](https://doi.org/10.1126/science.1082709) [Medline](#)
7. P. Högberg *et al.*, Large-scale forest girdling shows that current photosynthesis drives soil respiration. *Nature* **411**, 789 (2001). [doi:10.1038/35081058](https://doi.org/10.1038/35081058) [Medline](#)
8. A. Heinemeyer, I. P. Hartley, S. P. Evans, J. A. C. De la Fuente, P. Ineson, Forest soil CO₂ flux: Uncovering the contribution and environmental responses of ectomycorrhizas. *Glob. Change Biol.* **13**, 1786 (2007). [doi:10.1111/j.1365-2486.2007.01383.x](https://doi.org/10.1111/j.1365-2486.2007.01383.x)
9. D. Godbold *et al.*, Mycorrhizal hyphal turnover as a dominant process for carbon input into soil organic matter. *Plant Soil* **281**, 15 (2006). [doi:10.1007/s11104-005-3701-6](https://doi.org/10.1007/s11104-005-3701-6)
10. F. A. Dijkstra, W. X. Cheng, Interactions between soil and tree roots accelerate long-term soil carbon decomposition. *Ecol. Lett.* **10**, 1046 (2007). [doi:10.1111/j.1461-0248.2007.01095.x](https://doi.org/10.1111/j.1461-0248.2007.01095.x) [Medline](#)
11. J. E. Drake *et al.*, Increases in the flux of carbon belowground stimulate nitrogen uptake and sustain the long-term enhancement of forest productivity under elevated CO₂. *Ecol. Lett.* **14**, 349 (2011). [doi:10.1111/j.1461-0248.2011.01593.x](https://doi.org/10.1111/j.1461-0248.2011.01593.x) [Medline](#)
12. M. Heimann, M. Reichstein, Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* **451**, 289 (2008). [doi:10.1038/nature06591](https://doi.org/10.1038/nature06591) [Medline](#)
13. D. A. Wardle, O. Zackrisson, G. Hörnberg, C. Gallet, The influence of island area on ecosystem properties. *Science* **277**, 1296 (1997). [doi:10.1126/science.277.5330.1296](https://doi.org/10.1126/science.277.5330.1296)
14. D. A. Wardle *et al.*, Linking vegetation change, carbon sequestration and biodiversity: Insights from island ecosystems in a long-term natural experiment. *J. Ecol.* **100**, 16 (2012). [doi:10.1111/j.1365-2745.2011.01907.x](https://doi.org/10.1111/j.1365-2745.2011.01907.x)
15. M. Jonsson, D. A. Wardle, Structural equation modelling reveals plant-community drivers of carbon storage in boreal forest ecosystems. *Biol. Lett.* **6**, 116 (2010). [doi:10.1098/rsbl.2009.0613](https://doi.org/10.1098/rsbl.2009.0613) [Medline](#)

16. J. B. Gaudinski, S. E. Trumbore, E. A. Davidson, S. H. Zheng, Soil carbon cycling in a temperate forest: Radiocarbon-based estimates of residence times, sequestration rates and partitioning of fluxes. *Biogeochemistry* **51**, 33 (2000). [doi:10.1023/A:1006301010014](https://doi.org/10.1023/A:1006301010014)
17. Materials and methods are available as supplementary materials on *Science Online*.
18. K. Ihrmark *et al.*, New primers to amplify the fungal ITS2 region—evaluation by 454-sequencing of artificial and natural communities. *FEMS Microbiol. Ecol.* **82**, 666 (2012). [doi:10.1111/j.1574-6941.2012.01437.x](https://doi.org/10.1111/j.1574-6941.2012.01437.x) [Medline](#)
19. J. P. Yuan, H. C. Kuang, J. H. Wang, X. Liu, Evaluation of ergosterol and its esters in the pileus, gill, and stipe tissues of agaric fungi and their relative changes in the comminuted fungal tissues. *Appl. Microbiol. Biotechnol.* **80**, 459 (2008). [doi:10.1007/s00253-008-1589-9](https://doi.org/10.1007/s00253-008-1589-9) [Medline](#)
20. H. Wallander, U. Johansson, E. Sterkenburg, M. Brandström-Durling, B. D. Lindahl, Production of ectomycorrhizal mycelium peaks during canopy closure in Norway spruce forests. *New Phytol.* **187**, 1124 (2010). [doi:10.1111/j.1469-8137.2010.03324.x](https://doi.org/10.1111/j.1469-8137.2010.03324.x) [Medline](#)
21. A. Ekblad, H. Wallander, T. Näsholm, Chitin and ergosterol combined to measure total and living fungal biomass in ectomycorrhizas. *New Phytol.* **138**, 143 (1998). [doi:10.1046/j.1469-8137.1998.00891.x](https://doi.org/10.1046/j.1469-8137.1998.00891.x)
22. J. R. Ehleringer, N. Buchmann, L. B. Flanagan, Carbon isotope ratios in belowground carbon cycle processes. *Ecol. Appl.* **10**, 412 (2000). [doi:10.1890/1051-0761\(2000\)010\[0412:CIRIBC\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0412:CIRIBC]2.0.CO;2)
23. E. A. Hobbie, A. P. Ouimette, Controls of nitrogen isotope patterns in soil profiles. *Biogeochemistry* **95**, 355 (2009). [doi:10.1007/s10533-009-9328-6](https://doi.org/10.1007/s10533-009-9328-6)
24. B. Boström, D. Comstedt, A. Ekblad, Isotope fractionation and ¹³C enrichment in soil profiles during the decomposition of soil organic matter. *Oecologia* **153**, 89 (2007). [doi:10.1007/s00442-007-0700-8](https://doi.org/10.1007/s00442-007-0700-8) [Medline](#)
25. F. Hyodo, D. A. Wardle, Effect of ecosystem retrogression on stable nitrogen and carbon isotopes of plants, soils and consumer organisms in boreal forest islands. *Rapid Commun. Mass Spectrom.* **23**, 1892 (2009). [doi:10.1002/rcm.4095](https://doi.org/10.1002/rcm.4095) [Medline](#)
26. A. F. S. Taylor, P. M. Fransson, P. Högborg, M. N. Högborg, A. H. Plamboeck, Species level patterns in ¹³C and ¹⁵N abundance of ectomycorrhizal and saprotrophic fungal sporocarps. *New Phytol.* **159**, 757 (2003). [doi:10.1046/j.1469-8137.2003.00838.x](https://doi.org/10.1046/j.1469-8137.2003.00838.x)
27. E. A. Hobbie, R. A. Werner, Intramolecular, compound-specific, and bulk carbon isotope patterns in C₃ and C₄ plants: A review and synthesis. *New Phytol.* **161**, 371 (2004). [doi:10.1111/j.1469-8137.2004.00970.x](https://doi.org/10.1111/j.1469-8137.2004.00970.x)
28. R. J. Francey *et al.*, A 1000-year high precision record of δ¹³C in atmospheric CO₂. *Tellus B Chem. Phys. Meteorol.* **51**, 170 (1999). [doi:10.1034/j.1600-0889.1999.t01-1-00005.x](https://doi.org/10.1034/j.1600-0889.1999.t01-1-00005.x)
29. P. Högborg *et al.*, ¹⁵N abundance of surface soils, roots and mycorrhizas in profiles of European forest soils. *Oecologia* **108**, 207 (1996).

30. B. D. Lindahl *et al.*, Spatial separation of litter decomposition and mycorrhizal nitrogen uptake in a boreal forest. *New Phytol.* **173**, 611 (2007). [doi:10.1111/j.1469-8137.2006.01936.x](https://doi.org/10.1111/j.1469-8137.2006.01936.x) [Medline](#)
31. P. Höglberg *et al.*, Recovery of ectomycorrhiza after ‘nitrogen saturation’ of a conifer forest. *New Phytol.* **189**, 515 (2011). [doi:10.1111/j.1469-8137.2010.03485.x](https://doi.org/10.1111/j.1469-8137.2010.03485.x) [Medline](#)
32. R. P. Phillips *et al.*, Roots and fungi accelerate carbon and nitrogen cycling in forests exposed to elevated CO₂. *Ecol. Lett.* **15**, 1042 (2012). [doi:10.1111/j.1461-0248.2012.01827.x](https://doi.org/10.1111/j.1461-0248.2012.01827.x) [Medline](#)
33. L. Cheng *et al.*, Arbuscular mycorrhizal fungi increase organic carbon decomposition under elevated CO₂. *Science* **337**, 1084 (2012). [doi:10.1126/science.1224304](https://doi.org/10.1126/science.1224304) [Medline](#)
34. O. Alberton, T. W. Kuyper, A. Gorissen, Competition for nitrogen between *Pinus sylvestris* and ectomycorrhizal fungi generates potential for negative feedback under elevated CO₂. *Plant Soil* **296**, 159 (2007). [doi:10.1007/s11104-007-9306-5](https://doi.org/10.1007/s11104-007-9306-5)
35. H. Wallander, L. O. Nilsson, D. Hagerberg, E. Bååth, Estimation of the biomass and seasonal growth of external mycelium of ectomycorrhizal fungi in the field. *New Phytol.* **151**, 753 (2001). [doi:10.1046/j.0028-646x.2001.00199.x](https://doi.org/10.1046/j.0028-646x.2001.00199.x)
36. J. E. Nylund, H. Wallander, Ergosterol analysis as a means of quantifying mycorrhizal biomass. *Methods Microbiol.* **24**, 77 (1992). [doi:10.1016/S0580-9517\(08\)70088-6](https://doi.org/10.1016/S0580-9517(08)70088-6)
37. A. Ekblad, T. Näsholm, Determination of chitin in fungi and mycorrhizal roots by an improved HPLC analysis of glucosamine. *Plant Soil* **178**, 29 (1996). [doi:10.1007/BF00011160](https://doi.org/10.1007/BF00011160)
38. T. J. White *et al.*, in *PCR Protocols. A Guide to Methods and Applications* (Academic Press, Orlando, FL, 1990), pp. 315–322.
39. D. N. Frank, BARCRAWL and BARTAB: Software tools for the design and implementation of barcoded primers for highly multiplexed DNA sequencing. *BMC Bioinformatics* **10**, 362 (2009). [doi:10.1186/1471-2105-10-362](https://doi.org/10.1186/1471-2105-10-362) [Medline](#)
40. U. Kõljalg *et al.*, UNITE: A database providing web-based methods for the molecular identification of ectomycorrhizal fungi. *New Phytol.* **166**, 1063 (2005). [doi:10.1111/j.1469-8137.2005.01376.x](https://doi.org/10.1111/j.1469-8137.2005.01376.x) [Medline](#)
41. M. A. Larkin *et al.*, Clustal W and clustal X version 2.0. *Bioinformatics* **23**, 2947 (2007). [doi:10.1093/bioinformatics/btm404](https://doi.org/10.1093/bioinformatics/btm404) [Medline](#)
42. D. L. Swofford, *PAUP*: Phylogenetic Analysis Using Parsimony, version 4.0b10* (Sinauer, Sunderland, MA, 2003).
43. O. Franklin, P. Höglberg, A. Ekblad, G. I. Ågren, Pine forest floor carbon accumulation in response to N and PK additions: Bomb ¹⁴C modelling and respiration studies. *Ecosystems* (N. Y.) **6**, 644 (2003). [doi:10.1007/s10021-002-0149-x](https://doi.org/10.1007/s10021-002-0149-x)
44. D. A. Wardle *et al.*, Drivers of inter-year variability of plant production and decomposers across contrasting island ecosystems. *Ecology* **93**, 521 (2012). [doi:10.1890/11-0930.1](https://doi.org/10.1890/11-0930.1) [Medline](#)

45. S. Trumbore, Age of soil organic matter and soil respiration: Radiocarbon constraints on belowground C dynamics. *Ecol. Appl.* **10**, 399 (2000). [doi:10.1890/1051-0761\(2000\)010\[0399:AOSOMA\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0399:AOSOMA]2.0.CO;2)
46. E. Bosatta, G. I. Ågren, Exact solutions to the continuous-quality equation for soil organic matter turnover. *J. Theor. Biol.* **224**, 97 (2003). [doi:10.1016/S0022-5193\(03\)00147-4](https://doi.org/10.1016/S0022-5193(03)00147-4) [Medline](#)
47. I. Levin, B. Kromer, The tropospheric $^{14}\text{CO}_2$ level in mid-latitudes of the Northern Hemisphere (1959-2003). *Radiocarbon* **46**, 1261 (2004).
48. O. Ovaskainen, H. Rekola, E. Meyke, E. Arjas, Bayesian methods for analyzing movements in heterogeneous landscapes from mark-recapture data. *Ecology* **89**, 542 (2008). [doi:10.1890/07-0443.1](https://doi.org/10.1890/07-0443.1) [Medline](#)



Evaluation of N retention capacity by ectomycorrhizal fungi in a Norway spruce forest fertilized with nitrogen and phosphorus

Adam Bahr^a, Magnus Ellström^a, Johan Bergh^b and Håkan Wallander^a

^a Lund University, Microbial Ecology, Dept of Biology, SE-223 62 Lund, Sweden

^b Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre, SE-230 53, Alnarp, Sweden

Abstract

Mycelium of ectomycorrhizal fungi (EMF) encloses almost all fine roots of trees growing in boreal and boreo-nemoral forests. The EMF are dependent on belowground allocation of photoassimilated C by the tree, in return they deliver nutrients and water. The EMF mycelium increase the absorptive surface area of tree roots by two orders of magnitude and within one single gram of humus hundreds of meters of EMF mycelium can be found. This makes the EMF mycelium potentially important for the nitrogen (N) retention capacity of boreal forest soils. Previous studies have found coincidences between elevated N leakage and low EMF mycelium production, but it has still not been possible to separate the specific role of EMF from other N retaining processes (e.g. assimilation by tree roots and heterotrophic microbes). We approached this gap of knowledge in a fertilization experiment in a Norway spruce forest in south Sweden by: 1) Relating seasonal variations in N leakage to EMF production; 2) Analyzing if N leaching after fertilization was affected by combined addition of phosphorus (P). Nitrogen combined with P should hypothetically reduce production of EMF while it should promote tree N assimilation due to alleviation of N induced P limitation; 3) Addition of isotopically labeled N to EMF ingrowth mesh-bags to enable tracing of N assimilation as well as N leached through the EMF mycelium. We found a large N assimilation capacity of EMF mycelium ($0.31 \text{ mg } ^{15}\text{N g}^{-1} \text{ EMF mycelium day}^{-1}$, $SE = 0.03$), but the assimilation of EMF mycelium was not sufficient to hamper large immediate losses of N after fertilization. Further, tendencies of reduced N leaching and reduced EMF mycelium production after combined addition of N and P indicated that other processes have to be taken into account.

Introduction

When nutrients such as nitrogen (N) and phosphorus (P), that are important for plant biomass synthesis, become deficient, trees typically enhance belowground carbon (C) allocation to roots and root associated fungi to sustain the assimilation of these elements (Ericsson, 1995). In boreal and boreo-nemoral forests, that usually are N limited (Vitousek and Howarth, 1991), ectomycorrhizal fungi (EMF) can receive a large portion of the photoassimilated C (Simard et al., 2002). The ectomycorrhizal extramatrical mycelium (EMM) extends through the soil and assimilates N from both organic and inorganic sources (Smith and Read,

2008). This is generally thought of as a symbiosis in which the tree gains nutrients in exchange for the allocated C (Smith and Read, 2008). The relationship may however be more or less mutual (Karst et al., 2008), and it has recently been suggested that C allocation to EMF under N poor conditions could cause increased N retention within the EMM, resulting in aggravated N deficiency in the trees and further increased C allocation to the associated fungi in a positive feedback loop (Näsholm et al., 2013).

Coincidences of elevated N leaching and impaired EMM production found after N

deposition or fertilization has led to suggestions that active growth of EMF prevents N losses (Nilsson et al., 2007; Nilsson et al., 2012; Bahr et al., 2013). However, the capacity of EMF to reduce N leaching still remains uncertain since the effect of impaired EMM production, typically seen after N addition (Arnebrant and Söderström, 1992; Nylund and Wallander, 1992; Nilsson and Wallander, 2003; Nilsson et al., 2007; Högborg et al., 2011; Kjoller et al., 2012; Nilsson et al., 2012; Bahr et al., 2013), hasn't been separated from the direct effect of an increased N pool in the soil as well as other environmental variables. Apart from repressing the belowground C allocation and thus the EMF growth, enhanced availability of N may also alter the capacity of the present EMM network to take up N (Clemmensen et al., 2008).

Even though N is generally considered well retained in the N poor boreal and boreo-nemoral forest soils (Gundersen and Rasmussen, 1995), leaching of N may occur if the N retention capacity is exceeded due to extensive N input (Aber et al., 1998; Gundersen et al., 2006; Akselsson et al., 2010). Elevated N leaching has been recorded in boreo-nemoral forests as a result of N deposition (Nilsson et al., 2007; Akselsson et al., 2010; Bahr et al., 2013), N fertilization (Berdin et al., 1998) and clear-cutting (Akselsson et al., 2004). Further, deposition or fertilization with N may shift the limitation to other nutrients and resources (Tamm, 1991), and there have been findings of P limitation caused by addition of N in coniferous forests in the boreal region (Quesnel and Côté, 2009), boreo-nemoral region (Clarholm and Rosengren-Brinck, 1995) and nemoral region (Mohren et al., 1986; Valentine and Allen, 1990; Houdijk and Roelofs, 1993;

Braun et al., 2010). Alleviation of N induced P limitation by fertilization of P, has been shown to increase the autotrophic N retention capacity in coniferous forest soils (Stevens et al., 1993; Blanes et al., 2012), but the role of EMF were not tested in these studies.

Wallander and Nylund (1992) showed in laboratory experiments that EMM production was repressed by excess N treatment when P levels was adequate, however if P was deficient no repression of EMM production was found after N addition. The importance to take P into account when analyzing EMM production was also highlighted in a recent large scale field study in boreo-nemoral forests, where EMM production was negatively correlated with needle P content (Bahr et al., 2013). Even though the combined effect of N and P levels on EMM production has been analyzed in laboratory experiments (Wallander and Nylund, 1992) this, to our knowledge, still remains to be tested in the field.

In the present study we simultaneously analyzed N leakage and growth of EMM during four-month periods over one year in a Norway spruce (*Picea abies*) forest fertilized with N or N and P in combination. The temporal division of sampling was made to account for the large seasonal variation in both N leaching (Stevens et al., 1993; Piirainen et al., 1998; Wright et al., 2001) and EMM growth (Wallander et al., 2001). Production of EMM, which has been suggested to increase soil N retention (Aber et al., 1998; Nilsson et al., 2007; Högborg et al., 2011), usually peaks at late summer to early fall, while it almost ceases during the winter (Wallander et al., 2001). In contrast, large temporal soil water N flushes in the spring are typically explained by snow

melting (Aber et al., 1998; Piirainen et al., 1998), intense periods of precipitation and low plant assimilation (Wright et al., 2001).

Production of EMM was estimated with sand filled ingrowth mesh-bags. The response of EMM to apatite amendment was tested in some of the mesh-bags, and used as a proxy for P status since it has earlier been found that addition of the P rich mineral apatite stimulate EMM growth in P deficient soil (Wallander and Thelin, 2008). Isotopically labeled N was added to some of the ingrowth mesh-bags to quantify N assimilation by EMM (Clemmensen et al., 2008). The amount of labeled N passing through the EMM network was collected in ion exchange resins and used as a proxy for N leaching. To maximize the prerequisite for N leaching we also included N treated plots in denser (unthinned) forest stands, where the potential to assimilate N would be reduced since the photosynthetically active radiation can become limiting at a sufficient supply of water and nutrients (Aber et al., 1998).

Our aim was to analyze the N retention capacity of EMM under different nutrient conditions and seasons. It was hypothesized that (1) N addition would cause both enhanced N leaching and reduced EMM production. (2) EMM production should be further repressed when N addition was combined with P addition (if P becomes limiting for primary production in N treated plots). (3) N leaching should mainly occur in plots where apatite amendment stimulates EMM growth since this indicates P limitation and thus excess N. (4) Largest N losses were expected to co-occur with low EMM production in early spring, while elevated EMM production in autumn should counteract N leaching. (5) N fertilization was expected to cause reduced N

assimilation by EMM and increased N leaching in mesh-bags amended with ^{15}N .

Material and methods

Field site

The experiment was conducted in South Sweden at Tönnersjöheden research park (Lat. 56° 41'-42' Long. 13° 5'-7'), in the county of Halland, which is managed by the Swedish University of Agricultural Sciences. The experimental site consisted of 32 year old (at the initiation of the experiment) Norway spruce (*Picea abies*) forest, which was thinned during the winter 2011. The analysis was conducted at 24 plots (30-40 m x 25 m) with 4 different treatments (Table 1). 200 kg ha⁻¹ of N was added once (July 2011) as ammonium nitrate (Skog-CAN, Yara AB, Helsingborg, Sweden) to 18 of the 24 analyzed plots. Six of the N treated plots were also treated twice (July 2011 and July 2012) with 200 kg ha⁻¹ of P (in total 400 kg ha⁻¹) added as superphosphate (P20, Yara AB, Helsingborg, Sweden). Another 6 of the N treated plots were not thinned prior to the treatments and were thus forming denser stands (1500 stems ha⁻¹, SE = 40) than the thinned plots (940 stems ha⁻¹, SE = 70). The remaining 6 plots served as controls. The N plots were split into 5 m wide areas, and the fertilizers were distributed by hand to one area at a time to improve the homogenization of the distribution. Half of the plots, 3 of each treatment, were located on a blocky moraine soil while the other were located at sandy alluvial deposits with potentially larger percolation capacity. The soils were podzols with a humus depth ranging from 3 to 16 cm with a mean of 9.8 cm (*SD* = 3.1). Treatment at different plots was selected randomly.

Production of extramatrical ectomycorrhizal mycelium

Ingrowth mesh-bags were used to determine the production of EMM, a fine mesh (pore

size: 50 μ m) allowed for EMM ingrowth while it prevented tree roots to penetrate into the bag (Wallander et al., 2001). The mesh-bags were made cylindrical (length: 16 cm, diameter: 2 cm) to cover most of the active EMM region. They were filled with 70 g acid washed quartz sand (0.36–2.00 mm, 99.6% SiO₂, Ahlsell AB, Sweden) to reduce ingrowth of saprotrophic fungi due to lack of C. Some of the mesh-bags were amended with 0.5% of the P containing mineral apatite, since this can give an indication of P deficiency (Wallander and Thelin, 2008). An overview of the mesh-bags is given in Table 1. Parallel to the longest sides in each plot (at least 2 m from the borders) two transects were placed, and the mesh-bags were positioned systematically along these. Six sets of mesh-bags were installed at each plot. One set of mesh-bags, including non-amended and apatite amended bags (apatite bags were not installed at unthinned plots) were installed in July 2011 and left during the whole study period, until November 2012. To analyze seasonal variation in EMM production, non-amended mesh-bags were installed during consecutive four month periods (15 July 2011 – 15 November 2011, 15 November 2011 – 15 March 2012, 15 March 2012 – 15 July 2012 and 15 July 2012 – 15 November 2012). A hole, for each mesh-bag, was made with a soil corer (diameter: 2.0 cm) and the humus depth was noted. After harvest the mesh-bags were stored in a fridge (+4°C) for less than 3 days and then transferred to a freezer (-18°C).

Before analyses the humus depth was marked on the side of the mesh-bags, the bags were then opened by cutting a hole in one end and then gently pulling of a string of mesh along the whole mesh-bag. Along that string the frequency of hyphae was counted in vertical rows of 100 mesh holes.

This was done at three different depths; at the border between humus and mineral soil as well as in the middle of these two layers. The abundance of EMM in the mesh-bags was also estimated visually in a stereo microscope according to Wallander et al. (2001), with the use of a six graded scale. The sand from the mesh-bags were then split up into the humus part and the mineral part and pooled for each plot and period. Fungal content in these samples was further estimated by analyzing the ergosterol content. Ergosterol is a fungal specific membrane lipid that can be used as a fungal biomarker (Wallander et al., 2001). During degradation of fungal hyphae ergosterol becomes bound in sterol esters (Yuan et al., 2008) and the amount of free ergosterol has been suggested to better resemble living fungal mycelium (reviewed by Wallander et al., 2013). Free and total ergosterol was analyzed in 5 g sand from each of the pooled samples. Ergosterol was extracted in 5 ml methanol with 15 min sonication and 1 h 70°C water bath. 2.5 ml of the solution was then transferred into new 10 ml glass tubes together with 2.5 ml methanol for analyses of free ergosterol. To enable detection of total ergosterol (including the bound partition), 2.5 ml KOH solution (20% KOH in methanol) was added to the original tubes and they were shaken on a multivortex (Multi Reax, Heidolph, Germany) for 3 minutes. The ergosterol analyses were then continued according to Bahr et al. (2013). In brief: After extraction of ergosterol into the methanol based solvent, 1 ml H₂O was added to increase the polarity. After adding 2 ml cyclohexane, the samples were shaken on a multivortex to transfer ergosterol into the nonpolar phase and then centrifuged to enable phase separation into new tubes, another 2 ml cyclohexane was added to the original tubes and the phase separation was repeated. After

Table 1: Overview of treatments as well as number of lysimeters, mesh-bags (MB) and nitrogen labeling (^{15}N) samples included in the study. In the fertilized plots, 200 kg nitrogen (N) ha^{-1} was added as ammonium-nitrate, while 400 kg phosphorus (P) ha^{-1} was added as superphosphate.

		Control	N	NP	N, dense
Number of plots	Moraine soil	3	3	3	3
	Alluvial deposit soil	3	3	3	3
	Total	6	6	6	6
Lysimeters plot ¹	Alluvial deposit soil	4	4	4	4
Sand mesh-bags plot ¹	Whole period	6	6	6	6
	4 month periods	6	6		
Apatite mesh-bags plot ¹	Whole period	6	6	6	
^{15}N labeled mesh-bags plot ¹	July 2012 - Nov 2012	6	6		

evaporating the cyclohexane the ergosterol was dissolved in 400 μl methanol before ergosterol detection in a reversed-phase column (Chromolith C18 column, Merck and an Elite LaChrome C18 pre-column, Hitachi, Japan) high pressure liquid chromatograph (auto sampler L2130 with UV-detector L2400 by Hitachi, Japan). The ergosterol peak was detected at 280 nm with a flow rate of 1 ml min^{-1} .

Labeled nitrogen – trace experiment

The labeling experiment was implemented during the last study period (July 2012 – November 2012) at the N treated plots as well as the controls (Table 1). Labeled N was added as $^{15}\text{NH}_4\text{Cl}$ according to Clemmensen et al. (2008). Ammonium has been found preferentially assimilated by EMM, in contrast to NO_3^- (Finlay et al., 1992; Clemmensen et al., 2008), and there is larger interspecific variation in NO_3^- assimilation (Finlay et al., 1992). Further, NH_4^+ is by far the most common form of inorganic N found in Norway spruce forests soils (Tamm, 1991). To enable detection of leached N, 2 g ion-exchange resin beads (Amberlite® MB6113 mixed resin, BDH laboratory supplies, Poole, England) were put in the bottom of each mesh-bag. Labeling with ^{15}N was performed 2 days before harvest since Clemmensen et al. (2008) found this sufficient for EMM

assimilation in mesh-bags. We injected 5 ml $^{15}\text{NH}_4\text{Cl}$ (14.5 mM), corresponding to 17 kg N ha^{-1} , in the mesh-bags with a syringe inserted to a depth of 2 cm. Before harvest the mesh-bags were flushed twice with 10 ml H_2O . After harvest these mesh-bags were treated as the others, but after visual estimation of EMM a pooled sample of totally 10 g sand was combined from the mesh-bags of each plot. The pooled samples were put into 10 ml glass tubes together with 7 ml H_2O . The tubes were shaken for one minute in a multivortex (Muli Reax, Heidolph, Germany). Separately, each tube was then shaken on a single vortex (Vortex-genie 2 model: G560E, Scientific industries inc., Bohemia, USA) for ten seconds followed by immediate decantation of the liquid to a 50 ml polyethylene Saersted tubes. This process was repeated three more times after addition of another 5 ml H_2O to the original glass tubes. For further separation from mineral particles the 50 ml tubes were then vortexed for ten seconds before immediate decantation into new 50 ml tubes. After centrifuging the 50 ml tubes for three minutes at 1000 g the supernatant was removed and the mycelial pellet left to dry overnight at 40°C. The dried mycelium was weighed and put in tin capsules (SC0009, SerCon ltd., Crewe, United Kingdom) for further analysis (see below).

Ammonium was extracted from resin beads with the use of acid traps, according to IAEA (2001), in brief: The collected resin beads from all mesh-bags at each plot were pooled and split into two technical replicates per plot. Ammonium was extracted from the ion-exchange resin beads in 50 ml 1M KCl in plastic jars. After addition of 0.2 g MgO and an acid trap (a quartz filter treated with 10 μ l KHSO₄, sealed between two Teflon tapes), the plastic containers were immediately sealed. Liberated gaseous ammonia was slowly collected in the acid traps during three days in darkness at 100 RPM shaking. The quartz filters were then put into tin capsules and left to dry in a desiccator. Mycelial and resin bead samples were analyzed for the ratios of ¹⁵N/¹⁴N and ¹³C/¹²C as well as total N and C content at the stable isotope facility at the Department of Biology, Lund University. Samples were flash-combusted in a Flash 2000 elemental analyzer, and the isotopic ratios determined by a Delta V Plus isotope-ratio mass spectrometer (IRMS) connected to the elemental analyzer via the ConFlow IV interface (Thermo Scientific Inc., Bremen Germany)

Soil water sampling

Four suction lysimeters were installed at each of the 12 plots located at sandy alluvial deposit soil with potentially larger percolation capacity, where sufficient soil water percolation was expected. The lysimeters consisted of 2000 ml cylindrical containers connected with plastic tubing to ceramic filters put at 50 cm depth. Each month the lysimeters were set to approximately 0.6 bar vacuum pressure and then left for one month before collection of the samples. The total amount of soil water in each lysimeter was noted and 50 ml water samples were transferred to plastic tubes and stored in a fridge (+4°C) overnight before

pH measurements. The samples were then stored in a freezer (-18°C) until further analyses. Prior to N analyses water samples were pooled plot wise, in relation to the total sampled amount, for four month periods corresponding to the mesh-bag periods. To pinpoint possible N flushes due to snowmelt, winter and spring samples (November 2011 – April 2012) were pooled for each month separately. No water samples were collected during February 2011 due to frozen ground.

Needle chemistry

Previous year's needles were collected at three out of six plots (two from sandy alluvial deposit plots and one from moraine plots) of each treatment (in total needle samples were collected from 12 plots), during January 2013 to analyze the effect of fertilization on tree nutrient status. They were analyzed for N and P content at the Swedish university of agricultural sciences (department of soil and environment, Uppsala, Sweden) with an inductively coupled plasma optical emission spectrometry (ICP Optima 7300 DV, PerkinElmer Inc., Waltham, USA).

Statistics

The data was statistically analyzed with IBM SPSS statistics 21. Differences in parametric data (frequency of hyphae, ergosterol, needle chemistry, soil water chemistry and IRMS results) were tested with T-tests for 2 groups, ANOVA and Tukey's post hoc tests for 3 or more groups, while regressions were analyzed with Pearson correlations (R^2). The homogeneity of variances was verified with Levene's test. Differences in nominal data (visual estimation of EMM production) were tested with Mann-Whitney U for 2 groups, Kruskal-Wallis ANOVA for 3 or more groups, while regressions were analyzed with Spearman rank correlations (r_s). Ergosterol

content and soil water N values were log transformed before statistical analysis, apart from that no other transformations were applied. Only two-way T-tests were performed and independent tests were used to analyse differences between fertilization treatments while dependent tests were used for differences within a fertilization treatment (such as the effect of season or apatite amendment).

Results

No significant differences in EMM abundance were found between humus and mineral soil and the data was combined for each mesh-bag. Similarly, the two different soil types were combined due to lack of differences in EMM production. Due to good correspondence between visual estimation of EMM production and frequency of hyphae, only the latter (allowing for quantitative analysis) is shown.

Fertilization generally resulted in reduced EMM production according to frequency of hyphae (Fig. 1) and visual estimation (data not shown), while this could only be statistically verified (T-test, $P = 0.020$) according to ergosterol estimation during spring 2012 and a tendency (T-test, $P = 0.057$) of that during autumn 2012 (Fig. 2). Ingrowth in mesh-bags filled with pure sand was most repressed by combined N and P addition according to frequency of hyphae (ANOVA with Tukey post hoc, $P = 0.001$) and visual estimation (Kruskal-Wallis ANOVA, $P = 0.007$, data not shown), while no difference could be seen in ergosterol content (Fig 2.). Compared to unamended mesh-bags, ingrowth of EMM was larger in apatite amended bags in control plots according to frequency of hyphae (T-test, $P = 0.049$) and ergosterol content (T-test, $P = 0.045$). Ergosterol content was almost doubled in apatite amended mesh-bags at N fertilized plots compared to unamended

bags (T-test, $P = 0.035$), but that difference could not be detected according to frequency of hyphae or visual estimation of EMM production. At plots fertilized with both N and P, apatite amendment had no effect on EMM production according to any of the EMM estimations. Compared to control plots, ingrowth (based on frequency of hyphae) of EMM in apatite amended mesh-bags was lower ($P = 0.019$) in N treated plots while the ergosterol content tended to be opposite (Fig. 2), however not significant ($P = 0.438$).

Free ergosterol constituted an average of 29.7% ($SE = 2.5$) of the total ergosterol in mesh-bags at the different treatments and seasons. The proportion of free ergosterol was reduced during the winter at both control plots (ANOVA with Tukey, $P < 0.001$) and N fertilized plots (ANOVA with Tukey, $P < 0.001$), apart from that no other clear patterns could be revealed in regard to different treatments or seasons (Fig. 2). However, there was a large variation within treatments and seasons in the free partition of ergosterol, typically ranging from less than 10% to about 70%.

EMM biomass production during autumn 2012 was calculated to be 583 kg C ha⁻¹ ($SE = 48$) in control plots and 361 kg C ha⁻¹ in N fertilized plots. These data are based on the C content (IRMS analysis) in the mesh-bags (which was 1.18 mg C g sand⁻¹ in control plots and 0.73 mg C g sand⁻¹ in the N fertilized plots). Furthermore, we assumed that all C in the mesh-bags were of EMF origin, the EMM biomass contained 45% C, and that any transport of dissolved organic C into the mesh-bags was neglectable. The EMM biomass was significantly higher in control plots compared to N treated plots (T-test, $P = 0.001$).

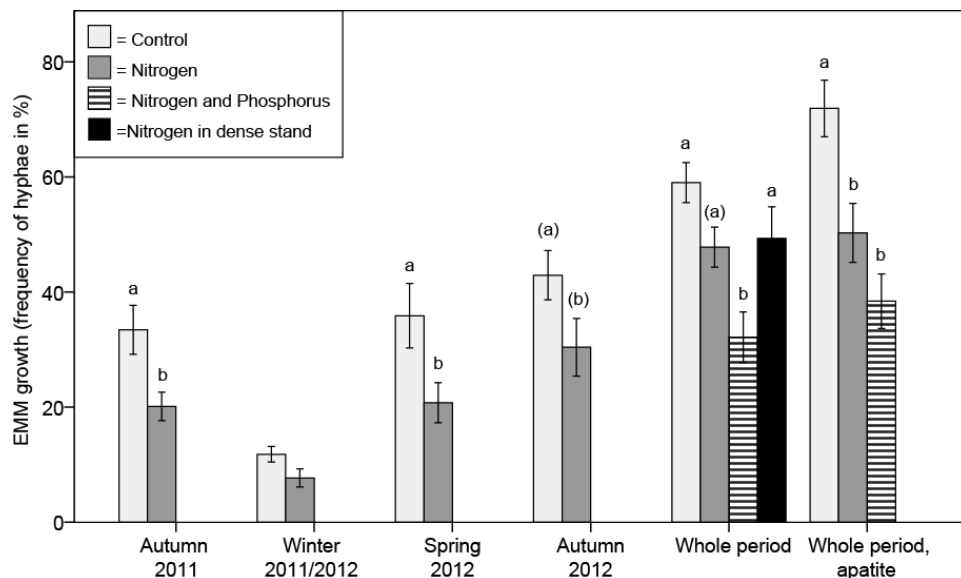


Fig. 1. Growth of ectomycorrhizal extramatrical mycelium (EMM), during 4 month incubation periods as well as during the whole period of the study (15 July 2011 until 15 November 2012), according to counting of mycelium along the mesh of the ingrowth bags. Shadings and patterns illustrate fertilization regimes. Samples from the same period that do not share letters are significantly different ($P < 0.05$) according to T-test for the four month periods and according to ANOVA with Tukey's post hoc test for the whole period. Error bars represent SE.

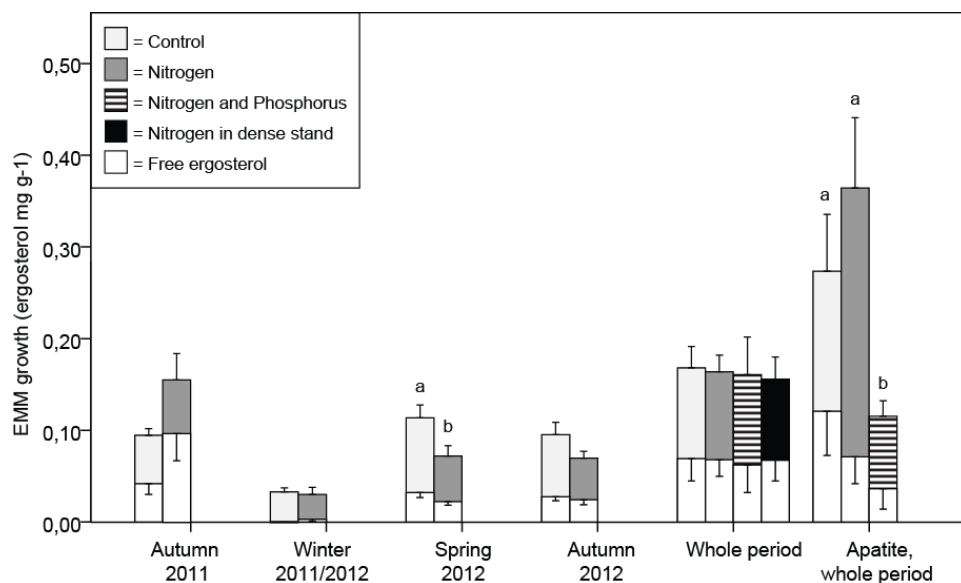


Fig. 2. Growth of ectomycorrhizal extramatrical mycelium (EMM), during 4 month incubation periods as well as during the whole period of the study (15 July 2011 until 15 November 2012), according to analysis of free and total ergosterol in sand from the ingrowth mesh-bags. Shadings and patterns illustrate fertilization regimes. Samples from the same period that do not share letters are significantly different ($P < 0.05$) in total ergosterol content according to T-test for the four month periods and according to ANOVA with Tukey's post hoc test for the whole period. Error bars represent SE.

Delta ^{13}C ratio of the EMM was -27.6% ($SE = 0.09$) and didn't differ between treatments. The average ergosterol concentration in the EMM biomass (calculated from C content according to IRMS, by estimating 45% C content of EMM biomass) was $0.40\ \mu\text{g g}^{-1}$ ($SE = 0.10$), and it didn't differ between treatments.

Only low levels of N leaching, on average $0.18\ \text{mg l}^{-1}$ ($SE = 0.02$), was detected during the pretreatment analysis of soil water in March 2011 (Fig. 3), consisting of 57% NO_3^- and 43% NH_4^+ . During the first period after fertilization, the levels of inorganic N in soil water at fertilized plots were elevated (ANOVA with Tukey, $P = 0.001$) to $34.5\ \text{mg l}^{-1}$ ($SE = 12.2$). Leaching of N then declined during the research period but elevated (ANOVA with Tukey, P

$= 0.015$) levels due to fertilization were still detected one year after the application (mean $= 3.00\ \text{mg l}^{-1}$, $SE = 0.68$), between July and November 2012. After the second winter, in February 2013, no enhanced N leaching could be statistically verified in N treated plots, but that sampling period did take place during low soil water percolation.

At control plots, needle concentration of P was below the deficiency level reported by Thelin et al. (2002) while N content seemed to be sufficient. Elevated levels of both N (ANOVA, mean $= 18.4$, $SE = 0.5$, $P < 0.001$) and P (ANOVA, mean $= 3.19$, $SE = 0.20$, $P < 0.001$) in needles was detected at plots fertilized with those nutrients, but there were no differences in needle N content between different treatments that included N fertilization (Table 2).

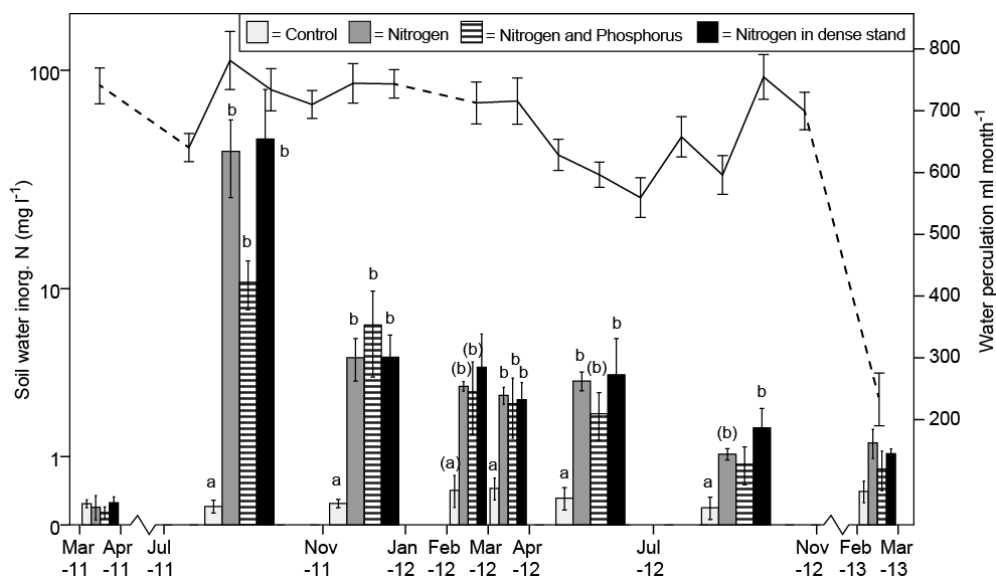


Fig. 3. Inorganic N concentration and volume of soil water collected in ceramic filter suction lysimeters. Shadings and patterns illustrate the fertilization regimes (that were initiated in July 2011). Samples from the same period that do not share letters are significantly different ($P < 0.05$) according to ANOVA with Tukey's post hoc test. Error bars represent SE.

Table 2: Content of nitrogen (N) and phosphorus (P) in previous year's needles, collected at half of the plots during January 2013 (one and a half year after fertilization). Average content at different fertilization treatments are given together with standard error (SE). Deficiency levels suggested by Thelin et al. (2002) are given.

Treatment	N (%)	SE	P (mg g ⁻¹)	SE
Control	16.1	0.4	1.1	0.1
N	17.8	0.6	1.2	0.1
NP	20.2	0.3	3.2	0.2
N dense	17.1	0.1	1.3	0.1
Deficiency	12		1.3	

The assimilation of the ¹⁵N (injected into the mesh-bags) in EMM (Fig. 4) was larger ($P = 0.013$) at control plots (1.13% of added ¹⁵N, $SE = 0.17\%$) than in N fertilized plots (0.58%, $SE = 0.07\%$). Based on that result it was estimated that the EMM had a potential to assimilate 217 g inorganic N ha⁻¹ day⁻¹ ($SE = 32$) at control plots and 113 g ha⁻¹ day⁻¹ ($SE = 13$) at fertilized plots. In contrast more ¹⁵N was leached ($P = 0.05$) to the resin placed at the bottom of the bags in N fertilized plots (mean = 4.8%, $SE = 0.98\%$) than in the controls (mean = 1.9%, $SE = 0.84\%$). However, no significant difference was found in ¹⁵N content per unit EMM biomass (0.31 mg ¹⁵N g⁻¹ day⁻¹, $SE = 0.03$, based on C content) collected from control and N treated plots. The growth of EMM during the autumn of 2012, when the labeling experiment was implemented, was positively correlated with recovery of ¹⁵N (Fig. 5), both according to frequency of hyphae ($R^2 = 0.57$, $P = 0.004$) and ergosterol analysis ($R^2 = 0.57$, $P = 0.004$).

Discussion

In the present study we found repressed EMM production starting within four months after N fertilization. Repressed EMM growth after N fertilization has been found in many earlier observations, although these measurements have usually been performed after several years of exposure to

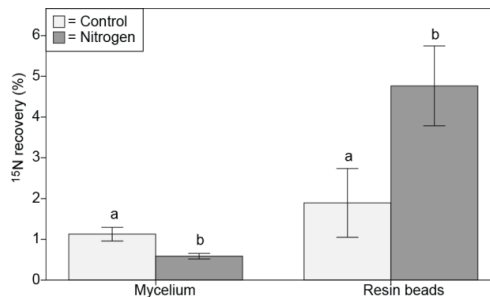


Fig. 4. Recovery of ¹⁵N added to the mesh-bags, in mycelium extracted from the ingrowth mesh-bags and in ion-exchange resin beads from the bottom of the mesh-bags. Shadings illustrate fertilization regimes. Samples of the same medium that do not share letters are significantly differed ($P < 0.05$) in total ergosterol according to T-test. Error bars represent SE.

elevated levels of inorganic N (e.g. Nilsson and Wallander, 2003; Nilsson et al., 2007; Kj  ller et al., 2012; Bahr et al., 2013).

However, even though N fertilization consistently repressed EMM growth according to frequency of hyphae and visual EMM estimation, ergosterol content didn't reveal that pattern as clear. Even though ergosterol content usually correlate well with other methods for fungal quantification (rev. by Wallander et al., 2013), inconsistencies have been reported (e.g. H  gberg, 2006; Bahr et al., 2013), and the methods likely represent different aspects of fungal biomass. The visual method may be better to estimate the proliferation and aggregation of fine hyphae while ergosterol content, to a larger extent is sensitive to the abundance of rhizomorphs. It is also possible that ergosterol accumulates in the mesh-bags during the incubation time, while visual estimation gives a snap shoot of the current situation. Ergosterol has been found to accumulate in soil during late successional stages (Clemmensen et al., 2013), and it has been suggested as being less prone to degradation during N addition and reduced belowground C allocation (Zhao et al., 2005).

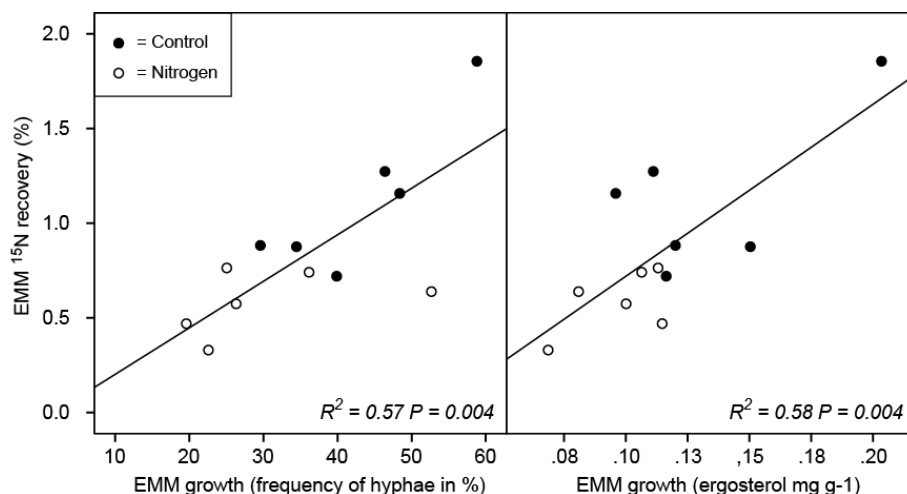


Fig. 5. Recovery of ¹⁵N added to the mesh-bags, in mycelium extracted from the ingrowth mesh-bags in relation to production of ectomycorrhizal extramatrical mycelium (EMM). EMM was estimated by counting of mycelium along the mesh of the ingrowth bags (A) and analysis of free and total ergosterol in sand from the ingrowth mesh-bags (B). Filled circles illustrate nitrogen fertilized plots.

In the long term, elevated soil fertility has been found to change the EMF community composition (Kjøller et al., 2012). This may affect the ergosterol content which has been shown to differ between, as well as within, different EMF species (Bermingham et al., 1995). It is however not likely that the short time period of the present study was sufficient for considerable changes in the EMF community. Delta ¹³C ratio of the EMM was -27.6 ‰ ($SE = 0.09$) and didn't differ between treatments. Further, the average ergosterol concentration in the EMM biomass was low ($0.40 \mu\text{g g}^{-1}$) in comparison to previous findings of $1.00 \mu\text{g g}^{-1}$ by Hagerberg et al. (2003), although, they found large variation between different years (0.63 - $1.30 \mu\text{g g}^{-1}$).

It was expected that analysis of free ergosterol would result in better correlations with the frequency of hyphae and visual estimations, since the free partition of ergosterol has been suggested as an indicator of living fungi (rev. by Wallander et al., 2013). However, there was a large variation

in free ergosterol, and no clear differences could be detected in regard to fertilization treatment or incubation time. However during the winter, there was almost no free ergosterol which could be caused by a stagnated production of new EMM. But, these results must be interpreted with caution since the ergosterol levels were very low in the winter and the level of free ergosterol was close to the detection limit. In comparison with previous analyses of ergosterol in ingrowth mesh-bags (Wallander et al., 2010), in which 90% consisted of the free form, relatively low amounts (30%) of free ergosterol was detected in the present study. This discrepancy might be related to the extraction method used for free ergosterol, which is more crude and contains compounds that interfere with the ergosterol signal and make quantification of free ergosterol less reliable. Further research regarding ergosterol degradation during different environmental conditions is needed to improve our understanding and interpretation of the ergosterol analysis. The interpretation of free ergosterol could be

improved by manipulative experiments examining how it is affected by fungal degradation during e.g. soil incubation with fungicide addition to prevent production of saprotrophic fungi, or with freeze-thaw treatments. Further, development of the method for analysis of free ergosterol might result in more accurate HPLC chromatograms and improved detectability.

Enhanced repression of EMM growth when N is combined with P fertilization has earlier been found in microcosms (Wallander and Nylund, 1992). Our results indicate that this also occurs under field conditions, since EMM production tended to be further repressed by combined addition of N and P. This is probably an effect of sustained belowground C allocation to EMM due to enhanced P limitation in N fertilized plots.

Since EMM production in control plots was elevated by apatite amendment, and the P levels in the needles were below deficiency levels while N content was above (Table 2), it is likely that P was limiting growth in control plots. This, together with previous observations of P affecting EMM production in unfertilized boreo-nemoral forest (Hagerberg et al., 2003; Berner et al., 2012; Bahr et al., 2013) show that, apart from N, it may be important to take P into account in studies of environmental variables affecting EMF. Future estimates of growth responses will reveal to what extent tree growth is limited by N, P or both nutrients.

The limitation of P probably became more severe after N addition and could have caused the enhanced ergosterol levels in the apatite mesh-bags in N treated plots (Fig. 2). The lack of, decline in the needle content of P after N fertilization may suggest that tree growth did not respond to N addition, or that the time period for a growth response

(about one year) is too short. The combination of N and P fertilization completely eradicated the positive effect of apatite on EMM growth and P levels in the needles rose far above deficiency levels indicating that any P limitation was relieved. Further studies are needed to state if the negative effect of P addition on EMM production (Fig. 1 and 2) is general, or if it only occurs when trees are initially P limited.

In relation to previous observations of annual EMM production of about 160 kg ha⁻¹ (rev. by Ekblad et al., 2013), the production of EMM at control plots was large, calculated to 583 kg ha⁻¹ during four months in late summer and early autumn. This can be compared to an aboveground NPP of 11.6 t ha⁻¹ y⁻¹ in a Norway spruce forest in Skogaby (located about 20 km from the present study) of similar age and fertility (Schulze, 2000). In Skogaby the production of belowground plant tissue was 40 % (7.4 t ha⁻¹ y⁻¹) of the total NPP. Thus, the estimated four month EMM production of 583 kg ha⁻¹ (the EMM production in the mesh-bags is similar to the soil environment) of the present study indicate that a substantial part of the C is allocated to EMF.

The abundant EMM was apparently not sufficient to retain all the added N, since an immediate flush of soil water N occurred after fertilization with up to about 100 mg l⁻¹. Elevated N losses were recorded at all fertilization treatments and not only where P was limiting. There was, however, a tendency of reduced N losses after fertilization at the plots fertilized with both N and P, which could be due to alleviation of the P limitation that was present in plots receiving N only (Stevens et al., 1993). Thus, N leakage after fertilization may be reduced by combined addition of P, but further studies are needed to verify this effect.

After the first autumn, soil water levels of N decreased to less than 10 mg l⁻¹ and one year after the application, during the second autumn, to about 1 mg l⁻¹. Average N levels was however still elevated at N fertilized plots, but only significantly so in unthinned forest where limited photosynthetically active radiation might restrain belowground C allocation (Aber et al., 1998) and thus also N assimilation. The rapid decline in N leaching after application is in accordance with previous findings of reduced soil water NO₃⁻ within a few years after interrupted N treatment (reviewed by: Högberg et al., 2011).

Contrary to our expectations, no enhanced N leaching was found during the spring when no active EMM growth was detected, indicating that other processes than EMM production are also important for N retention. The rapid reduction in N leaching may have overshadowed any seasonal effect on N leaching making it difficult to relate it to EMF growth. However, EMM production as well as N leaching was reduced in the NP treatment, which does not suggest that reduced EMM production necessarily enhance the risk of N leaching. For a better evaluation of the role of EMF to counteract N leaching, estimates of N assimilation is necessary, and by tracking ¹⁵N in the mesh-bags we found that EMM had a potential to retain 6 kg N ha⁻¹ month⁻¹ in the control plots while this declined to half in the fertilized plots due to less abundant EMM growth. This suggest a significant role of EMM in N retention, although only a small portion of the initial 200 kg N application can be assimilated during the first growing season. In contrast, EMF uptake may be sufficient to retain moderate levels of inorganic N several years after fertilization or due to elevated N deposition. This data is based on the EMM produced in

the mesh-bags during the experimental period, but if the total standing EMM biomass is assumed to have a similar assimilation potential, a different pattern will emerge. Wallander et al. (2004) estimated a standing biomass of EMM in a Norway spruce forest in southern Sweden to 5000 kg ha⁻¹. This will correspond to a monthly assimilation capacity of 46 kg ha⁻¹, meaning that 4 months would be enough to take up the whole application of 200 kg N ha⁻¹. It should be noted that the potential to assimilate N by EMM is probably underestimated since a portion of the N taken up will be translocated to the host tree during the two day incubation period. Näsholm et al. (2013) recently found that N fertilization resulted in enhanced allocation of ¹⁵NO₃⁻ to the host tree, which suggest that the N assimilation potential may be even more underestimated in the N fertilized plots. On the other hand, enhanced N leaching in the mesh-bags of N fertilized plots suggest lower N retention of the EMM in this treatment. In addition, the Näsholm et al. (2013) study was performed in a severely N limited forest while our study was done in a forest with sufficient N, which would guarantee efficient allocation of N to the host trees also in the control plots. However, a true estimate of the N assimilation potential by EMM requires that the amount of N allocated to the host trees is also quantified.

In the present study we show that EMF play an important role in the N retention but to explain N leaching, especially after fertilization with large doses of N, many other environmental variables has to be taken into account. These may be direct assimilation by tree roots, climate variables such as precipitation and snowmelt, growth of saprophytic fungi and chemical reactions between N and humus. A large initial flush

of N after the fertilization show that some of the added N cannot be retained. Usually this correspond to around 5% of the added amount after a standard fertilizer application (Nohrstedt, 2001). It is possible that N leaching could be prevented by more moderate application of the N fertilizer (Bergh et al., 2008), and similar to the work by Stevens et al. (1993), our results suggest that N leakage can also be reduced by combining N with a P fertilizer. However, this may only be relevant in P deficient soils and further studies are needed to evaluate this treatment in different types of forests.

Our findings of reduced ^{15}N retention by EMM after N fertilization supports earlier suggestions that EMM prevents N leaching which are based on correlations between elevated N losses and low EMM production (Nilsson et al., 2007; Kjølner et al., 2012; Bahr et al., 2013). Högborg et al. (2013) found that the fungal to bacterial ratio in the soil was the variable most correlated to N losses. It was however not clear to what extent saprophytic vs. mycorrhizal fungi contributed to the N retention (Högborg et al., 2013). In the present study, elevated percolation of isotopically labeled NH_4 in the ingrowth mesh-bags at the N fertilized plots is likely due to repressed EMM production. Still, saprophytic fungi maybe important for N retention in the natural soil

environment. Reduced N assimilation by EMM in N treated plots may however also been affected by changed specific N assimilation capacity per mycelial biomass after N fertilization (Finlay et al., 1992; Clemmensen et al., 2008), but it has been reported that interspecific differences regarding NH_4^+ assimilation are small (Finlay et al., 1992).

Conclusions

Elevated N losses coincided with reduced EMM production after N fertilization, but seasonal variation of EMM production was not correlated to seasonal variation in N leaching. It was thus not possible to draw any firm conclusions of the role of EMM in the total ecosystem N retention capacity. However, by tracing stable N isotopes added to ingrowth mesh-bags we were able to demonstrate enhanced assimilation and reduced leaching of labeled N in control compared to fertilized plots. EMM thus have a significant role in reducing N leaching but other factors are also important. We calculated a potential N retention capacity by EMM to more than $6 \text{ kg ha}^{-1} \text{ month}^{-1}$ at control plots, while this value was reduced to half in N fertilized plots.

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References

- Aber, J., McDowell, W., Nadelhoffer, K., Alison, M., Berntson, G., Kamakea, M., McNulty, S., Currie, W., Rustad, L., Fernandez, I., 1998. Nitrogen saturation in temperate forest ecosystems. *Bioscience* 48, 921-934.
- Akselsson, C., Belyazid, S., Hellsten, S., Klarqvist, M., Pihl-Karlsson, G., Karlsson, P.E., Lundin, L., 2010. Assessing the risk of N leaching from forest soils across a steep N deposition gradient in Sweden. *Environmental Pollution* 158, 3588-3595.
- Akselsson, C., Westling, O., Orlander, G., 2004. Regional mapping of nitrogen leaching from clearcuts in southern Sweden. *Forest Ecology and Management* 202, 235-243.
- Arnebrant, K., Söderström, B., 1992. Effects of different fertilizer treatments on ectomycorrhizal colonization potential in two Scots pine forests in Sweden. *Forest Ecology and Management* 53, 77-89.
- Bahr, A., Ellström, M., Akselsson, C., Ekblad, A., Mikusinska, A., Wallander, H., 2013. Growth of ectomycorrhizal fungal mycelium along a Norway spruce forest nitrogen deposition gradient and its effect on nitrogen leakage. *Soil Biology and Biochemistry* 59, 38-48.
- Berden, M., Nilsson, S.I., Nyman, P., 1998. Ion leaching before and after clear-cutting in a Norway spruce stand. Effects of long-term application of ammonium nitrate and superphosphate. (vol 93, pg 1, 1997). *Water Air and Soil Pollution* 101, 445-445.
- Bergh, J., Nilsson, U., Grip, H., Hedwall, P.O., Lundmark, T., 2008. Effects of frequency of fertilisation on production, foliar chemistry and nutrient leaching in young Norway spruce stands in Sweden. *Silva Fennica* 42, 721-733.
- Bermingham, S., Maltby, L., Cooke, R.C., 1995. A critical assessment of the validity of ergosterol as an indicator of fungal biomass. *Mycological Research* 99, 479-484.
- Berner, C., Johansson, T., Wallander, H., 2012. Long-term effect of apatite on ectomycorrhizal growth and community structure. *Mycorrhiza* 22, 615-621.
- Blanes, M.C., Emmett, B.A., Viñeña, B., Carreira, J.A., 2012. Alleviation of P limitation makes tree roots competitive for N against microbes in a N-saturated conifer forest: A test through P fertilization and ¹⁵N labelling. *Soil Biology and Biochemistry* 48, 51-59.
- Braun, S., Thomas, V.F.D., Quiring, R., Flückiger, W., 2010. Does nitrogen deposition increase forest production? The role of phosphorus. *Environmental Pollution* 158, 2043-2052.
- Clarholm, M., Rosengren-Brinck, U., 1995. Phosphorus and nitrogen fertilization of a Norway spruce forest-effects on needle concentrations and acid phosphatase activity in the humus layer. *Plant and Soil* 175, 239-249.
- Clemmensen, K.E., Bahr, A., Ovaskainen, O., Dahlberg, A., Ekblad, A., Wallander, H., Stenlid, J., Finlay, R.D., Wardle, D.A., Lindahl, B.D., 2013. Roots and associated fungi drive long-term carbon sequestration in boreal forest. *Science* 339, 1615-1618.
- Clemmensen, K.E., Sorensen, P.L., Michelsen, A., Jonasson, S., Ström, L., 2008. Site-dependent N uptake from N-form mixtures by arctic plants, soil microbes and ectomycorrhizal fungi. *Oecologia* 155, 771-783.
- Ekblad, A., Wallander, H., Godbold, D.L., Cruz, C., Johnson, D., Baldrian, P., Björk, R.G., Epron, D., Kieliszewska-Rokicka, B., Kjoller, R., Kraigher, H., Matzner, E., Neumann, J., Plassard, C., 2013. The production and turnover of extramatrical mycelium of ectomycorrhizal fungi in forest soils: role in carbon cycling. *Plant and Soil* 366, 1-27.
- Ericsson, T., 1995. Growth and shoot: root ratio of seedlings in relation to nutrient availability. *Plant and Soil* 168-169, 205-214.
- Finlay, R.D., Frostegard, A., Sonnerfeldt, A.M., 1992. Utilization of Organic and Inorganic Nitrogen Sources by Ectomycorrhizal Fungi in Pure Culture and in Symbiosis with *Pinus contorta* Dougl. ex Loud. *New Phytologist* 120, 105-115.
- Gundersen, P., Rasmussen, L., 1995. Nitrogen mobility in a nitrogen limited forest at Klosterhede, Denmark, examined by NH₄NO₃ addition. *Forest Ecology and Management* 71, 75-88.

- Gundersen, P., Schmidt, I.K., Raulund-Rasmussen, K., 2006. Leaching of nitrate from temperate forests - effects of air pollution and forest management. *Environmental Reviews* 14, 1-57.
- Hagerberg, D., Thelin, G., Wallander, H., 2003. The production of ectomycorrhizal mycelium in forests: Relation between forest nutrient status and local mineral sources. *Plant and Soil* 252, 279-290.
- Houdijk, A.L.F.M., Roelofs, J.G.M., 1993. The effects of atmospheric nitrogen deposition and soil chemistry on the nutritional status of *Pseudotsuga menziesii*, *Pinus nigra* and *Pinus sylvestris*. *Environmental Pollution* 80, 79-84.
- Högberg, M., Högbom, L., Kleja, D., 2013. Soil microbial community indices as predictors of soil solution chemistry and N leaching in *Picea abies* (L.) Karst. forests in S. Sweden. *Plant and Soil*, 1-16.
- Högberg, M.N., 2006. Discrepancies between ergosterol and the phospholipid fatty acid 18 : 2 omega 6,9 as biomarkers for fungi in boreal forest soils. *Soil Biology and Biochemistry* 38, 3431-3435.
- Högberg, P., Johannisson, C., Yarwood, S., Callesen, I., Näsholm, T., Myrold, D.D., Högberg, M.N., 2011. Recovery of ectomycorrhiza after 'nitrogen saturation' of a conifer forest. *New Phytologist* 189, 515-525.
- IAEA, 2001. Use of Isotope and Radiation Methods in Soil and Water Management and Crop Nutrition. (IAEA-TCS-14) International Atomic Energy Agency, Vienna, Austria.
- Karst, J., Marczak, L., Jones, M.D., Turkington, R., 2008. The mutualism-parasitism continuum in ectomycorrhizas: A quantitative assessment using meta-analysis. *Ecology* 89, 1032-1042.
- Kjøller, R., Nilsson, L.-O., Hansen, K., Schmidt, I.K., Vesterdal, L., Gundersen, P., 2012. Dramatic changes in ectomycorrhizal community composition, root tip abundance and mycelial production along a stand-scale nitrogen deposition gradient. *New Phytologist* 194, 278-286.
- Mohren, G.M.J., Burg, J., Burger, F.W., 1986. Phosphorus deficiency induced by nitrogen input in Douglas fir in the Netherlands. *Plant and Soil* 95, 191-200.
- Nilsson, L.O., Bååth, E., Falkengren-Grerup, U., Wallander, H., 2007. Growth of ectomycorrhizal mycelia and composition of soil microbial communities in oak forest soils along a nitrogen deposition gradient. *Oecologia* 153, 375-384.
- Nilsson, L.O., Wallander, H., 2003. Production of external mycelium by ectomycorrhizal fungi in a Norway spruce forest was reduced in response to nitrogen fertilization. *New Phytologist* 158, 409-416.
- Nilsson, L.O., Wallander, H., Gundersen, P., 2012. Changes in microbial activities and biomasses over a forest floor gradient in C-to-N ratio. *Plant and Soil* 355, 75-86.
- Nohrstedt, H.-Ö., 2001. Response of coniferous forest ecosystems on mineral soils to nutrient additions: A review of Swedish experiences. *Scandinavian Journal of Forest Research* 16, 555-573.
- Nylund, J.E., Wallander, H., 1992. Ergosterol analysis as a means of quantifying mycorrhizal biomass. *Methods in Microbiology* 24, 77-88.
- Näsholm, T., Högberg, P., Franklin, O., Metcalfe, D., Keel, S.G., Campbell, C., Hurry, V., Linder, S., Högberg, M.N., 2013. Are ectomycorrhizal fungi alleviating or aggravating nitrogen limitation of tree growth in boreal forests? 198, 214-221.
- Piirainen, S., Finér, L., Starr, M., 1998. Canopy and soil retention of nitrogen deposition in a mixed boreal forest in eastern Finland. *Water, Air, and Soil Pollution* 105, 165-174.
- Quesnel, P.-O., Côté, B., 2009. Prevalence of phosphorus, potassium, and calcium limitations in white spruce across Canada. *Journal of Plant Nutrition* 32, 1290-1305.
- Schulze, E.D., 2000. Carbon and nitrogen cycling in european forest ecosystems. Springer-Verlag GmbH.
- Simard, S.W., Jones, M.D., Durall, D.M., 2002. Carbon and nutrient fluxes within and between mycorrhizal plants, In: van der Heijden, M.G.A.S.I.R. (Ed.), *Ecological Studies. Mycorrhizal ecology*, pp. 33-74.
- Smith, S.E., Read, D.J., 2008. *Mycorrhizal symbiosis*, third edition. Academic Press, London.

- Stevens, P.A., Harrison, A.F., Jones, H.E., Williams, T.G., Hughes, S., 1993. Nitrate leaching from a Sitka spruce plantation and the effect of fertilisation with phosphorus and potassium. *Forest Ecology and Management* 58, 233-247.
- Tamm, C.O., 1991. Nitrogen in terrestrial ecosystems: questions of productivity, vegetational changes, and ecosystem stability. Springer-Verlag.
- Thelin, G., Rosengren, U., Nihlgård, B., 2002. Barrkemi på skånska gran- och tallprovytor - Förändringar mellan 1985 och 2000. Länsstyrelsen (Ed.). Länsstyrelsen i Skåne län, Kristianstad.
- Valentine, D.W., Allen, H.L., 1990. Foliar responses to fertilization identify nutrient limitation in loblolly pine. *Canadian Journal of Forest Research* 20, 144-151.
- Wallander, H., Ekblad, A., Godbold, D.L., Johnson, D., Bahr, A., Baldrian, P., Björk, R.G., Kieliszewska-Rokicka, B., Kjoller, R., Kraigher, H., Plassard, C., Rudawska, M., 2013. Evaluation of methods to estimate production, biomass and turnover of ectomycorrhizal mycelium in forests soils – A review. *Soil Biology and Biochemistry* 57, 1034-1047.
- Wallander, H., Göransson, H., Rosengren, U., 2004. Production, standing biomass and natural abundance of ^{15}N and ^{13}C in ectomycorrhizal mycelia collected at different soil depths in two forest types. *Oecologia* 139, 89-97.
- Wallander, H., Johansson, U., Sterkenburg, E., Brandström Durling, M., Lindahl, B.D., 2010. Production of ectomycorrhizal mycelium peaks during canopy closure in Norway spruce forests. *New Phytologist* 187, 1124-1134.
- Wallander, H., Nilsson, L.O., Hagerberg, D., Baath, E., 2001. Estimation of the biomass and seasonal growth of external mycelium of ectomycorrhizal fungi in the field. *New Phytologist* 151, 753-760.
- Wallander, H., Nylund, J.E., 1992. Effects of excess nitrogen and phosphorus starvation on the extramatrical mycelium of ectomycorrhizas of *Pinus sylvestris* L. *New Phytologist* 120, 495-503.
- Wallander, H., Thelin, G., 2008. The stimulating effect of apatite on ectomycorrhizal growth diminishes after PK fertilization. *Soil Biology and Biochemistry* 40, 2517-2522.
- Vitousek, P.M., Howarth, R.W., 1991. Nitrogen limitation on land and in the sea - how can it occur. *Biogeochemistry* 13, 87-115.
- Wright, R.F., Alewell, C., Cullen, J.M., Evans, C.D., Marchetto, A., Moldan, F., Prechtel, A., Rogora, M., 2001. Trends in nitrogen deposition and leaching in acid-sensitive streams in Europe. *Hydrology and Earth System Sciences* 5, 299-310.
- Yuan, J.P., Kuang, H.C., Wang, J.H., Liu, X., 2008. Evaluation of ergosterol and its esters in the pileus, gill, and stipe tissues of agaric fungi and their relative changes in the comminuted fungal tissues. *Applied Microbiology and Biotechnology* 80, 459-465.
- Zhao, X.R., Lin, Q., Brookes, P.C., 2005. Does soil ergosterol concentration provide a reliable estimate of soil fungal biomass? *Soil Biology and Biochemistry* 37, 311-317.

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