

# Forest soil carbon sink in the Nordic region

Per Gundersen (Ed.)

IGN Report  
December 2014

**Title**

Forest soil carbon sink in the Nordic region

**Authors**

Per Gundersen<sup>1</sup> (ed.), Shimon Ozeri Ginzburg<sup>1</sup>, Lars Vesterdal<sup>1</sup>, Teresa G. Bárcena<sup>1</sup>, Bjarni D. Sigurdsson<sup>2</sup>, Helena M. Stefansdóttir<sup>2</sup>, Edda S. Oddsdóttir<sup>3</sup>, Nicolas Clarke<sup>4</sup>, O. Janne Kjønaas<sup>4</sup>, Tryggve Persson<sup>5</sup>, Göran Ågren<sup>5</sup>, Bengt Olsson<sup>5</sup>, Mats Fröberg<sup>5</sup>, Erik Karlun<sup>5</sup>, Riitta Hyvönen Olsson<sup>5</sup>, Cecilia Akselsson<sup>6</sup>, Per Bengtson<sup>6</sup>, Salim Belyazid<sup>6</sup>, Håkan Wallander<sup>6</sup>, Andis Lazdiņš<sup>7</sup>, Zane Lībiete<sup>7</sup>, Dagnija Lazdiņa<sup>7</sup>

1. University of Copenhagen, 2. Agricultural University of Iceland,  
3. Icelandic Forest Research, 4. Norwegian Forest and Landscape Institute,  
5. Swedish Agricultural University, Uppsala, 6. Lund University,  
7. Latvian Forest Research Institute.

**Citation**

Gundersen, P. et al. (ed.) (2014): Forest soil carbon sink in the Nordic region.  
Department of Geosciences and Natural Resource Management, University  
of Copenhagen, Frederiksberg. 37 pp. ill.

**Publisher**

Department of Geosciences and  
Natural Resource Management  
University of Copenhagen  
Rolighedsvej 23  
DK-1958 Frederiksberg C  
Tel. +45 3533 1500  
ign@ign.ku.dk  
www.ign.ku.dk

**Responsible under the press law**

Gertrud Jørgensen

**ISBN**

978-87-7903-684-0

**Cover**

Karin Kristensen

**Cover Photo**

Shimon Ozeri Ginzburg

**Published**

This report is only published at [www.ign.ku.dk](http://www.ign.ku.dk)

**Citation allowed with clear source indication**

Written permission is required if you wish to use the name of the institute  
and/or part of this report for sales and advertising purposes.



*FSC-sink participants at an excursion to a new forest close to Reykjavik, May 2013. Changes in soil C stocks after afforestation was one of the main issues studied by the network. (Photo: Per Gundersen)*

## Preface

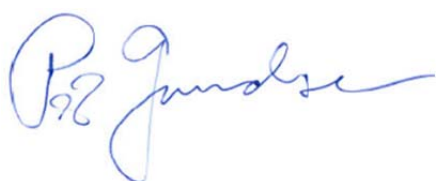
This report summarises the main results from the *Forest Soil Carbon Sink – Nordic Network (FSC-sink)* - a collaboration between Nordic/Baltic research groups. The aim of the networking was to quantify the potential carbon (C) sequestration in Nordic forest soils and to study its sensitivity to climatic and environmental change by synthesising the existing data and information on soil C from the region and by connecting national process and case studies.

The network was funded by the programme “*Climate Change Impacts, Adaptation and Mitigation in Nordic Primary Industries*” initiated by the Nordic Council of Ministers. It started in 2010 and had participants from Denmark, Iceland, Latvia, Norway and Sweden. It was formed as a spinoff from another network CAR-ES (Centre of Advanced Research on Environmental Services) that investigate the impact of forest management on environmental services such as C-sequestration, water quality, biodiversity, and soil quality.

At the closing workshop “The Forest Soil Carbon Sink in Northern Europe”, May 8-9, 2014, in Dragør, Denmark, the participants gave the following evaluation of the activities: “The network functioned as a highly appreciated forum for information exchange, inspiration and feedback on ideas across the sub-disciplines working with soil C (e.g. stock estimation, process fluxes, microbiology, soil fauna, and modelling). The networking broadened the perspective of the participating groups by working with and comparing over larger gradients in climate, N deposition, forest type and use-intensity etc. and it also sparked new ideas and lead to some spinoff projects.”

Over the years, more than 50 researchers and students from the Nordic-Baltic region have participated in workshops and research activities in the network. I wish to thank everyone for sharing their data, knowledge or views on soil carbon which made our networking happen. I also wish to thank PhD Shimon Ginzburg for taking a god share of the administrative duties in the networking.

Frederiksberg, December 2014



Per Gundersen, coordinator of FSC-sink

## Contents

Preface.....	3
Summary.....	5
Introduction - importance of soil organic carbon (SOC) .....	6
Influence of tree species .....	7
Effects of increased biomass harvest .....	9
Effect of elevated nitrogen (N) deposition.....	10
Effects of warming on SOC stability .....	13
Effect of land-use changes .....	14
Nordic SOC stocks.....	16
Role of mycorrhizal fungi as input to SOC.....	18
Process understanding and mechanistic models .....	19
Summary and conclusions .....	21
References .....	22
Appendix: Abstracts of papers and reports from the networking project.....	24
Influence of tree species on SOC.....	24
Effects of increased biomass harvest on SOC.....	26
Effect of elevated N deposition on SOC .....	29
Effects of warming on SOC stability .....	31
Effects of land use change on SOC .....	33
Nordic soil organic carbon stocks.....	34
Role of mycorrhizal fungi as input to SOC.....	35
Process understanding and mechanistic models .....	36

## Summary

A Nordic/Baltic network was established to connect research groups working on soil carbon storage and dynamics. The region stores vast amounts of carbon in soil organic matter that may be sensitive to increasing temperatures and intensified biomass harvest. The experimental research of the network focussed on the effects of tree species, harvesting regimes, nitrogen deposition, soil warming and land use change on soil organic carbon stocks and their sensitivity to change. Process studies particularly on belowground allocation of plant carbon and the role of mycorrhiza were also performed. Regional differences in the soil carbon stocks were explored in monitoring data and forest models were used for long term predictions.



*Organic layers on top of the mineral soil contribute to soil C stocks particularly under coniferous tree species. Sampling of organic layers under Norway spruce at Klosterhede, Denmark in a long term N addition experiment, August 2013. (Photos: Per Gundersen)*

## Introduction - importance of soil organic carbon (SOC)

Forests cover 60% of the land area in the five Nordic countries. These forests store massive amounts of carbon (C) and 50–80% of the C is stored belowground in soil organic matter (SOM). The trees sequester CO<sub>2</sub> from the atmosphere by photosynthesis to form biomass C, which is then in part released again by plant respiration, litter decomposition and burning of products. The ultimate long-term storage of the remaining C is in the soil organic carbon (SOC). To mitigate climate change, it is important to protect and possibly enhance the storage of C in soil organic matter. It is generally agreed that forest soils are currently sinks for C, but the rate is uncertain. Management practices (e.g. increased extraction of biomass for bioenergy) or climate warming may reduce the soil C sink or even turn forest soils into a source of CO<sub>2</sub>.

The *Forest Soil C-sink Nordic Network (FSC-sink)* was established to study the C stocks in SOM and their changes in response to management and environmental drivers. Estimating the rate of C sequestration in SOM is a challenging scientific task as the process is very slow and identifying a small change in a large stock entails high levels of uncertainty. Therefore, assessing soil C sequestration rate often involves an assessment approach combining long-term forest monitoring with modelling and other innovative comparison approaches.

The information obtained by the network is relevant for reporting under the Kyoto Protocol Articles Nos. 3.3 (afforestation, reforestation and deforestation) and 3.4 (forest management). There are several clearly defined requirements for Kyoto reporting under these articles that require country specific and scientifically approved functions and data. Our work support a global scientific effort to estimate the C-sink strength of forests by synthesising data and information on soil C stocks, with a focus on the Nordic and Baltic countries.

This report is a summary of our main results on the influence of management and environmental drivers on SOC stocks and of new results from process studies and modelling. An appendix provides the abstracts from the more than 30 original papers and reports produced by the network participants. This report is to our knowledge the first attempt to evaluate the potentials and drivers for forest soil C sequestration on a Nordic/Baltic level.

## Influence of tree species

We synthesised the current knowledge of tree species effects on soil C stocks (Vesterdal et al., 2013). There was evidence of consistent tree species effects on soil C stocks in forest floors, but effects were less clear in mineral soils. Proportional differences in forest floor and mineral soil C stocks among tree species suggested that C stocks can be increased by 200–500% in forest floors (with conifers building the largest forest floors) and by 40–50% in top mineral soil by tree species change (Fig. 1). However, these proportional differences between forest floors and mineral soils are not always additive: the C distribution between forest floor and mineral soil rather than the total C stock tends to differ among tree species.

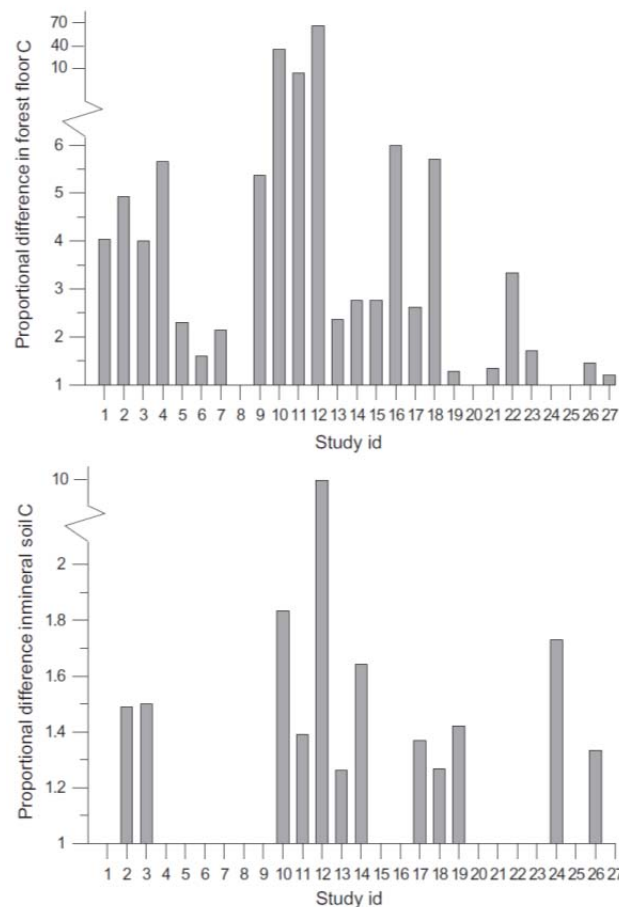


Fig. 1: Proportional differences between the maximum and minimum stock of C in (a) forest floors and (b) top mineral soils under different tree species based on published studies with significant ( $P < 0.05$ ) species effects (Vesterdal et al. 2013). Studies 1–18 are from temperate forests and studies 19–27 are from boreal forests. Missing values are due to either missing data or insignificant effects.

A common garden study with four species at eight sites in Denmark revealed consistently larger C stocks under conifers than under broadleaves both in the forest floor and in the mineral soil 40 years after planting (Gurmesa et al., 2013). Total soil C stocks increased consistently in the order oak < beech << Norway spruce, larch along the soil texture gradient of the sites. This suggests that some species may be better engineers for sequestration of C in stable form in mineral soil, but it is unclear whether the key mechanism is root litter input or macro-fauna (e.g. earthworm) activity.



*Aerial photo of a Danish common garden experiment with native broadleaf species, spruce and fir. © COWI 2006.*

In a Swedish study, Hansson et al. (2013) found that decomposition rate (per g of C) was markedly higher under birch than under spruce and pine resulting in lower C and N stocks in the organic layer. This effect was amplified by higher abundance and biomass of earthworms that seemed to be favoured by higher pH and palatable litter under birch. Earthworm bioturbation probably increased decomposition rate and damaged the ectomycorrhizal network (Hansson et al., 2013). In an inter-regional comparison of pine, spruce and birch, Olsson et al. (2012) found that the higher decomposition of organic matter under birch in southern Sweden coincided with moderately high earthworm populations, whereas the lack of a 'birch effect' in northern Finland was linked to the absence of burrowing earthworms (because of climatic constraints). The importance of earthworm and ant activity for pine, spruce, deciduous and alder forests in comparison with grasslands was illustrated in a study from south-eastern Sweden (Taylor et al., in review). For the top 20 cm of soil, the estimated soil turnover (i.e. the time in which all soil has been processed) by earthworms and ants was 50–500 years depending on ecosystem type and earthworm communities.

For targeted use of tree species to sequester soil C, we must identify the processes related to C input and output, particularly belowground that control C stock differences. We also need more information on forms and stability of C along with bulk C stocks to assess whether certain broadleaves store C in a more stable form.

## Effects of increased biomass harvest

We summarised the literature concerning the effect of harvesting on soil carbon stocks and flows in boreal and northern temperate forests to evaluate the evidence of significant losses increasing with biomass removal (Clarke et al., in review). Although model studies suggest reductions in soil C stocks when more C is removed in whole-tree harvesting, the empirical evidence was less clear. Some studies did report significant reductions in SOC after whole-tree harvesting compared with stem-only harvesting, while others showed no difference (Fig. 2). The differences tended to be less with increased time since harvest, but the studies were few. Better reestablishment, enhanced ground flora (gaining C) or indirect effects through microclimatic changes (reducing decomposition) after increased biomass harvest may compensate for C removal. There is not enough information available at present to draw firm conclusions about the long-term impact of intensified forest harvesting on these C cycling processes in Nordic soils. This has sparked a new meta-analysis project on data from Nordic forests. Properly conducted long-term experiments would enable us to clarify the relative importance of different harvesting practices on the soil C stores, and the conditions under which the size of the removals becomes critical. Both new experiments and existing long-term experiments are therefore very important.

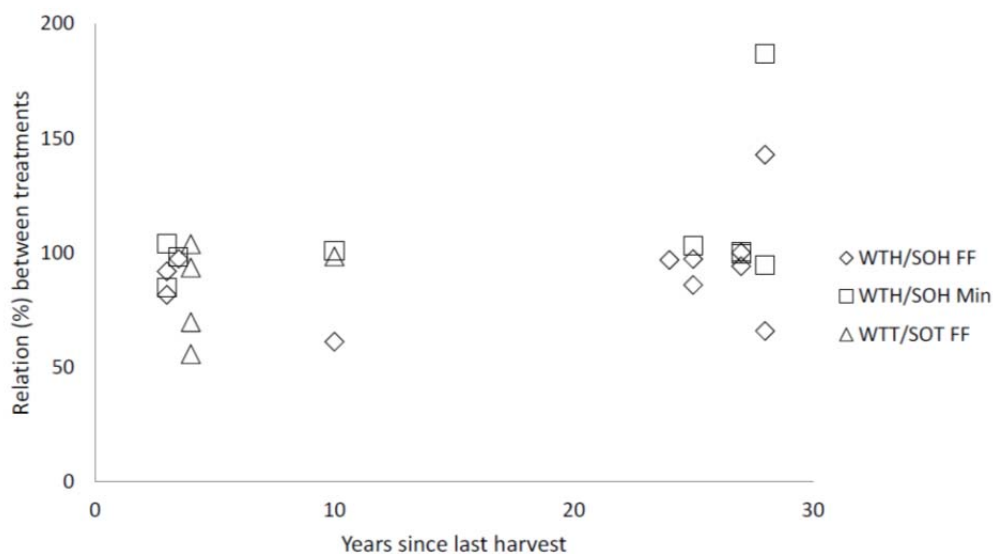


Fig. 2: Relative effect of harvest intensity on SOC. Whole-tree harvesting / stem-only harvesting (WTH/SOH, %) and whole-tree thinning / stem-only thinning (WTT/SOT, %) in the forest floor (FF) and upper mineral soil (Min) at different times after harvesting (Clarke et al. in review).

Tree-stump lifting is a way to increase the biomass harvest for bioenergy purposes. The environmental consequences of large scale stump harvesting were discussed (Persson, 2012; Persson, 2013). Stump harvesting (and removal of coarse roots) directly reduces the pool of new SOC and may also increase losses of older SOC through decomposition due the soil disturbance and mixing from the stump lifting. But as discussed above better establishment of the next forest stand and other interactions could compensate

such losses. A study by Strömgren et al. (2013) found significantly lower ecosystem C pool 25-years after a final harvest including stump lifting and slash removal compared to conventional harvest. But it is not known if this difference will persist in the long-term as remaining stumps and logging residues continue to decompose in the conventional harvest treatment. To overcome the lack of long-term empirical data forest C balances models have been used to simulate different harvest intensities (Eliasson et al. 2013; Hyvönen et al., 2012). The results showed that SOC losses were always less than the harvested biomass C and highest in the less fertile sites. With time difference between harvest regimes decrease and after 300 years of simulation 9% of the increased removal over the period was lost from the soil (Eliasson et al. 2013). However, a study by Grelle et al. (2012) suggest that the overall substitution efficiency and climate benefits of stump harvest are likely to be small although still uncertain.



*Stem harvesting in Finland in 2009 (left). Forest edges bordering agricultural land (right) receive dry deposition of N and a gradient in N input decreasing from the edge and about 100 m into the stand is formed. It makes edges ideal for studying the effects of N deposition on soil C processes and stocks. (Photos: Per Gundersen)*

## **Effect of elevated nitrogen (N) deposition**

Carbon and N are closely connected in SOM, as illustrated by the parallel accumulation of ecosystem and soil C and N during primary succession on the pristine volcanic island Surtsey, Iceland (Leblans et al. 2014, Stefansdottir et al. 2014). Both total ecosystem biomass and SOC stocks were strongly correlated with N input (atmospheric deposition and translocation by seabirds). The same strong correlation between C and N stocks were observed in organic layers formed when new forests were planted on ploughed mineral soils (Fig. 3). With this strong coupling of C and N, the N cycle in forests is a key to the understanding of C sequestration and of the long-term sink for C in soils. However, the extent to which elevated N deposition will increase soil C stocks by increasing forest productivity and subsequent C input to soil and/or by reducing the decomposition of soil organic matter has been debated. So far, evidence for a C sink due to N-input is largely based on observations from N fertilisation experiments, and the measured effects are variable.

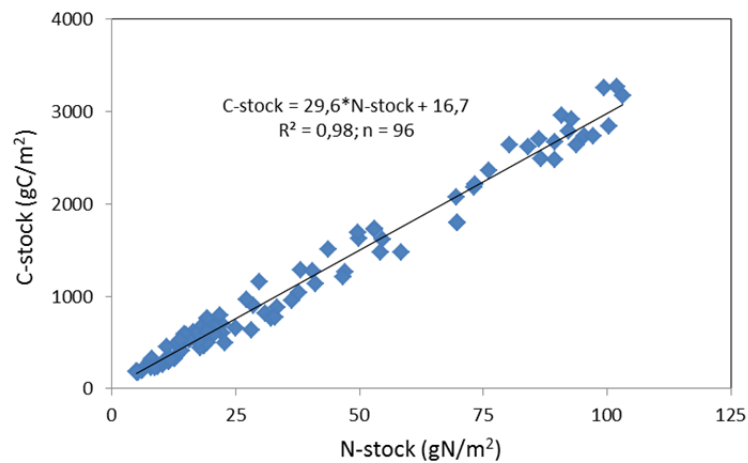


Fig. 3: Carbon and nitrogen accumulate together in soil organic matter. Data on forest floors from Gurmessa et al. (2013).

To elucidate the effect of N deposition on forest soil C stocks we investigated soils and C cycling processes in stand-scale N deposition gradients at the edges of five temperate coniferous forests (Fig. 4a) bordering on agricultural land (Ginzburg et al. In review) as well as in an N addition experiment with two decades of monthly spraying of N simulating elevated deposition (Ginzburg et al., in revision).

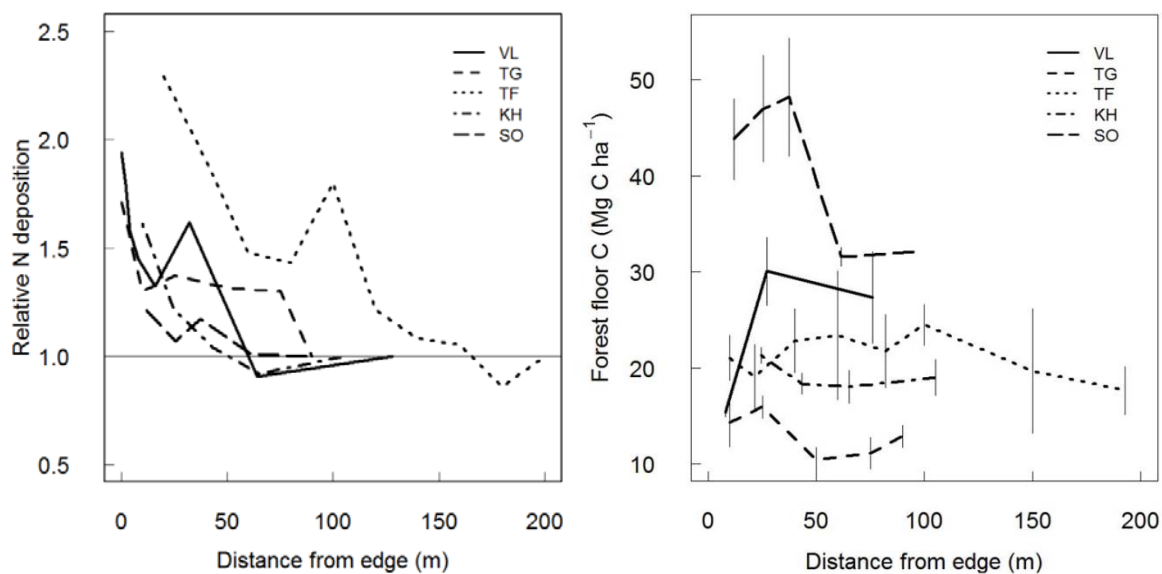


Fig. 4: Results from forest edges: a) nitrogen enrichment from deposition is found in all investigated edges, but (b) this did not generally increase forest floor C stock (Ginzburg et al., in review).

Nitrogen enrichment (defined as a relative decrease in the C/N ratios of needle litter and forest floor, or increased soil solution nitrate concentrations) was found both at high N input across the forest edges and in the N addition experiment. Overall, forest floor and mineral soil (0–5 cm) C stocks, assessed along the five edge N gradients (Fig. 4b) and in the experiment were not significantly related to N deposition. Only at the two locations which had the lowest N deposition, a significant higher C stock was found closer to the edge (Fig. 4b). Edge N deposition may, however, not be the only cause. Fine-root biomass and mycorrhiza mycelia production (not investigated in all edges) decreased with elevated N, indicating a *decreased* belowground C input with increased N deposition. (Reduced mycorrhiza mycelia with increased N availability were also found at the regional scale in Denmark and S-Sweden (Nilsson et al. 2012)). Decomposition (and respiration) was reduced under elevated N deposition in the edges, indicating a reduced turnover rate of soil organic matter. (Ginzburg et al., in revision) concluded that N deposition at rates common to agriculturally intensive regions in north-western Europe may reduce the turnover of soil organic matter, but that this positive effect on soil C stocks may be outweighed by decreases in belowground C inputs, ultimately resulting in no overall change in soil C stocks. These results contrast with previous studies reporting a significant positive impact of experimental N addition on C sequestration in forest soils. Since the investigated forests received high N deposition ( $>20$  kgN/ha/yr) we cannot know if low and moderate N deposition may enhance C sequestration (as indicated for the two edge sites with the lowest N deposition), but the effect is likely less pronounced than previously reported.



*Sampling of litterfall and throughfall in forest edges were performed to monitor the input of C and N to the soil. Here in Sitka spruce at Sønder Omme, Denmark in 2011. (Photo: Shimon Ginzburg)*

## Effects of warming on SOC stability

Decomposition rates of SOC are expected to increase as global temperatures rise, potentially creating a positive feedback on atmospheric CO<sub>2</sub> concentration thereby amplifying climate warming. Thus, studies on SOC stability and the decomposition response to temperature are needed particularly for the SOC rich soils of the Nordic/Baltic region. In a laboratory incubation of soil from a forest edge N gradients (Ginzburg and Gundersen, in revision), we observed a reduced temperature sensitivity ( $Q_{10}$ ) of SOC turnover at high N availability (low soil C/N ratio). Thus the respiration response to temperature is reduced at high N availability (Fig. 5). This result demonstrates for the first time that elevated N deposition moderates the temperature feedback (i.e. the effect of global warming) on decomposition in forest soils. The effect of warming was reduced roughly 20% by elevated N deposition.

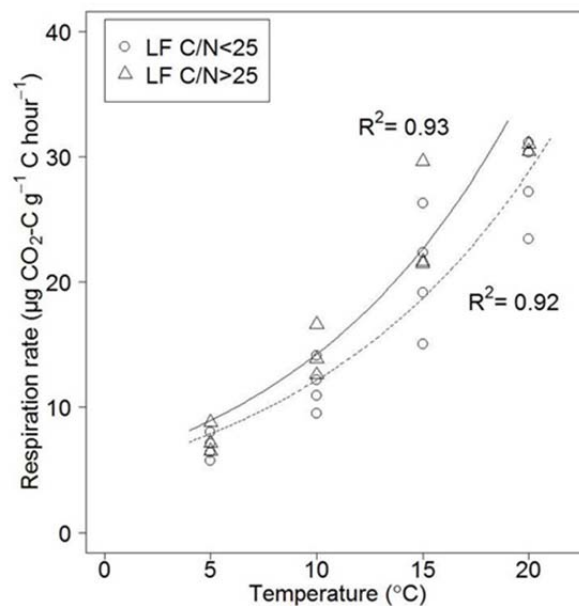


Fig. 5: The respiration response to increasing temperature is lowered at high (C/N<25) compared to low N availability (C/N>25) (Ginzburg & Gundersen, in revision).

Increasing CO<sub>2</sub> emissions from decomposition in a warmer world may potentially be compensated by better growth of trees in the future with elevated CO<sub>2</sub> and higher temperature. The growth responses to such interactions were studied by Sigurdsson et al. (2013) in an experiment in northern Sweden. There was no significant tree growth response to elevated CO<sub>2</sub> (c. 685 ppm) and higher air temperature (+3.9 °C) at ambient nutrient availability, but if nutrients were supplied the increment increased 25%. This illustrates the important role of soils in regulating the response to climate change and in northern Sweden growth response will likely be restricted by nutrients. However, warming of the whole system including the soils (which is challenging) is needed to study the full response.

A special opportunity to establish a unique soil warming experiment arose in Iceland (ForHot; Fig. 6) in a small forest (as well as in nearby grasslands) where displacement of geothermal heating by an earthquake created a temperature gradient (0-10°C above ambient) (O’Gorman et al. 2014). Gradients in grassland

could be established both with short (5 years) and long term (>30) warming. Collaborators from the network have become active in the experiments using their particular expertise to study the effect of warming on soil C and N processes. Most of the SOC and C- and N-process data from this experiment is currently under analysis, but part of the work focussing mainly on grasslands has already been included in two M.Sc. student theses' (Michielsen, 2014; Vande Velde, 2014) and an extended conference abstract (Sigurdsson et al., 2014). Results showed losses of SOC with warming both at the short and the long term. Grass productivity increased but not enough to compensate for the losses due to increased decomposition.



*Fig. 6: The location of the ForHot 'natural' soil warming gradients (5 transects with  $\Delta T$  from 0 to  $+10^{\circ}\text{C}$ ) in a small sitka spruce forest (left arrow) and a grassland (right arrow). The dead trees in the middle of the picture were located on soils warmed more than  $10^{\circ}\text{C}$  (O'Gorman et al. 2014). (Photo: Edda S. Oddsdottir)*

## Effect of land-use changes

The forest area in the Nordic and Baltic countries is increasing both through active afforestation and through natural succession on abandoned land. To investigate the effect of this land use transition, we conducted a meta-analysis of SOC stock change following afforestation in Northern Europe (Bárcena et al., 2014a). Effects (response ratios) were calculated for forest floors and mineral soils (0–10 cm and 0–20/30 cm layers) based on paired control (former land use) and afforested plots. We analysed the influence of forest age, former land use, forest type and soil textural class on SOC. Former land use was a major factor contributing to changes in SOC after afforestation. In former croplands, soil C change differed between soil layers and was significantly positive (20%) in the 0–10 cm layer. Afforestation of former grasslands had a small negative (non-significant) effect, indicating limited SOC change following this land-use change.

Inclusion of forest floor C stocks enhanced the positive effects of afforestation, especially in the case of conifers. By separating the periods <30 years and >30 years since afforestation, a shift from an initial loss to a later gain of soil C was revealed (Fig. 7).

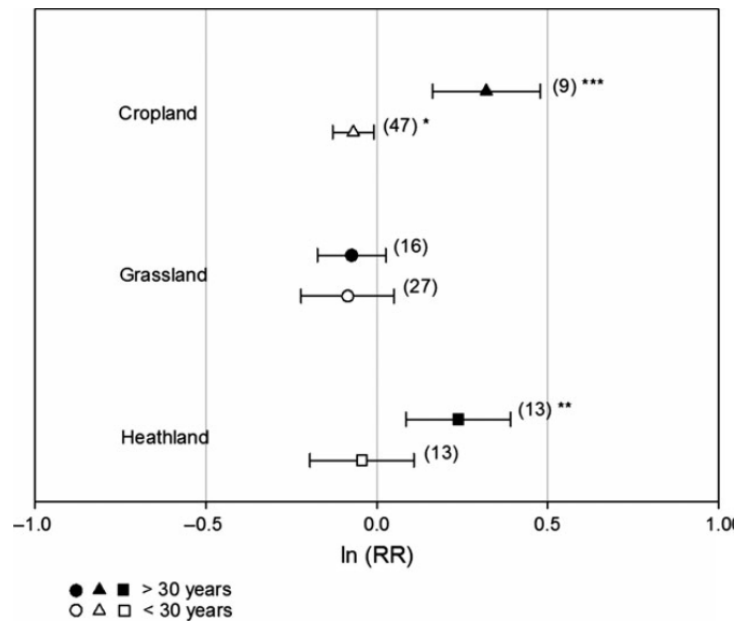


Fig. 7: Change of SOC (log response ratios, RR) less than 30 years (open symbols) and more than 30 years (closed symbols) since afforestation (separated for former land use classes) for 0–20/30 cm depth (Bárcena et al. 2014a).

We conclude that significant SOC sequestration occurs after afforestation of croplands, but not after afforestation of grasslands, and changes are small within a 30-year perspective. The studies of SOC build-up on the pristine volcanic island Surtsey, Iceland, also emphasised the time-lag for substantial changes in SOC. Where the N-inputs (from seabirds) were highest, the ecosystem biomass had reached normal values for grasslands after only 50 years, while the SOC were still only a fraction of normal grassland values. It is thus important to keep in mind that today's changes in SOC may partly be driven by past influences and that the full effect of e.g. land-use change and forest management may take many decades to fully appear, which by far exceeds the duration of most experiments that are used today to evaluate such effects.

A detailed case study of an extensive chronosequence in a Danish afforestation area (Vestskoven) confirmed the pattern found in the meta-analysis with an initial loss and a later gain (Bárcena et al., 2014b). It also indicated some gains in SOC below the plough layer that were not included in our (as well as other) meta-analyses of SOC changes. Other belowground impact of afforestation were also studied within the project, including effects on earthworm populations in Iceland and on root growth of various tree species (Sigurdsson and Gudleifsson, 2013; Hunziker et al. 2014). Time since afforestation had a significant effects on both density and diversity of earthworms.

## Nordic SOC stocks

An effort was done to compile SOC monitoring data from the Nordic and Baltic countries to get better data on the size of the SOC stock in the region and to analyse whether some of the effects on SOC stock describe above also influence the stocks at the large scale (Bengtson et al., in preparation). However, due to differences in methods, data property rights and use restrictions the compiled database currently have roughly 4300 forest inventory sites from national inventories of Sweden, Denmark and Latvia. The database contains soil C concentrations and stocks, along with information on other soil parameters, forest properties, annual mean temperature and precipitation (1971-2000) and N deposition for 2010 according to EMEP. For SOC stock mapping and analyses to identify factors controlling SOC stocks the data were harmonised and recalculated to represent the SOC stock to 1m depth (Fig. 8). Soil carbon stocks varied between <50 and >200 tC/ha (compared to 20 to 100 tC/ha in tree biomass) and was highest in the Southwestern region of the examined area and decreased moving eastwards and northwards.

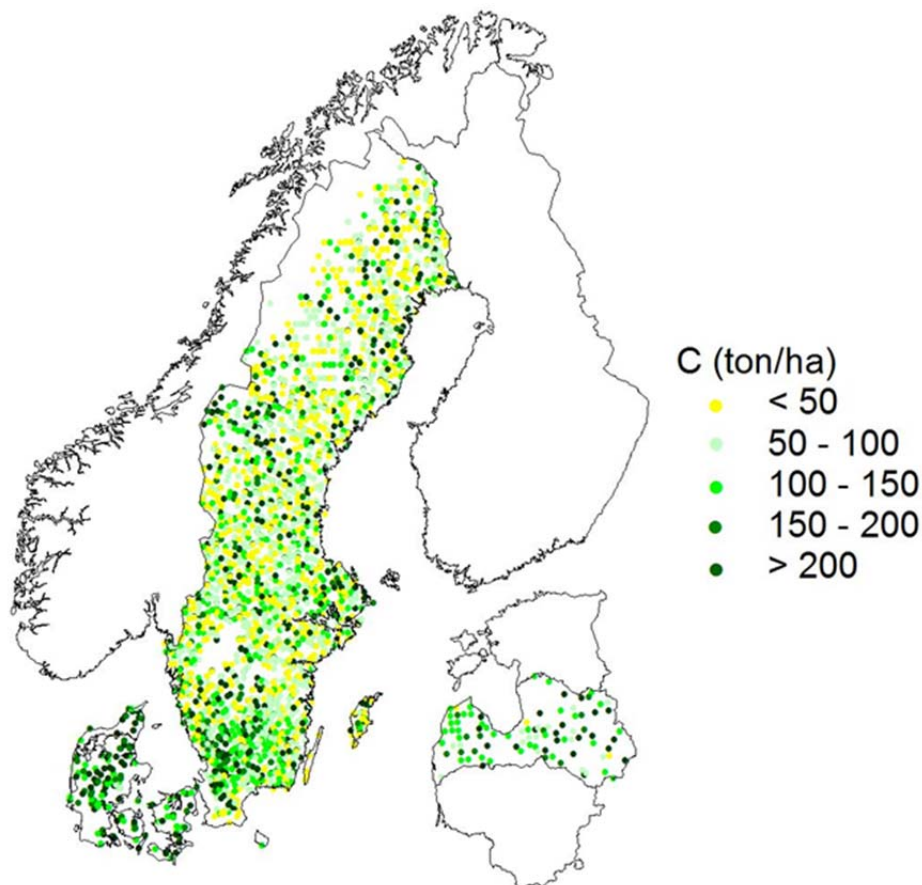


Fig. 8: Total carbon storage in the organic layer and the upper 100 cm in the mineral soil.

In order to identify the main drivers responsible for SOC accumulation in mineral soils a stepwise multiple regression was performed with temperature, N deposition and precipitation as continuous predictors, and stand type (coniferous or broadleaf) as categorical predictor. The results demonstrated that temperature, N deposition stand type all had an influence on the SOC stocks, while no effect of precipitation was found. Stocks generally increased with increasing temperatures (Fig. 9a), and there was an equally strong

relationship between SOC stocks and N deposition (Fig. 9b). However, since temperature and N deposition co-varies across the area we could not conclude if temperature or N deposition was the main driver of SOC accumulation.

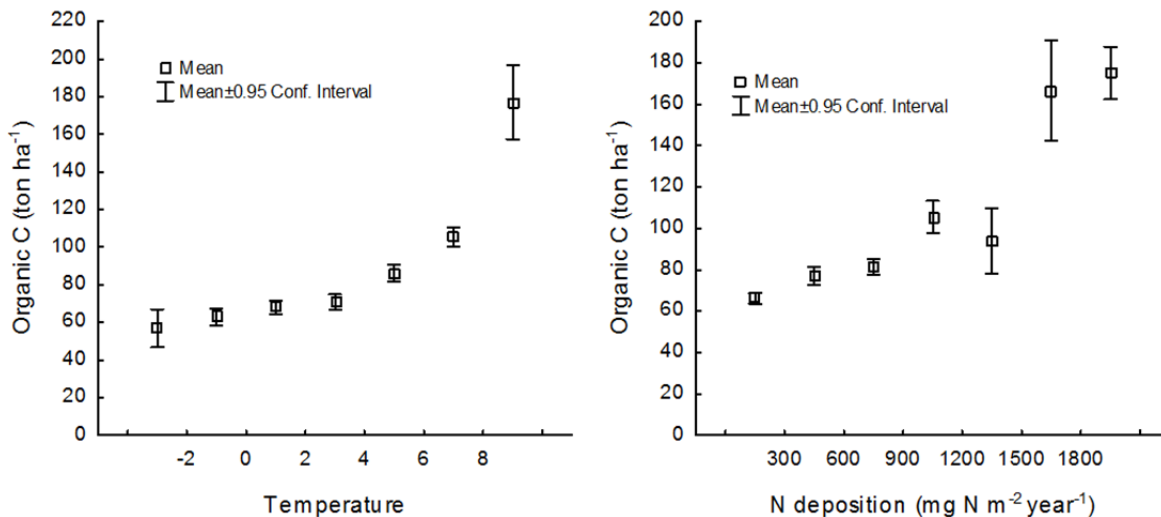


Fig. 9: The relationship between SOC stocks and temperature (left panel) and N deposition (right panel).

A more detailed analysis dividing the dataset in low vs high N deposition (> 9 kgN/ha/yr) showed that N deposition modulate the effect of temperature on SOC, i.e. in areas with low N deposition temperatures increased SOC stocks, while in areas exposed to high N deposition temperature did not appear to be a major driver of SOC, but a strong effect of N deposition was apparent. The spatial pattern of the SOC stocks thus indicate a positive effect of N deposition on the SOC stocks which was not found in the edge gradients and the experiment reported above (Ginzburg et al., in review, in revision). At the moderate N deposition across the region, the SOC apparently still respond to N, whereas at the relative high N depositions investigated in the edges there was no further response in SOC, or the response may occur deeper in the mineral soil that was not yet investigated in the edges.

A strong effect of stand type on SOC stocks was found, with the highest stocks in stands dominated by broadleaf trees. We could not conclude if this was a result of coniferous trees being more common in cold areas with low N deposition, or if it was a direct effect of the tree type. Combined with the experimental observations of tree species effects above (e.g. Vesterdal et al. 2013), this calls for more detailed analyses of species effects including SOC stocks in the whole soil profile.

## Role of mycorrhizal fungi as input to SOC

In boreal forest ecosystems, a large proportion of the carbon fixed by trees is allocated below ground to tree roots and ectomycorrhizal fungi that live in symbiosis with the roots. Despite the potential magnitude of the below-ground flux, it remains one of the least understood fluxes in the terrestrial carbon cycle. Research associated to the network has shed new light on the important role of mycorrhizal fungi for long-term carbon sequestration (Clemmensen et al., 2013; Ekblad et al., 2013; Wallander et al., 2011). Contrary to what was previously understood, i.e. that humus accumulation is regulated primarily by saprotrophic decomposition of above-ground litter, the new research suggest an alternative mechanism for the accumulation of organic matter in boreal forests: organic layers grow from below through the continuous addition of recently fixed carbon to the organic matter profile in the form of the remains of roots and associated mycelia. Using a method called  $^{14}\text{C}$  bomb-carbon modelling, it was demonstrated that 50 to 70% of stored carbon in a chronosequence of boreal forested islands was derived from this mechanism (Clemmensen et al., 2013). Furthermore, fungal biomarkers pointed to impaired degradation and preservation of fungal residues in late successional forests, indicating that fungal residues are important regulators of carbon accumulation as the chronosequence proceeds.

Environmental factors influencing mycorrhizal production and growth may thus have a great impact on the carbon sequestration capacity of forests. When estimating the production of ectomycorrhizal mycelium at around 140 different forest sites (Ekblad et al., 2013), it was found that production varied considerably between different forests and between years, from close to zero up to several hundred kg per ha per year. It was concluded that carbon availability is the key factor determining ectomycorrhizal mycelial production and possibly also its standing biomass in forests. However, mineral nutrient availability was also found to be important and Nilsson et al. (2012) showed that elevated levels of nitrogen may reduce ectomycorrhizal growth. Results from Wallander et al. (2011) showed that balanced fertilization (including all the necessary nutrients) appears to have less of an influence on ectomycorrhizal growth than pure nitrogen fertilization, especially at sites where the trees responded strongly to fertilization (indicating that the stand is far from being nitrogen saturated). Accordingly, below-ground litter production in the form of ectomycorrhizal biomass was sometimes reduced and sometimes unaffected by fertilization. Fertilization every second year had a smaller impact on ectomycorrhizal growth than fertilization every year, indicating that the former management regime is preferable from an ectomycorrhizal point of view.



*Sand filled mesh bag used for estimating ectomycorrhizal mycelial production. (Photo: Rasmus Kjøller)*

## Process understanding and mechanistic models

The work on modelling opened with an international workshop to gain an overview of the current understanding of belowground processes and their implementation in state-of-the-art models (Rosenstock et al. in review). The pathway by which carbon enters soils 'from below' is through plant allocation to roots, root exudates and mycorrhizal symbionts. As discussed above there is growing evidence that mycorrhizal residues are important precursors for the formation of SOM and that root exudates can be important drivers of decomposition through what is known as the priming effect. Although plant C allocation belowground and its response to resource availability is one of the most central ecosystem responses to global change, there has been relatively little progress incorporating these responses and their consequences into current ecosystem models. Consequently, the following five features need to be included in current ecosystem models in order to improve their predictive capacity with regard to the effects of global changes on ecosystem carbon stocks: (i) the partitioning of carbon to roots, root exudates and ectomycorrhizal fungi as a function of the availability of resources; (ii) the contribution of root growth and root turnover to soil organic matter formation; (iii) the contribution of ectomycorrhizal fungi to soil organic matter formation; (iv) the incorporation of priming as a driver of soil organic matter turnover; and (v) consideration of soil depth for each of these processes. Evidently, models that treat allocation as a function of any limiting resource should have triggers to shift allocation patterns when another resource becomes limiting. Examples of such triggers could include foliar nutrient ratios or climate interaction variables.

One of the potential models for prediction of climate effects on SOC is the integrated mechanistic model ForSAFE. It was used to simulate how different future climatic and deposition scenarios could affect the storage of SOC in Swedish forest soils (Belyazid et al., in preparation) by simulating the development of 640 managed forests, part of the Swedish National Forest Inventory. Two climate scenarios were contrasted: no change in climate, i.e. no trends in precipitation or temperature, and a changing climate according to SRES A2 emissions story line (with climate variables estimated by the Max Plank Institute's ECHAM5 model). Two N deposition scenarios were compared: the current legislation of the UN's LRTAP convention, and a hypothetical no-control on emissions scenario, whereby emissions and deposition of nitrogen remain elevated (at the 1980's levels). Based on the simulation results climate change is expected to cause a loss in soil carbon ( $>200 \text{ g/m}^2$  or  $>2 \text{ tC/ha}$ ), especially in the southern half of the country by 2100 (Fig. 10), while less than a third of the simulated sites (especially in the north) are expected to have an increase in soil carbon under the climate change scenario.

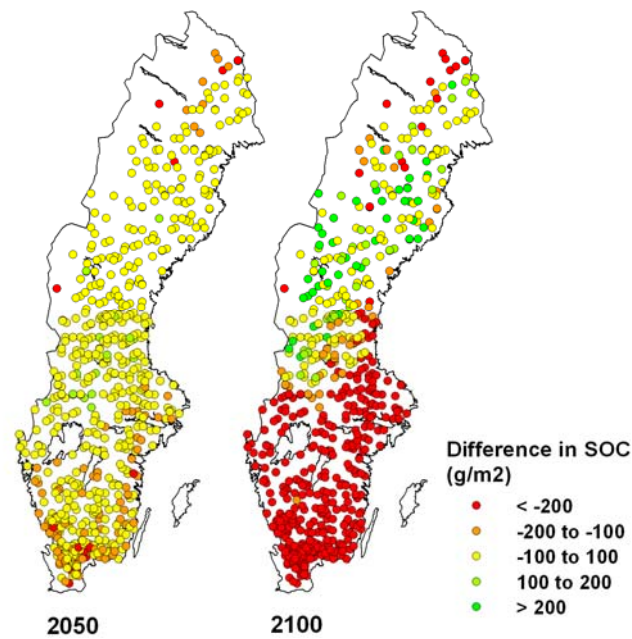


Fig. 10: Effect of climate change on SOC in Sweden. Shown as difference in SOC between the no climate change scenario (base) and the climate change scenario for 640 forest sites (Belyazid et al., in preparation). The N deposition was according to current legislation under both climates.

The loss of SOC that in the south could amount to 5 tC/ha is due to two main factors, in order of importance: (i) extensive droughts during the growing season (particularly between June and August in the southern half of Sweden) and (ii) increased air and soil temperatures throughout the country but more strongly in the northern half and outside the growing season. The reoccurrence of droughts in the south is expected to limit tree growth and thereby litter production in the longer term (by 2100), while the increased temperatures in the north are expected to contribute more to increased growth (by extending the growing period) than to promoting decomposition. It is often hypothesised that increased nitrogen loads would contribute to increased SOC stocks as also indicated by (Fig. 9b). This notion was supported by the simulations of the different N deposition scenarios, and more so in the absence of climate change. High nitrogen loads in the form of a “no control on emissions” scenario would lead to higher soil carbon stock in the centre of Sweden, followed by the south and less so in the north. The positive effect of increased N deposition on soil carbon in the south was diminished by the effect of climate change.

Another model study (Lazdiņš and Čugunovs, 2014) was performed on data from Latvia to evaluate feasibility of using the dynamic soil carbon stock change models Yasso and Yasso07 in the national greenhouse gas accounting for forest land, cropland and grassland.

## Summary and conclusions

Forest soils in the Nordic/Baltic region store between <50 and up to >200 tC/ha in SOC down to one meter based on 4000 monitoring plots in Sweden, Denmark and Latvia (compared to typically 20 to 100 tC/ha in standing biomass). The stocks increase with temperature (thus decreasing to the north and east) but not with precipitation.

A simulation of climate change in the region with a mechanistic forest model, ForSAFE, indicated that the SOC stocks particularly in the south of the region are sensitive to climate change (loosing up to 5 tC/ha in 2100) despite increased productivity. Supporting this, SOC losses were observed due to both short and long term warming in Icelandic grasslands, increases in SOC decomposition by geothermal warming was not fully compensated by increases in productivity. Laboratory incubations of SOC from an N deposition gradient however indicated that the response of SOC decomposition to warming may be moderated somewhat by N enrichment from elevated N deposition that may prevail in this century as well.

Increased biomass harvest is another threat to SOC storage. Whole tree harvesting and stump lifting were shown to reduce SOC compared to conventional harvesting in the short term. However, some compensating mechanisms reduce the effect with time, providing some resilience in SOC stocks. Forest models predict that a loss of 9% of the removed biomass C will be missing in SOC in the long term (centuries), but this effect is still uncertain.

Tree species influence SOC stock considerably with conifers storing most SOC in the organic layer, whereas broadleaf species (where earthworm abundance was highest) stored more in the mineral soil as observed in both common garden experiments and in SOC monitoring data. Potentially tree species choice may be used actively to promote SOC storage, but more emphasis on the effect of tree species on subsoil SOC is needed for safe recommendation of specific tree species aimed at SOC sequestration.

Nitrogen deposition seems to have a positive effect on SOC stocks across the region, but it is difficult to separate this effect from that of temperature because they co-vary. However there was not much support for an effect of N deposition from the experimental approaches used in the network. The SOC stocks were unchanged in local N gradients of forest edges and in a long term N addition experiment at N depositions >25 KgN/ha/yr. However, a positive effect of N on SOC may occur at lower N deposition rates.

The SOC stocks are enhanced by afforestation of croplands or barren land, but not on grasslands. Due to low litter and dead root input a lag phase with initial SOC losses is usually observed and a significant net gain is observed from 30 yrs after afforestation and onwards.

Our understanding of SOC processes and the balance between the inputs of photosynthetic C and the outputs by decomposition has increased. In particular research from the network points to mycorrhizal inputs as important for C sequestration and its variation with resource availability. Forest C and N models may need to incorporate knowledge on the belowground C allocation and its regulation to better predict the future effects of climate change, N deposition or changes in the harvest regimes.

## References

- Bárcena, T.G., Kiær, L.P., Vesterdal, L., Stéfansdóttir, H.M., Gundersen, P. and Sigurdsson, B.D., 2014. Soil carbon stock change following afforestation in Northern Europe: a meta-analysis. *Global Change Biology*, 20: 2393–2405.
- Bárcena, T.G., Gundersen, P., Vesterdal, L., 2014. Afforestation effects on soil organic carbon in former cropland: oak and spruce chronosequences resampled after 13 years. *Global Change Biology* 20: 2938–2952.
- Belyazid, S., Jönsson Belyazid, U., Akselsson, C., Gundersen, P., in preparation. Uncertain future of carbon storage in Swedish forest soils.
- Bengtson, P., Akselsson, C., et al. (in preparation). Identification of climatic and other drivers of importance for Nordic soil C stocks.
- Clarke, N., Gundersen, P., Jönsson-Belyazid, U., Kjønaas, O.J., Persson, T., Sigurdsson, B.D., Stupak, I., Vesterdal, L. In review. Influence of different tree-harvesting intensities on forest soil carbon stocks in boreal and northern temperate forest ecosystems. *Forest Ecology and Management*
- Clemmensen KE, Bahr A, Ovaskainen O, Dahlberg A, Ekblad A, Wallander H, Stenlid J, Finlay RD, Wardle DA, Lindahl BD, 2013. Roots and associated fungi drive long-term carbon sequestration in boreal forests. *Science* 339, 1615-1618.
- Ekblad A, Wallander H, Godbold DL, Cruz C, Johnson D, Baldrian P, Björk RG, Epron D, Kieliszewska-Rokicka B, Kjølter R, Kraigher H, Matzner E, Neumann J, Plassard C, 2013. The production and turnover of extrametrical mycelium of ectomycorrhizal fungi in forest soils: role in carbon cycling. *Plant and Soil* 366, 1-27.
- Ginzburg, S., Vesterdal, L., Vanguelova, E., Hansen, K., Schmidt, K.I., Gundersen, P. (in review). Does nitrogen deposition affect soil carbon stocks? – Evaluation of five nitrogen gradients in temperate forest edges. *Global Biogeochemical Cycles*
- Ginzburg, S., Schmidt, I.K., Kjølter, R., Vesterdal, L., Gundersen, P. (in review) Changes in soil carbon flows and sequestration rates following long-term chronic nitrogen additions to a Norway spruce forest. *Forest Ecology & Management*
- Ginzburg, S. and Gundersen, P. (in revision) Elevated N deposition moderates the temperature feedback on decomposition in forest soils. *Nature Communications*.
- Gurmesa, G.A., Schmidt, I.K., Gundersen, P. and Vesterdal, L., 2013. Soil carbon accumulation and nitrogen retention traits of four tree species grown in common gardens. *Forest Ecology and Management*, 309, 47-57.
- Hansson, K., Fröberg, M., Helmisaari, H.-S., Kleja, D.B., Olsson, B.A., Olsson, M. and Persson, T., 2013. Carbon and nitrogen pools and fluxes above and below ground in spruce, pine and birch stands in southern Sweden. *Forest Ecology and Management*, 309: 28-35.
- Hunziker M, Sigurdsson BD, Halldorsson G, Schwanghart W & Kuhn N 2014. Biomass allometries and coarse root biomass distribution of mountain birch in southern Iceland. *Icelandic Agricultural Sciences* 27, 111-125.
- Lazdiņš, A. and Čugunovs, M., 2014. Utilisation of Yasso model in projection of forestry and agricultural emissions - literature review. Report from Latvia State Forest Research Institute "Silava", 39 pp.
- Leblans, N. I. W., Sigurdsson, B. D., Roefs, P., Thuys, R., Magnússon, B., and Janssens, I. A., 2014. Effects of seabird nitrogen input on biomass and carbon accumulation after 50 years of primary succession on a young volcanic island, Surtsey. *Biogeosciences Discuss.*, 11, 6269-6302, 2014
- Michielsen, L., 2014. Plant communities and global change: adaptation by changes in present species composition or adaptation in plant traits. A case study in Iceland. M.Sc. thesis, University of Antwerp, Antwerp.
- Nilsson LO, 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.

- O’Gorman, E., Benstead, J.P., Cross, W.F., Friberg, N., Hood, J.M., Johnson, P.W., Sigurdsson, B.D. and Woodward, G., 2014. Climate change and geothermal ecosystems: natural laboratories, sentinel systems, and future refugia. *Global Change Biology*, 20, 3291–3299.
- Olsson, B.A., Hansson, K., Persson, T., Beuker, E. and Helmisaari, H.-S., 2012. Heterotrophic respiration and nitrogen mineralisation in soils of Norway spruce, Scots pine and silver birch stands in contrasting climates. *Forest Ecology and Management*, 269, 197-205.
- Persson, T., 2012. Preface - Tree stumps for bioenergy – harvesting techniques and environmental consequences. *Scandinavian Journal of Forest Research*, 27, 705-708.
- Persson, T., 2013. Preface - Environmental consequences of tree-stump harvesting. *Forest Ecology and Management*, 290, 1-4.
- Rosenstock, N.P., Ågren, G., Bengtson, P., Lindahl, B. and Subke, J.-A., in internal review. Effects on soil organic matter of global changes in resource stoichiometry – what is needed in mechanistic models.
- Sigurdsson, B.D. and Gudleifsson, B.E., 2013. Impact of afforestation on earthworm populations in Iceland. *Icelandic Agricultural Sciences*, 26, 21-36.
- Sigurdsson, B.D., Medhurst, J.L., Wallin, G., Eggertsson, O. and Linder, S., 2013. Growth of mature boreal Norway spruce was not affected by elevated [CO<sub>2</sub>] and/or air temperature unless nutrient availability was improved. *Tree Physiology*, 33, 1192-1205.
- Sigurdsson, B.D., N. Leblans, E.S. Oddsdottir, M. Maljanen and I Janssens, 2014. Effects of geothermal soil warming on soil carbon and nutrient processes in a Sitka spruce plantation. *Working Papers of the Finnish Forest Research Institute* (submitted).
- Stefansdottir, G., Aradottir, A. L., and Sigurdsson, B. D., 2014. Accumulation of nitrogen and organic matter during primary succession of *Leymus arenarius* dunes on the volcanic island Surtsey, Iceland, *Biogeosciences*, 11, 5763-5771.
- Vande Velde, K., 2014. Effects of short-term and long-term natural soil warming gradients on plant productivity, carbon and nitrogen stocks of a sub-arctic grassland. M.Sc. thesis, Universitiy of Antwerp, Antwerp, Belgium, 104 pp.
- Vesterdal, L., Clarke, N., Sigurdsson, B.D. and Gundersen, P., 2013. Do tree species influence soil carbon stocks in temperate and boreal forests? *Forest Ecology and Management*, 309, 4-18.
- Taylor, A.R., Lenoir, L., Vegerfors-Persson, B. and Persson, T. (in internal review). Ant and earthworm bioturbation in cold temperate ecosystems. *Functional Ecology*
- 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.

## Appendix: Abstracts of papers and reports from the networking project

*In order of appearance in the report chapters above.*

### *Influence of tree species on SOC*

Vesterdal, L., Clarke, N., Sigurdsson, B.D. and Gundersen, P., 2013. **Do tree species influence soil carbon stocks in temperate and boreal forests?** *Forest Ecology and Management*, 309, 4-18.

Information on tree species effects on soil organic carbon (SOC) stocks is scattered and there have been few attempts to synthesize results for forest floor and mineral soil C pools. We reviewed and synthesized current knowledge of tree species effects on SOC stocks in temperate and boreal forests based on common garden, retrospective paired stand and retrospective single-tree studies. There was evidence of consistent tree species effects on SOC stocks. Effects were clearest for forest floor C stocks (23 of 24 studies) with consistent differences for tree genera common to European and North American temperate and boreal forests. Support for generalization of tree species effects on mineral soil C stocks was more limited, but significant effects were found in 13 of 22 studies that measured mineral soil C. Proportional differences in forest floor and mineral soil C stocks among tree species suggested that C stocks can be increased by 200–500% in forest floors and by 40–50% in top mineral soil by tree species change. However, these proportional differences within forest floors and mineral soils are not always additive: the C distribution between forest floor and mineral soil rather than total C stock tends to differ among tree species within temperate forests. This suggests that some species may be better engineers for sequestration of C in stable form in the mineral soil, but it is unclear whether the key mechanism is root litter input or macrofauna activity. Tree species effects on SOC in targeted experiments were most consistent with results from large-scale inventories for forest floor C stocks whereas mineral soil C stocks appeared to be stronger influenced by soil type or climate than by tree species at regional or national scales. Although little studied, there are indications that higher tree species diversity could lead to higher SOC stocks but the role of tree species diversity per se vs. species identity effects needs to be disentangled in rigorous experimental designs. For targeted use of tree species to sequester soil C we must identify the processes related to C input and output, particularly belowground, that control SOC stock differences. We should also study forms and stability of C along with bulk C stocks to assess whether certain broadleaves store C in more stable form. Joint cooperation is needed to support syntheses and process-oriented work on tree species and SOC, e.g. through an international network of common garden experiments.

Gurmesa, G.A., Schmidt, I.K., Gundersen, P. and Vesterdal, L., 2013. **Soil carbon accumulation and nitrogen retention traits of four tree species grown in common gardens.** *Forest Ecology and Management*, 309, 47-57.

Tree species effects on soil carbon (C) accumulation are uncertain, especially with respect to the mineral soil C, and the consistency of such effects across soil types is not known. The interaction between C accumulation and nitrogen (N) retention among common tree species has also been little explored. Effects of four tree species on soil C and N stocks and soil water nitrate concentration below the root zone were evaluated in a common garden design replicated at eight sites in Denmark. The tree species were beech (*Fagus sylvatica* L.), oak (*Quercus robur* L.), larch (*Larix leptolepis* Kaempfer), and Norway spruce (*Picea abies* (L.) Karst.). After four decades, there were significant differences in forest floor C stocks among all four species, and C stocks increased consistently in the order oak < beech, Norway spruce < larch along the soil texture gradient of the sites. Forest floor N stocks only differed significantly between conifers and broadleaves. The observed differences in forest floor C and N stocks were attributed to differences in litter turnover rates among the tree species. Mineral soil C stocks were significantly higher in stands of Norway spruce than in stands of oak and beech while mineral soil N stocks did not differ significantly. Total soil C stocks were thus

significantly higher under conifers than under broadleaves. Even though forest floor C and N stocks decreased with finer texture, the C–N stoichiometry in forest floors was quite similar across sites. A significant difference in soil water nitrate concentration at 70–90 cm depth was found only between beech and oak. Nitrate concentrations were highest on fine-textured soils with high pH and low C/N ratio as well as on a site with high local N emissions. Nitrate concentrations were negligible on sandy acidic soils with high C/N ratio. We conclude that tree species may establish consistent differences in soil C and N stocks and N retention traits even along soil texture gradients.

Hansson, K., Fröberg, M., Helmisaari, H.-S., Kleja, D.B., Olsson, B.A., Olsson, M. and Persson, T., 2013. **Carbon and nitrogen pools and fluxes above and below ground in spruce, pine and birch stands in southern Sweden.** *Forest Ecology and Management*, 309: 28-35.

We synthesised results on soil carbon (C) and nitrogen (N) fluxes and the accumulation of soil organic C and N under adjacent 50-year-old Norway spruce, Scots pine and silver birch stands growing on similar soils and evaluated the different processes involved. C and N budgets were calculated. Spruce stands had larger stocks of C and N in biomass and soil than birch stands, with pine intermediate. The differences in soil stocks were mainly found in the organic layer, whereas differences in the mineral soil were small. The study showed that there is no simple answer to what is causing the differences in soil C and N stocks, because several processes are interacting. Spruce and pine trees had higher biomass and litter production than birch trees, but total litter inputs showed no significant difference between stands, because the rich ground vegetation under pine and birch contributed with substantial litter inputs, in contrast to the poor ground vegetation under spruce. Decomposition rate (per g of C) was markedly higher under birch than under spruce and pine resulting in lower C and N stocks in the organic layer. This effect was amplified by higher abundance and biomass of earthworms, favoured by higher pH and palatable litter under birch. Earthworm bioturbation probably both increased decomposition rate and damaged the ectomycorrhizal network with negative consequences for the formation of mycorrhizal litter and C storage. In conclusion, the direct effects of spruce, pine and birch litter on C and N pools and fluxes were modified by indirect effects of understorey structure, pH and earthworm responses.

Olsson, B.A., Hansson, K., Persson, T., Beuker, E. and Helmisaari, H.-S., 2012. **Heterotrophic respiration and nitrogen mineralisation in soils of Norway spruce, Scots pine and silver birch stands in contrasting climates.** *Forest Ecology and Management*, 269, 197-205.

Different tree species are often associated with different soil properties. Earlier studies have shown that Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.), the two dominant tree species in Fennoscandia, often generate soils with larger carbon (C) and nitrogen (N) pools than silver birch (*Betula pendula* Roth.). Consequently, we hypothesised that spruce and pine would create soils with slower turnover rates than birch. To test this, C and N pools and C and N mineralisation rates were determined in different soil layers (humus, 0–10 cm, 10–20 cm mineral soil) at two sites with contrasting climatic conditions. One site (Tönnersjöheden) was located in the temperate zone in SW Sweden and one (Kivalo) in the north boreal zone in N Finland. At both sites, experimental plots with the three tree species had been established more than 50 years before the study. Samples from the different soil layers were incubated at 15 °C in the laboratory for 30 days, and C and N mineralisation rates were determined. In addition, earthworm abundance was estimated at Tönnersjöheden but not at Kivalo (no sign of bioturbation). At Tönnersjöheden, soil C and N pools ( $\text{g C or N m}^{-2}$ ) were ranked spruce > pine > birch. C mineralisation rate ( $\text{mg CO}_2\text{-C g}^{-1} \text{C d}^{-1}$ ) was higher in the birch plots than in the other plots, but because of larger C pools in the spruce plots, field C mineralisation ( $\text{g CO}_2\text{-C m}^{-2} \text{year}^{-1}$ ) was higher for spruce than for pine and birch. Field net N mineralisation ( $80\text{--}90 \text{ kg N ha}^{-1} \text{year}^{-1}$ ) did not differ significantly between tree species, but nitrification rates ( $\mu\text{g NO}_3\text{-N g}^{-1} \text{C d}^{-1}$ ) in the topsoil were higher in the birch plots than in the other plots. The birch plots had larger populations of earthworms and a higher degree of bioturbation than any of the coniferous plots, which probably explains the higher turnover rate of

birch soil organic matter (SOM). At Kivalo, C and N soil pools were significantly larger in spruce than in birch plots, and C mineralisation rate was higher in birch and spruce humus than in pine humus. Net N mineralisation rate and annual field net N mineralisation ( $<4 \text{ kg N ha}^{-1} \text{ year}^{-1}$ ) were estimated to be very low, with no effect of tree species. Thus, the hypothesis of a 'birch effect' was supported at Tönnersjöheden, but only partly at Kivalo. The main difference seemed to be that the earthworms at Tönnersjöheden accelerated SOM decomposition under birch, whereas earthworm stimulation was negligible at Kivalo, probably because of climate-related limitations.

Taylor, A.R., Lenoir, L., Vegerfors-Persson, B. and Persson, T. (in internal review). **Ant and earthworm bioturbation in cold temperate ecosystems.** To be submitted to *Functional Ecology*

Earthworms and ants are the most important organisms in performing bioturbation (biological turnover of soils and sediments) in temperate ecosystems. We calculated the bioturbation performed by these groups in five contrasting vegetation types at two sites in south-eastern Sweden. For earthworms, these calculations were based on abundance/biomass data from field sampling, soil temperature records, laboratory egestion rates and estimates of temperature dependence of earthworm activity. For ants, the calculations were based on nest densities, nest weights and nest residence times. Earthworm bioturbation was moderately high to very high in broadleaf, alder and grassland plots and low in pine plots. Spruce plots showed great variation in bioturbation, which was high in calcareous soils (high pH) and low in acid soils. High bioturbation was strongly associated with presence of burrowing (endogeic and anecic) earthworms. Earthworm bioturbation was estimated at  $22 \pm 5$  and  $0.6 \pm 0.2 \text{ Mg dry weight ha}^{-1} \text{ y}^{-1}$  in soils with presence and absence of burrowing earthworms, respectively. Ant bioturbation was estimated at  $0.56 \pm 0.17$  and  $0.21 \pm 0.08 \text{ Mg dry weight ha}^{-1} \text{ y}^{-1}$  in high and low pH soils, respectively. Earthworm and ant bioturbation accounted for 97.5% and 2.5% of the total bioturbation, respectively, in the ecosystems with near-neutral soils. The corresponding figures in the ecosystems with acidic soils were 65% and 35%, respectively. These data imply that moderately high populations of burrowing earthworms ( $140 \text{ ind. m}^{-2}$ ) can turn over  $2000 \text{ Mg dry weight ha}^{-1}$  of fine soil (normal pool to a depth of 20 cm) in 90 years at sites with an annual mean soil temperature of  $7.7^\circ \text{C}$ . The equations developed can be used to calculate earthworm bioturbation at any location provided that earthworm community data (species composition, biomass) and monthly soil temperatures are available. So far, the equations do not include moisture effects on earthworm activity, which means that worm bioturbation during drought periods can be overestimated.

### *Effects of increased biomass harvest on SOC*

Clarke, N., Gundersen, P., Jönsson-Belyazid, U., Kjønaas, O.J., Persson, T., Sigurdsson, B.D., Stupak, I., Vesterdal, L. In review. **Influence of different tree-harvesting intensities on forest soil carbon stocks in boreal and northern temperate forest ecosystems.** *Forest Ecology and Management*

Effective forest governance measures are crucial to ensure sustainable management of forests, but so far there has been little specific focus in boreal and northern temperate forests on management effects, including harvesting effects, on soil organic carbon (SOC) stocks. This paper reviews the findings in the scientific literature concerning the effect of harvesting of different intensities on SOC stocks and fluxes in boreal and northern temperate forest ecosystems to evaluate the evidence for significant SOC losses following biomass removal. A brief overview of existing governance measures related to SOC is given, followed by a discussion on how scientific findings could be incorporated in guidelines and other governance measures. It appears that there is not enough data available at present to draw firm conclusions about the long-term impact of intensified forest harvesting on SOC stocks in boreal and northern temperate forest ecosystems. Properly conducted long-term experiments would enable us to clarify the relative importance of different harvesting practices on the SOC stores, and under which conditions the size of the removals becomes critical. At present, the uncertainty gap between the scientific results and the need for practically useable management guidelines might be bridged by expert opinions given to authorities and certification bodies.

Persson, T., 2012. **Preface - Tree stumps for bioenergy – harvesting techniques and environmental consequences.** Scandinavian Journal of Forest Research, 27, 705-708. (No abstract)

Persson, T., 2013. **Preface - Environmental consequences of tree-stump harvesting.** Forest Ecology and Management, 290, 1-4. (No abstract)

Strömgren, M., Egnell, G. And Olsson, B.A., 2013. **Carbon stocks in four forest stands in Sweden 25 years after harvesting of slash and stumps.** Forest Ecology and Management, 290, 59-66.

The long-term effect of slash and stump harvesting on carbon (C) stocks in soil, tree biomass, and total ecosystem were studied in four field experiments that commenced in 1980–1982 along a climatic gradient from north to south Sweden. The treatments consisted of complete tree harvesting, i.e., harvesting of slash, stumps, and stems (SSS); harvesting of stumps and stems, but leaving logging residues on site (SS); and, conventional stem-only harvesting (S). The northern site with *Pinus sylvestris* represented a relatively harsh, boreal climate (N-pine). Two additional sites were established in south-central Sweden with *Picea abies* (M-spruce) and *Pinus sylvestris* (M-pine) in a south-boreal climate. The fourth site with *Picea abies* (S-spruce) was established in south-west Sweden in the temperate zone. Ecosystem C stock in tree and soil was lower after SSS than after SS and S, however, there was no significant difference between S and SS. The treatment effect on C stock in tree biomass was site-specific rather than general. Stump-harvest (SS, SSS) increased C stock in N-pine, whereas a decrease was only observed for SSS in M-spruce. A logical explanation for the decreased C stock was the increased nutrient removal caused by harvest intensity. However, this could be counteracted by an increase in release of nutrients from the organic layer and a decrease in competition from the field vegetation promoted by soil disturbance due to stump harvesting. Soil C stock was lower after SSS than after S, due to lower C content in the organic layer after SSS (12 Mg ha<sup>-1</sup>) than S (18 Mg ha<sup>-1</sup>): no difference was detected in the mineral soil (0–20 cm). Soil C stocks after SS did not differ from S and SSS, but were lower in the organic soil layer after SS than after S. These results implied that stump harvest caused a lower C stock in the soil organic layer, 25 years after the harvest. However, this study did not show whether this difference would remain over time as remaining stumps and logging residues continue to decompose and the regenerated stand develops. The effects on the C stock in trees appear site- or time specific. More studies are needed to investigate the factors that control this stock, and the final carbon balance should be evaluated over at least one rotation period.

Eliasson, P., Svensson, M., Olsson, M. and Ågren, G.I., 2013. **Forest carbon balances at the landscape scale investigated with the Q model and the CoupModel – Responses to intensified harvests.** Forest Ecology and Management, 290, 67-78.

The increasing demand for solid biofuels, such as logging residue fuels, has highlighted the importance of considering that, in contrast to fossil fuels, biofuels are produced in dynamic ecosystems. The environmental effects of changes in management policy, whether positive and negative, are not obvious. For example, calculations of the carbon budget in single forest stands show that the carbon balance switches dramatically from uptake to loss at final felling. The time taken to recover the carbon losses after disturbance can span decades to centuries. However, forests are not managed on the single stand level but on the landscape scale. Thus, for example, final felling occurs by definition only once for each rotation period on the whole area considered in a single stand, but within the same time span, it occurs frequently on a fraction of the area in a landscape. The actual frequency and ratio of land area affected each year by final felling depend on the age distribution and rotation age of all stands present in the landscape. In order to reliably evaluate the consequences of new management policies, the aggregated effects of a number of individual stands need to be considered. Here we used two different ecosystem models (the Q model and the CoupModel) to compare the carbon budgets of conventional harvesting of stems on a single-stand level and on the landscape scale under different harvesting intensities. In the calculations, the landscape was assumed to consist of many stands, all of

different ages and each representing one year of a given rotation period. The results showed that the aggregated carbon balance in the forest landscape was less dramatic than that of a single stand. Provided that environmental factors and management policy remain unchanged, the aggregated carbon balance remains stable over time in any landscape. However, the carbon gains from harvesting and its effects on soil carbon stock occur on different time scales. While any change in harvesting system takes a long time to be fully implemented, changes in the proportion of increased removals take effect without delay, while components of soil organic carbon have response times longer than centuries. The carbon gain after introducing removal of logging residues starts to increase immediately at the first harvest in a landscape. The quantities of soil carbon lost with the increased removals are always less than the removals in biomass. Soil carbon losses show a declining response over time.

Grelle, A., Strömgren, M. and Hyvönen, R., 2012. **Carbon balance of a forest ecosystem after stump harvest.** *Scandinavian Journal of Forest Research*, 27, 762-773.

Stump harvest in forests can cause both reductions of CO<sub>2</sub> emissions through a decrease of decomposable substrate (direct effect) and emission increases as a consequence of deep and extensive soil disturbance (indirect effect). Here, the effects of stump harvest on net ecosystem CO<sub>2</sub> exchange (NEE) in a former Norway spruce stand in mid Sweden are presented. CO<sub>2</sub> exchange was continuously followed by eddy-covariance measurements during the first years after harvest. Differences in NEE from stump harvested and mounded (reference) plots were determined by soil-surface respiration measurements. Respiration from decaying stumps was estimated by a decomposition model. Fluxes indicated a direct effect (decreased efflux) during the first year after harvest that corresponded to the absence of decomposing stumps. During the following years, this emission reduction was increasingly counteracted by an indirect effect (increased efflux) of similar magnitude. This means that the expected emissions caused by extra soil disturbance occur with a certain delay and seem to increase with time. By these emissions, the substitution efficiency of stumps as bioenergy resource is reduced. Furthermore, at a time scale of centuries, instant combustion of stumps leads to a larger contribution to global warming than slow decomposition, because the stump carbon is available earlier in form of greenhouse gas. This is estimated by the time integral of emissions. Thus, despite the surprisingly low initial emissions, the overall substitution efficiency and climate benefits of stump harvest are likely to be small. The long-term consequences of stump harvest for the carbon budget are, however, still uncertain.

Hyvönen, R., Olsson, B.A. and Ågren, G.I., 2012. **Dynamics of soil C, N and Ca in four Swedish forests after removal of tops, branches and stumps as predicted by the Q model.** *Scandinavian Journal of Forest Research*, 27, 774-786.

We used the Q model to examine the dynamics of carbon (C), nitrogen (N) and calcium (Ca) in the litter/soil system in different scenarios of harvesting intensities, S (stems only), SSI (stems and slash, i.e. tops, and branches including needles) and SSIS (stems, slash and stumps including coarse roots). Empirical data from long-term field experiments in Sweden, two sites with Norway spruce and two with Scots pine with different levels of productivity, were used to calibrate the model against the stem-only treatment. The highest initial reduction in soil C, N and Ca stores was predicted for SSIS, and the reduction was more pronounced at low productive sites than at the high productive ones. Most of the decline in soil C and Ca stocks was offset by the litter production in the following forest stand. N showed an initial phase of immobilisation in stumps and coarse roots, while N was immediately released from tops and branches, which contained N-rich needles. Removal of stumps and coarse roots in combination with slash resulted in a similar load of inorganic soil N as for the S treatment, whereas the SSI treatment with stumps left in the soil initially reduced the inorganic soil N pool.

### *Effect of elevated N deposition on SOC*

Leblans, N. I. W., Sigurdsson, B. D., Roefs, P., Thuys, R., Magnússon, B., and Janssens, I. A., 2014. **Effects of seabird nitrogen input on biomass and carbon accumulation after 50 years of primary succession on a young volcanic island, Surtsey.** *Biogeosciences Discuss.*, 11, 6269-6302

What happens during primary succession after the first colonizers have occupied a pristine surface largely depends on how they ameliorate living conditions for other species. For vascular plants the onset of soil development and associated increase in nutrient (mainly nitrogen, N) and water availability is especially important. Here, we report the relation between N accumulation and biomass- and ecosystem carbon (C) stocks in a 50 year old volcanic island, Surtsey, in Iceland, where N stocks are still exceptionally low. However, 27 year old seagull colony on the island provided nutrient-enriched areas, which enabled us to assess the relationship between N stock and biomass- and ecosystem C stocks across a much larger range in N stock. Further, we compared areas on shallow and deep tephra sands as we expected that deep-rooted systems would be more efficient in retaining N. The sparsely vegetated area outside the colony was more efficient in N retention than we expected and had accumulated  $0.7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , which was ca. 60% of the estimated N input rate from wet deposition. The seagulls have added, on average,  $47 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , which induced a shift from belowground to aboveground in ecosystem N and C stocks and doubled the ecosystem "N use efficiency", determined as the ratio of biomass and C storage per unit N input. Soil depth did not significantly affect total N stocks, which suggests a high N retention potential. Both total ecosystem biomass and C stocks were strongly correlated with N stock inside the colony, which indicated the important role of N during the first steps of primary succession. Inside the colony, the ecosystem biomass C stocks ( $17\text{--}27 \text{ kg C ha}^{-1}$ ) had reached normal values for grasslands, while the soil organic carbon stocks (SOC;  $4\text{--}10 \text{ kg C ha}^{-1}$ ) were only a fraction of normal grassland values. Thus, it will take a long time until the SOC stock reaches equilibrium with the current primary production; during which conditions for new colonists may change.

Stefansdottir, G., Aradottir, A. L., and Sigurdsson, B. D., 2014. **Accumulation of nitrogen and organic matter during primary succession of *Leymus arenarius* dunes on the volcanic island Surtsey, Iceland,** *Biogeosciences*, 11, 5763-5771.

Initial soil development and enhanced nutrient retention are often important underlying environmental factors during primary succession. We quantified the accumulation rates of nitrogen (N) and soil organic matter (SOM) in a 37-year-long chronosequence of *Leymus arenarius* dunes on the pristine volcanic island Surtsey in order to illuminate the spatiotemporal patterns in their build-up. The *Leymus* dune area, volume and height grew exponentially over time. Aboveground plant biomass, cover or number of shoots per unit area did not change significantly with time, but root biomass accumulated with time, giving a root / shoot ratio of 19. The dunes accumulated on average  $6.6 \text{ kg N ha}^{-1} \text{ year}^{-1}$ , which was 3.5 times more than is received annually by atmospheric deposition. The extensive root system of *Leymus* seems to effectively retain and accumulate a large part of the annual N deposition, not only deposition directly on the dunes but also from the adjacent unvegetated areas. SOM per unit area increased exponentially with dune age, but the accumulation of roots, aboveground biomass and SOM was more strongly linked to soil N than time: a  $1 \text{ g m}^{-2}$  increase in soil N led on average to a  $6 \text{ kg C m}^{-2}$  increase in biomass and SOM. The *Leymus* dunes, where most of the N has been accumulated, will therefore probably act as hot spots for further primary succession of flora and fauna on the tephra sands of Surtsey.

Ginzburg, S., Vesterdal, L., Vanguelova, E., Hansen, K., Schmidt, K.I., Gundersen, P. (in review). **Does nitrogen deposition affect soil carbon stocks? – Evaluation of five nitrogen gradients in temperate forest edges.** Global Biogeochemical Cycles

Elevated long-term nitrogen (N) deposition to forest ecosystems has been hypothesized to increase soil organic carbon (SOC) stocks by increasing forest productivity and consequent carbon (C) input to soil and by reducing the decomposition of soil organic matter (SOM). Yet, the magnitude of this effect, which is largely based on observations from N fertilization experiments and studies at large spatial scale, is uncertain. To elucidate the effect of atmospheric N deposition on forest SOC stocks we investigated soils from stand scale N deposition gradients in edges of five temperate coniferous forests bordering agricultural land. Nitrogen enrichment across the forest edges was found in all stands and was reflected in gradients in forest floor and needle litter C/N ratios as well as soil solution nitrate concentrations. Overall, forest floor and mineral soil (0-5 cm) C stocks assessed along the N gradients were not significantly related to N deposition or to any of the above-mentioned indicators for N deposition impacts. Needle litter C inputs close to the edge were lower compared with the stand interior at sites receiving high local N deposition. Forest floor fine-root biomass in the forest floor increased with distance from the edge, indicating a decreased belowground C input from roots with increased N deposition. The respiration of SOM was reduced under elevated N deposition indicating reduced turnover rate of SOM. We concluded that N deposition at rates common to agriculturally intensive regions in north-Western Europe may reduce the turnover of SOM but this positive effect on SOC stocks may be outweighed by decreases in above- and belowground C inputs resulting in no overall change in soil C stocks. Our results contrast with previous studies reporting a significant positive impact of experimental N addition on SOC sequestration in temperate forest soils.

Ginzburg, S., Schmidt, I.K., Kjølner, R., Vesterdal, L., Gundersen, P. (in revision). **Changes in soil carbon flows and sequestration rates following long-term chronic nitrogen additions to a Norway spruce forest.** Forest Ecology and Management

Soils contain the largest fraction of terrestrial carbon (C). Understanding the controls of decomposition and storage of soil organic matter (SOM) is essential for predictions of the global carbon cycle. Nitrogen (N) has been suggested as an important factor affecting forest soil organic carbon (SOC) stocks through positive effects on tree growth and a negative effect on SOM decomposition, yet the magnitude of the effect is uncertain. We applied  $3.5 \text{ g N m}^{-2} \text{ year}^{-1}$  to a Norway spruce stand in Denmark since 1992 and during the period 2001-2013 we measured the effects of the added N on aboveground tree growth, fine root biomass and production, ectomycorrhizal mycelial (EM) production and species composition, forest floor C stocks, SOM decomposition, in-situ respiration and potential respiration of “young” and “old” organic matter. We hypothesized that intermediate chronic N additions would increase forest floor C stocks owing to reduced turnover rate of SOM while above- and belowground C inputs would be unchanged and decreased, respectively. We found that tree growth, foliar litterfall and moss growth were reduced by N addition especially since 2003. Fine root biomass, EM production and EM species diversity were all insignificantly lower in the N addition treatment indicating a general reduction in belowground C inputs, though fine root production was unchanged. Nitrogen additions seemed to reduce litter and SOM turnover during the first decade of the experiment thereby contributing positively to C stocks but we did not find evidence for it following two decades of continuous treatment. Contrary to our hypothesis we did not observe a significant increase in forest floor C stocks after one nor after two decades of N additions where the total forest floor C stocks for the control and N treatments were  $7.8$  and  $7.1 \text{ kg C m}^{-2}$ , respectively. We conclude that N deposition rates as those typically found in regions with intensive agricultural production in northern Europe may reduce SOM decomposition but in the long run above- and belowground C inputs can also be reduced resulting in no change (or even decline) in the forest floor C stocks by N deposition.

### *Effects of warming on SOC stability*

Ginzburg, S. and Gundersen, P. (in revision). **Elevated N deposition moderates the temperature feedback on decomposition in forest soils.** *Nature Communications*

Decomposition rates of soil organic matter (SOM) are expected to increase as global temperatures rise, potentially creating a positive feedback on atmospheric CO<sub>2</sub> concentration thereby amplifying climate warming. Therefore, much scientific focus is currently set upon assessing the temperature sensitivity of SOM. Conversely, nitrogen (N) input to forests is increasing globally and may reduce SOM decomposition rates. Here we show that enhanced N deposition into forests can reduce the temperature sensitivity of both young (labile) and old (recalcitrant) SOM. We used SOM from a stand-scale N availability gradient evolved from decades of elevated N deposition gradually decreasing from the edge into the forest. Soils from the N gradient were incubated in microcosms to measure decomposition as heterotrophic respiration rate. Respiration and its temperature sensitivity (Q<sub>10</sub>) decreased with increasing N availability (decreasing C/N ratio) for both young and old SOM indicating that elevated N deposition negatively affect global warming.

Sigurdsson, B.D., Medhurst, J.L., Wallin, G., Eggertsson, O. and Linder, S., 2013. **Growth of mature boreal Norway spruce was not affected by elevated [CO<sub>2</sub>] and/or air temperature unless nutrient availability was improved.** *Tree Physiology*, 33, 1192-1205.

The growth responses of mature trees exposed to elevated [CO<sub>2</sub>] (CE; 670–700 ppm) and long-term optimized nutrient availability or elevated air temperature (TE; +3.9 °C) were studied in situ in northern Sweden in two 3 year field experiments using 12 whole-tree chambers in ca. 40-year-old forest. The first experiment (Exp. I) studied the interactions between CE and nutrient availability and the second (Exp. II) between CE and TE. It should be noted that only air temperature was elevated in Exp. II, while soil temperature was maintained close to ambient. In Exp. I, CE significantly increased the mean annual height increment, stem volume and biomass increment during the treatment period (25, 28, and 22%, respectively) when nutrients were supplied. There was, however, no significant positive CE effect found at the low natural nutrient availability. In Exp. II, which was conducted at the natural site fertility, neither CE nor TE significantly affected height or stem increment. It is concluded that the low nutrient availability (mainly nitrogen) in the boreal forests is likely to restrict their response to the continuous rise in [CO<sub>2</sub>] and/or TE.

O’Gorman E, Benstead JP, Cross WF, Friberg N, Hood JM, Johnson PW, Sigurdsson BD & Woodward G 2014. **Climate change and geothermal ecosystems: natural laboratories, sentinel systems, and future refugia.** *Global Change Biology* 20, 3291–3299.

Understanding and predicting how global warming affects the structure and functioning of natural ecosystems is a key challenge of the 21st century. Isolated laboratory and field experiments testing global change hypotheses have been criticised for being too small-scale and overly simplistic, whereas surveys are inferential and often confound temperature with other drivers. Research that utilises natural thermal gradients offers a more promising approach and geothermal ecosystems in particular exhibit a range of temperatures within a single biogeographic area, allowing us to take the laboratory into nature rather than vice versa. By isolating temperature from other drivers, its ecological effects can be quantified without any loss of realism, and transient and equilibrial responses can be measured in the same system across scales that are not feasible using other empirical methods. Embedding manipulative experiments within geothermal gradients is an especially powerful approach, informing us to what extent small-scale experiments can accurately predict the future behaviour of real ecosystems. Geothermally heated areas also act as sentinel systems by tracking responses of ecological networks to warming and helping to maintain ecosystem functioning in the landscape by providing sources of organisms that are pre-adapted to different climatic conditions. Here, we

highlight the emerging use of these systems in climate change research, identify novel research avenues, and assess their roles for catalysing our understanding of ecological and evolutionary responses to global warming.

Vande Velde, K., 2014. **Effects of short-term and long-term natural soil warming gradients on plant productivity, carbon and nitrogen stocks of a sub-arctic grassland.** M.Sc. thesis, University of Antwerp, Antwerp, Belgium, 104 pp.

Maintaining long-term climate manipulation experiments to study the long-term effects of warming at ecosystem level is extremely expensive. Hence, very few long-term studies exist and many of those are simulation studies, extrapolating current climate response models. Here, changes in plant productivity and ecosystem carbon (C) and nitrogen (N) stocks along natural short-term (i.e.: ~5 years) and long-term (i.e.: very likely minimum of 3 centuries) soil warming gradients in the sub-arctic grassland system were studied to shed some light on the subject. Increased soil temperature (TS) is expected to cause changes in the cycling of C and N through the soil, which influences plant productivity and ultimately results in changes of ecosystem C and N stocks. However, the increased changes in C and N cycling might also be transient. Whether changes are transient or not was studied by comparing the short- and long-term temperature gradients. In order to better understand the mechanisms behind changes in plant productivity and in ecosystem C and N stocks, several components of the ecosystem were studied along the soil temperature gradients which all included study plots at the following TS elevations: ambient TS (i.e.: control) and approximately 1°C, 3°C, 5°C and 10°C above ambient TS. After short-term warming, soil C and N stocks were significantly lower and (root) biomass significantly decreased at high TS elevation (i.e.: +5°C and +10°C). These results suggest that decomposition rates increased, resulting in increased emission of C- and N- based greenhouse gases. The much smaller root system at high TS elevation might have exacerbated the loss of N by failing to immobilize the increasing soil N availabilities. After long-term warming soil C stocks were also significantly lower at high TS elevation. However, in this case soil N stocks showed no significant differences and the productivity of vascular plants even increased with increasing TS. These results indicate that after long-term warming the warmed plants and microbes are able to maintain the high N stocks and availability, supporting enhanced plant productivity. However, this warming induced increase in productivity is too small to compensate for the soil C stocks, which strongly declined. This thesis thus supports the hypothesis that global warming will result in large C losses from northern soils that can be expected to feedback positively to global warming.

Michielsen, L., 2014. **Plant communities and global change: adaptation by changes in present species composition or adaptation in plant traits. A case study in Iceland.** M.Sc. thesis, University of Antwerp, Antwerp.

Climate change is expected to have the largest impact on northern ecosystems at high latitudes. Models predict that temperature increase in these areas will be twofold greater compared to the rest of the world. The geothermal conditions in southern Iceland offer an exceptional opportunity to study the impact of warming on northern high-latitude ecosystems. Hot springs and fumaroles induce temperature gradients in different valleys. These temperature gradients are excellent natural manipulation experiments that allow studying the response of these northern grassland ecosystems to temperature increases. In one of the two studied valleys, these natural temperature gradients have been present for centuries, but an earthquake in 2008 resulted in new geothermal activity and associated temperature gradients in an adjacent valley. This difference in the warming time frame makes it possible to study differences in short term and long term warming on similar vegetation. The main research question was whether soil warming would induce a change in plant community structure or would result in adaptations of plant traits. For the latter aim, three target species (*Agrostis capillaris*, *Poa pratensis* and *Ranunculus acris*) were studied. Our results indicate that soil warming induces a decrease in overall biodiversity and favours plant species preferring a nitrogen-rich environment. Total plant coverage and the plant height for the three target species solely experience a

positive temperature effect in the century-long warmed valley. These results indicate that the two strategies to adapt to warming cannot be seen as separate consequences of warming. Moreover, our results suggest different main drivers for adaptation in the two studied grasslands. We speculate these drivers to be temperature stress in the short term warmed grassland and the temperature-induced nitrogen-increase the driver in the century-long warmed grassland. Species adaptation to higher temperatures in the long term could explain this difference.

### *Effects of land use change on SOC*

Bárcena, T.G., Kiær, L.P., Vesterdal, L., Stéfansdóttir, H.M., Gundersen, P. and Sigurdsson, B.D., 2014. **Soil carbon stock change following afforestation in Northern Europe: a meta-analysis.** *Global Change Biology*, 20: 2393–2405

Northern Europe supports large soil organic carbon (SOC) pools and has been subjected to high frequency of land-use changes during the past decades. However, this region has not been well represented in previous large-scale syntheses of land-use change effects on SOC, especially regarding effects of afforestation. Therefore, we conducted a meta-analysis of SOC stock change following afforestation in Northern Europe. Response ratios were calculated for forest floors and mineral soils (0–10 cm and 0–20/30 cm layers) based on paired control (former land use) and afforested plots. We analyzed the influence of forest age, former land-use, forest type, and soil textural class. Three major improvements were incorporated in the meta-analysis: analysis of major interaction groups, evaluation of the influence of non-independence between samples according to study design, and mass correction. Former land use was a major factor contributing to changes in SOC after afforestation. In former croplands, SOC change differed between soil layers and was significantly positive (20%) in the 0–10 cm layer. Afforestation of former grasslands had a small negative (non-significant) effect indicating limited SOC change following this land-use change within the region. Forest floors enhanced the positive effects of afforestation on SOC, especially with conifers. Meta-estimates calculated for the periods <30 years and >30 years since afforestation revealed a shift from initial loss to later gain of SOC. The interaction group analysis indicated that meta-estimates in former land-use, forest type, and soil textural class alone were either offset or enhanced when confounding effects among variable classes were considered. Furthermore, effect sizes were slightly overestimated if sample dependence was not accounted for and if no mass correction was performed. We conclude that significant SOC sequestration in Northern Europe occurs after afforestation of croplands and not grasslands, and changes are small within a 30-year perspective.

Bárcena, T.G., Gundersen, P., Vesterdal, L., 2014. **Afforestation effects on soil organic carbon in former cropland: oak and spruce chronosequences resampled after 13 years.** *Global Change Biology* 20: 2938–2952.

Chronosequences are commonly used to assess soil organic carbon (SOC) sequestration after land-use change, but SOC dynamics predicted by this space-for-time substitution approach have rarely been validated by resampling. We conducted a combined chronosequence/resampling study in a former cropland area (Vestskoven) afforested with oak (*Quercus robur*) and Norway spruce (*Picea abies*) over the past 40 years. The aims of this study were (i) to compare present and previous chronosequence trends in forest floor and top mineral soil (0–25 cm) C stocks; (ii) to compare chronosequence estimates with current rates of C stock change based on resampling at the stand level; (iii) to estimate SOC changes in the subsoil (25–50 cm); and (iv) to assess the influence of two tree species on SOC dynamics. The two chronosequence trajectories for forest floor C stocks revealed consistently higher rates of C sequestration in spruce than oak. The chronosequence trajectory was validated by resampling and current rates of forest floor C sequestration decreased with stand age. Chronosequence trends in topsoil SOC in 2011 did not differ significantly from those reported in 1998, however, there was a shift from a negative rate (1998:  $-0.3 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ) to no change in 2011. In contrast SOC stocks in the subsoil increased with stand age, however, not significantly ( $P = 0.1$ ), suggesting different C dynamics in and below the former plough layer. Current rates of C change estimated by

repeated sampling decreased with stand age in forest floors but increased in the topsoil. The contrasting temporal change in forest floor and mineral soil C sequestration rates indicate a shift in C source-sink strength after approximately 40 years. We conclude that afforestation of former cropland within the temperate region may induce soil C loss during the first decades followed by a recovery phase of yet unknown duration.

Sigurdsson, B.D. and Gudleifsson, B.E., 2013. **Impact of afforestation on earthworm populations in Iceland.** *Icelandic Agricultural Sciences*, 26, 21-36.

Earthworms were collected from different vegetation types in East and West Iceland. The vegetation types in East Iceland were Siberian larch (*Larix sibirica*) forests, native mountain birch (*Betula pubescens*) woodlands and open heathlands. The study areas in West Iceland were Sitka spruce (*Picea sitchensis*), lodgepole pine (*Pinus contorta*) forests, mountain birch woodlands and open heathlands. Four earthworm species (*Dendrobaena octaedra*, *Dendrodrilus rubidus*, *Aporrectodea caliginosa*, *Lumbricus rubellus*) were identified at both study areas and two additional ones in the West Iceland (*Aporrectodea rosea* and *Octolasion cyaneum*). No significant differences were detected in average earthworm species number and biomass between treeless heathlands and forests in East or West Iceland. There were, however, significant differences between the native deciduous forests and the coniferous plantations in West, but not East Iceland. Time since afforestation was found to have a significant effect on both earthworm diversity and density and should always be included in future studies. All earthworm parameters were positively related to soil N and amount of monocots, but negatively related to soil C/N ratio, tree LAI and tree height. Soil pH had no significant influence on any of the earthworm parameters. The most noteworthy finding was that earthworms were generally found in similar biomass and species richness in the exotic coniferous plantations in Iceland compared to the treeless heathlands, even if earthworm species composition showed strong changes. The findings apply to the first 50 years after establishment of coniferous trees, but an unexpected, large increase in earthworm biomass and species richness in the oldest thinned Siberian larch forests in East Iceland make any generalisation about future trends uncertain. Further earthworm studies in the oldest coniferous forests in Iceland are therefore still needed.

### **Nordic soil organic carbon stocks**

Bengtson et al. (in preparation). **Identification of climatic and other drivers of importance for Nordic soil C stocks.**

Monitoring data on SOC stock to 1m depth from roughly 4300 forest inventory sites of Sweden, Denmark and Latvia were compiled in the Nordic and Baltic countries. In a stepwise regression the influence of forest properties, annual mean temperature and precipitation (1971-2000), and N deposition (for 2010 according to EMEP models) on mineral soil SOC stocks were analysed. Soil carbon stocks were highest in the Southwestern region of the examined area and decreased moving eastwards and northwards. The regression analysis showed that the rate of N deposition modulate the effect of temperature on soil carbon sequestration in boreal and temperate forests. In areas with low N deposition rates increased temperatures might result higher soil organic carbon sequestration. In contrast, in areas exposed to high N deposition temperature does not appear to be a major driver of soil carbon sequestration, while there is a strong effect of N deposition. We can also conclude that mineral soil SOC stocks down to 100 cm are higher in broadleaf forests compared to coniferous forests, irrespectively of the temperature and N deposition rates.

### *Role of mycorrhizal fungi as input to SOC*

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.

A substantial portion of the carbon (C) fixed by the trees is allocated belowground to ectomycorrhizal (EM) symbionts, but this fraction usually declines after fertilization. The aim of the present study was to estimate the effect of optimal fertilization (including all the necessary nutrients) on the growth of EM fungi in young Norway spruce forests over a three year period. In addition, the amount of carbon sequestered by EM mycelia was estimated using a method based on the difference in delta C-13 between C-3 and C-4 plants. Sand-filled ingrowth mesh bags were used to estimate EM growth, and similar bags amended with compost made from maize leaves (a C-4 plant) were used to estimate C sequestration. Fertilizers had been applied either every year or every second year since 2002 and the estimates of EM growth started in 2007. The application of fertilizer reduced EM growth to between 0% and 40% of the growth in the control plots at one site (Ebbegårde), while no significant effect was found at the other three sites studied. The effect of the fertilizer was similar in sand-filled and maize-compost-amended mesh bags, but the total production of EM fungi was 3-4 times higher in maize-compost-amended mesh bags. The fertilizer tended to reduce EM growth more when applied every year than when applied every second year. The amount of C sequestered in maize-compost-amended mesh bags collected from unfertilized treatments was estimated to be between 0.2 and 0.7 mg C g sand<sup>-1</sup> at Ebbegårde and between 0.2 and 0.5 mg C g sand<sup>-1</sup> at Grangshammar. This corresponds to between 300 and 1100 kg C per ha, assuming a similar production in the soil as in the mesh bags. Fertilization at the Ebbegårde site reduced carbon sequestration, which confirmed the results based on estimates of fungal growth (ergosterol levels). A correlation was found between fungal biomass and delta C-13 in mesh bags amended with maize compost. Based on this, it was estimated that a fungal production of 1 µg ergosterol corresponded to 0.33 mg of sequestered carbon. In conclusion, the effect of the fertilizer on EM growth seemed to be dependent on the effect of the fertilizer on tree growth. Thus, at Ebbegårde, where tree growth was less stimulated by the fertilizer, EM growth was reduced upon fertilization. At other sites, where tree growth was more stimulated, the fertilizer did not influence EM growth. The large amounts of carbon sequestered during the experiment may be a result of fungal residues remaining in the soil after the death of the hyphae.

Clemmensen KE, Bahr A, Ovaskainen O, Dahlberg A, Ekblad A, Wallander H, Stenlid J, Finlay RD, Wardle DA, Lindahl BD, 2013. **Roots and associated fungi drive long-term carbon sequestration in boreal forests.** *Science* 339, 1615-1618.

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 C-14 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.

Ekblad A, Wallander H, Godbold DL, Cruz C, Johnson D, Baldrian P, Björk RG, Epron D, Kieliszewska-Rokicka B, Kjoller R, Kraigher H, Matzner E, Neumann J, Plassard C, 2013. **The production and turnover of extrametrical mycelium of ectomycorrhizal fungi in forest soils: role in carbon cycling.** Plant and Soil 366, 1-27.

There is growing evidence of the importance of extrametrical mycelium (EMM) of mycorrhizal fungi in carbon (C) cycling in ecosystems. However, our understanding has until recently been mainly based on laboratory experiments, and knowledge of such basic parameters as variations in mycelial production, standing biomass and turnover as well as the regulatory mechanisms behind such variations in forest soils is limited. Presently, the production of EMM by ectomycorrhizal (EM) fungi has been estimated at similar to 140 different forest sites to be up to several hundreds of kg per ha per year, but the published data are biased towards *Picea abies* in Scandinavia. Little is known about the standing biomass and turnover of EMM in other systems, and its influence on the C stored or lost from soils. Here, focussing on ectomycorrhizas, we discuss the factors that regulate the production and turnover of EMM and its role in soil C dynamics, identifying important gaps in this knowledge. C availability seems to be the key factor determining EMM production and possibly its standing biomass in forests but direct effects of mineral nutrient availability on the EMM can be important. There is great uncertainty about the rate of turnover of EMM. There is increasing evidence that residues of EM fungi play a major role in the formation of stable N and C in SOM, which highlights the need to include mycorrhizal effects in models of global soil C stores.

Nilsson LO, 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.

Background and aims: Under chronically elevated N deposition, N retention mainly occur at high soil C-to-N ratio. This may be mediated through soil microbes, such as ectomycorrhizal (EM) fungi, saprotrophic fungi and bacteria, and the aim of this study was to evaluate the relationship between soil microbes and forest floor C-to-N ratios.

Methods: Soil samples from 33 Norway spruce (*Picea abies* (L.) H. Karst) forests in Denmark and southern Sweden in a forest floor C-to-N ratio gradient (ranging from 14 to 35) were analysed regarding the content of phospholipid fatty acids (PLFAs) to estimate their soil microbial community composition and the relative biomasses of different microbial groups. The relation of EM biomass to total fungal biomass was estimated as the loss of the fungal PLFA 18:2 $\omega$ 6,9 during incubation of soils and the production of EM mycelia was estimated using fungal in-growth mesh bags. The soil microbial variables were correlated to forest floor C-to-N ratio, NO<sub>3</sub> - leaching, soil pH and stand age.

Results: Fungal proportions of microbial biomass, EM to total fungi and EM mycelial production were all positively related to C-to-N ratio, while NO<sub>3</sub> - leaching was negatively related to C-to-N ratio.

Conclusions: Both EM and saprotrophic fungi change with forest floor C-to-N ratios and appear to play a central role in N retention in forest soil. A better understanding of the mechanisms behind this process may be revealed if the role of recalcitrant fungal metabolites for N retention (and soil C sequestration) can be identified. Research along this line deserves further studies.

### *Process understanding and mechanistic models*

Rosenstock, N.P., Ågren, G., Bengtson, P., Lindahl, B. and Subke, J.-A., in internal review. **Effects on soil organic matter of global changes in resource stoichiometry – what is needed in mechanistic models.**

Forests soils are tremendous reservoirs of carbon. Small changes in soil carbon stocks could cause very large increases or decreases in atmospheric carbon dioxide levels. A number of aspects of global change, including anthropogenic increases in atmospheric nitrogen deposition and atmospheric CO<sub>2</sub> levels have the potential to affect soil carbon stocks. Plant responses to shifts in resource stoichiometry caused by global change are now increasingly understood to have important effects on processes of soil carbon accumulation. Autotrophic partitioning of belowground carbon

to root growth, mycorrhizal symbionts, and exudation (insofar as it causes rhizosphere priming) are each uniquely important processes for soil carbon stocks that have been shown to respond to nitrogen additions and elevated CO<sub>2</sub> levels. Explicit modeling of these carbon flows as a function of plant nutrient status as well as modeling major carbon fluxes as a function of soil depth could improve models' ability to simulate changes in soil carbon stocks in response to global change. We outline the evidence that supports the explicit inclusion of these processes in terrestrial ecosystem models and describe the progress that has been made in developing models that do so. We conclude by discussing the current understanding of the controls on soil carbon turnover as well as identify research priorities to increase the utility of ecosystem models as predictive tools to improve our understanding of the effects of global change on ecosystem carbon pools.

Belyazid, S., Jönsson Belyazid, U., Akselsson, C., Gundersen, P., in preparation. **Uncertain future of carbon storage in Swedish forest soils.**

While Swedish forests hold the potential of being strong carbon sinks, they remain nonetheless huge potential sources if net respiration exceeds sequestrations. To investigate if Swedish forest soils will be sinks or sources of carbon by the end of the current century, the integrated forest ecosystem model ForSAFE was used to simulate the response of forest covers and soil carbon pools at 640 sites in Sweden. The simulations showed that while extremely elevated nitrogen loads could possibly increase the sequestration of carbon in forest soils, this effect is likely to be cancelled by future climatic changes particularly if involving summer droughts.

Lazdiņš, A. and Čugunovs, M., 2014. **Utilisation of Yasso model in projection of forestry and agricultural emissions - literature review.** Report from Latvia State Forest Research Institute "Silava", 39 pp.

The scope of the study is to evaluate possibilities to use dynamic soil carbon stock change models Yasso and Yasso07 in the greenhouse gas (GHG) accounting in Latvia in forest land, cropland and grassland. The evaluation was done on the base of the GHG inventory and literature review. Latvia is one of few European countries, where land use, land use change and forestry sector plays important role in GHG balance in Latvia. The soil carbon pool is one of the most significant and at the same time – less investigated component of the GHG accounting. In spite of the requirement to use higher tier method for key sources of emissions, Latvia is still using default emission's factors for organic soils. According to the study results Yasso07 model can be used in Latvia to account carbon stock changes in soil in forest land, cropland and grassland; however the most beneficial is use of the model in cropland and grassland, where proportion of organic soils is small and the model can cover more than 90 % of these land use categories. Comprehensive study on elaboration and validation of the necessary calculation parameters should be implemented before broader use of the model, because earlier applications of Yasso on agricultural lands no always resulted with success. Yasso can be applied also to dry and drained mineral soils in forest lands to estimate carbon stock changes in soil and dead biomass. However, there is urgent need to elaborate methodology for estimation of carbon stock changes and non-CO<sub>2</sub> emissions in drained and naturally wet organic soils. Implementation of modelling approach requires periodic field measurement information, which can be used for quality control purposes as well as to improve calculation parameters. Field measurement data can be obtained in permanent monitoring plots in forest land, grassland and cropland, which can be established on the base of existing monitoring systems.

DEPARTMENT OF GEOSCIENCES AND  
NATURAL RESOURCE MANAGEMENT  
UNIVERSITY OF COPENHAGEN

ROLIGHEDSVEJ 23  
DK-1958 FREDERIKSBERG C

TLF. +45 3533 1500  
[WWW.IGN.KU.DK](http://WWW.IGN.KU.DK)