Lars Vesterdal, September 2014

Soil carbon stocks in Suserup Forest

Introduction

In contrast to managed forests, the biomass in form of wood is left on site to decay in unmanaged forests. As a consequence of this, the carbon input to soils is substantially higher than in managed forests in which most of the aboveground biomass is removed from the site.

Unmanaged forests are extremely rare in Europe, but the few remaining reserves may serve to support case studies of baseline C stocks for different forest ecosystems and inform us on the influence of forest management on C stocks of the forest ecosystem. Protection of important habitat for forest-related biodiversity, e.g. dead wood, is often among the main aims for establishment of forest reserves. However, establishment of forest reserves may affect provisioning of several other ecosystem services, e.g. carbon sequestration. The influence of non-intervention forests should consequently be studied to identify possible trade-offs between increased habitat for biodiversity and other ecosystem services. Furthermore, data from unmanaged forest sites will be valuable for testing ecosystem models simulating effects of biomass export from forests.

The significance of unmanaged forests for sequestration of CO_2 is currently being debated. The high biomasss, large amounts of dead wood and high carbon stock in soils in some non-intervention forests (Mund & Schulze, 2006; Vesterdal & Christensen, 2007) have led to suggestions that non-intervention forests will serve as efficient sinks for atmospheric CO_2 (Knohl et al., 2003; Thomsen, 2011). However, large *stocks* of C are often interpreted as a sign of high rates of C *sequestration*, and it is ignored that managed forests do not only contribute to C sequestration on site but also substitute fossil fuels (Eriksson et al. 2007; Lippke et al. 2011). It is difficult to study the role of unmanaged forests as only few forests in Europe have sufficient continutity as unmanaged forests to expect steady state conditions to occur. A study of so-called old-growth forests" at the global level suggested that such forests also sequester C in spite of being several centuries old (Luyssaert et al., 2008). However, it could be questioned whether these forest sites were suitable to represent conditions of unmanaged forests with long continuity. Suserup Forest has been only very slightly affected by human intervention during the last 200 years and is more developed in terms of steady state conditions than many other European forest reserves as evidenced by the large amount of dead wood (Vesterdal & Christensen, 2007).

Previous inventories of Suserup Forest in 1992 and 2002 included only representative assessments of carbon in biomass and dead wood. The soil carbon stock was assessed only in a few soil profiles within the part of the forest with the longest continuity as forest reserve (Vesterdal and Christensen 2007). The aim of this subproject was to assess soil carbon pools in a representative manner within the forest reserve with particular focus on the two areas of the forest differing in time since abandonment of management including grazing.

Materials and methods

Soils were sampled using a strategic sampling approach. Sampling points within areas A and B were selected in the center of every second column within the 50x50 km grid of the forest (Fig. 1). This strategy resulted in 22 plots sampled within part A (longest continuity of non-intervention, dominated by beech and ash) and 11 plots sampled within the smaller area B (grazing within the forest until <100 years ago, dominated by oak and ash). We only sampled the upland parts of the forest and excluded the wet riparian parts close to the lake (area C).

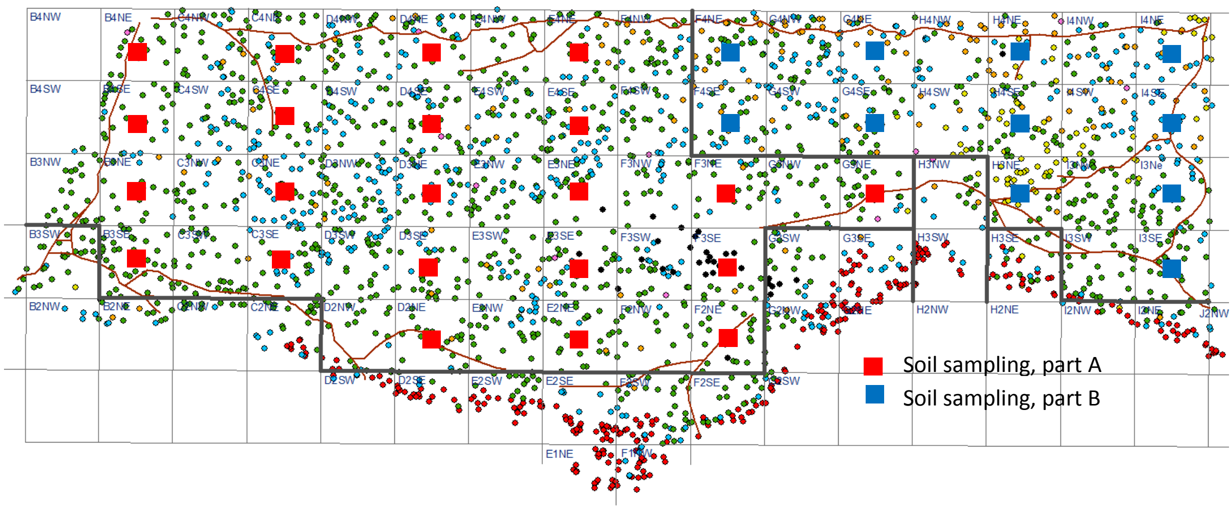

***Fig. 1**. Soil sampling design based on 50x50 m grid and distribution of sample points to areas A (long continuity of forest reserve) and B (heavy grazing until 1792).*

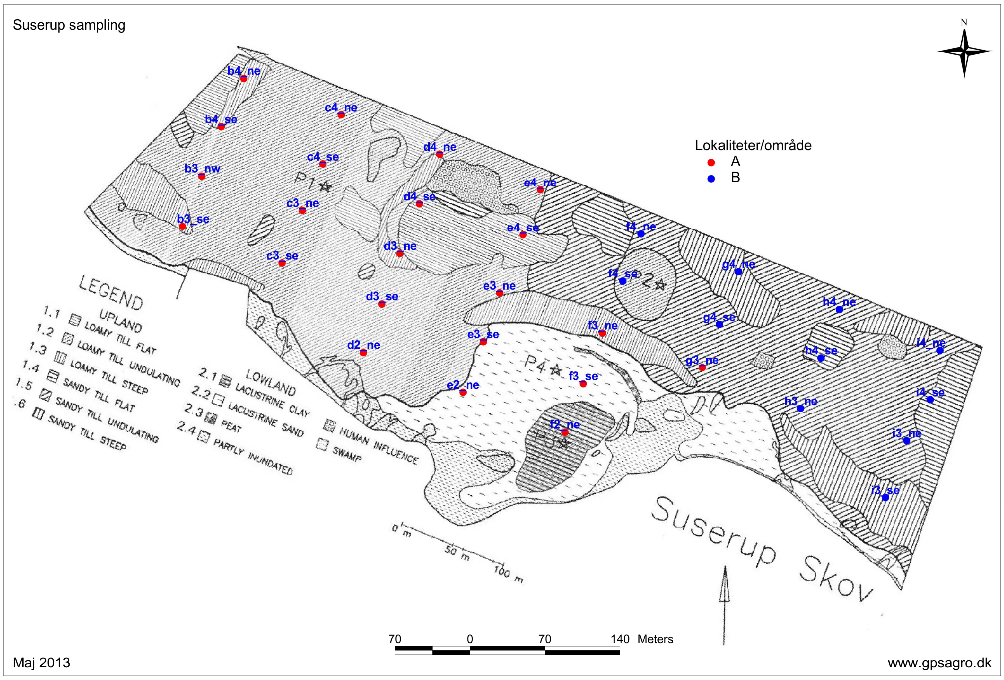

***Fig. 2.** Soil sampling design by parent materials and topography. Map from Vejre and Emborg (1996).*

Soils were sampled in late May 2013 in a circular plot (r=2 m) with four samples from the cardinal points (N, S, E, W) and one sample from the center of the plot. Forest floors were sampled on an area basis using a frame of 25x25 cm (Vesterdal et al., 2008). All materials accumulated on top of the mineral soil were sampled. Mineral soils were sampled in the same spot where the forest floor had been removed by coring down to 75 cm. Soil samples were pooled in the field for the layers 0-10 cm, 10-25 cm, 25-50 cm and 50-75 cm.

Fig. 3*. Example of plot design (plot D3_NE). View from east to west, May 2013.*

Fig. 4. *Forest floor sampling and sampling of mineral soil layers (0-10, 10-25, 25-50, 50-75 cm).*

Bulk density and stone content of mineral soils were assessed in selected plots by digging of mini soil profiles and use of bulk density rings (100 cm^3) in the layers 0-10, 10-25 and 25-50 cm. Four plots were selected in area A (B4_se, C3_ne, D4_ne, E3_ne) and area B (F4_ne, G4_se, h4_se, I3_ne) for mini profiles. Bulk density in the layer 50-75 cm was estimated by use of a Danish pedotransfer function based on carbon concentration and soil type (Vejre et al., 2003).

In the laboratory, forest floors were dried at 55 °C and weighed. A subsample was dried at 105°C to correct for moisture content. The material was subsequently finely ground by a ball mill following a cutting mill (Retsch SM2000 and Retsch MM2, Retsch, Germany). The mineral soil was sieved (2mm) and this fine fraction was finely ground by an electrical mortar (Retsch RM100, Retsch, Germany). We tested the presence of inorganic carbon in the deepest soil samples (25-50 cm and 50-75 cm) by addition of 1 M HCl. If effervescence was observed and/or pH was ≥6 (14% of all samples), carbonate removal prior total C analysis was performed by adding a solution of 6% (w/v) H2SO3 to ground soil samples. Addition of H2SO3 continued until it no longer yielded a reaction and samples were thereafter allowed to dry (Skjemstad & Baldock, 2006). Total organic C and N concentrations were determined on oven dried (60 °C) ground samples by dry combustion, based on the Dumas method (Matejovic, 1993) using a FLASH 2000 EA NC Analyzer (Thermo Fisher Scientific, Waltham, MA, USA).

Forest floor C and N content was calculated by multiplying C and N concentrations with forest floor mass. The forest floor mass was calculated based on dry weight (105 °C). The bulk density calculation for any mineral soil layer (i) was done according to:

$$\rho_i = (W{<}2mm_i) / (Vol_{auger} - Vol_{>2\,mm} - Vol_{roots})$$

Where δ_i denotes the bulk density in g cm^{-3}, $W{<}2mm_i$ is the dry weight of the fine fraction in grams and Vol_{auger}, $Vol_{>2\,mm}$, Vol_{roots}, correspond to the volumes (cm^3) of the auger section, the coarse fraction and roots,

$$SOC_i\ (Mg\ ha^{-1}) = BD_i\ (1- (1/100\ \rho_{i,\ 2mm}))\ d_i\ \ C_i$$

where BD_i is the bulk density of the layer in g cm^{-3}, $\rho_{i,2mm}$ is the relative volume of the coarse fraction (%) including stones and roots, d_i is the soil layer depth in cm and C_i is the carbon concentration in mg g^{-1}. Carbon content in the coarse fraction (> 2 mm) was neglected.

Results and Discussion

Forest floor C stocks were very similar within the two parts of the forest, and the C stock averaged ca. 7 Mg ha^{-1} (Table 1). Forest floor N stocks were slightly higher in part B and C/N ratios were correspondingly lower. Mineral soil C stocks were relatively similar within the four sampled layers but there was a trend for lower C stock in Part B in the three layers within 0-50 cm. Nitrogen stocks were very similar in mineral soil layers of parts A and B, but C/N ratios were lower in part B in 0-10, 25-50 and 0-75 cm layers.

Table 1. *Carbon and nitrogen stocks as well as C/N ratios (mean values and SEM in brackets) in forest floors and mineral soil layers in parts A and B and the entire sampled area of Suserup Forest.*

	Forest area	Forest floor	0-10 cm	10-25 cm	25-50 cm	50-75 cm
Carbon, Mg ha^{-1}	A	6.9 (0.9)	32.4 (1.1)	36.8 (1.7)	39.9 (2.5)	17.9 (1.1)
	B	7.1 (0.7)	29.6 (1.5)	33.8 (2.5)	34.1 (3.0)	19.9 (2.8)
	Total forest	6.9 (0.6)	31.5 (0.5)	35.8 (1.4)	38.0 (2.0)	18.5 (1.2)
Nitrogen, kg ha^{-1}	A	150 (17)	2322 (71)	1896 (81)	1123 (58)	578 (32)
	B	190 (19)	2205 (100)	1736 (124)	1122 (85)	695 (109)
	Total forest	164 (13)	2283 (58)	1843 (68)	1123 (47)	617 (42)
C/N ratio	A	45.1 (1.3)	14.0 (0.3)	12.9 (0.2)	14.4 (0.7)	12.5 (0.4)
	B	37.5 (1.3)	13.4 (0.2)	13.0 (0.3)	12.1 (0.3)	11.9 (0.9)
	Total forest	42.5 (1.3)	13.8 (0.2)	12.9 (0.2)	13.6 (0.5)	12.3 (0.4)

Soil carbon stocks in the entire sampled soil profile were slightly higher in part A (134±5 Mg ha^{-1}) than in part B (125±7 Mg ha^{-1}), but the difference was not significant (P=0.29, Fig. 5). There was no difference (P=0.67) in total soil N stocks in part A (6.1±0.2 Mg ha^{-1}) and part B (6.0±0.3 Mg ha^{-1}) but C/N ratios differed significantly (P=0.05) with lower C/N ratio in the entire soil profile in part B (Fig. 6).

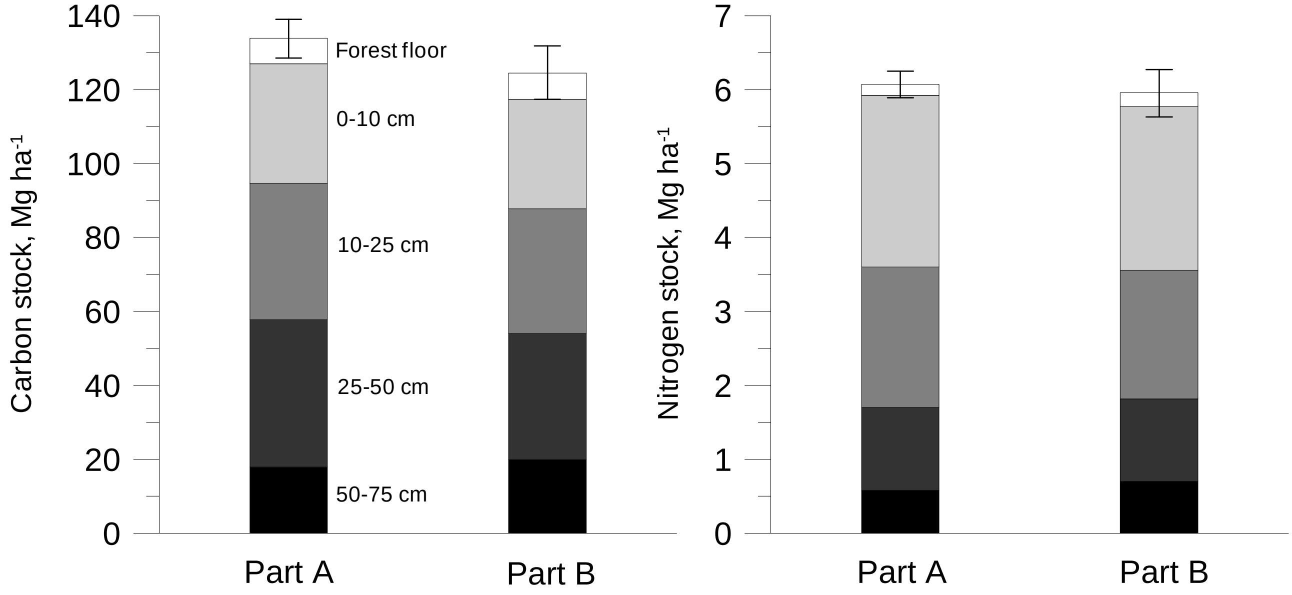

Fig. 5*.Total soil C and N stocks and the contribution of individual soil layers in parts A (22 plots) and B (11 plots) of Suserup Forest. Bars indicate SEM.*

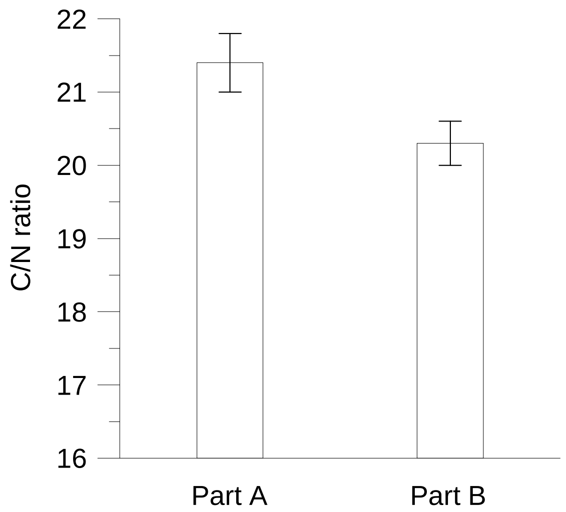

Fig. 6*. C/N ratios of the entire soil profile in parts A and B of Suserup Forest.*

The results generally confirmed the high soil C stocks in Suserup Forest as suggested from the study by Vesterdal & Christensen (2007) based on a few soil profiles in part A of the forest. Vejre et al. (2003) reported only 88 Mg C ha^{-1} to 1 m in comparable managed forests on for the dominant soil type of Suserup Forest (Alfisols). This value is by far lower than the 130 Mg ha^{-1} estimated for forest floors and mineral soil to only 75 cm in this study. Vesterdal & Christensen (2007) reported a mean C stock in forest floor of 4.5 Mg C ha^{-1} and 137 Mg C ha^{-1} in the entire soil profile to 1 m, whereas the estimated C stock to 75 cm was only about 115 Mg C ha^{-1}. The current representative sampling of soils in Suserup Forest therefore provide evidence of higher soil C stocks for both parts of the forest than suggested by previous studies. We hypothesize that the high input of organic matter to soils because of no or limited harvesting has been a main factor contributing to maintenance of high soil C stocks in Suserup Forest. There is limited evidence for higher SOC stocks in unmanaged compared to managed forests in Europe. In 130 inventory plots in Germany there was no effect of management system on SOC pools, i.e. no legacy effect of past and present management (Wäldchen et al., 2013). In the US, Hoover et al. (2012) found more forest floor C in North American old-growth stands, but no difference in mineral soil C stocks, and in German unmanaged forests Grüneberg et al. (2013) reported more forest floor C and more particulate organic matter in mineral soil which represent forms of C that are most labile to disturbances.

The results for the two parts of the forest indicated that soil C stocks were slightly lower in part B which was grazed until 1792 followed by seeding of oak (Emborg et al., 1996), i.e. subject to a more recent period of more open conditions (Heilmann-Clausen et al., 2007). This difference in soil C stocks might reflect lower C inputs through time to the soil in this part of the forest compared to the more undisturbed part. The C/N ratio of the forest floor as well as mineral soil differed most clearly between parts A and B. The lower C/N ratio indicating higher soil N status in part B could be attributed to the longer-term presence of grazing animals. However, a more important factor is probably that part B is dominated by tree species known to increase N status of the soil through production of foliar litter with high N status (lower C/N ratio), i.e. ash, oak and maple, while part A is dominated by beech, which is known to produce litter with lower N status (Vesterdal et al., 2008).

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