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Decay of Scots pine coarse woody debris in boreal peatland forests: Mass loss and nutrient dynamics

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1. Introduction

Organic matter accumulation occurring over thousands of years makes peatlands huge stores of soil carbon, and conversely, potentially major sources of CO_2 to the atmosphere if disturbed. Peatland use typically requires lowering of the water table, which consequently exposes the peat to aerobic decomposition. Warming and drying due to climate change may also negatively impact these carbon stores by increasing the rate of peat decomposition (Gorham, 1991; Dise, 2009). To improve their wood production capacity, peatlands have been extensively drained especially in northern Europe, where they cover large areas and are thus an important resource (Paavilainen and Päivänen, 1995; Päivänen and Hånell, 2012). According to Ojanen et al. (2013), forestry-drained boreal peatlands are currently cooling the climate as overall sinks of carbon: Both the growing tree stand and soil are sinks of carbon in nutrient-poor sites, while the fast growth of trees and consequent carbon storage offset the losses from soil in fertile sites. Although their assessment considered above- and below-ground litter production and organic matter decomposition, inputs and decay of coarse woody debris (CWD) were not, however, included due to methodological constraints. The impact of CWD on soil C and the overall GHG balance of these peatlands cannot be accurately estimated without knowing CWD decomposition rates first. In fact, we are unaware of any studies on CWD decomposition carried out in peatland forests, drained or otherwise, even though other litter types there have been quite intensively studied (e.g., Lieffers, 1988; Domisch et al., 2000; Moore et al., 2005; Laiho et al., 2004; Vávřová et al., 2009).

Mineral soil forests, conversely, have been the focal point of numerous CWD decay investigations (e.g., Krankina et al., 1999; Harmon et al., 2000; Mäkinen et al., 2006). The input of CWD is essential to carbon storage and cycling in forests (Harmon et al., 1986; Krankina et al., 1999; Laiho and Prescott, 1999; Ganjegunte et al., 2004). Its precise role in organic matter accumulation, and in relation to other aboveground litter types, is contingent upon forest type, successional stage, disturbance type and intensity, and management regime (Krankina et al., 2002; Laiho and Prescott, 2004). For instance, in Rocky Mountain coniferous forests, 17% of accumulating C could be attributed to CWD on a lodgepole pine (*Pinus contorta* Dougl. ex Loud.) site and 30% on a subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) site (Laiho and Prescott, 1999). In terms of hydrology and nutrition, peatland forests are inherently different from upland (mineral soil) forests (Westman and Laiho, 2003; Päivänen and Hånell, 2012), which is likely to affect the patterns and dynamics of decomposition, carbon and nutrient cycling within. Thus, the patterns and dynamics of CWD decay are not necessarily transferable from mineral to peat soils.

Although the input of coarse woody debris (CWD) as litter in forests may be large, it is nutritionally poorer than most other forest litter types and typically a small contributor to ecosystem-level nutrient cycling (Laiho and Prescott, 2004). However, its importance to forest productivity should not be judged simply based on that. As Brais et al., (2006) pointed out in Canadian eastern boreal forest, CWD dynamics within the context of stand-replacing natural disturbances (e.g., insect outbreaks, fires), which leave substantial amounts of fresh CWD behind, as well as the timing of nutrient release relative to regenerating-stand requirements also need to be considered. In such forest, they demonstrated that N and P release through CWD decay can at times account for notable proportions of the N and P bound in the biomass of the post-disturbance stand. However, it must be noted that in boreal forests of Nordic countries as in Finland, large and sudden CWD inputs as these are uncommon in part due to intensive forest management practices and a dense forest road network. Although large-scale storm damage may occur, fallen stems would not be left to decay but instead salvage harvested in forests managed for wood production, which represent 91% of the forest land area in Finland (Ylitalo and Ihalainen, 2013). Hence, it is necessary to approach the question from a different angle: Can deliberate retention of large pieces of CWD (i.e., logs) make a difference in forest nutrition and nutrient conservation in the post-harvest stand?

Nutrient imbalance is a challenge to tree growth on forestry-drained peatlands, where P and K are commonly growth-limiting (Päivänen and Hånell, 2012). Although soil nutrient pools may satisfy the demands of the first post-drainage tree crop (Westman and Laiho, 2003), this may not be the case for the subsequent stand developing after regeneration felling. Clearcutting upsets carbon and nutrient cycling processes, which has repercussions for site productivity (Nieminen et al., 2017; Sarkkola et al., 2016) as well as downstream water ecosystems (Nieminen, 2003, 2004) due to

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increased leaching of nutrients. However, significant accumulation of nutrients into CWD could reduce the loss of nutrients from the ecosystem and thus partially remedy these problems.

On account of slow rates of nutrient release (i.e., decrease in the total content of nutrients in decaying CWD), often being even slower than CWD mass loss, several studies have emphasized the role of CWD as a long-term nutrient pool and source (Ganjegunte et al., 2004; Palviainen et al., 2008; Shortle et al., 2012; Johnson et al., 2014). The release patterns depend on the nutrient in question, however, and data are still rather sparse, as due to methodological reasons, concentrations (mass unit of nutrient per mass unit of CWD) have been quantified more often than contents (total mass of nutrient in defined piece of CWD), which hampers reliable estimation of the release dynamics (e.g., Laiho and Prescott, 2004). Net release of base cations, especially K, may begin relatively early, but generally the release patterns of most elements studied have shown considerable variability (Laiho and Prescott, 2004). In addition to release, also retention (unchanged nutrient contents) and accumulation (increased nutrient contents) have been observed. Accumulation of N or P, especially, into CWD during decomposition has often been observed and attributed to their limited availability on site (Laiho and Prescott, 1999). Wood-decaying fungi are known to hoard N and P from the soil and forest floor into CWD, as well as translocate N and P from older to newer, fresh carbon sources through their vast network of mycelial cords (Wells and Boddy, 1990, 1995; Clinton et al., 2009; Boberg et al., 2014). Currently, however, there are no data from peatland forests, whose soil nutrient pools differ greatly from those in mineral soils (e.g., Westman and Laiho, 2003).

To assess the role of CWD in carbon and nutrient cycling of boreal forestry-drained peatlands, we investigated the decomposition of Scots pine (*Pinus sylvestris* L.) logs incubated in three climatically and nutritionally different sites in the European boreal zone for 10–15 years. Scots pine predominates in these drained peatland forests and was therefore the species of choice. Log nutrient dynamics during decomposition were studied at our primary experimental site (south boreal) which included both control (i.e., forested) and clearcut treatments. Since we were interested namely in the longer-term (10–15 years) nutrient dynamics of CWD and its potential significance in the nutrient management of drained peatland forests after harvesting, we focused on the nutrient dynamics of the wood component, which, unlike pine bark, is generally known to decay slowly and accumulate N and/or P (e.g., Krankina et al., 1999). In addition to N, P, and base cations, we present results on less commonly reported elements in CWD decomposition studies, e.g., Fe, Al, as they may affect the fluxes of other nutrients (Nieminen and Jarva, 1996) and provide insight into decomposer fungi activity (Ostrofsky et al., 1997). Our aims were to (i) determine log decay rates (i.e., mass loss as a function of time) and assess whether or not they differ between sites and between control–clearcut treatments; (ii) identify trends in nutrient dynamics (i.e., total nutrient contents in the logs as a function of time) in wood during decay with and without forest canopy. Our investigation was based on repeated measurements of logs approximately 2 m long, and introduces a novel methodology for CWD decomposition experiments.

2. Material and methods

2.1. Experimental design

Our sites for studying CWD decomposition were the same as those used by Vávřová et al. (2009) for studying the decay of fine woody debris (FWD) (clearcut not included in their study). The sites are located in the following subzones of the boreal vegetation zone: north boreal (NB) (Rovaniemi, Finland), south boreal (SB) (Padasjoki, Finland), and hemiboreal (HB) (Väätsa, Estonia) (Table 1).

Initially a treed minerotrophic mire drained in 1933, the north boreal site has developed into *Vaccinium myrtillus* type of drained peatland forest (Vasander and Laine, 2008). The trees composing the stand originated prior to drainage. Over the study period (2001–2011) at NB, both temperature and rainfall exceeded thirty-year averages (1981–2010) (Table 1). The south boreal site was once a treed mire with an ombrotrophic center and minerotrophic lagg, which have since transformed after drainage in 1915 into dwarf shrub type and *Vaccinium vitis-idaea* type, respectively. The stand became established after seed tree cutting and is the second forest generation post drainage, i.e., the trees in the stand have only grown in drained conditions. Both the forested control and clearcut treatments spanned both site types. During the study period (2000–2015) at SB, mean annual temperature and precipitation were higher than thirty-year averages (Table 1). Previously a rich fen drained in 1959, the hemiboreal site was ploughed and planted with Scots pine in 1961. It has since developed into an herb-rich type (Vasander and Laine, 2008) of drained peatland forest. Weather data for the entire study period (2002–2015) at HB were not available, but thirty-year averages indicated that it had the warmest and wettest climate of the three sites (Table 1). The surface peat (20 cm layer) concentration (mg g^{-1}) of N at the sites increased in the order of south boreal (13.9–16.9), north boreal (24.6), and hemiboreal (33.7), while that of P south boreal (0.67–0.77), hemiboreal (0.86), and north boreal (1.72) (Vávřová et al., 2009). C:N ratios in the peat increased as

Table 1
Characteristics of the study sites.

Site	Coordinates	Site type[a]	Drainage year(s)[b]	Peat depth (cm)	Stand volume[c] (m^3 ha^{-1})	T air, 1981–2010, (°C) mean annual	Precipitation, 1981–2010, (mm) mean annual	T air, study period[d], (°C) mean annual	Precipitation, study period[d], (mm) mean annual
North boreal	66 °21′N, 26 °37′E	MT	1933, –50, –85	30–90	139	0.5[e]	562[e]	1.1[e]	603[e]
South boreal	61 °22′N, 25 °07′E	DsT/VT	1915, –33, –54	300/100	165/209	4.1[e]	583[e]	4.6[e]	617[e]
Hemiboreal	58 °59′N, 25 °27′E	HrT	1959	235–300	187	5.6[f]	755[f]	N/A	N/A

T, temperature.
[a] HrT: herb-rich type; MT: *Vaccinium myrtillus* type; VT: *Vaccinium vitis-idaea* type; DsT: dwarf shrub type (see Vasander and Laine, 2008).
[b] Includes initial and successive maintenance operations.
[c] As of 2009.
[d] Study period according to site: North boreal, 2001–2011; South boreal, 2000–2015; Hemiboreal, 2002–2015. Weather data for study period not available at hemiboreal site.
[e] Calculated from weather data of the Finnish Meteorological Institute according to Venäläinen et al., 2005.
[f] According to Estonian Weather Service (2016) data from Türi weather station.