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Review

Influence of different tree-harvesting intensities on forest soil carbon stocks in boreal and northern temperate forest ecosystems

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A B S T R A C T

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 governance measures in relation to management effects, including harvesting effects, on soil organic carbon (SOC) stocks. This paper reviews the findings in the scientific literature concerning the effects 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. An 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. The currently available information does not support firm conclusions about the long-term impact of intensified forest harvesting on SOC stocks in boreal and northern temperate forest ecosystems, which is in any case species-, site- and practice-specific. Properly conducted long-term experiments are therefore necessary to enable us to clarify the relative importance of different harvesting practices on the SOC stores, the key processes involved, 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 and other governance measures might be bridged by expert opinions given to authorities and certification bodies.

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1. Introduction

There are many carbon (C) pools in forest ecosystems, and recent discussion on the C neutrality of forest harvesting (e.g. Schulze et al., 2012; Bright et al., 2012; Holtsmark, 2013) has mainly focussed on the more easily quantified and often well-documented above-ground tree biomass. However, a large part of the total C stock in boreal and northern temperate forest ecosystems is found belowground, both in soil organic matter (SOM) and living biomass, and this needs to be considered in any discussion of the effects of forest harvesting on C sequestration in forest ecosystems. In particular, the soil contains a large reservoir of older C, which has a slow build-up from input through photosynthesis, a long turnover time, and the potential to be stored for a long time. Forest management influences a number of the factors affecting SOM turnover, such as the chemical quality of the C compounds (labile or stable), site conditions (temperature and precipitation), and soil properties (moisture, pH, nutrient status) (Jandl et al., 2007). Release of soil organic C (SOC) to the atmosphere may change as a result of soil disturbance, including that resulting from forest operations. It is therefore important that this C stock be protected, and that forest governance should take this into account.

Processes leading to changes in the C stocks are here termed C fluxes. The C balance of a managed forest ecosystem at any given time is determined by the difference between the input flux (net primary productivity, which is given by the difference between photosynthesis and autotrophic respiration) and output fluxes (heterotrophic respiration and leaching) together with biomass removals by harvest. Litter input, both aboveground and belowground, and thinning and final felling harvest residues transfer C between biomass stocks and soil C stocks, while decomposition and mineralisation (heterotrophic respiration) as well as leaching of dissolved organic carbon (DOC) decrease the soil C stock (Jandl et al., 2007).

Forest harvesting has several potential effects relevant to SOC stocks and fluxes, including:

- Biomass removals by harvest remove C (woody litter, logs etc.) that in the long term would otherwise contribute to SOC formation during decomposition (Covington, 1981).
- A decrease in litter inputs reduces the heterotrophic respiration (Kowalski et al., 2004), whereas root death following thinning or harvest could lead to an increase in heterotrophic respiration (Powers et al., 2005).
- Biomass removal may also stimulate a vigorous ground flora (Fahey et al., 1991) and/or support a fast development of a new aggrading stand (Fleming et al., 2006) that together may increase litter C input compared to pre-harvest.
- High nutrient removals in harvested biomass could increase the risk for reduced productivity after thinning (Helmisaari et al., 2011) or final harvesting (Walmsley et al., 2009).
- Harvest could increase the soil temperature, and this might lead to increased decomposition and hence increased C release from the soil by heterotrophic respiration (Covington, 1981), as well as increased leaching of DOC (Nieminen, 2004). Increases in both output fluxes would depend on sufficient precipitation and soil moisture.
- Soil water status can change following harvest due to decreased evapotranspiration. This could either increase leaching by runoff water (Nieminen, 2004; Laudon et al., 2009) or inhibit decomposition by unfavourably high moisture conditions (Prescott et al., 2000); however, a higher water table could either promote or reduce decomposition, depending on previous soil moisture content.
- Soil mixing caused by harvesting machines (or during stump removal) might increase decomposition of soil organic matter (Jandl et al., 2007) or soil compaction might decrease decomposition rates (Prescott et al., 2000) and affect productivity (Powers et al., 2005).

Many of these processes will be occurring at the same time in the period shortly after harvesting (Schmidt et al., 1996). It is clear that many effects will be site-specific, and that they may change with time. Differences or changes in harvesting technologies will also affect the outcome (Yanai et al., 2003). Thus, observed changes in C stocks and fluxes will vary from one site to another, depending on the relative strengths of these effects. Since SOC stocks are determined by the balance between C inputs from productivity and the loss by decomposition, mineralisation and leaching at the rotation scale (Jandl et al., 2007), higher forest growth through management and lower decomposition due to less favourable temperature and moisture regimes for microorganisms in more densely stocked managed stands (Vesterdal et al., 1995) may modify the sink-source relationship and to some extent make up for the harvest losses.

Sustainability of forest management including harvesting is safeguarded by management guidelines, certification systems, and in some cases legislation (e.g. the European Union's directive on the use of energy from renewable sources, European Parliament and Council, 2009). Harvesting effects on SOC have until recently not often been explicitly included in management guidelines or Programme for the Endorsement of Forest Certification (PEFC) or Forest Stewardship Council (FSC) certification systems, although some more recent certification systems do include maintenance of forest C sinks (Stupak et al., 2011). Additionally, guidelines dealing with e.g. soil damage by forest machinery and minimisation of erosion will often support protection of SOC.

This paper will briefly summarise the findings in the scientific literature concerning the effect of harvesting of different intensities on SOC stocks and fluxes in boreal and northern temperate forests, to evaluate the evidence for significant additional losses with increasing biomass removal. A brief overview of existing governance measures related to SOC is also given, followed by a discussion on how scientific findings could be incorporated in guidelines and other governance measures.

2. The scientific basis

2.1. Determination of C stock changes

To quantify potentially small changes in SOC stocks after harvesting, precise determination of SOC is needed. Unfortunately, the large spatial variability in SOC stocks makes detection of significant changes difficult and requires the collection of a large number of samples to obtain a representative result. Factors influencing the spatial distribution of SOC include soil type and texture, geological substrate, climate (temperature, precipitation and moisture content), altitude, slope, past and present land use, and management practices (Doblas-Miranda et al., 2013). Apart from SOC concentrations, bulk density, stone content, and soil depth all have to be determined, and all of these vary greatly (Schrumpf et al., 2011). Care has to be taken not to compress the sample during sampling; this is especially important for bulk density determination. Pedotransfer functions to estimate bulk density should be used with caution, as the errors involved may be considerable (Schrumpf et al., 2011). In many studies, the organic layer is considered separately from the mineral soil; however, separation

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