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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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ABSTRACT

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.

Contents

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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 of these during sampling is not always easy, and different field personnel may make different judgements. Harvesting operations might further increase the variability in SOC due to soil disturbances by harvesting machines and due to uneven distribution of the residues.

2.2. Stem-only harvesting

After stem-only harvesting (SOH), the soil may receive an additional input of organic matter in harvest residues, including branches, twigs, needles, and leaves, and also from dead roots. The input of harvest residues after clear cutting might explain the temporary increase in the C content of the soil that has been observed in a period of up to two decades after harvesting (Hendrickson et al., 1989; Johnson and Curtis, 2001). The soil is also exposed to more light (affecting ground vegetation and thus litter input), higher moisture content, and greater fluctuations in temperature following SOH (Jónsson and Sigurdsson, 2010), all of which can influence decomposition of both harvest residues and older SOM. Decomposition of large amounts of easily decomposed needles and leaves will typically lead to increased soil respiration linked to a pulse of increased CO_2 release. At the same time, harvest results in a reduction in autotrophic respiration after the roots die (Kowalski et al., 2004). Other greenhouse gases, such as methane (CH_4), can also respond to SOH. While upland forests generally consume CH_4 from the atmosphere at low rates, it was recently shown that they can become minor sources of CH_4 after SOH (Sundqvist et al., 2014), probably because of elevated groundwater levels after harvest. Clear-cutting on sites dominated by Norway spruce (*Picea abies*) has been shown to cause increased export of DOC (Nieminen, 2004; Laudon et al., 2009), due to both increased DOC concentrations and increased water fluxes after harvesting (Sørensen et al., 2009).

A meta-analysis of harvesting effects in temperate forests by Nave et al. (2010) found that forest floor C storage declined by 30 ± 6% after harvesting, whereas the mineral horizons showed no significant overall change. Variation in harvesting effects on mineral soil C stock was best explained by soil type; for example, alfisols and spodosols showed no significant changes in mineral soil C, while this was lost in inceptisols and ultisols. Tree species was also an important factor: losses in forest floor C were significantly smaller in coniferous/mixed stands (−20%) than in hardwoods (−36%) (Nave et al., 2010). Sandy soils may be sensitive to harvesting effects because organic matter in sandy soils is poorly protected (Carlyle, 1993). A recent study in Sweden, making use of the National Forest Inventory, found a mean reduction of 16.5% in the organic layer C content during the first 32–50 years following harvest in different forest types (Georgiadis, 2011). The reduction in SOC stock might be attributed to reduced litter C input together with increased decomposition of organic matter due to higher soil temperatures when the soil surface becomes exposed to the sun.

The reduction in SOC stock after harvesting observed in the organic layer has previously been believed to be quite large, up to 50% in the first 15–20 years (Covington, 1981; Federer, 1984). Especially the chronosequence study by Covington (1981) has led to the paradigm of a significant SOC loss after harvest. However, resampling of the chronosequence study two decades later did not reveal major losses of organic layer C (Yanai et al., 2003). Factors such as mechanical mixing of the organic layer with the mineral soil during harvesting and replanting have been suggested as explanation for this apparent reduction in the organic layer C stock (Federer, 1984; Ryan et al., 1992; Yanai et al., 2000, 2003). Huntington and Ryan (1990) and Johnson et al. (1991) observed mixing of material from the organic horizon with the mineral soil after harvesting in broadleaf forest in New Hampshire, while the total SOC content remained unchanged. These results emphasise the need to address the whole soil profile in field studies of harvesting effects on SOC stocks.

In two Swedish Norway spruce stands, total soil (i.e. organic + mineral soil) C stock was reduced by 17–22% 15–16 years after harvesting (Olsson et al., 1996). The effect was different in the organic layer compared with the mineral soil: the entire reduction was observed in the organic layer, while the C stock of the mineral soil in some cases increased. In a Scots pine (*Pinus sylvestris*) stand in southern Sweden no change was observed in the total soil C stock, while in a northern Scots pine stand the soil C stock was reduced by 7% (Olsson et al., 1996). Pennock and van Kessel (1997) found that organic C in the upper 45 cm in a *Populus tremuloides*/*Picea glauca* forest in Saskatchewan increased by 8% 1–5 years after harvesting. An explanation for observed increased C content in the mineral soil might be decomposition of roots remaining in the soil after harvesting (Powers et al., 2005; Sanchez et al., 2006). Root depth distribution is likely to be an important factor here (Rosengren et al., 2005), although even a shallow-rooting species like Norway spruce will provide root litter input to the mineral soil (Leppälammi-Kujansuu et al., 2014).

The reduction in SOC content has previously been mostly linked with the labile C fraction (Carlyle, 1993), suggesting that observed differences in effects of harvesting on SOC content might in some cases be explained by differences in the stability of the soil's C fractions, with formation of more recalcitrant compounds acting to stabilise the SOC content. Recent research indicates, however, that organic matter persists not because of the intrinsic properties of the organic matter itself, but because of physicochemical and biological influences from the surrounding environment that reduce the probability and the rate of decomposition (Schmidt et al., 2011). This indicates that the persistence of SOC is not primarily a molecular property, but an ecosystem property. Thus, conflicting results from various studies might be related to site specific factors such as e.g. moisture differences. Drier sites are more prone to losses, and at sites with a growing season precipitation deficit, harvest will increase the soil moisture content and reduce the number of periods where decomposition may be limited by drought. In other cases, harvest may lead to soil moisture saturation that can inhibit decomposition of organic matter in coniferous forest (Prescott et al., 2000). In an oak forest in Wisconsin, surface litter decomposition was found to be lower after harvesting than in an unharvested area (Yin et al., 1989), possibly related to higher soil moisture after the clear-cut, and the faster decomposition which was observed by Prescott (1997) in an old-growth forest relative to a clear-cut may have been due to higher moisture in the surface layers in the old-growth forest during the summer. A study on the effect of harvest and moisture regime on decomposition found that decomposition rates after harvest were comparable to those in uncut reference stands; differences in decomposition rates were found depending on site moisture level, with initial mass loss greater at a moist site than at a moderately dry or wet site (Symonds et al., 2013).

Modelling has shown results comparable to those of some empirical studies. A modelling study with the Finnish Yasso model indicated that the soil reached a minimum level of SOC 16–22 years after harvesting, with a mean value 9% below the pre-harvest value (Peltoniemi et al., 2004). Modelling results have suggested that there could also be long-term effects following clear-cutting with a reduction in SOC amounting to 14% after two 100-year rotations compared to pre-harvesting conditions (Liski et al., 1998).

Forests are managed on the stand scale, but C budgets resulting from management might also be evaluated at the landscape scale. Modelling results have shown that harvesting effects on the aggregated C balance at landscape level may be less dramatic than for individual stands, as the landscape level includes many stands at different ages and stages of development (Eliasson et al., 2013). This is likely to be important considering the concerns that have been raised (e.g. Schulze et al., 2012) about the long-term C neutrality of forest harvesting for bioenergy.

2.3. Thinning

In pre-commercial thinning, biomass is left on-site, while in stem-only thinning (SOT) the stems are removed. In whole-tree thinning (WTT), all above-ground compartments are removed: effects of this are considered in Section 2.5 on whole-tree harvesting. Effects of thinning on SOC in boreal and northern temperate systems appear to be mixed. Vesterdal et al. (1995) found that the C stock in the organic layer of Norway spruce stands was negatively correlated with stem-only thinning intensity (83%, 67% and 50% of the basal area) as compared to the unthinned control. The difference in C stock between three different experimental sites was greater than that due to thinning intensity, which illustrates the importance of site specific factors. In a study carried out 33 years after thinning from 3190 to densities of 2070, 1100 and 820 trees per hectare, Nilsen and Strand (2008) found no significant treatment effects on organic layer and mineral soil C stock. In Quebec, the C stock in the organic horizon in a *P. tremuloides* forest increased one to two years after removal of 61% (i.e. thinning) and 100% (i.e. clear cut) of the basal area, although there was no increase when only 33% of the basal area was removed (Brais et al., 2004). The increase in organic layer C stock could have been related to increased input from abundant well-decomposed coarse woody debris shortly after harvesting. However, Hu (2000) found no significant difference in soil organic matter due to thinning intensity two to three years after removal of 25%, 45%, 65% and 100% of the basal area on three Norway spruce sites in eastern Norway, so this short-term effect is not always observed. Jurgensen et al. (2012) showed that C stocks in the surface mineral A horizon of red pine (*Pinus resinosa*) stands in Minnesota decreased in thinning regimes with 10%, 25% and 35% basal area removal, but not in stands where 50% of the basal area was removed. However, thinning had no impact on C stocks in the forest floor and combined A and B mineral horizons (30 cm depth) in both red pine and northern hardwood stands.

Thinning leads to a temporary reduction in above-ground biomass and thus to reduced annual C input with canopy litterfall. There are, however, large C inputs related to the residues left on-site in pre-commercial or stem-only thinning and belowground litter may also increase in the following years as root systems of removed trees die and decompose. Additionally, there may be changes in soil temperature and/or moisture after thinning (Aussenac, 1987; Carey et al., 1982). The size of the effect depends on the degree of thinning (Jónsson and Sigurdsson, 2010) and other factors in the experimental designs used may also have contributed to the variation in the observed results (Jurgensen et al., 2012), as well as differences in the time period between thinning and the time of sampling. In cases where thinning has little effect on SOC content, the explanation may be that the C input recovers quite rapidly following a temporary reduction and that changes in soil temperature and moisture are small (Carlyle, 1993). Furthermore, increased light penetration may stimulate ground vegetation and its litter production until canopy closure. Decomposition in the organic layer can be stimulated, at least temporarily (Jandl et al., 2007), but can also be reduced or remain unchanged (Prescott et al., 2000).

2.4. Selection cutting

Selection cutting is a harvesting method designed to create an uneven-aged or all-aged stand structure by harvesting single trees or small groups of trees. It is believed that this has ecological benefits, including increased carbon sequestration, as well as producing a more constant flow of marketable timber. It is most suitable for shade-tolerant species and has been used in some hardwood or mixed forests. Selection cutting might minimise C loss from the soil after harvesting since the impact of harvesting is spread out in time instead of being concentrated at a single point in time, and the impact in any given year may be restricted to establishment of single-tree gaps. A simulation study by Taylor et al. (2008) indicated that selective cutting, i.e. continuous cover forestry, would increase SOC stocks. In Norway, Nilsen and Strand (2013) found that the difference in organic and mineral layer SOC stocks between a selectively harvested stand and an even-aged and thinned stand established after clear-cutting in the early 1930s was 21 Mg C/ha, with the selectively cut stand having the higher SOC content; however, it was calculated that the even-aged forest had stored more C in tree biomass including roots at the time of measurement (210 Mg C/ha compared with 76 Mg C/ha in the selectively harvested stand). Modelling a pine forest using the Edinburgh Forest Model showed that a management regime where 10–20% of tree biomass was harvested annually provided a better combination of high wood yield and C storage compared with even-aged plantations with a 60 year rotation period (Thornley and Cannell, 2000). In Germany, Wäldchen et al. (2013) found no difference in SOC stocks in beech-dominated stands with different past forest management including selective cutting vs. coppicing with standards (i.e. scattered individual stems allowed to grow through several coppicing cycles).

2.5. Whole-tree harvesting

Whole-tree harvesting (WTH) or WTT lead to increased removal of branches and tops in harvest residues compared to SOH or SOT. These residues can then be used for example as a source of bioenergy. The way the harvest residues are handled may affect SOC stocks. After SOH, harvest residues may be distributed across the clear-cut area, although this is not always the case with modern forestry operations. Harvest residues may be deployed in trails where the harvesting machines drive in order to reduce their impacts on the soil (Nisbet et al., 2002). This latter approach will involve large areas with no input from harvest residues and smaller areas that receive large inputs, i.e. large spatial heterogeneity in input of C to soils. To some extent the effect is similar to WTH where the harvest residues are left in piles prior to removal. Where these residues are piled, the size of the pile could have an effect on the C and nutrient inputs to the soil in the period (commonly up to a few months) before it is removed. In a single-tree experiment with Scots pine, Smolander et al. (2013) found that increasing amounts of harvest residues were associated with increased organic matter concentration, C mineralisation, and glucose-induced respiration. In addition, not all the residues are removed during WTH; it is common that 60–80% is removed (Helmisaari et al., 2011). A number of studies have compared the effects of WTH and WTT with those of SOH and SOT, respectively, in boreal and northern temperate conditions, and long-term effects have been modelled (Table 1). In most field studies, there was either no significant difference or WTH led to a reduction in SOC, most often but not only in the organic layer, compared with SOH. Differences between effects of SOH and WTH tended to be larger in the organic layer than the mineral soil, as also pointed out by Thiffault et al. (2011) (Fig. 1). A clear trend with time since last harvesting is not apparent from our analysis when including all data in Table 1. Large spatial variability in SOC following harvest may explain why the majority of the studies reviewed (Table 1) could not reveal significant effects on SOC between harvesting methods.

Table 1
Overview of studies comparing effects on soil organic carbon of whole-tree harvesting and thinning with stem-only harvesting and thinning in boreal and north temperate conditions. Field and model studies are separated, after which studies are grouped according to the main results. SOH = stem-only harvesting, SOT = stem-only thinning, WTH = whole-tree harvesting, WTT = whole-tree thinning. AU = Austria, CA = Canada, CN = China, DK = Denmark, FI = Finland, SE = Sweden, UK = United Kingdom, US = United States. Ab = *Abies balsamea*, Bp = *Betula papyrifera*, Lg = *Larix gmelinii*, Pa = *Picea abies*, Pbl = *Populus balsamifera*, Pbn = *Pinus banksiana*, Pg = *Populus grandidentata*, Pm = *Picea mariana*, Pre = *Pinus resinosa*, Pru = *Picea rubens*, Psi = *Picea sitchensis*, Pst = *Pinus strobus*, Psy = *Pinus sylvestris*, Pt = *Populus tremuloides*.

Source	No. in Fig. 1	Country	Dominant tree species	Final harvesting (H)/thinning (T)	Years after last harvesting or thinning	Field (F)/modelling (M)	Effect on soil C
Roberts et al. (1998)		CA	Bp	H	3	F	Litter and organic layer depth reduced four years after harvest, more effect after SOH than WTH at two of three sites
Staaf and Berg (1980)		SE	Psy	H	3.5	F	Carbon content of organic horizon reduced 3.5 years after slash removal
Bélanger et al. (2003)	1	CA	Pm	H	3	F	Less C in organic layer after WTH than SOH. No significant difference in mineral soil
Saarsalmi et al. (2010)	2	FI	Psy	H	24–25	F	Organic layer C stock significantly lower 23–25 years after WTH than after SOH in a more fertile stand; no significant difference in a less fertile stand. No significant differences in the mineral soil
Vesterdal et al. (2002)	3	DK	Pa	H	25–28	F	Organic layer C content in one plantation unaffected by harvesting intensity, reduced by 35% after WTH in the other plantation
Kaarakka et al. (2014)	4	FI	Pa	T + H	10	F	Repeated WTT or WTH led to decreased total C pool in combined organic + mineral soil 10 years after final harvesting compared to SOT or SOH
Brandtberg and Olsson (2012)	5	SE	Pa, Psy	H	26–28	F	C concentration at 5–10 cm depth in mineral soil significantly lower after WTH compared with SOH 25 years after harvesting. No significant difference at other depths
Hendrickson et al. (1989)	6	CA	Pre, Pg, Pst, Pt	H	3	F	C content increased in the organic horizon after SOH and in the mineral soil after both treatments compared with an uncut area; the increase in the mineral soil was greatest after WTH
Olsson et al. (1996)	7	SE	Pa, Psy	H	14–17	F	No general effect of harvesting intensity after 15–16 years, with or without removal of needles
Symonds et al. (2013)		CA	Pm	H	0.5–4	F	Decomposition rates similar after SOH and WTH
Smolander et al. (2013)	8	FI	Psy	T	4–13	F	No significant differences in SOM, microbial biomass or C mineralisation at two sites
Thiffault et al. (2006)		CA	Ab, Pm, Pbn	H	13–23	F	No significant differences
Rosenberg and Jacobson (2004)	9	SE	Pa, Psy	T	4	F	No significant difference in soil C content after WTT and SOT
Tamminen et al. (2012)		FI	Pa, Psy	T	3–30	F	No significant differences between SOT and WTT
McLaughlin and Phillips (2006)		US	Pru, Ab	H	17	F	No reduction in total soil C content 17 years after WTH compared with before harvesting and a reference plot
Wall and Hytönen (2011)		FI	Pa	H	30	F	No significant difference between treatments 30 years after harvesting
Wall (2008)	10	FI	Pa	H	3.5	F	Significantly higher organic stocks in litter layer four growing seasons after SOH compared with WTH. Where branches removed but foliage left on-site, organic matter stock in litter layer not significantly different from WTH for areas without slash and not significantly different from SOH when expressed for total harvested area. No significant differences in the humus layer or upper mineral soil
Vanguelova et al. (2010)	11	UK	Psi	H	28	F	Significantly higher C stocks in a peaty gley soil after WTH compared to SOH
Smolander et al. (2008)	12	FI	Pa	T	5–10	F	No significant difference in SOC in the organic layer or in mass loss from litterbags after five years. Rate of C mineralisation in laboratory incubation lower 10 years after WTT compared with SOT
Smolander et al. (2010)		FI	Pa	T	11–19	F	Amount of C in microbial biomass not affected by removal of harvest residues, but lower rate of C mineralisation in laboratory incubation experiments. Effects of removal of residues greatest at two least fertile sites
Hyvönen et al. (2000)		SE	Pa, Psy	H	16	F + M	C content in organic layer 50% greater in a highly productive (10.1 $m^3 ha^{-1} yr^{-1}$) spruce forest and 100% greater in a low-productive (3.7 $m^3 ha^{-1} yr^{-1}$) pine forest 16 years after SOH relative to WTH, compared with Olsson et al. (1996)
Jiang et al. (2002)		CN	Lg	H		M	Soil carbon and litter lower after WTH than SOH
Peng et al. (2002)		CA	Pm, Pbn, Bp, Pt, Pbl	H		M	Soil C stock lower after WTH than SOH
Merganičová et al. (2005)		AU	Pa	T		M	Soil C content lower after WTT than SOT, especially when needles removed
Bengtsson and Wikström (1993)		SE	Pa	H		M	Soil C content lower after WTH than SOH, but differences small; 35–50% less C in soil after SOH compared to no biomass removal
Ågren and Hyvönen (2003)		SE	Pa, Psy	H		M	Negligible effect of SOH compared to no harvesting after 150 years; if WTH the soil C content on national scale reduced by 59 Tg after 150 years

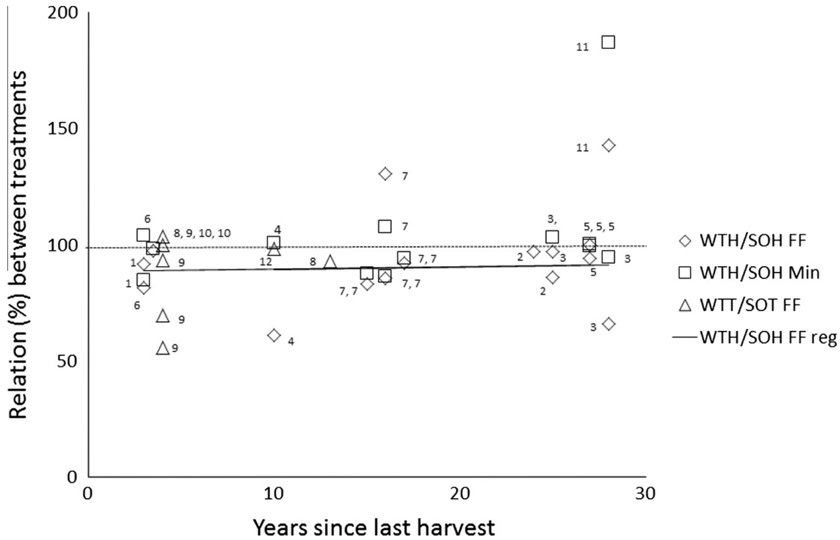

Fig. 1. Effects of harvest intensity expressed by the relative change in % of SOC with whole tree harvesting or thinning relative to stem only harvesting or thinning (SOH = stem-only harvesting, SOT = stem-only thinning, WTH = whole-tree harvesting, WTT = whole-tree thinning) in the forest floor (FF) and upper mineral soil (Min), based on field studies in Table 1. Numbers in the figure refer to the studies with the same numbers in Table 1. Only studies in which SOH and WTH stocks were directly compared and with number of years (±1) since last harvesting/thinning known were included. Note that some studies include several sites, which are shown separately where possible. Dashed line = 100%. Solid line (WTH/SOH FF reg) is a linear regression for WTH/SOH in the forest floor, omitting study No. 11 (see text for explanation).

Additionally, some studies compared post-harvest SOC stocks in WTH and SOH plots where pre-harvest SOC stocks had not been measured, leading to uncertainty with regard to the starting values.

The study by Vanguelova et al. (2010, No. 11 in Fig. 1) is unusual because SOC stocks after WTH were considerably higher than after SOH. This was explained by on-site retention of harvesting residues in SOH increasing the rate of mineralisation of existing SOC stocks resulting in a loss of SOC (Vanguelova et al., 2010). The study was also unusual because the soils were peaty gleysols, i.e. very different from the better drained mineral soils in most other studies; the results may therefore not be comparable. This supports the importance of soil type in influencing the effects of harvesting on SOC. If this study is left out of the analysis because of the different soil type, mean WTH/SOH in the forest floor was 90% (SD 16%), while a regression of WTH/SOH (%) in the forest floor against time still showed no clear time trend (Fig. 1). The analysis thus suggests that a reduction in SOC content after WTH compared with SOH may be likely, at least on mineral soils that are not waterlogged. However, a universal effect cannot be shown.

In contrast to field studies, modelling studies have consistently reported that WTH and WTT lead to a reduction in SOC content compared with SOH and SOT, respectively. The reason for this difference between field and modelling studies is not clear, but it may be that further development of the models is necessary to adequately deal with the large number of factors that can affect SOC stocks after harvesting. In addition, changes in the field may be difficult to detect due to the high spatial variability.

A meta-analysis by Johnson and Curtis (2001) summarised results from 26 studies from different parts of the world, including ecosystems that were very different from boreal or northern temperate forests but also boreal/northern temperate studies such as Hendrickson et al. (1989) and Olsson et al. (1996). After WTH, the C stock of the top mineral soil was reduced by on average 6%, while it increased after SOH with on average 18%. This increase was observed most often in coniferous stands, and was often seen in the years shortly after harvesting, presumably due to the harvesting residues being incorporated into the soil (Johnson and Curtis, 2001).

To evaluate the long-term ability of forest soils to store C after WTH, it is also necessary to consider the effect of WTH on forest growth in the next rotation. Because a large proportion of the trees' nutrients are in the branches, twigs, and needles/leaves, removal of these will reduce the supply of nutrients to the soil. This could lead to nutrient deficiencies in the long term, which in turn could lead to reduced growth in the next rotation. If growth is lower, the ability of trees to sequester C, as well as the litter input to the soil, will be reduced. Intensified biomass removal in WTH might therefore lead to reduced SOC as a result of lower biomass production (Vesterdal et al., 2002). The risk of a negative feedback mechanism via reduced net primary productivity on SOC will clearly be greater in nutrient-poor sites (Raulund-Rasmussen et al., 2008) but might be remedied by fertilisation. If only the branches are removed while the needles and leaves remain on-site, as suggested in some management guidelines (e.g. Swedish Forest Agency, 2008), the nutrient loss may be considerably less. There are a number of studies from boreal and northern temperate forests of the effect of harvesting method on growth in the next rotation. Although many studies found growth reductions after WTH or WTT compared with SOH or SOT, respectively, at least where compensatory fertilisation was not applied (Proe and Dutch, 1994; Jacobson et al., 2000; Vesterdal et al., 2002; Egnell and Valinger, 2003; Walmsley et al., 2009; Helmisaari et al., 2011; Tveite and Hanssen, 2013), universal effects on soil productivity and tree growth were not reported (Vesterdal et al., 2002; Thiffault et al., 2011; Ponder et al., 2012; Fleming et al., 2014; Hazlett et al., 2014; Morris et al., 2014). It is clear that the effect, if present, varies depending for example on tree species (Egnell and Leijon, 1999; Tveite and Hanssen, 2013), soil type (Morris et al., 2014) and thickness of the organic layer (Hazlett et al., 2014). For example, Tveite and Hanssen (2013) found that results for Scots pine stands from a long-term thinning experiment after 20 years indicated a non-significant growth loss of 5% for WTT vs. SOT while Norway spruce stands showed a significant growth loss of 11% after 25 years. Reasons for this difference might include that the branches and needles in the harvesting residues account for a greater share of the total aboveground biomass in Norway spruce than in Scots pine (Merilä et al., 2014). In some studies, the stands had not reached canopy closure at the time of study, so that treatment effects could possibly develop later (Ponder et al., 2012; Fleming et al., 2014; Morris et al., 2014).

2.6. Stump extraction

Stump extraction has in recent decades been suggested primarily as a method to limit fungal attacks to root systems, so most studies were previously carried out in this context. In addition, stump extraction is now used for providing biofuels. Complete-tree harvesting (CTH), in which residues as well as stumps were removed, is also considered here. Until recently very little work had been done on the effects of stump extraction on SOC. There is concern that large-scale disruption of forest floors might lead to release of CO_2 from increased SOM decomposition and mineralisation, as well as increased DOC leaching (Walmsley and Godbold, 2010). This would be comparable to the effects of certain types of site preparation, where a net loss of soil C may increase with degree of disturbance (Jandl et al., 2007). Indeed, in countries where site preparation is part of the planting procedure following clear cutting, it might be difficult to separate the effects of site preparation and stump removal, especially in areas where site preparation has been extensive. Strömgren and Mjöfors (2012) compared effects of stump harvesting, harrowing and patch scarification on CO_2 efflux and found that in the second year the flux was 10% higher after stump harvesting and harrowing than after patch scarification. Effects of stem and stump harvesting together with deep soil cultivation, i.e. two intensive treatments in combination, were recently studied by Egnell et al. (2015). Although soil C pools were lower following this combination of treatments, tree biomass was significantly increased, so that the total C pool was not significantly affected. Again, this is comparable to the effects of site preparation: the effect of improved biomass production after site preparation can outweigh the loss of SOC (Örlander et al., 1996). The results also show the importance of looking at changes in the total C pool (soil + biomass) to determine the effect of silvicultural practices on forest C balances (Egnell et al., 2015); however, they also illustrate a situation where biomass production is occurring at the expense of C storage in the soil pool.

The results reported in the literature on effects of stump harvesting are variable. In British Columbia, Hope (2007) found that there were no significant differences in SOC stocks in the forest floor or mineral soil with or without removal of stumps and compared with a control in either year 1 or year 10 after treatment, except that there was less C in the mineral soil 10 years after in the control. There was also a significant increase in C concentration (but not stock) in the mineral soil between years 1 and 10. Scarification after stump harvesting, on the other hand, led to a significant reduction in the C stock of the forest floor by nearly 50% (Hope, 2007). In an experiment in Finland without additional site preparation, stump harvesting had no significant effect on C stocks in either the organic layer or the 0–10 cm layer in the mineral soil after 33 years, although the organic layer was thinner after stump removal (Karlsson and Tamminen, 2013). In contrast, mineral soil C concentrations were on average 24% lower more than 20 years after stump extraction at sites in the northwest US (Zabowski et al., 2008). A reduction of CO_2 emissions due to a decrease in decomposable substrate was found in the first year after stump harvesting by Grelle et al. (2012), which was however followed by increased CO_2 emissions resulting from the extensive soil disturbance. Some of the observed variation in the results may be attributable to time since harvesting: short-term effects might be attributable to the disturbance created by stump removal, while longer-term effects might in addition be affected by reduced C inputs.

Effects of SOH, removal of stems and stumps (but not harvesting residues), and CTH were compared by Strömgren et al. (2013) at four Swedish sites 25 years after harvesting and replanting with manual patch scarification. Soil C stock was lower after CTH than after SOH, but the difference was only significant in the organic layer C stock; no effect was found in the mineral soil. Soil C stock after removal of only stems and stumps did not differ from the other two treatments, but was lower in the organic layer than after SOH (Strömgren et al., 2013). Responses to treatments as well as contrasting results between different long-term studies may be related to scarification practices which in some countries are a customary part of the planting procedure. Studies which entail scarification, without testing for scarification effects by themselves, will show combined effects of two treatments.

Kataja-aho et al. (2012) compared effects of stump harvesting at Norway spruce sites with those of a traditional site preparation method, mounding. No differences were found in organic matter stocks between treatments; however, CO_2 production was higher in the stump removal plots, which indicates a higher loss of soil C, possibly due to increased soil disturbance and/or differences in the microbial community. Increased N mineralisation was also found after stump harvesting (Kataja-aho et al., 2012), which might have implications for future tree growth (Helmisaari et al., 2014).

Effects of CTH compared with WTH and SOH have been modelled using the Q model (Hyvönen et al., 2012). The highest initial reduction in SOC was predicted after CTH, and this reduction was greater at low-productive sites than at high-productive ones. However, most although not all of the decline in SOC stock was offset by the end of the rotation period by litter production in the subsequent forest stand.

2.7. Conclusions regarding the scientific results

Experimental results indicated increasing SOC loss with increasing harvest intensity or increasing soil disturbance at some sites but little or no effect at other sites, and there is no basis for firm generalisations (Thiffault et al., 2011). Although this may to some extent be due to differences in the experimental setup, a likely site specific vulnerability to SOC loss is implied that needs to be characterized and understood. Thiffault et al. (2011) emphasised the importance of the organic layer, both as a nutrient reservoir and as a mediator against disturbance to the deeper soil layers; however, they pointed out that this does not preclude forest operations such as site preparation that affect the organic layer.

Although experimental results show variable effects of harvesting on SOC, models predict losses of SOC, though less in the long term. The reasons for the discrepancy between field studies and modelling results need to be understood. Understanding of the soil C balance implemented in the models may be lacking some inputs or processes important for SOC accumulation (Thiffault et al., 2011). Also, the difficulties involved in determining small differences in SOC stocks in the field, especially because of their large spatial variability, may play a role (Jandl et al., 2007). Altogether, this suggests a need for well-designed new experiments to improve our understanding of the processes, preferably along gradients of factors such as temperature and moisture, and including process studies which may serve as indicators of both short- and long-term changes.

Losses of SOC after harvesting and differences between harvesting intensities might be transient and no longer detectable after a period of some decades. This would indicate resilience in the forest ecosystem with processes compensating SOC losses that we need to identify and understand. However, limited availability of long-term experimental data currently precludes firm conclusions about the long-term impact of intensified forest harvesting on SOC stocks in boreal and northern temperate forest ecosystems, suggesting a need for continuation of existing long-term experiments.

Even where there are clear negative effects of harvesting on SOC stocks, it is important to note that this may be mitigated or indeed completely outweighed by improved tree growth in the next rotation (Egnell et al., 2015). It is important to look at the changes in the total C stocks if one of the major goals of forest management is to sequester carbon and thereby mitigate global warming. At the same time, it is important to evaluate the net effects of biomass production at the expense of soil C accumulation in relation to the potential for long-term storage of C.

3. Governance

Effective forest governance measures are crucial to ensure sustainable forest management. Sustainability principles and criteria have therefore to be incorporated into policy frameworks and support schemes, as well as management guidelines and certification systems. Although there is great site-to-site variation, science-based and operationally practical management guidelines might be developed with the help of expert judgement (Vance et al., 2014). In addition, it is vital that governance measures are accepted by stakeholders. 'Soft' governance measures, e.g. management guidelines and certification systems, may often be more adaptable to changes and local conditions, and more inclusive of stakeholder inputs, than legislation, and thus more easily accepted (Stupak et al., 2013).

Comparisons of management guidelines have been made for countries, states or provinces with boreal and/or temperate forests (Stupak et al., 2013). Although it is possible to learn from other countries, it is probably rarely advisable simply to copy their guidelines because of local differences. However, comparison of different countries' guidelines may help to identify broad areas of agreement that should be included, while leaving details to be worked out nationally or even at a more local level (Lattimore et al., 2009; Berch et al., 2012; Stupak et al., 2013). This would increase local empowerment, in accordance with the subsidiarity principle, and also emphasises the importance of training of forest managers.

Although many countries have produced national recommendations and guidelines for biomass extraction to encourage this taking place in agreement with the principles of sustainable forest management, the focus has so far been largely on nutrient management and avoidance of soil damage by compaction or erosion, and there has been little specific focus on SOC stocks. Regarding certification systems, harvesting effects on SOC have until recently not often been explicitly included in Programme for the Endorsement of Forest Certification (PEFC) or Forest Stewardship Council (FSC) certification systems, although some mainly newer standards do include requirements focussing on the forests' contribution to the C cycle (Stupak et al., 2011). Aside from strict forest certification systems, there are other certification systems, standards and suggestions for criteria related to bioenergy production, some of which are relevant to preservation of SOC stocks also in forests (Martikainen, 2010a, 2010b). For example, "biomass production must not be at the expense of important carbon sinks in the vegetation and in the soil" (Project Group on Sustainable Production of Biomass, 2007), "biomass production shall not endanger important carbon stocks" (Hjulfors and Hjerpe, 2010) and "the use of agrarian and forestry residual products for feedstock production, including lignocellulosic material, shall not be at the expense of long-term soil stability and organic matter content" (Roundtable on Sustainable Biofuels, 2010).

The European Union's directive on the use of energy from renewable sources (RED, European Parliament and Council, 2009) includes a mandatory sustainability scheme for biofuels (defined as liquid or gaseous fuel for transport) and bioliquids. Although it is stated in Point 4 of Article 17 of the RED that biofuels and bioliquids shall not be obtained from land that was continuously forested in January 2008 and is no longer continuously forested, this is in the context of land-use change and thus does not prohibit forest harvesting for bioenergy purposes, which is not considered as land-use change if forest is replanted or allowed to regrow naturally (cf. International Sustainability and Carbon Certification, 2010). Other land areas with high SOC stocks, such as wetlands and peatlands, are similarly protected. Furthermore, in the rules for calculating the greenhouse gas impact of biofuels and bioliquids given in the RED's Annex V, a 20-year period is used for estimation of C stock accumulation, which is clearly far too short a time for forest SOC stocks to accumulate again after harvesting.

The RED was followed by a report on sustainability criteria for the use of solid and gaseous biomass sources in electricity, heating and cooling (European Commission, 2010), recommending the extension of binding EU sustainability criteria for biofuels/bioliquids to solid/gaseous biomass used for electricity and heating/cooling. These recommendations are not mandatory. If in the future liquid or gaseous biofuels are to be prepared from forest biomass on a commercial basis (which will necessarily involve more intensive use of forest biomass), the sustainability criteria given in the RED will apply.

4. Discussion

Forest soil contains a large stock of C; of particular importance is SOC which has a slow build-up, a long turnover time, and the potential to be stored for a long time. The rate of the C release back to atmosphere from SOC may increase after ecosystem disturbance, for example as an effect of harvesting, although this has not always been observed. How could management guidelines and other forms of governance be further developed to support the preservation of SOC in the context of harvesting intensity? Such guidelines should ideally rest on sound, quantitative and generalizable knowledge based on research. However, published effects of both WTH and SOH in boreal and northern temperate forests vary greatly, and there is not enough information currently available to draw any general conclusions about their long-term impact on ecosystem C cycling. Effects are species-, soil-, site- and practice-specific (Helmisaari et al., 2014). In addition, most field studies were carried out within a few decades of harvesting and therefore cannot at present provide information about long-term effects. Effects may be less dramatic if measured at the landscape level rather than the stand level if SOC stocks are restored during the rotation of the subsequent stand following WTH, as effects at stand level will be integrated over a larger spatial scale. In the case of effects of WTH, there appears to be some discrepancy between results from empirical studies and results from modelling. The reasons for this are unclear but it is possible that some soil processes are not well enough simulated by existing models or that field studies fail to gauge the often relatively small changes in large and spatially variable SOC stocks (Jandl et al., 2007). Properly planned new studies and resampling of soils in existing studies to obtain long-term data may provide valuable information on the mechanisms responsible for observed contrasting effects of harvesting intensity and methodology on SOC storage in soils, which can then be used to improve the models. A better experimentally based understanding of the SOC loss and gain processes after harvest is needed to identify the mechanisms that may protect SOC stocks even under intensified use. Thus new studies should not only focus on SOC stock changes but also on processes such as decomposition and mineralisation as well as C fluxes. There is a need for studies not only on forest floors but also on mineral soil including subsoil where leached DOC and root-derived C may have been stored. Studies should be carried out under a range of conditions, preferably along gradients of relevant factors such as moisture (Thiffault et al., 2011) and temperature. In addition, although some studies included ground vegetation (e.g. Fahey et al., 1991; Olsson and Staaf, 1995; Finér et al., 2003; Palviainen et al., 2005), the interacting effect of ground vegetation on harvesting-related C dynamics still requires further research.

In the absence of new studies, meta-analysis might be used to identify patterns in experimental data, and this approach has been used by e.g. Johnson and Curtis (2001) and Nave et al. (2010). However, for some factors (e.g. ground vegetation) there may not be enough experimental results at present to make meta-analysis feasible. Where enough data do exist, stratification may be necessary because responses are likely to vary due to different site conditions.

Existing information indicates that factors such as tree species composition (hardwood vs. coniferous/mixed) and soil type are important in determining the impact of harvesting on SOC (Nave et al., 2010). A recent synthesis of tree species effects on SOC stocks and distribution within the soil profile reported that broadleaves tend to store more SOC in mineral soil whereas conifers tend to store more SOC as forest floor C (Vesterdal et al., 2013). It is possible that these factors might also affect differences between SOH and WTH, although this cannot be demonstrated at present. Tree species composition and soil type could however be considered in management guidelines: even though the mechanisms responsible for the observed effects are not completely clear, expert opinion might be used to bridge the knowledge gaps.

During whole-tree harvesting, foliage biomass and some of the harvesting residues should be left on-site: current guidelines suggest 30–40% (Merilä et al., 2014; Helmisaari et al., 2014). In practice, this may happen anyway as only about 60–80% of logging residues are normally removed (Helmisaari et al., 2011). However, skilled machine operators might be able to remove more. Depending on how and where the residues are left in the field, this may reduce the nutrient and organic matter loss and thus minimise the risk for decreased growth in the next rotation and degradation of soil fertility in the long term. It is particularly important for nutritional sustainability that the residues are left on-site for a period in order for needles or leaves to fall off and thus reduce the risk for nutrient depletion, and this has indeed often been done. Even if only a small part of the trees' organic matter is located in the needles or leaves, the nutrients stored in these are important for growth in the next rotation and therefore also litter inputs, which in turn will be important for replenishing and maintaining the SOC stores. If the residues are stored in larger piles prior to being removed from the site, the input of nutrients from remaining needles/leaves on different parts of the site will vary greatly, which may again affect the growth of the new generation of trees.

Avoidance of physical damage to the soil via erosion or compaction (which will protect SOC) is already well-covered in many management guidelines, although these are not always followed in practice, possibly for economic reasons.

Current governance measures may state that SOC stocks are to be protected during forest operations, but in general little or no direct guidance is given as to how this is to be achieved. Partly this is due to the diverging results from various experiments, which is connected to the complexity of the processes involved, the difficulties associated with measuring the changes (Jandl et al., 2007), and the number of factors that affect the SOC stock. Until more knowledge is available, the gap of uncertainty between the scientific results and the need for practically useable management guidelines and clear indicators can only be bridged by expert opinion given to authorities and certification bodies (Stupak et al., 2007). Properly conducted long-term experiments would be able to clarify the relative importance of different harvesting practices on the SOC stocks, which are the key factors affecting the loss of SOC, and under which conditions the magnitude of the removals becomes critical. Importantly, such experiments would also provide new data for testing of models, thus improving their ability to predict long-term effects of different harvesting methods under varying site conditions and hopefully bridging any gap between modelling results and field observations. Both well-designed new experiments and continuation of existing long-term experiments are therefore very important.

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References

Ågren, G.I., Hyvönen, R., 2003. Changes in carbon stores in Swedish forest soils due to increased biomass harvest and increased temperatures analysed with a semi-empirical model. For. Ecol. Manage. 174, 25–37.

Aussenac, G., 1987. Effets de l'éclaircie sur l'écophysiologie des peuplements forestiers. Schweiz. Z. Forstwes. 138, 685–700.

Bélanger, N., Paré, D., Yamasaki, H., 2003. The soil acid-base status of boreal black spruce stands after whole-tree and stem-only harvesting. Can. J. For. Res. 33, 1874–1879.

Bengtsson, J., Wikström, F., 1993. Effects of whole-tree harvesting on the amount of soil carbon: model results. New Zealand J. For. Sci. 23, 380–389.

Berch, S., Curren, M., Dymond, C., Hannam, K., Murray, M., Tedder, C., Titus, B., Todd, M., 2012. Criteria and guidance considerations for sustainable tree stump harvesting in British Columbia. Scand. J. For. Res. 27, 709–723.

Brais, S., Harvey, B.D., Bergeron, Y., Messier, C., Greene, D., Belleau, A., Paré, D., 2004. Testing forest ecosystem management in boreal mixedwoods of northwestern Quebec: initial response of aspen stands to different levels of harvesting. Can. J. For. Res. 34, 431–446.

Brandtberg, P.-O., Olsson, B.A., 2012. Changes in the effects of whole-tree harvesting on soil chemistry during 10 years of stand development. For. Ecol. Manage. 277, 150–162.

Bright, R.M., Cherubini, F., Astrup, R., Bird, N., Cowie, A.L., Ducey, M.J., Marland, G., Pingoud, K., Savolainen, I., Strømman, A.H., 2012. A comment to "Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral": important insights into greenhouse gas accounting. GCB Bioenergy 4, 617–619.

Carey, M.L., Hunter, I.R., Andrew, I., 1982. *Pinus radiata* forest floors: factors affecting organic matter and nutrient dynamics. New Zealand J. For. Sci. 12, 36–48.

Carlyle, J.C., 1993. Organic carbon in forested sandy soils: properties, processes and the impact of forest management. New Zealand J. For. Sci. 23, 390–402.

Covington, W.W., 1981. Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods. Ecology 62, 41–48.

Doblas-Miranda, E., Rovira, P., Brotons, L., Martínez-Vilalta, J., Retans, J., Pla, M., Vayreda, J., 2013. Soil carbon stocks and their variability across the forests, shrublands and grasslands of peninsular Spain. Biogeosciences 10, 8353–8361.

Egnell, G., Jurevics, A., Peichl, M., 2015. Negative effects of stem and stump harvest and deep soil cultivation on the soil carbon and nitrogen pools are mitigated by enhanced tree growth. For. Ecol. Manage. 338, 57–67.

Egnell, G., Leijon, B., 1999. Survival and growth of planted seedlings of *Pinus sylvestris* and *Picea abies* after different levels of biomass removal in clear-felling. Scand. J. For. Res. 14, 303–311.

Egnell, G., Valinger, E., 2003. Survival, growth, and growth allocation of planted Scots pine trees after different levels of biomass removal in clear-felling. For. Ecol. Manage. 177, 65–74.

Eliasson, P., Svensson, M., Ohlsson, M., Ågren, G.I., 2013. Forest carbon balances at the landscape scale investigated with the Q model and the CoupModel – responses to intensified harvests. For. Ecol. Manage. 290, 67–78.

European Commission, 2010. Report from the Commission to the Council and the European Parliament on Sustainability Requirements for the Use of Solid and Gaseous Biomass Sources in Electricity, Heating and Cooling.

European Parliament and Council, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC.

Fahey, T.J., Hill, M.O., Stevens, P.A., Hornung, M., Rowland, P., 1991. Nutrient accumulation in vegetation following conventional and whole-tree harvest of Sitka spruce plantations in North Wales. Forestry 64, 271–288.

Federer, C.A., 1984. Organic matter and nitrogen content of the forest floor in even-aged northern hardwoods. Can. J. For. Res. 14, 763–767.

Finér, L., Mannerkoski, H., Piirainen, S., Starr, M., 2003. Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting. For. Ecol. Manage. 174, 51–63.

Fleming, R.L., Leblanc, J.-D., Hazlett, P.W., Weldon, T., Irwin, R., Mossa, D.S., 2014. Effects of biomass harvest intensity and soil disturbance on jack pine stand productivity: 15-year results. Can. J. For. Res. 44, 1566–1574.

Fleming, R.L., Powers, R.F., Foster, N.W., Kranabetter, J.M., Scott, D.A., Ponder, F., Berch, S., Chapman, W.K., Kabzems, R.D., Ludovici, K.H., Morris, D.M., Page-Dumroese, D.S., Sanborn, P.T., Sanchez, F.G., Stone, D.M., Tiarks, A.E., 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5-year seedling performance: a regional comparison of Long-Term Soil Productivity sites. Can. J. For. Res. 36, 529–550.

Georgiadis, P., 2011. Accumulation of Carbon and Nitrogen in Swedish Forest Soils Over Stand Age (M.Sc. Thesis), Swedish University of Agricultural Sciences, Uppsala, Sweden.

Grelle, A., Strömgren, M., Hyvönen, R., 2012. Carbon balance of a forest ecosystem after stump harvest. Scand. J. For. Res. 27, 762–773.

Hazlett, P.W., Morris, D.M., Fleming, R.L., 2014. Effects of biomass removals on site carbon and nutrients and jack pine growth in boreal forests. Soil Sci. Soc. Am. J. 78, S183–S195.

Helmisaari, H.-S., Hanssen, K.H., Jacobson, S., Kukkola, M., Luiro, J., Saarsalmi, A., Tamminen, P., Tveite, B., 2011. Logging residue removal after thinning in Nordic boreal forests: long-term impact on tree growth. For. Ecol. Manage. 261, 1919–1927.

Helmisaari, H.-S., Kaarakka, L., Olsson, B.A., 2014. Increased utilization of different tree parts for energy purposes in the Nordic countries. Scand. J. For. Res. 29, 312–322.

Hendrickson, O.Q., Chatarpaul, L., Burgess, D., 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. 19, 725–735.

Hjulfors, L.N., Hjerpe, K., 2010. Sustainable bioenergy production. Defining Principles and Criteria. <http://www.bioenergypromotion.net/project/publications/task-3.1.-final-report-on-sustainable-production-of-bioenergy#.UPkKHh2bhdc> (accessed 25.06.14).

Holtsmark, B., 2013. Quantifying the global warming potential of CO_2 emissions from wood fuels. GCB Bioenergy. http://dx.doi.org/10.1111/gcbb.12110.

Hope, G.D., 2007. Changes in soil properties, tree growth, and nutrition over a period of 10 years after stump removal and scarification on moderately coarse soils in interior British Columbia. For. Ecol. Manage. 242, 625–635.

Hu, J., 2000. Effects of Harvesting coniferous Stands on Site Nutrients, Acidity and Hydrology. Doctor Scientiarum Theses 2000:29, Agricultural University of Norway, Ås, Norway.

Huntington, T.G., Ryan, D.F., 1990. Whole-tree-harvesting effects on soil nitrogen and carbon. For. Ecol. Manage. 31, 193–204.

Hyvönen, R., Olsson, B.A., Lundkvist, H., Staaf, H., 2000. Decomposition and nutrient release from *Picea abies* (L.) Karst. and *Pinus sylvestris* L. logging residues. For. Ecol. Manage. 126, 97–112.

Hyvönen, R., Olsson, B.A., 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. Scand. J. For. Res. 27, 774–786.

International Sustainability and Carbon Certification, 2010. ISCC 202 Sustainability Requirements for the Production of Biomass, ISCC Draft 10-01-19 V 1.13.

Jacobson, S., Kukkola, M., Mälkönen, E., Tveite, B., 2000. Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. For. Ecol. Manage. 129, 41–51.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253–268.

Jiang, H., Apps, M.J., Peng, C., Zhang, Y., Liu, J., 2002. Modelling the influence of harvesting on Chinese boreal forest carbon dynamics. For. Ecol. Manage. 169, 65–82.

Johnson, C.E., Johnson, A.H., Huntington, T.G., Siccama, T.G., 1991. Whole-tree clear-cutting effects on soil horizons and organic matter pools. Soil Sci. Soc. Am. J. 55, 497–502.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Manage. 10, 227–238.

Jónsson, J.A., Sigurdsson, B.D., 2010. Effects of early thinning and fertilization on soil temperature and soil respiration in a poplar plantation. Icelandic Agric. Sci. 23, 97–109.

Jurgensen, M., Tarpey, R., Pickens, J., Kolka, R., Palik, B., 2012. Long-term effect of silvicultural thinnings on soil carbon and nitrogen pools. Soil Sci. Soc. Am. J. 76, 1418–1425.

Kaarakka, L., Tamminen, P., Saarsalmi, A., Kukkola, M., Helmisaari, H.-S., Burton, A.J., 2014. Effects of repeated whole-tree harvesting on soil properties and tree growth in a Norway spruce (*Picea abies* (L.) *Karst.*) stand. For. Ecol. Manage. 313, 180–187.

Karlsson, K., Tamminen, P., 2013. Long-term effects of stump harvesting on soil properties and tree growth in Scots pine and Norway spruce stands. Scand. J. For. Res. 28, 550–558.

Kataja-aho, S., Smolander, A., Fritze, H., Norrgård, S., Haimi, J., 2012. Responses of soil carbon and nitrogen transformations to stump removal. Silva Fennica 46, 169–179.

Kowalski, A.S., Loustau, D., Berbigier, P., Manca, G., Tedeshi, V., Borghetti, M., Valentini, R., Kolari, P., Berninger, F., Rannik, Ü., Hari, P., Rayment, M., Mencuccini, M., Moncrieff, J., Grace, J., 2004. Paired comparisons of carbon exchange between undisturbed and regenerating stands in four managed forests in Europe. Global Change Biol. 10, 1707–1723.

Lattimore, B., Smith, C.T., Titus, B.D., Stupak, I., Egnell, G., 2009. Environmental factors in woodfuel production. Opportunities, risks, and criteria and indicators for sustainable practices. Biomass Bioenergy 33, 1321–1342.

Laudon, H., Hedtjärn, J., Schelker, J., Bishop, K., Sørensen, R., Ågren, A., 2009. Response of dissolved organic carbon (DOC) following forest harvesting in a boreal forest. Ambio 38, 381–386.

Leppälammi-Kujansuu, J., Aro, L., Salemaa, M., Hansson, K., Kleja, D.B., Helmisaari, H.-S., 2014. Fine root longevity and carbon input into soil from below- and aboveground litter in climatically contrasting forests. For. Ecol. Manage. 326, 79–90.

Liski, J., Ilvesniemi, H., Mäkelä, A., Starr, M., 1998. Model analysis of the effects of soil age, fires and harvesting on the carbon storage of boreal forest soils. Eur. J. Soil Sci. 49, 407–416.

Martikainen, A., 2010a. Sustainable bioenergy production: identification and description of sustainability initiatives and certification systems in the BSR. <http://www.bioenergypromotion.net/extranet-1/publications/sustainable-bioenergy-production-identification-and-description-of-sustainability-initiatives-and-certification-systems-in-the-bsr#.UPkJph2bhdd> (accessed 25.06.14).

Martikainen, A., 2010b. Sustainable bioenergy production: comparative analysis of sustainability initiatives and certification systems. <http://www.bioenergypromotion.net/extranet-1/publications/sustainable-bioenergy-production-comparative-analysis-of-sustainability-initiatives-and-certification-systems#.UeUBF9JM9dc> (accessed 25.06.14).

McLaughlin, J.W., Phillips, S.A., 2006. Soil carbon, nitrogen and base cation cycling 17 years after whole-tree harvesting in a low-elevation red spruce (*Picea rubens*)-balsam fir (*Abies balsamea*) forested watershed in central Maine, USA. For. Ecol. Manage. 222, 234–253.

Merganičová, K., Pietsch, S.A., Hasenauer, H., 2005. Testing mechanistic modelling to assess impacts of biomass removal. For. Ecol. Manage. 207, 37–57.

Merilä, P., Mustajärvi, K., Helmisaari, H.-S., Hilli, S., Lindroos, A.-J., Nieminen, T.M., Nöjd, P., Rautio, P., Salemaa, M., Ukonmaanaho, L., 2014. Above- and below-ground N stocks in coniferous boreal forests in Finland: implications for sustainability of more intensive biomass utilization. For. Ecol. Manage. 311, 17–28.

Morris, D.M., Kwiaton, M.M., Duckert, D.R., 2014. Black spruce growth response to varying levels of biomass harvest intensity across a range of soil types: 15-year results. Can. J. For. Res. 44, 313–325.

Nave, L.E., Vance, E.D., Swanston, C.W., Curtis, P.S., 2010. Harvest impacts on soil carbon storage in temperate forests. For. Ecol. Manage. 295, 857–866.

Nieminen, M., 2004. Export of dissolved organic carbon, nitrogen and phosphorus following clear-cutting of three Norway spruce forests growing on drained peatlands in southern Finland. Silva Fennica 38, 123–132.

Nilsen, P., Strand, L.T., 2008. Thinning intensity effects on carbon and nitrogen stores and fluxes in a Norway spruce stand (*Picea abies* (L) Karst.) stand after 33 years. For. Ecol. Manage. 256, 201–208.

Nilsen, P., Strand, L.T., 2013. Carbon stores and fluxes in even- and uneven-aged Norway spruce stands. Silva Fennica 47. http://dx.doi.org/10.14214/sf.1024.

Nisbet, T.R., Welch, D., Doughty, R., 2002. The role of forest management in controlling diffuse pollution from the afforestation and clearfelling of two public water supply catchments in Argyll, West Scotland. For. Ecol. Manage. 158, 141–154.

Olsson, B.A., Staaf, H., 1995. Influence of harvesting intensity of logging residues on ground vegetation in coniferous forests. J. Appl. Ecol. 32, 640–654.

Olsson, B.A., Staaf, H., Lundkvist, H., Bengtsson, J., Rosén, K., 1996. Carbon and nitrogen in coniferous forest soils after clear-felling and harvests of different intensity. For. Ecol. Manage. 82, 19–32.

Örlander, G., Egnell, G., Albrektson, A., 1996. Long-term effects of site preparation on growth in Scots pine. For. Ecol. Manage. 86, 27–37.

Palviainen, M., Finér, L., Mannerkoski, H., Piirainen, S., Starr, M., 2005. Changes in the above- and below-ground biomass and nutrient pools of ground vegetation after clear-cutting of a mixed boreal forest. Plant Soil 275, 157–167.

Peltoniemi, M., Mäkipä, R., Liski, J., Tamminen, P., 2004. Changes in soil carbon with stand age – an evaluation of a modelling method with empirical data. Global Change Biol. 10, 2078–2091.

Peng, C., Jiang, H., Apps, M.A., Zhang, Y., 2002. Effects of harvesting regimes on carbon and nitrogen dynamics of boreal forests in central Canada: a process model simulation. Ecol. Model. 155, 177–189.

Pennock, D.J., van Kessel, C., 1997. Clear-cut forest harvest impacts on soil quality indicators in the mixedwood forest of Saskatchewan. Geoderma 75, 13–32.

Ponder Jr., F., Fleming, R.L., Berch, S., Busse, M.D., Elioff, J.D., Hazlett, P.W., Kabzems, R.D., Kranabetter, J.M., Morris, D.M., Page-Dumroese, D., Palik, B.J., Powers, R.F., Sanchez, F.G., Scott, D.A., Stagg, R.H., Stone, D.M., Young, D.H., Zhang, J., Ludovici, K.H., McKenney, D.W., Mossa, D.S., Sanborn, P.T., Voldseth, R.A., 2012. Effects of organic matter removal, soil compaction and vegetation control on 10th year biomass and foliar nutrition: LTSP continent-wide comparisons. For. Ecol. Manage. 278, 35–54.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff, J.D., Stone, D.M., 2005. The North American long-term soil productivity experiment: findings from the first decade of research. For. Ecol. Manage. 220, 31–50.

Prescott, C.E., 1997. Effects of clearcutting and alternative silvicultural systems on rates of decomposition and nitrogen mineralization in a coastal montane coniferous forest. For. Ecol. Manage. 95, 253–260.

Prescott, C.E., Maynard, D.G., Laiho, R., 2000. Humus in northern forests: friend or foe? For. Ecol. Manage. 133, 23–36.

Proe, M.F., Dutch, J., 1994. Impact of whole-tree harvesting on second-rotation growth of Sitka spruce: the first 10 years. For. Ecol. Manage. 66, 39–54.

Project Group on Sustainable Production of Biomass, 2007. Testing Framework for Sustainable Biomass: Final Report from the Project Group "Sustainable Production of Biomass".

Raulund-Rasmussen, K., Stupak, I., Clarke, N., Callesen, I., Helmisaari, H.-S., Karltun, E., Varnagirytė-Kabašinskienė, I., 2008. Effects of very intensive biomass harvesting on short and long term site productivity. In: Röser, D., Asikainen, A., Raulund-Rasmussen, K., Stupak, I. (Eds.), Sustainable Use of Forest Biomass for Energy – A Synthesis with Focus on the Nordic and Baltic Region, Managing Forest Ecosystems, vol. 12. Springer, pp. 31–78.

Roberts, B.A., Deering, K.W., Titus, B.D., 1998. Effects of intensive harvesting on forest floor properties in *Betula papyrifera* stands in Newfoundland. J. Veg. Sci. 9, 521–528.

Rosenberg, O., Jacobson, S., 2004. Effects of repeated slash removal in thinned stands on soil chemistry and understorey vegetation. Silva Fennica 38, 133–142.

Rosengren, U., Göransson, H., Jönsson, U., Stjernquist, I., Thelin, G., Wallander, H., 2005. Functional biodiversity aspects on the nutrient sustainability in forests – importance of root distribution. J. Sust. For. 21, 77–100.

Roundtable on Sustainable Biofuels, 2010. RSB Principles & Criteria for Sustainable Biofuel Production, Version 2.0, RSB-STD-01-001.

Ryan, D.F., Huntington, T.G., Martin, C.W., 1992. Redistribution of soil nitrogen, carbon and organic matter by mechanical disturbance during whole-tree harvesting in northern hardwoods. For. Ecol. Manage. 49, 87–99.

Saarsalmi, A., Tamminen, P., Kukkola, M., Hautajärvi, R., 2010. Whole-tree harvesting at clear-felling: impact on soil chemistry, needle nutrient concentrations and growth of Scots pine. Scand. J. For. Res. 25, 148–156.

Sanchez, F.G., Tiarks, A.E., Kranabetter, J.M., Page-Dumroese, D.S., Powers, R.F., Sanborn, P.T., Chapman, W.K., 2006. Effects of organic matter removal and soil compaction on fifth-year mineral soil carbon and nitrogen contents for sites across the United States and Canada. Can. J. For. Res. 36, 565–576.

Schmidt, M., Macdonald, S., Rothwell, R., 1996. Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Can. J. Soil Sci. 76, 531–540.

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. Nature 478, 49–56.

Schrumpf, M., Schulze, E.D., Kaiser, K., Schumacher, J., 2011. How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? Biogeosciences 8, 1193–1212.

Schulze, E.-D., Körner, C., Law, B.E., Haberl, H., Luyssaert, S., 2012. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. GCB Bioenergy 4, 611–616.

Smolander, A., Kitunen, V., Kukkola, M., Tamminen, P., 2013. Response of soil organic layer characteristics to logging residues in three Scots pine thinning stands. Soil Biol. Biochem. 66, 51–59.

Smolander, A., Kitunen, V., Tamminen, P., Kukkola, M., 2010. Removal of logging residue in Norway spruce thinning stands: long-term changes in organic layer properties. Soil Biol. Biochem. 42, 1222–1228.

Smolander, A., Levula, T., Kitunen, V., 2008. Response of litter decomposition and soil C and N transformations in a Norway spruce thinning stand to remove logging residue. For. Ecol. Manage. 256, 1080–1086.

Sørensen, R., Ring, E., Meili, M., Högbom, L., Seibert, J., Grabs, T., Laudon, H., Bishop, K., 2009. Forest harvest increases runoff most during low flows in two boreal streams. Ambio 38, 357–363.

Staaf, H., Berg, B., 1980. Distribution of organic matter, carbon and plant nutrients in soil in the early phase after clear-cutting of a Scots pine forest; with and without removal of logging slash. Swedish Coniferous Forest Project Internal Report 100.

Strömgren, M., Mjöfors, K., 2012. Soil-CO_2 flux after patch scarification, harrowing and stump harvest in a hemi-boreal forest. Scand. J. For. Res. 27, 754–761.

Strömgren, M., Egnell, G., Olsson, B.A., 2013. Carbon stocks in four forest stands in Sweden 25 years after harvesting of slash and stumps. For. Ecol. Manage. 290, 59–66.

Stupak, I., Asikainen, A., Jonsell, M., Karltun, E., Lunnan, A., Mizaraite, D., Pasanen, K., Pärn, H., Raulund-Rasmussen, K., Röser, D., Schröder, M., Varnagirytė, I., Vilkriste, L., Callesen, I., Clarke, N., Gaitnieks, T., Ingerslev, M., Mandre, M., Ozolinčius, R., Saarsalmi, A., Armolaitis, K., Helmisaari, H.-S., Indriksons, A., Kairiukstis, L., Katzensteiner, K., Kukkola, M., Ots, K., Ravn, H.P., Tamminen, P., 2007. Sustainable utilisation of forest biomass for energy – possibilities and problems, policy, legislation, certification and recommendations. Biomass Bioenergy 31, 666–684.

Stupak, I., Lattimore, B., Titus, B.D., Smith, C.T., 2011. Criteria and indicators for sustainable forest fuel production and harvesting: a review of current standards for sustainable forest management. Biomass Bioenergy 35, 3287–3308.

Stupak, I., Titus, B., Clarke, N., Smith, T., Lazdins, A., Varnagirytė-Kabašinskienė, I., Armolaitis, K., Peric, M., Guidi, C., 2013. Approaches to soil sustainability in guidelines for forest biomass harvesting and production in forest and plantations. In: Proceedings of the Workshop W6.1 Forest Bioenergy and Soil Sustainability, EuroSoil Congress 2012.

Sundqvist, E., Vestin, P., Crill, P., Persson, T., Lindroth, A., 2014. Short-term effects of thinning, clear-cutting and stump harvesting on methane exchange in a boreal forest. Biogeosci. Discuss. 11, 4637–4667. http://dx.doi.org/10.5194/bgd-11-4637-2014.

Swedish Forest Agency, 2008. Rekommendationer vid uttag av avverkningsrester och askåterföring. Swedish Forest Agency Meddelande 2/2008 (in Swedish).

Symonds, J., Morris, D.M., Kwiaton, M.M., 2013. Effect of harvest intensity and soil moisture regime on the decomposition and release of nutrients from needle and twig litter in northwestern Ontario. Boreal Environ. Res. 18, 401–413.

Tamminen, P., Saarsalmi, A., Smolander, A., Kukkola, M., Helmisaari, H.-S., 2012. Effects of logging residue harvest in thinnings on amounts of soil carbon and nutrients in Scots pine and Norway spruce stands. For. Ecol. Manage. 263, 31–38.

Taylor, A.R., Wang, J.R., Kurz, W.A., 2008. Effects of harvesting intensity on carbon stocks in eastern Canadian red spruce (*Picea rubens*) forests: an exploratory analysis using the CBM-CFS3 simulation model. For. Ecol. Manage. 255, 3632–3641.

Thiffault, E., Hannam, K.D., Paré, D., Titus, B.D., Hazlett, P.W., Maynard, D.G., Brais, S., 2011. Effects of forest biomass harvesting on soil productivity in boreal and temperate forests – a review. Environ. Rev. 19, 278–309.

Thiffault, E., Paré, D., Bélanger, N., Munson, A., Marquis, F., 2006. Harvesting intensity at clear-felling in the boreal forest: impact on soil and foliar nutrient status. Soil Sci. Soc. Am. J. 70, 691–701.

Thornley, J.H.M., Cannell, G.R., 2000. Managing forests for wood yield and carbon storage: a theoretical study. Tree Phys. 20, 477–484.

Tveite, B., Hanssen, K.H., 2013. Whole-tree thinnings in stands of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*): short- and long-term growth results. For. Ecol. Manage. 298, 52–61.

Vance, E.D., Aust, W.M., Strahm, B.D., Froese, R.E., Harrison, R.B., Morris, L.A., 2014. Biomass harvesting and soil productivity: is the science meeting our policy needs? Soil Sci. Soc. Am. J. 78, S95–S104.

Vanguelova, E., Pitman, R., Luiro, J., Helmisaari, H.-S., 2010. Long-term effects of whole tree harvesting on soil carbon and nutrient sustainability in the UK. Biogeochemistry 101, 43–59.

Vesterdal, L., Dalsgaard, M., Felby, C., Raulund-Rasmussen, K., Jørgensen, B.B., 1995. Effects of thinning and soil properties on accumulation of carbon, nitrogen and phosphorus in the forest floor of Norway spruce stands. For. Ecol. Manage. 77, 1–10.

Vesterdal, L., Jørgensen, F.V., Callesen, I., Raulund-Rasmussen, K., 2002. Skovjordes kulstoflager – sammenligning med agerjorde og indflydelse af intensiveret biomasseudnyttelse. In: Christensen, B.T. (Ed.), Biomasseudtag til energiformål – konsekvenser for jordens kulstofbalance i land- og skovbrug. DJF rapport Markbrug, vol. 72, pp. 14–28 (in Danish).

Vesterdal, L., Clarke, N., Sigurdsson, B.D., Gundersen, P., 2013. Do tree species influence carbon stocks in temperate and boreal forests? For. Ecol. Manage. 309, 4–18.

Wäldchen, J., Schulze, E.D., Schoning, I., Schrumpf, M., Sierra, C., 2013. The influence of changes in forest management over the past 200 years on present soil organic carbon stocks. For. Ecol. Manage. 289, 243–254.

Wall, A., 2008. Effect of removal of logging residue on nutrient leaching and nutrient pools in the soil after clearcutting in a Norway spruce stand. For. Ecol. Manage. 265, 1372–1383.

Wall, A., Hytönen, J., 2011. The long-term effects of logging residue removal on forest floor nutrient capital, foliar chemistry and growth of a Norway spruce stand. Biomass Bioenergy 35, 3328–3334.

Walmsley, J.D., Godbold, D.L., 2010. Stump harvesting for bioenergy – a review of the environmental impacts. Forestry 83, 17–38.

Walmsley, J.D., Jones, D.L., Reynolds, B., Price, M.H., Healey, J.R., 2009. Whole tree harvesting can reduce second rotation forest productivity. For. Ecol. Manage. 257, 1104–1111.

Yanai, R.D., Arthur, M.A., Siccama, T.G., Federer, C.A., 2000. Challenges of measuring forest floor organic matter dynamics: repeated measures from a chronosequence. For. Ecol. Manage. 13, 273–283.

Yanai, R.D., Currie, W.S., Goodale, C.L., 2003. Soil carbon dynamics after forest harvest: an ecosystem paradigm reconsidered. Ecosystems 6, 197–212.

Yin, X., Perry, J.A., Dixon, R.K., 1989. Influence of canopy removal on oak forest floor decomposition. Can. J. For. Res. 19, 204–214.

Zabowski, D., Chambreau, D., Rotramel, N., Thies, W.G., 2008. Long-term effects of stump removal to control root rot on forest soil bulk density, soil carbon and nitrogen content. For. Ecol. Manage. 255, 720–727.