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Review

The effects of logging residue extraction for energy on ecosystem services and biodiversity: A synthesis

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ABSTRACT

We review the consequences for biodiversity and ecosystem services from the industrial-scale extraction of logging residues (tops, branches and stumps from harvested trees and small-diameter trees from thinnings) in managed forests. Logging residue extraction can replace fossil fuels, and thus contribute to climate change mitigation. The additional biomass and nutrients removed, and soils and other structures disturbed, have several potential environmental impacts. To evaluate potential impacts on ecosystem services and biodiversity we reviewed 279 scientific papers that compared logging residue extraction with non-extraction, the majority of which were conducted in Northern Europe and North America. The weight of available evidence indicates that logging residue extraction can have significant negative effects on biodiversity, especially for species naturally adapted to sun-exposed conditions and the large amounts of dead wood that are created by large-scaled forest disturbances. Slash extraction may also pose risks for future biomass production itself, due to the associated loss of nutrients. For water quality, transient and carbon stocks are mostly restored over decadal time perspectives. We summarize ways of decreasing some of the negative effects of logging residue extraction on specific ecosystem services, by changing the categories of residue extracted, and site or forest type targeted for extraction. However, we found that suggested pathways for minimizing adverse outcomes were often in conflict among the ecosystem services assessed. Compensatory measures for logging residue extraction may also be used (e.g. ash recycling, liming, fertilization), though these may also be associated with adverse environmental impacts.

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1. Introduction

Increasing the contribution of bioenergy to total energy production is one means by which societies can reduce their reliance on finite fossil fuel resources and help mitigate anthropogenic climate change. The increased use of bioenergy is however changing land-management regimes over large areas, with a range of potential implications for biodiversity and ecosystem services. As both biodiversity (Cardinale et al., 2012; Hooper et al., 2012) and the direct and indirect material and energy contributions provided by ecosystems (i.e. ecosystem services) are vital to societal well-being (Millennium Ecosystem Assessment, 2005), concerns are being raised regarding the potential implications of extracting biomass for bioenergy in different production land-uses. To increase the production of bioenergy from agriculture crops may involve changes of land use (Lapola et al., 2010; Joly et al., 2015), while the outtake of bioenergy from already managed forests generally involves more subtle modification of the current management. The consequences of logging residue extraction for biodiversity and the ecosystem services provided by production forest lands are therefore less clear.

Forest-based bioenergy can be sourced by extracting additional biomass from production forest lands, or involve the use of industrial by-product residues from timber production (black liquor, sawdust, bark, etc.). In cases where biomass extraction is increased, specific concerns may be raised regarding the socio-ecological implications of these practices, which may limit the extent to which this resource is exploited (Verkerk et al., 2011). These concerns arise because bioenergy wood extraction involves both increased disturbance and outtake of biomass and nutrients from forests, which may exacerbate biodiversity loss and reduce the provision of ecosystem services. Consequently, while increased extraction of biomass for bioenergy can be consistent with renewable energy targets (e.g. in EU: Directive 2009/28/EC), it may conflict with environmental policy targets. There is thus a need to synthesize the scientific knowledge regarding the consequences of bioenergy wood extraction, and the extent to which bioenergy wood extraction can be modified to ensure the maintenance of biodiversity and ecosystem services.

Here we review the consequences for biodiversity and ecosystem services from the industrial-scale extraction of logging residues in managed forests. This extraction includes tree tops and branches (hereafter “slash”), stumps from harvested trees, and small-diameter trees provided from stand thinnings. This biomass is often referred to as logging residues, due to their lack of use as saw timber or for pulp and paper, and is otherwise left in the forest to degrade. The extraction of logging residues does not itself motivate production forestry, but value-adds to standard industrial wood harvesting. For this review we systematically surveyed the scientific literature that evaluated consequences of slash, stump and small-
diameter tree extraction, by contrasting the biodiversity or ecosystem services delivery from forests with and without logging residue extraction, while being otherwise managed consistently. In that way, we draw conclusions about the consequences of forest bioenergy extraction for biodiversity and ecosystem services. From a compilation of important ecosystem services in Finland (Jappinen and Heliölä, 2015), we selected services that we identify as potentially being affected by extraction of logging residues and focus on them in our assessment: regulating and maintenance services (soil quality, climate regulation, pollination, control of pests), provisioning ecosystem services (wood, reindeer, game, fish, and berries), and cultural services (recreation and nature-related heritage).

2. Methods

We searched for peer-reviewed scientific literature that contrasted the biodiversity and ecosystem services outcomes from forests primarily managed for the production of merchantable wood, with or without the additional extraction of logging residues. Searches were made in Scopus and Web of Science (the core version) in October 2016. We searched by article titles, abstracts and key words using the following search string: (logging* OR forest* OR plantation*) AND (residu* OR slash* OR stump* OR biofuel* OR bio-fuel* OR bio-energ* OR bioenerg* OR whole-tree* OR “whole-tree”* OR “whole tree”*) AND (harvest* OR extract* OR remov* OR “clear cut”* OR clear-cut* OR clearcut* OR clear-cuts OR “clear fell”* OR clear-fell* OR clearfell*). Search strings were designed to capture the practice of harvesting slash and stumps after clear-felling, as well as slash, stumps, and small diameter trees during thinning operations. The term “whole-tree harvesting” refers to the extraction of both stems and slash (but typically not stumps) from clear-cuts.

The search resulted in totally 7579 papers. We made a first screening of titles to remove papers that were not relevant, resulting in 636 remaining papers. Based on the content of the abstract, we divided these papers into three categories. The first category contained studies presenting outcomes from quantitative comparisons of extraction/non-extraction of logging residue wood. This category formed the basis for the systematic overview of the literature (279 papers listed in Appendix A and shown in Figs. 2–8). We included manipulative and natural management experiments for which areas with and without logging residue extraction were compared, as well as assessments based on modelling and simulations. We also included whole-tree harvest, due to equivalent site-level consequences. We did not include studies that only discuss possible consequences without formal calculations. The second category of studies contained articles that did not compare extraction/non-extraction but were relevant when evaluating the consequences of bioenergy wood extraction. Relevant papers not found in the literature search but otherwise known by the authors were added to this category. In the third category were those papers deemed irrelevant upon closer inspection and excluded. We collected information from category 1 studies (see above) regarding (i) where and how the research was conducted and the specific type of logging residue extracted (slash or stumps or small-diameter tree, tree species); (ii) if and how biodiversity or ecosystem services was affected (positive effect means an increased quantity and a negative effect a decreased quantity of the ecosystem service or biodiversity), and (iii) factors that influence this effect.

3. Background

3.1. The practice of logging residue extraction

Extraction of logging residues has two main consequences: additional biomass and nutrients are removed and soils and other structures are disturbed (Fig. 1). The disturbance results from both the removal of the wood and from the traffic impacts of the machinery used to do so. This affects several environmental factors, which in turn may affect biodiversity and the delivery of ecosystem services (Fig. 1: 4.1–4.8).

Slash and stump extraction implies additional forest machinery usage, and therefore additional soil disturbance, compared to stem-only harvest. However, the techniques used for logging, slash harvest and stump lifting, differs widely among countries. For example, in Finland and Sweden, where a cut-to-length harvesting system is used, slash is left in large piles at the clear-cut by the harvester, and is hauled with a forwarder in a second operation. Some parts of the slash is normally used to armour strip roads, regardless of whether slash is harvested for energy purposes. In other parts of the world, including North America, a full tree harvesting system is common practice in which whole trees are skidded to the landing where deliming and bucking takes place. Stump harvest involves an additional soil disturbance, which includes mixing of soil layers. A common technique to harvest stumps in Finland and Sweden is to use a hydraulic excavator equipped with a stump harvest tool, which breaks up and lifts the stumps (Berg, 2014). In contrast, stump lifting in North America has mostly been made to combat root-rot, by the use of a backhoe, or a bulldozer equipped with a brush blade and a rear splitting edge (Hope, 2007; Zabowski et al., 2008). Apart from removing the stumps, blading often removes parts of the topsoil from the site. These differences are reflected in the design of studies on slash and stump harvesting effects. Furthermore, it is important to note that experimental studies often involve more intensive biomass removal than occurs in practical operations (Thiffault et al., 2015). However, in experimental plots heavy machinery is often kept out, which can reduce the observed impacts relative to those in forestry.

In managed boreal forests, extracted slash generally consists of fine woody debris, i.e. dead wood with a diameter <10 cm (e.g. Dahlberg et al., 2011). However, where trees are larger, the diameter for slash may likewise increase (as in Tasmania: Grove, 2009). How much slash is extracted at a site-level depends on forestry, policy and markets, and varies widely among countries, with higher values reported from Sweden and Finland than for France and North America (Thiffault et al., 2015).

4. Results and discussion

Most of the research on the effect of logging residue extraction has been conducted in Northern Europe and North America (Fig. 2). The research activity has strongly increased over time, with, on average, 1.1 publications per year in the 1980s, 3.9 in the 90s, 8.5 in the 2000s and 22.1 from 2010 to 2016.

4.1. Soil quality and nutrient retention

Increased nutrient export was via nutrient budget evaluations early recognized as a potential threat to the sustainability of logging residue extraction (Mäkkinen, 1972; Weetman and Webber, 1972). It was found that whole-tree harvesting resulted in a 2–4 times greater export of nutrient elements than stem-only harvest, due to the higher nutrient concentrations in foliage and branches compared to stem wood. This increased removal of nutrients (Fig. 1) is potentially affecting biomass production (see 4.2) and water quality (see 4.4). The soil quality is not only influenced by nutrient loss but also the physical attributes of the soil may be affected (see 4.1.2).
4.1.1. Nutrient stocks and nutrient export in harvested biomass

The capital of nitrogen (N), phosphorus (P) and other plant nutrients (such as the base cations K, Ca, and Mg) of forest ecosystems are contained in both plant biomass and the soil. Nutrient cycles at the local scale means a continuous flux of this capital between soil and plants, but there is also an exchange of nutrients with other systems. Thus, there are processes in which the ecosystem capital can increase (e.g., deposition, fixation, weathering, and fertilization) or be lost (e.g., harvest, leaching, erosion, and volatilization in fire). Maintenance of the nutrient capital is an ecosystem service providing resources for biomass production.

4.1.1.1. Nitrogen. N is usually the element that limits plant production in boreal and temperate zones (Tamm, 1991; LeBauer and Treseder, 2008). In N limited ecosystems, N cycling between plants and decomposers is very efficient, with minute losses in growing forests. However, following clear-cutting leaching losses of N can be substantial (Likens et al., 1970; Bergholm et al., 2015). This is often shown as a post-harvest peak in nitrate concentrations in runoff water and is a consequence of the disturbance of the N cycle between plants and decomposers, in which plant uptake is ceased whereas mineralization of organic matter and N in the soil and logging residues continues (Bergholm et al., 2015). Thus, we expect harvesting of slash not only to mean a loss of the N capital of the site, but also to remove a source of nitrogen that could be lost to leaching. Slash left on the ground may also influence the establishment of ground vegetation as well as soil temperature and moisture which influence mineralization of soil organic matter and inorganic N in the soil (Stevens and Hornung, 1990). However, the direction of these effects probably varies with the amounts of slash left and the climate conditions. Therefore slash harvesting, besides the inevitable direct impact on the total N capital of the site, also may influence N mineralization indirectly in a more unpredictable way (see 4.4.1).

The results of our literature survey largely agree with these expectations (Fig. 3). A larger number of studies indicate a depletion of N stocks after slash and stump extraction than found an increase. On the other hand, there are also many studies that found no impact, in particular with respect to N content in soil, soil water, field layer, and trees of the following stands. The strongest support that N stocks are depleted was found for budget evaluation studies at the ecosystem scale. This result probably reflects the fact that harvesting biomass inevitably means gross nutrient removals from
ecosystems, and many budget evaluations are confirming and quantifying such losses.

4.1.1.2. Phosphorous. Second to N, P is the most important nutrient element for forest production. Important exceptions are very old tropical soils and thick organic soils (e.g. drained peatlands) where P is the limiting element (Vitousek et al., 2010; Huotari et al., 2015). In contrast to ecosystem N losses, which can be easily compensated with N fertilisers originating from atmospheric N₂, the ecosystem P stock is a more finite resource. There were fewer studies reporting effects on P than on N, but the results were largely similar to those on N (Fig. 3).

4.1.1.3. Base cation loss and acidification. Soil acidification is strongly connected to nutrient cycling, in particular cycling of the base cations. Accumulation of base cations in forest biomass is associated with soil acidification whereas decomposition of the biomass, and weathering of soil minerals, are acid-neutralizing processes (Nilsson et al., 1982; van Breemen et al., 1983). Hence, logging residue extraction implies that the acidification of soil will be neutralized to a lesser extent (Löfgren et al., 2017). Thus, we expect decreases on base cations stocks and availability in the soil, which implies loss of acid neutralizing capacity, and thus reduced base saturation and lowered pH. In line with this, we found a large number of studies demonstrating that logging residue extraction often results in the depletion of base cations stocks, whereas the opposite effects are rarely observed (Fig. 3). This was particularly true for base cation stocks at the ecosystem scale, exchangeable base cation contents in soils, and base cations in runoff water.

4.1.2. Physical soil quality

Logging may have different impacts on the physical properties of soils. Heavy machinery can cause soil compaction (i.e., increased soil bulk density and reduced porosity) that may reduce permeability for roots, air, and water. Heavy machinery can also cause deep ruts on sensitive soils, which together with a raised groundwater table following clear-cutting can change site hydrology (see 4.4). We found 11 studies on slash harvest effects on soil bulk density, porosity or resistance to penetration, of which the majority (8) reported no, or no overall effect, whereas three studies reported increased bulk density. This indicates that slash harvesting normally has little effect on the physical conditions of the soil. The few studies on stump harvesting indicate that the effects could be larger than for slash harvest and vary also with soil type and the machinery used for stump lifting. The few studies on other aspects of soil physical conditions indicate that slash harvest mostly results in increased soil temperature, and in one study out of three, soil moisture decreased.

4.2. Future biomass production

Production of woody biomass is the most economically important provisioning ecosystem service in managed forests. The amount of woody biomass produced (i.e. stand productivity) depends on site productivity, which is the potential to produce stem wood assuming optimal management. Site productivity depends on physical and climate properties and their impact on the availability of nutrients, water, light, and the length of the growing season. However, woody biomass production also depends on the forest management applied and impacts from, for instance, pests

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**Fig. 3.** Effects of logging residue extraction on stocks and concentrations of N, P and base cations (including soil acidification) in different ecosystem compartments and physical soil quality. Negative and positive responses mean extraction of logging residues results in decreased or increased nutrient stocks, concentrations, or changes in a physical variable respectively, in different compartments.
concluded that tree growth was reduced by 3% based on 168 experimental sites worldwide, Achat et al. (2015) nevertheless, the number of experiments with significant effects exceeds those with positive effects in both categories. Out of the 80 experiments with slash extraction, significant negative effects on biomass production were reported from 31% of the experiments, whereas positive effects were reported from 33%, leaving 66% with no treatment effect (Fig. 4). Some studies based their results on analyses of growth of individual trees or seedlings rather than on the ecosystem service relevant stand level. Splitting the studies into those providing tree-level data versus stand-level data did not alter the main pattern in the outcomes. Since net release of N and P from logging residues is not immediate (Palviainen et al., 2004), a time lag should be expected before a nutrient export related treatment effects appears (cf. Egnell, 2011). Therefore, the studies were split into those presenting data <10 years or ≥10 after treatment. Again, this split did not change the overall result, with the majority of experiments finding no effect. Nevertheless, the number of experiments with significant negative effects exceeds those with positive effects in both categories. Out of the 23 experiments with stump extraction, significant negative effects were reported from 13% of the experiments, positive effects from 30%, and no effect from 57%. Thus, for slash extraction negative effects dominate over positive effects, while a weak opposite tendency was found for stump extraction.

Our outcome is in line with a review of studies in the Nordic countries which concluded that, although treatment effects were absent in most studies, there was a negative trend following slash extraction in Norway spruce forests, particularly on poor sites, whereas no such trend was found in Scots pine forests (Egnell, 2017). Studies on stump extraction effects were few, but the results indicate no effect in Norway spruce stands, and a weak positive effect in Scots pine stands (Egnell, 2017). In a meta-analysis based on 168 experimental sites world-wide, Achat et al. (2015) concluded that tree growth was reduced by 3–7% in the short to medium term (1–33 years, with the majority of experiments having a response time of 10 years or less) after slash extraction. However, their meta-analysis also included intensive treatments whereby all organic matter including the topsoil was removed and is therefore not fully comparable with the results presented here.

For the seven modelling studies, five (71%) suggested decreased growth, one increased growth, and one no effect following slash extraction. The positive effect was suggested by Peckham et al. (2013), whose explanation for the result was that the applied model allows plants and microbes to compete for available N, and that left biomass (slash) with a low C to N ratio resulted in an immobilization of N as decomposers exploited that biomass. An important note given was that this effect is short-lived. The decreased growth response in most modelling studies is probably due to the changed nutrient mass balance when the nutrient rich slash is also harvested, which decrease the nutrient availability for the subsequent stand.

Previous reviews are in line with the results presented here, showing that although the majority of studies show no negative effect for slash extraction negative effects on biomass production have been recorded in several studies of slash (but not stumps), both over a short and a longer time scale. Thus, we conclude that slash extraction is associated with risks for decreased biomass production, while that does not seem to be case for stumps (Fig. 4).

4.2.2. Effects on biomass production from slash extraction during stand thinning

Seven studies reported on growth responses in the residual stand following slash extraction during thinning operations, encompassing 32 unique experimental sites with data collected during 5–20 years after harvest. Decreased growth was reported from 31% of the experiments and increased growth from 6%, with growth not affected in the remaining studies (Fig. 4). Thus, the weak trend towards a negative growth response appears to be similar for slash extraction during thinning as at final felling. As the residual stand remaining after thinning is ready to respond to nutrients released one may expect a clearer response from residue extraction at thinnings, further enhanced by the mulching effect of the slash left on site. One reason for the consistent outcomes may stem from the much smaller amount of nutrients released following a thinning as compared to final felling. In a review based on 41 experimental sites in the Nordic countries, Egnell (2017) concluded that slash extraction during thinning shows more consistent growth reductions than during final felling. In practical operations, additional transports and the fact that slash cannot be used to reinforce strip roads can also increase damages on the remaining trees, but this is often not accounted for in experiments. We conclude that slash extraction during thinning is associated with some risk for growth losses.

4.3. Global warming mitigation

Forests are important for global climate regulation mainly due to the large exchange of greenhouse gases with the atmosphere (Forkel et al., 2016), their substantial carbon stores (Dixon et al., 1994), and the effects of the surface biogeophysics (Bright et al., 2015). Increasing carbon sequestration in biomass and soil, as well as relocating biomass to harvested wood products may help mitigate climate change (Bonan, 2008). A substantial proportion of forest carbon is found in the soil, amounting to 48% in temperate and 64% in boreal forests (Pan et al., 2011). This pool turns over slowly, keeping carbon out of the atmosphere for extended periods of time.

Logging residue extraction may reduce the carbon sink in the forest since it involves the removal of organic matter in litter and

Fig. 4. Effect of logging residue extraction on biomass production (i.e. stand productivity or tree growth).
woody debris that otherwise could have contributed to the soil carbon pool (Johnson and Curtis, 2001). However, the types of fresh organic material used for bioenergy is subjected to gradual decomposition, and only a small fraction is diverted to more stable (long-term) forms of carbon sequestration (Prescott, 2010). Consequently, the difference in carbon stocks associated with logging residue extraction may initially be large, but will diminish over time. Another concern is that increased soil disturbance due to stump extraction may cause more rapid turnover of soil carbon (Walmsley and Godbold, 2010).

We found 69 studies of the effects on carbon following extraction of logging residues, the majority (83%) investigating effects of slash extraction (branches, tops, needles, and sometimes forest floor; in a few cases also including stumps) and the rest investigating stump removal only. 86% of studies were empirical, while 14% involved modelling. Most studies quantified the effects on carbon stocks in soil and decomposing litter (74%), while the others investigated soil microbiological activity (e.g. respiration, microbial biomass, and enzyme activity). Studies of slash usually included carbon in decomposing (woody) litter, while studies of stumps only considered carbon in soil and humus, i.e. not the stump itself.

4.3.1. Effects of slash extraction on global warming mitigation

Empirical and modelling studies often come to different conclusions regarding the effects of slash extraction on carbon stocks in litter and soil. The majority of empirical studies (63%) show no effect, indicating a fast recovery of the carbon stocks, while 25% report negative and 12% positive effects (Fig. 5A). The modelling studies, on the other hand, consistently indicated negative effects of logging residue extraction, regardless of forest type or time horizons. This discrepancy between empirical and modelling studies may indicate a lack of feedback processes in the carbon-turnover models. A factor probably contributing to the low frequency of negative effects in the empirical studies is the combination of small treatment effects due to the relatively fast decomposition of slash and large spatial variation.

The effect of slash extraction on soil microbial activity is negative in most studies (53%), while no effect is also frequently found (33%), and more rarely there is a positive effect (13%) (Fig. 5A). Slash has been found to have a stimulating effect on soil microbiological activity (Smolander et al., 2010) potentially increasing turnover rates in older soil carbon. However, such priming effects are complex and the increased microbial activity is mainly associated with microorganisms specialized in decomposing fresh organic matter (Fontaine et al., 2003). Nevertheless, reported cases of higher soil carbon stores following slash extraction have been attributed to reduced soil mineralization rates compared to when residues are retained (Vanguelova et al., 2010).

4.3.2. Effects of stump extraction on global warming mitigation

Studies of the removal on carbon in humus and soil at stump extraction are sparse in comparison to slash extraction. Most of the empirical studies show no effect on the soil carbon (55%), with the remaining studies showing negative effects (Fig. 5B). All modelling studies show negative effects on the carbon pool. Microbial activity following stump harvest either increases or is unaffected (Fig. 5B). Stump extraction creates patches of exposed mineral soil within a stand. Within such patches, the abundance of soil decomposers is generally lower, while in undisturbed parts of clear-cuts there are few direct effects of stump extraction (Kataja-aho et al., 2011). There are concerns that increased carbon turnover may occur due to soil disturbance (Walmsley and Godbold, 2010). However, the effect on decomposers has only been measured for a few years after harvest (Hyvonen et al., 2016; Kataja-aho et al., 2016). The empirical results from northern coniferous forests show limited and transient effects on carbon stocks and respiration rates following stump extraction (Kaarakka et al., 2016; Strömgren et al., 2013; Pumpanen et al., 2004), indicating that this concern may exceed the actual implications for carbon stocks.

4.3.3. Net climate effect of logging residue extraction

The net carbon balance in the forest is a critical determinant of the climate impact from logging residue extraction, since the emissions from harvesting, transports and processing are small in comparison to carbon stock changes (Lindholm et al., 2010; Repo et al., 2012). Seen over longer time perspectives, forest bioenergy may be close to carbon neutral. However, this does not equal climate neutrality due to that the CO2 release from combustion takes place earlier than the CO2 release in the non-harvest case. This means that there is a climate impact that will decrease over time (Hammar et al., 2015). Modified forest management, e.g. fertilization and prolonged rotation periods, could compensate for the loss in carbon by logging residue extraction, which should result in a shorter time before the carbon stores are restored to the level of those of stem-only harvesting (Repo et al., 2015). Life cycle assessments of the consequences of increased utilization of forest bioenergy quantify all emissions from the energy system and compare to a reference (fossil) energy system. The results of such assessments depend on many factors, such as the choice of reference energy system, forest structure, management, and site conditions (Lamers and Junginger, 2013). Including substitution of fossil alternatives, a climate benefit of forest bioenergy is achieved.

Fig. 5. Effects on soil organic carbon (SOC) and microbial activity responses. Number of scientific papers comparing with/without logging residue extraction (slash – only slash; stump – only stumps or slash and stumps). Note that positive effects on microbial activity may lead to a decrease in SOC.
over medium to long terms, while over the short term (1-2 decades) the results is varying more (Bentsen, 2017).

4.4. Water quality

The additional disturbance caused by the extraction of logging residues can influence water quality and increase the exposure of aquatic biota to toxic substances. A decrease in water quality could be due to an increased stream export of nutrients (see 4.1), dissolved organic carbon (DOC), and particles that lead to eutrophication and decreased water transparency. This could in turn influence aquatic biodiversity, recreational opportunities (e.g., for swimming and fishing), and the provision of clean water. Among toxic substances, Hg is of great concern, since Hg concentrations in freshwater fish are often already at levels that WHO deems as potentially harmful in many areas of the northern hemisphere (e.g., Åkerblom et al., 2014; Depew et al., 2013). Thus, increased exposure to Hg may contribute to negative effects on fishing, which is valuable both as a source of recreation and as a food resource (see 4.6.4). The literature on the effects of logging residue extraction on water quality focuses on two main issues: i) increased export of nutrients in soil and runoff water; and ii) increased export of trace metals (especially Hg) and metals such as Al, Pd, Cd, Zn, and Fe, either attached to organic matter and particles or as a result of soil acidification (Fig. 6).

4.4.1. Effects on nutrient concentrations in water

Forest harvesting and subsequent site preparation may increase loadings and concentrations of nutrients in water as a result of increased erosion, mineralization, and nitrification (Kreutzweiser et al., 2008). Stump extraction can potentially result in a higher degree of disturbance that may increase this problem. Indeed, higher N concentrations have been detected in runoff water after stem and stump extraction compared to stem-only harvest (Eklof et al., 2012). Stump extraction may both increase N export due to the higher degree of disturbance and the removal of dead wood that would otherwise immobilize N during decomposition (Palviainen et al., 2010; Palviainen and Finér, 2015). For slash extraction, the effects are not straightforward. It has been proposed that slash left on site increase the export of N and P because the mineralization rate may be enhanced under slash piles, and the uptake of N and P low because the re-establishment of vegetation is prevented (Rosén and Lundmark-Thelin, 1987). Slash itself is also a source of nutrients, and P in particular may be released during the early phases of decomposition (Palviainen et al., 2004; Asam et al., 2014). Indeed, significantly higher concentrations of P (Rodgers et al., 2010; Asam et al., 2014) and inorganic N (Rosén and Lundmark-Thelin, 1987; Staaf and Olsson, 1994; Lindroos et al., 2016) have been found in soil water below slash piles than in areas without slash. In contrast, Palviainen et al. (2004) proposed that slash might act as a N sink, as the decomposition consumes N and increase microbial immobilization. This expectation is supported by the fact that studies of N and P concentrations in runoff water have either found a lower export of P and N with slash removal than when left on site (Asam et al., 2014) or found no effect (Kaila et al., 2014, 2015). Also in a modelling study, the removal of slash was predicted to lower nutrient concentrations in runoff water due to a reduction in decomposing material on site (Zanchi et al., 2014), while in another, N was predicted to remain relatively unchanged when extracting both slash and stumps (Lauren et al., 2008). The observed variation in the outcome could be due to that the effect in stream water may be influenced by, e.g., pile distribution and coverage (Kaila et al., 2015), P adsorption capacity, soil type, N deposition (Lauren et al., 2008) and whether the needles fall off before extraction or not (Lindroos et al., 2016). To conclude, logging residue extraction can affect nutrient exports beyond that associated with standard forestry operations, but the resultant effects are variable and highly site specific. Only after stump extraction, but not slash extraction, field studies have detected increased runoff of nutrients (Fig. 6). It is unknown whether the increased nutrient load can cause eutrophication that influence aquatic fauna and flora, recreational opportunities, and the provision of clean water at landscape scales.

4.4.2. Effects on trace metal concentrations in water

Increased mobilization of metals may occur after logging as a result of soil acidification, altered hydrological pathways, and increased erosion of DOC and particles that metals are attached to (Kreutzweiser et al., 2008). It has been hypothesized that logging residue extraction increases this problem due to the removal of biomass and additional soil disturbance causing erosion and changes in hydrological pathways (Walmsley and Godbold, 2010). However, no study has shown such an effect on DOC and trace metal concentrations (but for Al, see Dahlgren and Driscoll (1994)).

On the contrary, several studies show no effect on DOC, or on a range of metals assessed (Kikkilä et al., 2014) including Hg (Eklof et al., 2012, 2013; Ukonmaanaho et al., 2016, see 4.6.4).

Soil acidification is especially important for the pH sensitive
4.5. Biodiversity

According to the Convention on Biological Diversity (1992), species should be maintained in viable populations in their natural surroundings. Such a target is meaningful at larger spatial scales, but not at the scale of forest stands. This is because at the stand scale, species continually face some risk of extinction due to the dynamics of forests and of small populations. Thus, knowledge of landscape-scale processes is required to evaluate the potential to maintain viable populations. Nevertheless, stand level studies are valuable, as if there are no effects at a stand scale effects at a landscape scale are unlikely.

Logging residue extraction potentially affects several ecological groups (Fig. 7). First, a large proportion of forest biodiversity is dependent on dead wood, and the extraction of wood for bioenergy therefore means the loss of potential habitat. Second, logging residue extraction affects understorey vegetation due to increased levels of disturbance and via its effects on the availability of nutrients in the soil. Third, ground-living organisms may be affected, since structural diversity decreases when bioenergy wood is removed. Finally, one aspect that is rarely recognized is the potential effect on aquatic biota (4.4., see however Mlambo et al., 2015, who observed no effects).

Negative effects on biodiversity (i.e. species richness or viability of populations) have been reported, but the majority of studies find no effect, or both positive and negative effects (Fig. 7). The variety of responses can partially be explained by the fact that different ecological groups and biodiversity determinants have been studied over different temporal and spatial scales.

4.5.1. Dead wood-dependent organisms

To understand the implications of logging residue extraction for dead wood-dependent biodiversity at landscape scales, the first step is to assess to what extent organisms use slash and stumps in comparison to other dead wood categories (see 4.5.1.1). Second, the importance of slash and stumps as habitat may be compared with total landscape-level dead wood availability, since this will reflect potential habitat availability and loss (4.5.1.2). Third, the extent to which logging residue extraction increases landscape-level extinction risks can be assessed, as indicated by the population densities of species found within remaining stumps and slash.

Finally, another type of threat that has been hypothesized is that piles of slash and stumps created prior to their extraction, results in the formation of ecological traps for insects (Victorsson and Jonsell, 2013a), which may cause further population decreases (see 4.5.1.4).

4.5.1.1. Species for which slash and stumps constitute habitat.

Slash and stumps constitute habitat for many species; in a study of various forest types in a Swedish managed forest landscape, 53% of the dead wood-dependent species (beetles, fungi, and lichens) were recorded on slash or stumps (Hiron et al., 2017). Many species on national red-lists have also been found in slash or stumps, even though there tend to be more red-listed species in other types of dead wood (e.g., Hiron et al., 2017). Thus, even though slash and stumps occur in high abundance, some of the species inhabiting these substrates are regarded as rare or declining, which typically means they occur in very low densities. For species occurring in low densities in abundant habitats, it is extremely hard to estimate their distribution area or other aspects relevant to determining their red-list status (Cocoş et al., 2017). Therefore, the conservation status of rare species using slash and stumps is generally uncertain, and for this reason we cannot overly rely on their red-list status.

Slash and stump extraction not only affects fresh logging residues, but can also damage dead wood left as legacies from earlier harvests (Rudolph and Gustafsson, 2005; Rabinowitz-Jokinen and Vanha-Majamaa, 2010; Löhmus et al., 2013). Thus, it has been suggested that for stands clear-felled for the first time the risk for losing substantial amounts of old dead wood is increased, in comparison to stands managed with industrial forestry methods over multiple rotations (Hiron et al., 2017).

4.5.1.2. Slash and stumps in relation to total dead wood availability.

The degree to which bioenergy extraction affects the landscape-level availability of dead wood habitat depends on (i) population densities in slash and stumps in comparison to other categories of dead wood, and (ii) the proportion of landscape level dead wood that consists of slash and stumps.

Overall, the number of species per volume of dead wood is of the same magnitude in slash and stumps as in dead wood created by natural tree mortality (beetles: Abrahamsson and Lindbladh, 2006; Brin et al., 2013; Andersson et al., 2015; fungi: Kuhart et al., 2015). However, individual species can vary from not utilizing slash and...
stumps at all, to inhabiting slash or stumps at much higher population densities than are found for any other type of dead wood (Svensson et al., 2016).

In some clear-cuts in boreal forests, stumps constitute up to 40% of the total volume of above-ground dead wood (Erjäätä et al., 2010; Rabinowitsch-Jokinen and Vanha-Majamaa, 2010), whereas slash (fine woody debris) may constitute about 10% (Rabinowitsch-Jokinen and Vanha-Majamaa, 2010). These proportions result from both the input of dead wood at cutting (which is of the same magnitude for slash and stumps) and the decomposition rate (which is high for slash, intermediate for stumps and low for snags and logs; Ranius et al., 2014). Because both slash and stumps persist for a much shorter time period than is encompassed by a full rotation length in managed forests, the landscape-level contribution of stumps and slash to total dead wood availability will be considerably lower than these figures.

Removal of slash and stumps will decrease the landscape-level populations for a large proportion of all dead wood-dependent species. Stumps are used by more species than slash, and thus stump extraction has more negative effects on biodiversity than slash extraction (Svensson et al., 2016; Hiron et al., 2017). For several species this decrease will be substantial, since slash and stumps occurring after final harvest constitute the main habitat (Svensson et al., 2016; Hiron et al., 2017). It has been argued that such species have been generally favored by the recent increase of logging residues due to forest management, and therefore it is only a minor problem if their habitat decreases (Dahlin et al., 2011). However, historically these species may have been abundant in habitats that are rare in today’s managed forest landscapes. For instance, they may have once been favored by the large input of dead wood and sun exposure provided by forest fires, which are now suppressed in managed forest landscapes. Because forest fires tend to create large amount of snags and stumps, but not slash, this historical context should be considered especially when determining the conservation implications for stump-inhabiting species.

4.5.1.3. Risk for loss of species due to habitat loss. Even if slash and stumps are removed from many clear-cuts, in most managed forest landscapes plenty of slash and stumps will still be left, at least for the more abundant tree species. Therefore, it is not likely that species will go extinct from landscapes because the disappearance of slash and stumps, but rather due to the potential negative impacts on population densities in remaining dead wood items. The effect on population densities can be assessed by comparing species richness and species occupancy on dead wood items within clear cuts or landscapes which differ in the extent of logging residue extraction (Ranius et al., 2017). At stand level, stump extraction has been found to reduce the number of dead wood-dependent beetle species per stump (Victorsson and Jonsell, 2013b), and reduced abundances have been observed for soil invertebrates (Taylor and Victorsson, 2016). Furthermore, for a species of lichen the colonization rate of individual stumps increased with the number of stumps acting as dispersal sources in the near vicinity (Caruso et al., 2010). This indicates that there are threshold levels of logging residue amounts that must be retained to avoid species disappearance from forest stands. However, it is not yet known for any species what this threshold level is. Only one study of this kind has been done at a landscape scale, and then the number of negatively affected beetle species was about the same as those positively affected by stump extraction in surrounding forests (Ranlund and Victorsson, 2018).

At the landscape level, the effect of logging residue extraction on persistence of dead wood-dependent species has only been analyzed using computer simulations. An analysis of theoretical species with characteristics assumed to correspond to red-listed wood dependent-species suggests that slash and stump extraction at 10% of all clear cuts may be sufficient to cause specialized species, with poor colonization ability, to go extinct (Johansson et al., 2016). However, it remains an open question how many species possess these characteristics, or whether species possessing this precise combination of characteristics occur at all.

4.5.1.4. Piling of extracted slash and stumps. When stumps are harvested, they are typically stored in piles where they are dried for two years. This raises the potential that such stump piles may act as ecological traps, as dead wood-dependent insects can be attracted to breed on these piles, with their reproductive investment lost when the piles are later removed and offspring destroyed. However, the only existing study testing whether stumps do act as ecological traps provides little support for that hypothesis (Victorsson and Jonsell, 2013a; Fig. 3). At slash extraction, slash is also put into piles on the clear-cuts. In oak slash (which is a non-dominating tree species in Northern Europe with many associated flora and fauna) several red-listed saproxylic beetles have been found in the upper part of the piles. For that reason it is suggested that the impact of oak slash extraction can be minimized if this upper third is left on site (Hedin et al., 2008).

4.5.2. Understorey vegetation

Stump extraction increases the amount of exposed mineral soil ( Kataja-aho et al., 2011), while slash extraction in particular reduces the amount of nutrients. Likewise, slash and stump extraction requires increased use of machinery, which causes additional damage to vegetation, soils and dead wood. Slash extraction also involves the removal of woody material from the ground, which may affect the conditions for the vegetation. Thus, at least in the short term the species composition of the understorey vegetation is often affected, but the effect on species richness is often neither clearly positive nor negative (Fig. 3).

Stump extraction has sometimes been observed to increase vascular plant species richness, and has also been found to increase the risk for stand colonization by invasive plant species (Kay et al., 2008). In other studies there have been no such effects ( Tarvainen et al., 2015; Rudolph and Stengbom, 2016), which may be because even without stump extraction, the soils are strongly disturbed by clearcutting and subsequent soil scarification.

Slash extraction has been found to affect plant species composition up to 20 years after logging ( Bräkenhielm and Liu, 1998). There are several possible explanations for this: slash extraction may increase the area available for plant establishment ( Fabbio et al., 2002), reduce nitrogen availability for plant uptake (Olsson and Staf, 1995), and limit soil shading (Astrom et al., 2005; Dynesius et al., 2008). In other cases no effects have been detected ( Slesak et al., 2016). Some of the differences in results may stem from variation in soil types, associated nutrient availability and the relative extent and type of soil disturbance ( Bräkenhielm and Liu, 1998; Kershaw et al., 2015).

4.5.3. Ground-living organisms

The presence or removal of slash and stumps affects habitat for ground-living organisms, and residue extraction can have both positive and negative effects on these species (Fig. 7). Slash increases microhabitat complexity, which may positive for ground-living invertebrates, such as Carabids (Nitterus et al., 2004; Sktowski, 2017) and spiders (Castro and Wise, 2009). For beetles, a negative effect on species richness has been observed during the first few months after slash extraction (Gunnarsson et al., 2004), but opposite effects may occur after several years (Nitterus et al., 2007). Even though small vertebrates may use slash as shelter, the effect of slash removal is typically small or absent.
(Homyack et al., 2014; Fritts et al., 2015, 2016; Moses and Boutin, 2001; Ponder, 2008; see however Yamada et al., 2016).

4.5.4. Conclusions: biodiversity

Slash and stumps are indeed utilized by many dead wood-dependent species. For certain species, which probably are naturally adapted to the large amounts of sun-exposed dead wood formed at large-scaled disturbances, slash and stumps are important for landscape-level population sizes. However, for most species the main part of the landscape-level populations occur in other dead wood categories. Among them there are many rare and threatened species for which it is probably a more effective conservation measure to retain more unmanaged forests, rather than to avoid logging residue extraction. Simulations indicate that intensive slash and stump extraction can possibly lead to landscape-level species extinctions, but these simulations have not been validated with field data. Conclusively, logging residue extraction has negative effects on dead wood-dependent species due to habitat loss. Also species not dependent on dead wood are affected by logging residue extraction, but for these groups it is often less obvious whether the effects on species richness are positive or negative.

4.6. Provision of non-wood forest products

4.6.1. Berries

Berry picking on forestland is in some regions important both as a provisioning ecosystem service, since the commercial value of the berries picked is substantial, and as a cultural ecosystem service, since this activity provides recreational value for many people. In the literature survey, we did not find any studies of the effects of logging residue extraction on berry production, but the effect on cover or abundance of berry-producing plant species has been studied. In four studies from Northern Europe, no impact of either slash or stump extraction was detected on the cover or biomass of Vaccinium myrtillus (bilberry), V. vitis-idaea (lingonberry) or Rubus idaeus (raspberry) (Bräkenhielm and Liu, 1998; Tarvainen et al., 2015; Hyvönen et al., 2016; Rudophi and Strengbom, 2016), whereas negative responses of V. myrtillus to slash and stump extraction have been found in one study each (Olsson and Staaf, 1995; Kataja-aho et al., 2011). In a North American study both Fragaria virginiana (Virginia strawberry) and Rubus ursinus (California blackberry) were identified as indicator species for stump harvested stands, whereas the introduced species Rubus armeniacus (Armenian blackberry) along with Vaccinium parviflorum (Red huckleberry) were found to be indicator species of stands where stumps were left un-harvested (Kaye et al., 2008). These results are in line with the general changes observed in the vegetation during the first few years after logging residue extraction, which favour and disfavour different species. To conclude, logging residue extraction does not seem to be an important threat to berry picking, but few studies are available to draw firm conclusions.

4.6.2. Mammalian game species

No studies from our literature search directly assessed the implications of logging residue extraction for game species. However, inferences can be made from studies assessing how the foraging patterns of large hunted ruminants respond to changes in the availability of slash. Slash is a food resource for browsing ruminants, as it consists of stems, leaves, shoots, and bark, which these mammals consume (Mansson et al., 2007). Thus, slash extraction has the potential to negatively affect the population sizes or health of game species (Edenius et al., 2014). This is especially the case for tree species preferably consumed by ruminants. Negative impacts may be reduced by increasing foraging access to any slash that is left permanently on site, or in the period prior to its extraction (Heikilä and Härkönen, 2000; Edenius et al., 2014). Furthermore, the time of the year of extraction is important; if stands are harvested in the autumn or early winter, the slash could be left as forage until the late spring or early summer, at which point these desiccated residues could be extracted for bioenergy with limited implications for browse availability (Edenius et al., 2014). To conclude, extracting the slash of regularly consumed tree species has the apparent potential to reduce valuable food resources for game species, and thereby negatively affect their population densities or the health of individuals.

4.6.3. Reindeer herds

Semi-domesticated reindeer (Rangifer tarandus) are essential for indigenous people in the boreal north, both as a source of meat and material, and as a part of cultural identity (Brämlund, 2015). No studies in our literature search assessed the implications of logging residue extraction on reindeer. However, this practice is likely to have some effect on the winter nutrition of reindeer populations through its effect on lichens, which may constitute up to 80% of their winter and early spring food resources (Heggberget et al., 2002). Slash extraction may improve ground-living lichen coverage in clear cuts, by reducing ground shading and soil coverage caused by logging residues (Kivinen et al., 2010; Åkujärvi et al., 2014). Furthermore, as dispersed slash piles can act as a barrier to reindeer foraging and digging, the extraction of logging residues could slightly increase access to food resources (Helle et al., 1990). However, these potential benefits may be offset by the additional soil disturbance and damage to lichen communities associated with the process of logging residue extraction (Kivinen et al., 2010). In summary, whereas logging residue extraction can be expected to alter the availability to important food resources for reindeer populations to some extent, the current evidence remains insufficient to draw clear conclusions.

4.6.4. Fish

High Hg concentrations in top predators make a risk for human consumption of these animals. It is mainly organic forms of Hg, methylmercury (MeHg), that biomagnifies in food webs. Increased Hg in fish during the last century primarily originate from diffuse anthropogenic atmospheric deposition due to fossil fuel use among others. Forestry operations may mobilize atmospheric Hg retained in the soils. Forest harvest and forest machinery usage have been found to increase stream MeHg concentrations (Porvari et al., 2003; Munthe and Hultberg, 2004; Skyllberg et al., 2009), due to impacts on soil hydrology, temperature, and redox conditions. The effects of logging residue extraction are less studied, but more extensive soil disturbance and disruption of the physical soil structure when stumps are extracted have been suggested to increase soil compaction and the number of water-filled local depressions. These depressions may constitute habitats for anaerobic bacteria capable of methylating inorganic Hg to MeHg (Eklof et al., 2018). However, elevated concentrations of MeHg after stump harvest have only been detected in soils (Eklof et al., 2018) and groundwater (Magnusson, 2017), but not in runoff waters (Eklof et al., 2012, 2013; Ukonmaanaho et al., 2016).

For Hg methylation, extraction of slash may have the opposite effect compared to stump extraction, if conditions under piles of logging residue left on site make habitats for Hg methylating microorganisms. On the other hand, slash could also protect the soil from disturbance during forest operations that in turn might decrease the hydrological connection between Hg methylation hotspots and surface waters. However, empirical studies on this are lacking.
In conclusion, there is some risk that logging residue extraction, especially stump extraction, could increase the MeHg in runoff and bioaccumulation in aquatic food-webs. This would potentially worsen the situation in boreal Fennoscandia and Northern America of high Hg in inland fishes. However, there is only limited empirical support for this.

4.7. Regulatory services

4.7.1. Control of forest pests

A few insects and fungi species are forest pests since they damage or kill living trees. Removing stumps and slash have been suggested as a method to decrease damages by pest species in the next forest generation. This expectation has indeed been met for root rot fungi (Fig. 8); stump extraction strongly reduces stand-level disease occurrence within a few decades (Cleary et al., 2013). Also slash extraction may reduce the risk for infection of some fungi, even though slash extraction is not enough to ensure their eradication from the stand (Hansson, 2006; Bernhold et al., 2006).

In Northern Europe, five insect pest species are potentially affected by logging residue extraction: the pine weevil (Hylobius abietis) and four bark beetles (Schroeder, 2008). For the pine weevil, the roots of stumps within clear-cuts are important breeding habitats, and stump extraction may decrease damages, even though the observed effects have been small (Orlander and Nilsson, 1999). Stumps and slash are used but not favored breeding habitats for bark beetles, so logging residue extraction is likely to have only little effect on their landscape-level habitat availability. The timing of harvesting, piling, and removal of slash and stumps may be important for determining the effect of slash and stump extraction on pest species (Poit, 2012). Since stumps harbour enemies to bark beetles (Hedgren, 2007; Brin et al., 2013), stump extraction may potentially have a negative effect on biological control, but it is unknown if this will have any significant implications for the risk of damage.

There have been concerns regarding the possible increased risk of damage due to slash and stumps extraction, as their storage in piles can attract pest insects; however, there is no empirical evidence for this. On the contrary, a study on bark beetles suggests that this only affects where within a clear cut insect damages take place, rather than increasing the total extent of damages (Hedgren et al., 2003).

4.7.2. Pollination

Clear-cuts are species rich habitats for pollinating bees and wasps (Rubene et al., 2015). Logging residue extraction may potentially affect the habitat suitability of clear-cuts for these species, as both dead wood (removed at logging residue extraction) and exposed patches of soil (formed especially at stump extraction) are used for nesting by different species. The observed effects on vegetation (section 4.5.2) may also influence bee and wasp fauna. However, we have found no studies assessing the effect of logging residue extraction on pollination or important pollinating species. Thus, pollination may potentially be affected by slash and stump extraction, but current evidence is insufficient to draw any conclusions.

4.8. Cultural services

4.8.1. Recreation

In the literature survey, we found no direct assessments of the effects of logging residue extraction on recreation. However, conclusions can be drawn from more general knowledge about visual preferences among the public (Gundersen et al., 2016).

Slash is generally perceived as untidy and disturbing and also reduces accessibility in a forest. Removal of slash is thus generally positive for recreation and the appreciation of a landscape. However, the removal must be made with care. Ruts and damages to paths, vegetation and soils caused by forestry operations are normally unwelcome from a recreational perspective (Gundersen et al., 2016).

Studies on the impacts of stump extraction on recreational values are rare and with a very limited content (Framstad et al., 2009; Gundersen et al., 2016). They indicate that stump extraction has a negative effect on landscape appreciation immediately after extraction. Later on, when the vegetation has started to recover, people tend to become less indignant (e.g. Edwards and Lacey, 2014; Gundersen et al., 2016). Most preference studies have been designed to capture people’s proximate views of a forest, often as close as on stand level or smaller (Gundersen et al., 2016). This raises the possibility that stump extraction is perceived differently from a more distant perspective. Studies from the late 1980s show that the very idea of stump extraction made people upset, since they associated it with ‘uncaring’ forms of forest management (Framstad et al., 2009; Gundersen et al., 2016). This attitude may have changed today, when environmental concerns are framed differently, specifically with respect to climate change mitigation acting as an important positive influence on attitudes to bioenergy (Edwards and Lacey, 2014).

4.8.2. Nature-related heritage

We are not aware of any scientific literature that deals directly with the impact of logging residue extraction on nature-related or
cultural heritage. We know however that extraction of slash and stumps typically results in increased use of machinery in forests. Machines cause severe damage to nature and culture related heritage (Framstad et al., 2009; Unander and Claesson, 2015). Stump extraction interferes also with the ground in a way that could eradicate cultural monuments and soil layering that compose pre-historical and historical remnants of human activities. On the other hand, the extraction of slash makes monuments and other remnants more visible, which may lead to enhanced knowledge and their protection.

5. Synthesis

5.1. Pros and cons of logging residue extraction

The primary societal benefit of logging residue extraction is the provision of a low-carbon emission renewable energy source. However, the additional biomass and nutrients removed, and soils and other structures disturbed, have several potential ways of affecting ecosystem services and biodiversity, which often are negative. To weigh the pros and cons of utilizing logging residues for bioenergy is not only a question of the facts regarding implications for ecosystem services and biodiversity, but also a question of values. Different stakeholders will emphasize different aspects and thus opinions regarding how much logging residue extraction is desirable will vary.

The extraction of logging residues for bioenergy can be viewed as an intensification of production forestry, with higher biomass removal and increased machine-related disturbances than what occurs with forestry aimed solely at timber and pulp production. Consistent with this perspective, we found evidence that logging residue extraction exacerbates the negative consequences of intensive forestry with respect to soil quality, future biomass production, water quality, biodiversity associated with dead wood, and nature-related heritage. For some of these aspects, for instance water quality and biodiversity, negative effects of logging residue extraction are in many ways an extension of the disturbances associated with stem-only harvesting. For these ecosystem services, the negative effects of logging residue extraction are clear, but still likely rather small in comparison to the impact of conventional production forestry itself. On the contrary, the additional impact of harvesting slash on soil nutrient pools is comparatively larger, because there are more nutrients in slash than in stemwood. Furthermore, stump extraction may have stronger effects on the physical soil properties, since the harvesting of stumps often has larger effects on the soils in comparison to stem-only harvesting. For some aspects, the marginal effect of logging residue harvest is small compared to stem-only harvest. This is the case for the resistance to pest insects and berry production. Finally, for several aspects there are also some positive effects, such as for recreation and pest fungi control.

5.2. Various temporal and spatial scales of effects and of studies

Effects on ecosystem services are generally assessed at various temporal and spatial scales. Some effects, such as soil quality, biomass production, and nature-related heritage, can be understood by assessing them only at a stand level. For berries, reindeer herding, water quality, and recreation the effects are almost solely evaluated at the stand scale, but assessments at a landscape scale are also necessary to evaluate what the wide scale effects will mean for people using these resources. Biodiversity considerations are even more complicated by spatial aspects, because the outcomes at a landscape scale are not only the sum of the consequences at the stand-level, but are also driven by emergent landscape-scale processes. This is also the case for the related issue of mammalian game, pollinator, and forest pest populations.

Due to logistical and financial constraints, and the relatively recent origins of logging-residue extraction, short-term studies are more common than long-term studies. For some ecosystem services, short terms studies may provide adequate insights because the effects of concern are expected to primarily occur in the years immediately following extraction. Impacts on the recreational value of a stand are one example. Similarly, most of the local-scale effects on biodiversity occur a few years after extraction, though it may take many years to detect potential landscape-scale effects (Johansson et al., 2016). For soil quality, climate regulation, and biomass production we found a higher proportion of long-term studies than for the other aspects. This presumably stems from the fact that any meaningful response of these ecosystem services to logging residue extraction will take place over longer time scales. Nevertheless, even for these aspects additional long-term studies are desirable, to detect possible effects in subsequent forest generations.

5.3. Modifying logging residue extraction to minimize its negative effects

The consequences of logging residue extraction depend on which wood types are extracted, and within which forest types and localities extraction takes place. Thus, altering the specifics of what is extracted and where these activities occur may minimize the negative effects of logging residue extraction on biodiversity or ecosystem services. We have identified key related elements in this regard, but found little overlap among the ecosystem services considered (Table 1). For example, to avoid conflicts with recreation, stump extraction should not be conducted close to urban areas, but this also means that extraction is excluded from stands with the lowest transportation costs. Likewise, whereas slash extraction has less negative effects than stump extraction on dead wood-dependent biodiversity, slash extraction is more negative with respect to soil nutrient drainage and future biomass production. Additional trade-offs were identified with respect to water quality and biodiversity, as stumps in wet site conditions should be retained to preserve water quality, but from a biodiversity perspective such stumps are less valuable than those occurring in dry site conditions (Ols et al., 2013). In summary, there appears to be a need to balance the conflicting implications of logging residue extraction for different biodiversity goals and ecosystem services outcomes at a landscape level.

5.4. Compensation

Since the consequences of logging residue extraction are in several ways qualitatively similar to other forestry operations, the potential exists to compensate for the undesirable effects of logging residue extraction by modifying other aspects of forest management. For example, the ash that results from burning forest biomass can be returned to forest lands to mitigate soil acidification and increase stand productivity on some soil types (Moilanen et al., 2013), and thereby compensate for production losses from logging residue extraction. Fertilization may also be used to compensate for the effects of increased nutrient removal rates on forest growth (cf. Helmisäari et al., 2011). However, fertilizer usage in turn raises questions regarding the associated impacts on other ecosystem services.

It has been suggested that high stumps should be created to compensate the habitat loss caused by slash and stump extraction, and especially in the case of slash extraction, this can be a cost-efficient solution (Ranius et al., 2014). The number of high stumps...
needed to fully compensate for these activities is quite high however, which may explain why such compensatory actions are not occurring.

5.5. Knowledge gaps

For production forestry in the boreal zone, many studies focus on climate regulation, site productivity and water quality, while for instance pollination and provision of non-timber forest products have been much less studied (Pohjannies et al., 2017). Also for logging residue extraction, pollination and non-timber forest products have been rarely assessed. It is also notable how rarely cultural services have been studied.

In recent years, the research on environmental consequences of logging residue extraction has nevertheless been growing rapidly. As described in 5.1, short-term and stand-scale studies are more frequent than long-term and landscape-scale studies. This leaves substantial knowledge gaps with respect to the landscape scale implications for many of the issues considered, including biodiversity and several key ecosystem services, including water quality, the risks of pest and pathogen outbreaks, pollination rates, and the provision of berries, game mammals and fish. This calls for monitoring programs to assess environmental changes at landscape scales, in which logging residue extraction may be only one of several factors driving observed changes. In the interim period before long-term effects are observable in the field, simulation studies will play an important role as a means of predicting outcomes, identifying knowledge gaps and designing monitoring programs.

5.6. Conclusion

Global incentives for reducing greenhouse gas emissions are likely to increase. The use of logging residues for bioenergy involves the further intensification of disturbance regimes and extraction levels from production ecosystems. Extensive research mainly at a stand level has revealed what are potentially the most important associated risks. However, more research and monitoring is needed to understand the long-term consequences of these practices at landscape scales. In such efforts, the consequences of logging residue extraction should preferably be studied in conjunction with other potential drivers of change in production forest lands, whether part of climate change adaptation and mitigation strategies (Felton et al., 2016) or otherwise.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.12.048.

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