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Realizing the energy potential of forest biomass in Sweden – How much is environmentally sustainable? ☆

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A B S T R A C T

Harvesting of wood for bioenergy purpose will probably increase in importance in the future, in order to replace fossil fuel. However, the environmental impact of increased harvesting might be considerable, e.g. on soil and water chemistry, biodiversity and long-term productivity, and in this study we investigate thresholds for sustainable harvesting volumes. The study is based on scientific reviews of the impact of harvesting of logging residues (slash and stumps) on forest production, biodiversity, acidification, eutrophication and toxic substances. We define sustainability by using environmental objectives decided by the Swedish parliament (which are based on the Aichi targets), and relate the harvesting impact to these objectives within different harvesting scenarios, by using expert judgment. We demonstrate that an increase in harvesting of logging residues by 2.5 times might be sustainable. However, we also identify a number of risks and the sustainability depends on a number of requirements that should be fulfilled, such as ash-recycling. It was found that factors related to biodiversity conservation (defined in the goals 'Sustainable Forests' and 'A Rich Diversity of Plant and Animal Life') were limiting factors both for slash- and stump harvesting, and that risk of acidification (defined in the goal 'Natural Acidification Only') also limit slash harvesting. We also include harvesting of brushwood and energy wood from conservation cutting in the discussion, since these assortments might be important in the future.

1. Introduction

Increased use of energy from renewable sources (e.g. wind, solar and biomass), in combination with energy savings, is considered to be an important part of steps aimed at reducing greenhouse gas emissions (Börjesson et al., 2017; EU Directive 2009/28/EC). In this paper we assess the environmental impacts of primary (trees or tree parts that previously had no industrial use) biomass harvesting in Sweden, particularly biomass harvested for bioenergy purposes from forestland (forest fuel originating from plantations or semi-natural forests), as well as short rotation forestry (SRF), and wood from overgrown agricultural land. In Fennoscandia, the main source of biomass besides industrial residue products (e.g. shavings, sawdust and bark), are residues from clear-cuts and thinnings in the form of slash and stumps. This more intense harvesting may have tangible impacts on a number of environmental issues related to forestry.

Sweden has a long history of large-scale, industrial forestry and agriculture. Forestry in Sweden is regulated by the Swedish Forestry Act, and the Swedish Environmental Code, as well as by the Forestry Policy, which includes goals for high levels of sustainable production and environmental values. Land use has been combined with conservation in set-aside nature reserves, and in voluntarily set-aside habitats and structures, and environmental considerations must be taken into account in connection with all forestry activities. Today, forestry is important, not only for the supply of timber and pulp-wood, but also for the production of biomass for bioenergy, such as slash and stumps. However, at present, only a relatively small proportion of the slash and an even smaller proportion of the stumps are harvested annually (Table 1). On farmland, food production is concentrated in the most productive areas, while other areas, such as meadows and pastures are

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Table 1
Land cover in Sweden, in 1000 ha, and forest area with different management (Swedish Forestry Agency, 2014a,b).

Land cover		Area, 1000 ha		Proportion (%)	
Agricultural land		3409		8	
Water		4015		9	
Other land		9044		20	
Forest		28,276		63	
	Protected forest area		1978		7
	Voluntarily set-aside area		1112		4
	Unproductive forest area[a]		2995		11
	Remaining area for forest production		22,191		78
Total area		44,744	28,276	100	100
Management			Annual area of forest management, 1000 ha yr^{-1}		
Notified[b] final felling			239		
Commercial thinning			450		
Notified[c] slash harvest			118		
Notified[c] stump harvest			2		
Short rotation forestry[d]			11		

[a] Forest land producing <1 m^3 ha^{-1} $year^{-1}$.
[b] Final felling has to be notified (reported) to the Swedish forestry agency if larger than 0.5 ha.
[c] The realized harvested area is lower, but data are missing.
[d] On agricultural land.

successively abandoned and overgrown with brush-wood and trees, or used for other purposes, such as short-rotation forestry (SRF). In this industrial landscape there are also habitats that are difficult to manage (waste-land) with biomass of only minor commercial interests (e.g. brush-wood and dead wood). The forestry industry has mainly been harvesting semi-natural forests with relatively long rotation periods, instead of intensively managed plantations, and less important trees and habitats have been left for conservation purposes. However, as the biomass market grows, all land and all biomass might become of interest. More intensive harvesting in forests and agricultural areas is likely to have an impact on soil and water quality and biodiversity, and consequently the pressure on the ecological systems is likely to increase. The decision to increase the amount of biomass harvested therefore needs to be considered carefully. Recent research has focused on the environmental impact of biomass harvesting, including a number of synthesis papers (Egnell et al., 2006; Dahlberg et al., 2011; Thiffault et al., 2011; Bouget et al., 2012; Helmisaari et al., 2014; de Jong et al., 2014; Achat et al., 2015; Berch et al., 2015).

Different kinds of forest management have an impact on different environmental factors. This impact can be considered as negative or positive depending on the management goals and the basis of the evaluation. In general, most people agree that a disturbance owing to legally approved forest management is acceptable as long as that disturbance is in accordance with the long-term sustainable use of the forest resource. However, the concept of sustainability is complex, with many different definitions and components (Holden et al., 2014). Sustainability includes social, economic and environmental dimensions (WCED, 1987), and the forest principles adopted at UNCED (1992) are generally accepted as guidelines for sustainability. To define a useful concept of sustainability that can be evaluated, we need to provide much more detail about what 'sustainability' means. However, as the description of sustainability becomes more detailed, this increases the conflict between proponents with different opinions. Sustainability is a social concept, based on values. In this assessment we focus only on the environmental aspect of sustainability, and we define the concept in relation to democratically agreed objectives for the environment, decided by the Swedish parliament (Government Offices of Sweden, 2016).

Sweden has 16 environmental quality objectives (EQOs) (http://www.miljomal.se/sv/Environmental-Objectives-Portal/). In general, most of these objectives are based on the Aichi biodiversity targets (https://www.cbd.int/sp/targets/) decided by the Convention on Biological Diversity, and they form part of the implementation of biological diversity targets in Sweden. More specifically we use the following environmental objectives: 'Natural Acidification Only' (objective no. 3), 'A Non-Toxic Environment' (objective no. 4), 'Zero Eutrophication' (objective no. 7), 'Sustainable Forests' (objective no. 12), and 'A Rich Diversity of Plant and Animal Life' (objective no. 16). Each of the objectives includes a number of more detailed specifications and indicators to make the objectives useful for evaluating sustainable harvesting in forests. There is also a time-dimension which is defined as the 'Generation goal' in which the government state that 'the basic conditions for solving the environmental problems we face are to be achieved within one generation'. One generation means about 25 years. However, the response of the biological systems varies depending on type of management and ecosystem. Even if the basic conditions for the goal 'A Rich Diversity of Plant and Animal Life' will be achieved within 25 years in the forest landscape (e.g. creating high-quality habitats) it will take at least one rotation periods until the whole landscape is affected. In this assessment we consider any harvesting that reduces the possibility of achieving the environmental objectives as 'excessive environmental impact' because the management is not environmentally sustainable in relation to the goals.

There is no specific environmental objective for forest production. However, forest production is included in the 'Sustainable Forest' objective and long-term sustainable forestry over multiple rotation periods is a specific goal of the Forestry Policy of Sweden. Therefore, in this analysis, we also assess the impact of increased harvest intensity on long-term forest production. There is also an objective on greenhouse gas emission (GHG), 'Reduced Climate Impact' (objective no. 1): this objective is not included in the assessment because decreasing GHG emissions is the underlying reason for using bioenergy (Cintas et al., 2017), although its GHG mitigation potential have been questioned (Haberl et al., 2012).

The primary objective of this synthesis was to assess possible thresholds for sustainable harvesting of biomass for energy purposes in Sweden, based on reviews in this issue of *Forest Ecology and Management* that examine the environmental impact of biomass harvesting (Egnell, 2017; de Jong and Dahlberg, 2017; Löfgren et al., 2017; Olsson et al., 2017) together with different harvesting scenarios, and by relating this to the EQOs. The impact of harvesting different types of biomass that are less commonly used for energy production, such as brushwood and SRF is also discussed. By comparing the potential energy output of different harvesting scenarios we investigate the sustainable energy potential of biomass from managed Swedish forests. We have assessed only the superimposed impact on the environment that could occur as a result of the complementary harvest of slash and stumps for the bioenergy market. Traditional forestry and agriculture already have tangible environmental impacts without additional biomass harvest for energy. In the future, not using bioenergy from forests is also likely to have an environmental impact. If so, other types of renewable or non-renewable energy sources, with their associated environmental impacts, would be used. However, we have not included this alternative in our analysis, but restricted it to the environmental impact of bioenergy biomass harvest from forestland and farmland.

2. Assessment approach

Data collected in 2013 (Swedish Forestry Agency, 2014a,b) indicate that slash from clear-cuts and thinnings (Table 1) are the most important primary biomass for energy in Sweden. Therefore, we have conducted a more detailed analysis to estimate sustainable harvesting quantities of slash. As the size of the biomass market increases, stumps are likely to become more important as a source of biomass in the future and, therefore, stumps were included in the assessment. Brushwood on abandoned agricultural land and SRF were also included in the discussion.

2.1. Harvesting of logging residues and stumps from clear-cuts, and slash from thinning operations

The impact of more intense harvesting practices differs depending on harvesting volume, the type of biomass, and from where in the landscape the biomass is harvested, as well as on a number of other factors. To be able to assess the impact of these different variables on the environmental sustainability of harvesting, we considered a range of different harvesting scenarios in our analysis (Table 2). To estimate the environmental impact of the different scenarios in relation to the EQOs, we invited 40 specialists to attend to two workshops to give their expert opinion (Perera et al., 2011, Appendix A). Invitations to participate in the discussion were sent not only to Swedish researchers working on projects of relevance to biomass harvesting and its environmental impacts, but also to former researchers working at authorities and organizations involved in forestry and environmental issues.

First, a literature review, based on recent research (de Jong et al., 2014), was sent to all the specialists. A workshop was then convened at which the specialists were divided into small groups based on their area of expertize: that is, biodiversity and conservation, forest production and management, acidification and eutrophication, and toxic substances. Within each group, the impact of the different harvesting scenarios was discussed in relation to the EQOs. The different scenarios were categorized as either scenarios that would increase the likelihood of achieving the objective, scenarios that would decrease the likelihood of achieving the objective, or scenarios that would have no impact on the likelihood of achieving the objective. The designation of a scenario into one of these three categories was based on both 'hard-facts' collated from the literature review and other sources, such as the threshold values for population decrease at the landscape level of different species groups in relation to harvesting scenarios and, in the absence of 'hard-facts', on expert opinion. All the specialists then met for a plenary session to agree on their estimates and, if necessary, to adjust the predicted outcomes of the various scenarios. The outcome of this workshop was sent out to a broader group for comments and suggestions.

Table 2
Predicted annual bioenergy potential in harvested slash and stump biomass (assumed energy content 17.6 GJ per Mg dry matter) for different biomass harvest intensity scenarios in Swedish forests. The harvesting of slash during both final fellings and thinnings is assumed, whereas stumps are harvested during final felling only. The harvested proportion of available biomass is based on the assumption that 30% of available biomass would remain on the harvested site, primarily owing to technical constraints. Figures based on data from the National Forest Inventory and assessment of future harvest levels 2010–2019 in a business as usual scenario (Swedish Forest Agency, 2014a).

Biomass type	Proportion of harvested area in the landscape, in which additional biomass for energy use is harvested (%)		Proportion of total available biomass in the landscape harvested for energy use (%)		Energy potential (PJ yr^{-1})	
	Slash	Stumps	Slash	Stumps	Final fellings only	Final fellings and thinnings
Slash and stumps	80	30	56	21	112	155
	60	30	42	21	94	126
	40	30	28	21	76	97
	80	20	56	14	101	140
	60	20	42	14	83	112
	40	20	28	14	61	83
	80	10	56	7	86	130
	60	10	42	7	68	101
	40	10	28	7	50	72
Slash only	80	0	56	0	76	115
	60	0	42	0	58	86
	40	0	28	0	40	58

A second workshop was convened with almost the same group of experts as the first workshop, to discuss under what kind of restrictions the results were valid. A second discussion dealt with possible compensatory measures that would enable additional biomass to be harvested for energy without jeopardizing the EQOs. The outcome of these discussions were discussed by all the specialists, and some adjustments were made to increase the compatibility between the different EQOs.

2.2. Scenarios used in the analysis

For technical reasons some slash and stump biomass remain on site in practical harvest operations. In all the scenarios discussed here we have assumed a 70% stand level extraction rate of the potentially available biomass of both slash and stumps. However, at the landscape level, the proportion of cut-blocks with additional harvesting of logging residues ranged between 40% and 80% for slash, and between 0% and 30% for stumps (Table 2). Thus, the total proportion of harvested biomass compared with available biomass in the landscape varied between 28% and 56% for slash and between 0% and 21% for stumps.

Table 2 shows the estimated energy potential of harvested logging residues (slash and stumps) according to the different harvest intensity scenarios used for assessing the environmental impact. The energy potential estimates are based on predicted stem-wood harvest levels between 2010 and 2019 in a 'business as usual' scenario according to the latest assessment of the future harvest potential in Swedish forests, SKA15 (Swedish Forest Agency, 2015). These assessments are based on data from the National Forest Inventory and empirical models used to estimate forest growth, including mortality and harvest levels. In short, the business as usual scenario assumes that current forest management practices continue. This includes annual harvest levels that are below the annual growth and silvicultural ambitions that are similar to current practices. It was assumed that stumps were harvested in clear-cuts only, whereas it was assumed that slash was harvested in both clear-cuts and in thinnings. The assumed energy content of the harvested biomass in slash and stumps was estimated to be 17.6 GJ per ton dry biomass.

Based on these estimates, the energy potential of the different biomass harvesting scenarios range from 40 PJ yr^{-1} for the least intensive biomass harvest scenario to 155 PJ yr^{-1} for the most intensive biomass harvest scenario (Table 2). From an energy production point of view, it is important that the biomass harvest intensity can be maintained at high levels without violating the EQOs. In the following sections, we summarize the outcome of the experts' discussion and define the levels at which biomass can be harvested for bioenergy while maintaining the sustainability of Swedish forests from an environmental perspective.

3. Outcome of expert opinions and synthesis

3.1. Forest production

Forest production in the northern temperate and boreal forests of Sweden is limited by nutrient availability, primarily by nitrogen (N) (Tamm, 1991), as well as by phosphorus (P) availability in more fertile till soils (Giesler et al., 2002), whereas P and potassium (K) availability limit growth in forested peat soils (Moilanen et al., 2013). Repeated fertilization is therefore a silvicultural practice that can result in a sustained increased growth in these forests (Bergh et al., 2014). The amount of nutrients that are available could be affected in several ways by slash and stump harvest. Compared with stumps and stem-wood, slash contains relatively large amounts of nutrients (Mälkönen, 1972; Iwald et al., 2013). Thus slash harvest results in the direct loss of the nutrients in the slash from the site which potentially will lead to reduced forest production, an issue early discussed in nutrient budget evaluations of whole-tree harvesting (Mälkönen, 1972; Weetman and Webber, 1972; Boyle et al., 1973; Kimmins, 1977). If slash is left in the forest it could have a mulching effect, keeping competing vegetation away and could possibly also increase the mineralization rates of nutrients tied up in organic compounds (Emmett et al., 1991). Residual biomass left after stem-wood harvest is also a carbon source that is exploited shortly after harvest by decomposers. As a result, available N could be immobilized in decomposer biomass, meaning that there is temporarily less N available for the subsequent tree crop. Furthermore, coarse biomass, such as a stump, decomposes slowly and, therefore, immobilizes N for a long period (Palviainen et al., 2010; Bergholm et al., 2015). Stump harvest also causes a similar type of soil disturbance as that caused by mechanical site preparation by eliminating competing vegetation. This could have a positive impact on nutrient availability for the subsequent tree crop – at least during the establishment phase. Furthermore, this soil disturbance seems to have a positive effect on natural regeneration – primarily by pioneer species such as birch (*Betula* spp.) and pine (*Pinus* spp.) (Tarvainen et al., 2015). This, together with the fact that stump biomass is less nutrient rich compared with slash (Hellsten et al., 2013), could be the reason why stand productivity in the subsequent stand seems to be unaffected or even stimulated by stump harvest (Egnell, 2016). There are more factors that could affect nutrient availability and growth of the subsequent tree crop following logging residue harvest in a clear-cut than in a residual stand following logging residue harvest in thinnings. This could be the reason why the production loss tends to be more consistent following slash harvest in thinnings than following slash harvest in clear-cuts (Helmisaari et al., 2011).

Stand productivity following clear-cut is not only affected by the site productivity, which is primarily limited by nutrient availability, but also by regeneration success, tree species, stem density, and silvicultural measures. This includes factors such as microclimate, pathogens, browsers, seedling survival, and recruitment through natural regeneration (Nilsson et al., 2010). This could be crucial for stand productivity in an individual stand. However, the empirical data suggest that the impact of slash and stump harvest on seedling survival is moderate (Egnell, 2017), although recruitment of natural regeneration could be favoured by the soil damage caused by slash and stump harvest (McInnis and Roberts, 1994; Saksa, 2013; Hyvönen et al., 2016). Furthermore, in practical operations the efficiency and quality of mechanical site preparation may be improved if residual biomass is also harvested (Saarinen, 2006).

Ash recycling following slash harvest is recommended by the Swedish Forest Agency (2008), primarily to mitigate soil acidification. A review of ten field experiments on till soils showed that stand productivity was not significantly affected by ash recycling on any of the sites (Jacobson et al., 2014). However, poor sites tended to show a small productivity loss and more productive sites tended to show a small gain. Following slash harvest on peat soils, ash recycling or other types of nutrient compensation are prerequisites to sustain stand productivity (Huotari et al., 2015).

Given the condition that no fertilizer is applied to compensate for nutrient losses, the assessment of the sustainability of forest production at the different harvest intensity levels indicated that slash and stump harvest at final felling would be likely to limit forest production only when slash is harvested from a greater area than 80% of the total annual area finally cut in the country, and that stump harvest could go beyond the maximum intensity assessed (30%) without limiting forest production. However, harvesting slash from thinnings is predicted to negatively affect forest production. This assessment has some evidence base – but opinions from the expert group have had a strong impact on the outcome. For slash harvest in thinnings most studies show no effect or reduced growth, thus, the judgement was that negative effects should be expected over all sites in a managed forest landscape. The ambiguous empirical evidences from slash harvest in final felling suggest that slash harvest could be sustainable on a majority of site types. But, when slash harvest is practiced on a substantial part of the annual clear-cut area in Sweden (80% or more), the expert group recommended suggesting that stand productivity would be negatively affected. The basis for this recommendation is that at these intensities sites unsuitable for slash harvest would also be targeted. This includes sites with fine textured, moist or wet soils or frost-prone sites where slash harvest may cause regeneration problems (based on data from the Swedish National Forest Inventory, Per Nilsson, pers.com., http://www.slu.se/en/Collaborative-Centres-and-Projects/the-swedish-national-forest-inventory/). The direct forest productivity effect of the moderate stump harvest intensity assessed here ($\leqslant$30% of the annual clear-cut area) is, based on the limited empirical evidence available, assumed to be negligible. Any changes in forest owners behaviour as a response to new market opportunities has not been taken into account in this assessment.

There is ambiguous evidence suggesting that poor sites are more sensitive to harvesting than more fertile sites (Egnell and Leijon, 1999; Fleming et al., 2014). Thus, leaving poor sites would not change the picture. Nutrient compensation counteracts the growth loss in thinnings (Helmisaari et al., 2011). This supports the view that the negative effects on forest production resulting from more intense harvests are largely due to reduced nutrient availability. Given that nutrient availability explains much of the production loss, it is easy to compensate for by fertilization. This includes conventional fertilization with N primarily, but also ash recycling on peat lands and on more fertile till soils. In the latter case, ash should preferably be combined with a N-fertilizer. Long-term depletion of carbon and associated effects on tilth, water holding capacity, and nutrient storage were not considered as issues relevant for forest production in the long-rotation forestry practiced in Sweden at northern temperate to boreal climate conditions. The rapid removal of harvested biomass, which would speed up regeneration measures, together with genetically improved seedlings and/or fast-growing tree species could also counteract growth losses owing to slash and stump harvest. All these counteracting measures could also be performed when slash and stumps are not harvested, giving a new production level baseline for the reference case.

Another way of reducing the negative effects on forest production is to target stumps rather than nutrient-rich slash and to focus more on slash harvest in clear-cuts rather than in thinnings. A harvesting technology that left most of the nutrient-rich foliage in the forest would also be beneficial (c.f. Egnell and Leijon, 1999). If the increased natural regeneration following stump harvest is accepted as a crop, and thereby contributes to production in the subsequent stand, it could counteract productivity losses. However, using the currently available harvesting technology, stump harvest is more expensive than slash harvest, suggesting that in practice slash would be targeted before stumps. Furthermore, natural regeneration also includes less commercial tree species that often are removed during cleaning. Finally, although these suggested measures to maintain forest production may increase the biomass harvested for energy purposes, they also need to be considered in the light of other sustainability issues.

3.2. Environmental objectives: "Sustainable Forests" and "A Rich Diversity of Plant and Animal Life"

The EQOs 'Sustainable Forests' and 'A Rich Diversity of Plant and Animals' state that 'Biological diversity must be preserved', 'Species habitats and ecosystems and their functions and processes must be safeguarded' and that 'Species must be able to survive in long-term viable populations with sufficient genetic variation' (http://www.miljomal.se/sv/Environmental-Objectives-Portal/). This means that forestry, including biomass harvesting for energy, must be combined with viable populations of all species. At the landscape level, the status of threatened species must be improved. The most important factors affecting these species are the composition of forest habitats, the abundance of crucial resources, the continuity of resources and connectivity at the landscape level (Sverdrup-Thygeson and Lindenmayer, 2003).

Forests with high conservation values are unevenly distributed in the landscape. In areas with a high proportion of old forests with long continuity and high connectivity in the landscape, the conditions are better for maintaining conservation values. The opposite is true for landscapes with a long history of forests managed primarily for forest production, including regular clear-cutting, cleaning and thinning (Olsson et al., 2012). The environmental objective is more likely to be achieved if biomass is primarily harvested in well-managed forests, while forests with conservation values remain extensively managed. This means that with regulation at the landscape level, including strategic landscape planning, the potential for sustainable bioenergy harvesting would be high. However, in general, the potential for landscape strategies are limited and the decision to harvest depends on other factors such as proximity to industries, infrastructure, land-owner's interest, and other market factors. In this analysis we therefore assumed that all kinds of production forests might be affected, which lower the potential for sustainable harvesting.

Another important factor affecting sustainability is the kind of biomass that is harvested. Few red-listed species are adapted to slash from spruce (*Picea abies*), and the situation is similar for pine (*Pinus sylvestris*), whereas slash from deciduous trees is more complicated because a number of red-listed species are adapted to different qualities of slash from deciduous trees (de Jong and Dahlberg, 2017). By restricting harvesting of logging residues to coniferous forest, and by only focusing on the dominating tree-species in the landscape, any potential negative impact should be minimized. However, there are acceptable exceptions. In well-managed stands of, for example, oak (*Quercus* spp.) or beech (*Fagus silvatica*), it might be possible to harvest slash and small diameter trees of the dominant tree-species.

Harvesting of logging residues might also affect other substrates or habitats, such as snags, logs and groups of trees that are left at clear-cutting in order to achieve conservation objectives (Rudolphi and Gustafsson, 2005). When harvesting logging residues there is a risk that all kinds of substrates are included. There is also a risk of increased soil damage when collecting the wood substrate.

Increased harvesting of logging residues would decrease the total volume of dead wood. If the wood that is removed mainly consists of thin branches and the tops of spruce or pine, with a relatively low quality for biodiversity, the biodiversity cost is probably low. Nevertheless, a decrease in dead wood volume is likely to have a negative effect on biodiversity. One solution might be to compensate for the removal of low-value dead wood with some high-value dead wood, e.g. high-stumps and coarse woody debris (CWD). A study by Ranius et al. (2014) demonstrated that this strategy would be beneficial for conservation and would increase the sustainable harvest potential. However, no practical guidelines for how such compensation might be carried out have been developed, and the most realistic scenario is that the loss of dead wood harvested for bioenergy not will be compensated by CWD.

Based on assumptions above (planning will not be carried out at a landscape scale, primarily biomass from spruce and pine is harvested, conservation considerations are not negatively affected, and conservation measures are not increased to compensate for harvesting) and recent studies (e.g. Johansson et al., 2016; de Jong and Dahlberg, 2017), the expert group concluded that the risk of species extinction increases when slash harvest is practiced on more than 50% of the clear-cuts in the landscape, thus the environmental goal will be more difficult to achieve. For stumps, the threshold value might be as low as 10–20%, depending on the species composition in the landscape, and where in the landscape the harvesting occurs (Table 3, Appendix B). The extinction risk of rare specialist species increases to 50% when 20% of the stumps are harvested. When the stump harvest increases to 30% of the clear-cuts in the landscape, common specialist species are also affected (Johansson et al., 2016). By concentrating the harvest in landscapes and substrates with few specialist species, the impact of harvest on rare species should be less, especially for rare dispersal-limited species.

Table 3
Limiting criteria for Swedish forestry according to the assessment and based on production and environmental targets related to slash and stump harvest. For each target, the intensity levels are related to a number of assumptions, which are described in the text. The most important assumption is found in the Comment column.

Target	Limiting criteria at landscape levels	Comment
Forest production	(A) Final felling: limitations only at high (>80%) harvest intensity (B) Final felling + thinning: Limitations at all harvest intensities	No fertilization to compensate production loss
Sustainable forestry (biodiversity)	(A) Slash harvest: acceptable at harvest intensities below ca 50% of final fellings (B) Slash and stump harvest: acceptable at harvest intensities 50% slash and 20% stumps, of final fellings	Based on the assumption that mainly coniferous wood is used Loss of wood substrate for organisms is limiting in particular at stump harvest
A non-toxic environment	Acceptable at harvest intensities below ca 80% slash and 30% stumps of final fellings	
Natural acidification only	Acceptable at harvest intensities below ca 50% slash of final fellings	Ash recycling according to recommendations
Zero eutrophication	No limitation	Slash harvest may reduce N leakage, stump harvest may act in the opposite direction

3.3. Environmental objective: 'Natural Acidification Only'

Three of the specifications related to the EQO 'Natural Acidification Only' (Swedish Environmental Protection Agency, 2016) are to ensure that: (1) the contribution of land use to the acidification of soil and water is counteracted by adjusting forestry to the acidification sensitivity of the site; (2) independently of liming, lakes and watercourses achieve at least good status regarding acidification in accordance with the Water Quality Management Ordinance (The Swedish Code of Judicial Procedure: SFS 2004:660, http://www.riksdagen.se/en/); and (3) the acidification of soils does not accelerate corrosion of technical material and archaeological objects in the soil, and does not harm the biodiversity of land and surface water ecosystems.

Compared with stem-only harvest, extraction of slash and stumps diminishes the return to the soil of basic compounds that are bound to these tree parts. The effects are largest after slash harvest because the base cation concentrations, charge balancing organic acid anions, are much higher in branches and needles compared with those in the stumps (Hellsten et al., 2013; Iwald et al., 2013). Hence, from an acidification and energy point of view, it is more attractive to harvest stumps (Iwald et al., 2013). The acidification effects on pH in soils and waters would vary tangibly in space and time. Historically accumulated organic carbon, partly stored as protonated organic acids, is the most important factor for creating variations in soil pH (Binkley and Högberg, 2016). In surface waters, the pH variation is generally determined by the buffer capacity created by soil derived weak organic acids and bicarbonate (Löfgren et al., 2017). Compared with stem-only harvest, the short-term effects are likely to be diminished alkalinisation for a few decades after harvest, followed by a slightly more acidic status until next harvest. In surface waters, small effects are expected and mainly in the most acid-sensitive systems (Löfgren et al., 2017).

Acidification effects of slash harvest in soils and soil water, particularly in the form of reduced base cations, have been documented in field trials (Thiffault et al., 2011; Achat et al., 2015). Long-term experiments show that the effects on soil and water diminish over time and that statistically significant differences have in some cases disappeared after approximately 30 years (Zetterberg et al., 2013). Model and mass balance estimates often show larger effects than empirical data from experiments, indicating that there are feed-back mechanisms in the ecosystem that were not taken into account in the models (Paré and Thiffault, 2016; Zetterberg et al., 2016).

Similar experimental data are lacking for surface waters; however, based on model simulations and theoretical considerations, Löfgren et al., 2017) conclude that the acidification effects related to slash harvest diminish along the hydraulic flow path from a harvested stand and downhill to a stream. In the short-term, differences are likely to be seen in soil water but they are likely to be very small in most surface waters.

Studies have highlighted the potential importance of sea-salt deposition for the acidification sensitivity of surface waters (Löfgren et al., 2017). A high flux of sea-salt through the soils gives a stronger coupling between acidity accumulated in solid matter and soil solution owing to the increased ionic strength (Gustafsson and Kleja, 2005). In the long-term perspective (multiple forest generations), surface water acidification related to slash harvest may occur, particularly in catchments in south-western Sweden with high sea-salt deposition and soils generating alkalinity (bicarbonate) during part of the year (Löfgren et al., 2017). In permanently acid forest streams, the effect of slash harvest is probably negligible. At water body level (i.e. the spatial units used by water authorities: related to EQO-specification 2, the acidity status is generally more influenced by other types of land cover and land use, making it difficult to determine the effects of slash harvest (Ågren and Löfgren, 2012).

The soils at stand level are therefore the most sensitive spatial units where slash harvest acidification effects should be judged (EQO-specifications 1 and 3). If no compensatory measures are taken, acidification is potentially most pronounced at this level, becoming less important the further away from the stand the discharging water flows. Furthermore, the acidification effects diminish over time because the differences between stem-only harvest and slash harvest become smaller.

To counteract acidification effects on soils and waters, the Swedish Forest Agency (2008) recommends wood-ash recycling when the net removal of basic compounds in slash corresponds to more than 0.5 ton ash/ha. Below this threshold, the acidification effects are assumed to be so limited that compensation measures are not needed (Swedish Forest Agency op. cit.). Additionally, from pure economic reasons and due to lack of net-income to the forest owner, there are very few low-quality stands where slash is harvested. Potential conflicts with the environmental quality objective '*Natural acidification only*' are thereby kept at a minimum at these poor sites. Generally, wood-ash recycling has immediate effects on pH and base saturation in the humus layer and after some years also in the mineral soils (Reid and Watmough, 2014). Wood-ash recycling may also increase the buffer capacity in surface waters. There are few wood-ash recycling experiments where the effects on surface waters have been studied, but available results indicate that the effects are small at the currently recommended maximum dose of 3 ton ash/ha or up to 6 ton/ha during a forest generation (Swedish Forest Agency, 2008). Higher doses than recommended, as well as treatment of riparian zones, may increase the effects on surface waters (Tulonen et al., 2002; Löfgren et al., 2009; Norström et al., 2011; Johansson, 2014).

If wood-ash recycling is performed according to the recommendations by the Swedish Forest Agency (2008), the expert judgement was that the environmental quality objective '*Natural acidification only*' should be achieved in all scenarios (Table 2). This presupposes that ash of good quality is available in the amounts necessary for all scenarios. According to estimations from 2013, about 300,000 ton ash can be produced annually, if ashes where the Zn, P and K concentrations are a bit lower than the target values and the Cr concentrations are a bit higher than the target levels, are accepted (Monica Lövström, Swedish EnergyAshes, pers. com.) The amounts vary between years, depending on the market situation for bioenergy products such as slash, and due to the current market situation the estimated amounts of ash annually produced can be expected to be a bit lower at present. 300,000 ton ash would enable approximately 100,000 ha of clear-felled forest to receive the recommended dose of 3 ton/ha. However, the clear-felled area amounts to approximately 200,000 ha annually (Table 1), placing limitations on the ability to achieve this EQO at the national level at high harvest intensity scenarios (Table 2). Theoretically, the ash production is enough to compensate and allow for whole-tree harvesting (WTH) of approximately 50% of the clearfelled area. In 2014, the area notified for slash harvesting was approximately 105,000 ha, out of which only ca 50% in reality was slash harvested (www.skogsstyrelsen.se/en/AUTHORITY/Statistics/). Besides ash production limitations, there are also logistical problems as well as the problem of polluted ash being mixed in with the wood ash, further restricting the possibilities for wood-ash recycling. Thus, the expert recommendation was that it would be important to prioritize wood-ash recycling in the most acid-sensitive areas. In areas were the use of wood-ash is constrained, other forms of base compensation, such as liming, could be taken into consideration.

3.4. Environmental objective: '*Zero Eutrophication*'

According to the environmental objective '*Zero Eutrophication*', 'Nutrient levels in soil and water must not be such that they adversely affect human health, the conditions for biological diversity or the possibility of varied use of land and water'. Thus, the objective covers both eutrophication of soils caused by high nitrogen loads (deposition or fertilization) and eutrophication of surface waters caused by nitrogen and phosphorus leaching from land use and point sources. The risks related to forest management mainly relate to the risk of nitrogen leaching to surface waters (Kreutzweiser et al., 2008; Löfgren et al., 2014), and, therefore, we have focussed on that aspect. Effects both on soil water (stand level) and surface water (landscape level) are evaluated (Appendix B).

Agricultural activities and point sources such as sewage treatment plants are the main anthropogenic sources of nitrogen in Swedish surface waters, whereas the effect of forest management is limited (7% of the Swedish anthropogenic nitrogen loads on the Baltic Sea, Brandt et al., 2008). The nitrogen leaching from forest management may be affected by harvesting intensity, by soil disturbances related to management practices and by wood ash recycling, if the latter induces nitrification (Kreutzweiser et al., 2008).

Two to three times more nitrogen is removed by harvesting slash compared with harvesting stems (Olsson et al., 1996). Stump harvesting also increases the removal of nitrogen; however, the nitrogen content of stumps is considerably lower than that of slash (Hellsten et al., 2013). The increased nitrogen removal creates a 'nitrogen relief' (Akselsson and Westling, 2005) that may lead to both less nitrogen leaching after clear-felling and less nitrogen accumulating in forest soils. Ring et al. (2015) studied the effect of different slash harvest intensities on nitrate concentrations in soil water at two sites. The results were ambiguous: lower concentrations of nitrate tended to occur at higher harvesting intensities at one site, but not at the other site.

Stump harvesting may increase the risk for nitrogen leaching as a result of soil disturbances connected to harvesting, influencing the decomposition of organic matter and vegetation cover. This has been experimentally documented for both soil water (Staaf and Olsson, 1994) and surface water (Eklöf et al., 2012). However, model and mass-balance studies also indicate that stumps and roots can be important nitrogen sinks, which may decrease the risk of nitrogen leaching after stump harvesting (Bergholm et al., 2015; Hyvönen et al., 2012). However, to date, this has not been demonstrated empirically. Further field measurements are required to quantify possible effects.

Wood ash recycling does not affect the nitrogen input to the system, since the nitrogen amounts in wood ash are very small. However, wood ash recycling may affect pH, and thus mineralization of nitrogen and nitrogen leaching. In general, wood-ash recycling experiments performed in newly planted or growing forests in Sweden have not reported increased nitrogen concentrations in either soil water (Ring et al., 2006; Wang et al., 2010; Arvidsson and Lundkvist (2003) or surface water (Norström et al., 2011). Westling et al. (2004) found elevated nitrogen concentrations in soil water when wood ash was applied directly after clear-felling on soils lacking ground vegetation. When vegetation recovered, the same sites did not exhibit elevated nitrate leaching 3–7 years after treatment. According to the recommendations by the Swedish Forest Agency (2008), clear-felled areas without vegetation should not be treated with wood ash.

In addition to the findings of these research studies, a number of assumptions were taken into account during the scenario discussions. The assumptions were that: (1) nitrogen fertilization is performed according to the Swedish Forest Agency recommendations (Swedish Forest Agency, 2014b), which means regionally defined maximum doses and no optimized fertilization according to Bergh et al. (2008); (2) wood-ash recycling is performed according to the Forest Agency recommendations (2008) (i.e. not on non-vegetated areas directly after clear-felling); and (3) lakes and streams are surrounded by vegetated buffer zones where no intense forest management practices (e.g. transport, stump harvesting, fertilization, or wood-ash recycling) are performed.

Based on these assumptions, harvesting of slash and stumps were judged to have no or slightly positive effects on the environmental objective '*Zero eutrophication*'. Harvesting may reduce the risk of nitrogen leaching through the removal of nitrogen, but the disturbance caused by stump harvesting may increase the risk. The risk of enhanced nitrogen leaching due to wood-ash-induced nitrification was assumed negligible.

In the scenarios with slash harvesting but no stump harvesting (Table 2), the short-term net effect was assumed to be a slight lowering of the nitrogen concentrations in soil water due to the nitrogen relief. In the scenarios with both slash and stump harvesting the positive effect of slash removal and the negative effect of stump harvesting were judged to be of equal importance, thereby having no net effect on the nitrogen concentration in soil water. The effects on surface waters were assessed to be negligible for all scenarios (Appendix B).

3.5. Environmental objective: 'A Non-Toxic Environment'

Harvesting biomass for energy purposes in conventional forestry and recycling of wood ash can influence the loads, fluxes and availability of heavy metals and other harmful substances in the forest environment. However, these issues are not covered by one EQO but by three. The EQO 'A Non-toxic Environment' primarily focuses on fluxes of harmful chemical products in society, with marginal focus on toxic substances in the forest environment, except for the accumulation of lead in forest humus. The EQO 'Sustainable Forests' has several focus areas, of which one is the functional integrity of forest soils, and includes the issue of mercury methylation and transport of methylmercury to surface waters and aquatic food-chains. The EQO 'A Safe Radiation Environment' covers recycling of ^{137}Cs-contaminated wood-ash in forests, which became an issue after the Chernobyl nuclear power plant accident in 1986. For simplicity, all these issues are considered here under the heading 'A Non-toxic Environment'.

Mercury has accumulated in Swedish forest soil owing to long-term deposition from natural and anthropogenic sources. Although deposition of Hg has decreased, the strong retention of Hg in the soil (Aastrup et al., 1991) has caused Hg concentrations in the soil to persist at a high level. In addition, methylation of inorganic Hg, which can take place in both soils and waters, produces an organic form of Hg, methylmercury, which is a highly toxic and bioavailable form of Hg. Transport of methylmercury to surface waters and assimilation in aquatic food-webs results in elevated concentrations in predatory fish such as perch and pike. The concentration of methylmercury in freshwater fish in Sweden has decreased by 20% from a peak level between 1965 and 2001, and the decrease has been most pronounced in southern Sweden. Nevertheless, the threshold value for Hg in fish for human consumption set by the World Health Organization (0.5 mg kg^{-1} Hg in fish muscle tissue) was still exceeded in fish in more than 50% of the lakes in Sweden after 2000 (Åkerblom et al., 2014). The EU threshold value for Hg in fish, which aims to protect fish-eating organisms such as birds and mammals, is 0.02 mg kg^{-1} Hg in fish muscle tissue (2008/105/EC). This threshold value is exceeded in fish in all Swedish lakes and streams.

Studies in Sweden, Finland and Canada have reported elevated methylmercury concentrations in runoff water following soil disturbance caused by logging operations. Based on assumptions and field studies in Sweden, Finland and Canada, logging operations were thought to be responsible for 10–25% of the elevated Hg concentrations detected in freshwater fish (Bishop et al., 2009). However, an updated review by Eklöf et al. (2016), has suggested that these calculations may be too narrow and high given that more recent studies have shown a greater variation in forestry effects. Several key factors causing these effects have been identified. Firstly, low-oxygen microenvironments, such as water-filled cavities, are hotspots for mercury methylation. Secondly, increased mobilization of methylmercury and inorganic Hg take place through subsurface flows and more superficial groundwater flow paths through the upper, organic, soil horizons. Thirdly, leaching of organic matter in dissolved or particulate form increases after logging operations and is a carrier of Hg from soil horizons rich in Hg (Eklöf et al., 2016).

It has been hypothesized (Eklöf et al., 2012) that the additional soil disturbance caused by stump harvest and hauling could result in increased Hg methylation and transport in runoff; however, recent studies have not provided firm experimental evidence to support this hypothesis (Eklöf et al., 2016). Nevertheless, cavities in the soil caused by stump harvest as well as slash-covered strip roads do seem to be hotspots for Hg methylation (Eklöf et al., 2016). Thus, there is no strong evidence that stump harvest cause additional methyl mercury load to aquatic systems compared to e.g. site preparation. On the other hand, implementing the general knowledge about the methylation and transport processes in practical forestry has a potential to reduce the formation and transport of methyl mercury at various forestry operations such as stump harvest and site preparation.

The risk of increased heavy metal load and availability due to ash recycling is another area of concern. Wood ash originating from forest biomass normally has low levels of these substances, but there is a risk that recycling contaminated wood ash could elevate the levels of heavy metals, organic pollutants and radioactive caesium in soil and water (e.g., Olsson et al., 2017; Huotari et al., 2015). Studies on heavy metals have largely focussed on whether ash recycling in forests affects the levels of Cd followed by Pb, Cr, Cu, Ni and Zn. A few of studies have demonstrated that ash recycling can increase the Cd content of the forest floor (e.g. Ingerslev et al., 2014; Rumpf et al., 2001), however, Cd has low bioavailability and most ash-recycling studies have shown no or negligible effects on the Cd concentrations in soil and runoff water, plants and fungi.

The Swedish authorities have issued regulations and recommendations to avoid the risk of increasing toxic metal contaminants in the environment. The Swedish Forest Agency (2009) has put forward recommendations on logging residue harvest and nutrient compensation with wood ash, which dictate that wood ash should be well burned to reduce the content of organic pollutants and maximum levels of heavy metals and organic pollutants. Wood ash for recycling should be chemically stabilized to give a slow reaction and dissolution. Maximum recommended doses and concentrations of heavy metals in the ash are calculated based on the mass balance concept so that the load of heavy metals with wood ash should not exceed the export of heavy metals in harvested biomass. The Swedish Radiation Safety Authority has issued rules on how ash contaminated with radio-caesium should be handled and disposed. The Swedish Forest Agency (2009) has put forward recommendations on environmental considerations for stump harvesting based on general precautionary principles, which focus on avoiding stump harvest on sensitive sites and soil types. For example, soil disturbance and compactions should be minimized by avoiding stump harvesting on soils with low bearing capacity, and there should be buffer zones near waterways, wetlands and other protected objects where no stump harvest or hauling takes place.

When the specialists considered the different harvesting scenarios, it was assumed that current recommendations by authorities on stump harvesting and ash recycling are followed. A consequence of that is that there is no easily defined level of slash and stump harvesting where exceeding the recommended limits is in conflict with the ability to achieve the EQO '*A Non-toxic environment*', as defined here. Instead, the effect of logging operations and wood-ash recycling on the presence and transport of pollutants depends mostly on the extent to which the recommendations are followed. With regards to contaminants in recycled ash, the availability of ash suitable for recycling is limited by the availability of ash of good quality and because the rationale for ash recycling is stronger in southern Sweden than in the North. Wood-ash recycling is limited in the regions that received a high deposition of ^{137}Cs in 1986 and, thus, the recycling of wood ash contaminated with radio caesium is a marginal problem. The risk of methylation and transport of methylmercury can be expected to increase with increasing harvest intensity at the landscape level because this might include sites unsuitable for harvest. The Swedish Forest Agency recommends that stump harvesting at the site scale should not exceed 75–85% by volume, but gives no guidance about harvesting rates at the landscape scale. Stronger protection levels (e.g., wider buffer zones) would further limit the harvestable proportion at the site scale and would also result in a reduction of harvestable biomass in the landscape. Thus, the most intensive stump harvest level (30% of all clear-cuts in the landscape) of the scenarios assessed can likely be reached without violating the precautionary principles and recommendations of stump harvesting put forward by the Swedish Forest Agency (2009). This level of stump harvesting is therefore not likely to reduce the ability to reach environmental objectives for reducing the risk of mercury in the environment if the recommendations are consistently followed.

3.6. Production and harvesting of other types of biomass

There is a biomass potential beyond slash, stumps and wood from cleaning and thinning operations. One important source is biomass from short-rotation forestry (SRF) with *Salix* and *Populus* planted on agricultural land (Dimitriou and Mola-Yudego, 2017). Other sources include biomass removed during conservation management in deciduous woodland (Götmark, 2013) and brushwood from agricultural land, forested land and urban areas (Ebenhard et al., 2017). Today, the harvesting volumes of these types of biomass are very low. Examples of potential harvesting sites are road-sides, power-lines or overgrown agricultural land such as abandoned fields, meadows and pastures. For conservation purposes, increased harvesting of brushwood, as well as conservation management of deciduous woodland, are positive factors that might increase the likelihood of achieving the EQO 'A Rich Diversity of Plant and Animal Life'. Many species in these environments are adapted to open, or semi-open conditions and require sun-exposure. However, steering is important because unregulated logging in these environments might have a negative impact on the biodiversity. The effect on soil and water of removing brushwood from forest land is likely to be comparable to the effects of slash removal. Thus, the effect on 'Zero Eutrophication' and 'A Non-toxic Environment' is likely to be negligible whereas the effect on 'Natural Acidification Only' is assumed to be negative. The magnitude of the effect on 'Natural Acidification Only' would be dependent on the amount of brushwood removed. In analogy with forestland and if the harvest does not exceed biomass corresponding to a maximum of 0.5 ton ash ha^{-1}, the potential effects would be acceptable (Swedish Forest Agency, 2008). The effect of removal of brushwood from agricultural land and urban areas on soil and water is assumed to be negligible. Another potential source of biomass comes from harvesting by coppicing and pollarding, which also would have a positive impact on biodiversity with potentially big conservation values. However, in spite of their large potential, none of these examples are likely to contribute a significant volume of wood for bioenergy production in the near future.

4. Discussion

The baseline in this study was conventional stem-wood harvest and, therefore, it is only the effects in excess of conventional harvesting of stems that were assessed. One important assumption in this paper an extraction rate of 70% at stand level. Today, this is a realistic assumption (Thiffault et al., 2015). However, future technological developments might change the picture. Based on this assessment the experts opinion was that, assuming that the recommendations from the Swedish Forest Agency are followed as a prerequesite, slash can be harvested on 50% of the annually thinned and clear-cut areas in Sweden without reducing the possibility of achieving the environmental objectives. Slash harvesting potential is limited by the EQOs 'Sustainable Forests' and 'Natural Acidification Only' (Table 3). Assuming that the recommendations from the Swedish Forest Agency are followed, the experts opinion was that stumps can be harvested on up to 10–20% of the clear-cut area. Stump harvesting potential is limited by the environmental objective 'Sustainable Forests' (Table 3). According to the experts judgement, the environmental objectives 'Zero Eutrophication' and 'A Non-toxic Environment' are not the prime limiting objectives and they would allow for slash harvesting on 80% of the thinned and clear-cut areas and stump harvesting on 30% of the clear-cut area (the maximum areas assessed here) without affecting the possibility of achieving these objectives. The assessments are based on the assumptions given in chapter 3, e.g. that the recommendations about nitrogen fertilizations are followed and that soil disturbance and compaction is avoided. The impact on forest production is also moderate; however, nutrient compensation to maintain production might be needed following slash harvest, mainly in thinning operations. The willingness among forest owners to invest in measures to increase forest production, where fertilization is one of the more efficient ones, is highly influenced by their belief in future markets. Markets for more valuable forest products such as saw timber are the most important. However, it cannot be ruled out that a potentially large bioenergy market, together with discussions about a future bio-economy, would increase their willingness. This has not been taken into account in this assessment. Based on these figures, an EQO-sustainable harvest level of slash and stumps could provide the energy industry with 70 PJ annually from final fellings and 100 PJ annually if slash from thinnings are considered as well. The conclusions are based on a number of important assumptions summarized in Appendix B that mainly relate to ash recycling, type of harvested substrate, and avoidance of certain habitats, sites or parts of the landscape.

The conclusions that are drawn here depend on the method of obtaining the expert opinion (Sutherland, 2006; Martin et al., 2011), which always includes a tangible degree of uncertainty. Basically, evidence from field experiments, other field investigations and modelling were used to assess the environmental value of harvested woody biomass (e.g. slash, stump or brushwood), and the consequences of removing this wood (Thiffault et al., 2011). There are some examples of in the literature (e.g. requirements of dead wood) and simulations of different harvesting scenarios and the impact on different species (Bütler et al., 2004). However, the process of relating these consequences to environmental objectives (the expert assessment) is crucial. Furthermore, the environmental objectives are not always defined as exactly as desired for this type of analysis. However, by using a relatively large group of scientists, who presented their results in the form of a concensus, and by applying precautionary principles related to the assessed EQO, we are confident that the recommended biomass harvesting levels presented here are on the safe side (i.e. the possible harvesting volume could be higher without having a negative impact). However, taking also socio-economic parameters into consideration might have given a different results on the sustainable volume.

When land-owners formally apply for clear-felling (a requirement for all clear-cuts of >0.5 ha in Sweden), they can also give notification of their intention to harvest slash and/or stumps. In 2014, there was notification of slash harvesting on 105,000 ha, which is around half of the yearly clear-felling area, which between 2000 and 2012 varied between 180,000 and 220,000 ha (www.skogsstyrelsen.se/en/AUTHORITY/Statistics/). However, data based on interviews show that the realized area of slash harvest was only half of the notified area, i.e. about 25% of the clear-felling area (www.skogsstyrelsen.se/en/AUTHORITY/Statistics/). Out of the slash harvested area, ash production allows for applications with the recommended dose (3 ton ha^{-1}) on approximately half of this area (see above). This is the most limiting factor for obtaining the EQO 'Natural Acidification Only' related to slash harvest.

There was notification of the intention to harvest stumps on 1% of the clear-felling area. Our assessment shows that the present volume of slash and stump harvest is sustainable, and that the harvesting potential is higher. Short rotation forestry, brushwood and wood from conservation management adds to that potential. Unprocessed wood for bioenergy purposes, including industrial residues (bark, sawdust, shavings), slash, stumps, round-wood, small diameter trees, excluding imports, produce around 180 PJ per year (Swedish Forestry Agency, 2015). Out of this, 37 PJ comes from slash (36 PJ) and stumps (1 PJ). Our calculations, based on our conservative assessment, show that the potential is 98 PJ/year for slash and stumps in Sweden. Ebenhard et al. (2017) have estimated the potential for brushwood to be 26 PJ/year. However, there are risks associated with this increase in harvest and production intensity, and a number of crucial questions remain to be answered. When considering goals related to biodiversity and surface waters, we believe that strategies that include management at the landscape scale are necessary to increase harvesting volumes.

5. Future studies

Although there has been a substantial amount of research into the effects of slash and stump harvesting and ash recycling in recent years, there is still room for further improvements. We conclude that existing long-term field experiments are likely to play an important role in future studies on the effects of slash and stump harvesting and ash recycling on tree growth, biodiversity and soil and water quality in different time-scales. It is therefore important that these long-term field experiments are maintained. The establishment of new long-term experiments would be justified, to represent a wider range of forest types, soil types, vegetation types and climatic zones. As well as experimental measurements, the use of dynamic models based on these empirical data could be useful for increasing our understanding of the various processes. Furthermore, improved models could be used to better predict long-term effects.

More stump harvesting experiments are required to provide a more reliable assessment of the effect of stump harvesting on tree growth, mineralization and leaching of nitrogen, and methylation and leaching of mercury. Furthermore, stump extraction methods need to be developed that reduce the risk of stump harvest causing soil damage that leads to methylmercury being transported to groundwater and surface waters and ultimately into aquatic food chains.

There are data from numerous experiments regarding the growth effects of slash harvesting in final fellings. The main effort now should be focussed on using larger data sets to identify patterns such as site or species specificity in the response and to increase our knowledge about the duration of the effects. There have been fewer thinning experiments: additional experiments would reduce the uncertainties in the assessments. Ash recycling in combination with nitrogen fertilization has the potential to reduce growth losses after slash harvesting. More studies on the effects of this kind of treatment on tree growth, nitrogen leaching and acidification are required to be able to assess fully the potential positive and/or negative effects.

Comparisons between mass balance models and empirical data in long-term experiments indicate that there are feedback processes in the soils that are not accounted for in the models, introducing uncertainties in the model assessments. We need to increase our understanding of the processes and feedback mechanisms to reduce these uncertainties, and dynamic modelling exercises using data from long-term experiments would also be useful tools to test and identify unknown processes.

We also need to increase our understanding of the effects of slash harvesting and ash recycling on soils and surface waters in different types of catchments so as to be able to prioritize ash-recycling measures. This can be achieved using catchment modelling, and the continued development of catchment models is thus important. Mapping the most acidification sensitive surface waters is also important for prioritizing ash-recycling measures. Finally, future studies should also focus on how to implement the large body of existing knowledge in decision-support tools for management planning at the operational scale.

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Appendix A. Workshop participants, their expertise and affiliation

Name	Expertise	Affiliation	Name	Expertise	Affiliation	Name	Expertise	Affiliation
Åkerblom, Staffan	Soil: heavy metals	Swedish University of Agricultural Sciences	von Hofsten, Henrik	Forest production	Skogforsk	Persson, Tryggve	Soil: acidification	Swedish University of Agricultural Sciences
Andersson, Stefan	Soil: acidification	Swedish Forestry Agency	Isacsson, Gunnar	Biodiversity: beetles	Swedish Forestry Agency	Ranius, Thomas	Biodiversity: Beetles	Swedish University of Agricultural Sciences
Akselsson, Cecilia	Soil: acidification	Lund University	Jacobsson, Staffan	Forest production	Skogforsk	Ring, Eva	Soil: heavy metals	Skogforsk
Belyazid, Salim	Soil: acidification	Lund University	Johansson, Therese	Biodiversity: Beetles	Swedish University of Agricultural Sciences	Roberntz, Peter	Forest production	WWF
Bertills, Ulla	Soil: acidification	Swedish Environm. Protection Agency	de Jong, Johnny	Biodiversity	Swedish University of Agricultural Sciences	Rudolphi, Jörgen	Biodiversity: Bryophytes	Swedish University of Agricultural Sciences
Bishop, Kevin	Soil: heavy metals	Uppsala University	Jonsell, Mats	Biodiversity: Beetles	Swedish University of Agricultural Sciences	Sikström, Ulf	Forest production	Skogforsk
Dahlberg, Anders	Biodiversity: Fungi	Swedish University of Agricultural Sciences	Karlsson, Per-Erik	Soil: acidification	IVL	Stenari, Britt-Marie	Soil: heavy metals	Chalmers
Djupström, Line	Biodiversity: Beetles	Swedish University of Agricultural Sciences	Kubartova, Ariana	Biodiversity: Fungi	Swedish University of Agricultural Sciences	Stendahl, Johan	Soil: acidification	Swedish University of Agricultural Sciences
Drott, Andreas	Soil: acidification	Swedish Forestry Agency	Land, Magnus	Soil: acidification	Formas	Taylor, Astrid	Biodiversity: Arthropods	Swedish University of Agricultural Sciences
Egnell, Gustaf	Forest production	Swedish University of Agricultural Sciences	Löfgren, Stefan	Soil: acidification	Swedish University of Agricultural Sciences	Wallander, Håkan	Soil: acidification	Lund University
Eklöf, Karin	Soil: heavy metals	Swedish University of Agricultural Sciences	Gustafsson, Jon-Peter	Soil: acidification	Swedish University of Agricultural Sciences	Victorsson, Jonas	Biodiversity: beetles	Swedish University of Agricultural Sciences
Eriksson, Hillevi	Soil: acidification	Swedish Forestry Agency	Lundborg, Anna	Soil: acidification	Swedish Energy Agency	Åkerblom, Staffan	Soil: heavy metals	Swedish University of Agricultural Sciences
Fölster, Jens	Soil: acidification	Swedish University of Agricultural Sciences	Magnusson, Tord	Soil: acidification	Swedish University of Agricultural Sciences			
Hazell, Per	Forest production	Swedish Forestry Agency	Olsson, Bengt	Soil: heavy metals	Swedish University of Agricultural Sciences			

Appendix B

Harvested biomass of different extraction combinations and consequences for the achievement of the Environmental Quality Objectives. The arrows indicate whether the likelihood of achieving the objective increases (↗) or decreases (↘) depending on what extraction combination is used. Horizontal arrows (→) indicate that achievability of the objective is not affected at all by the measure. In certain cases the assessment is that the consequences will have some positive or negative effect on achievability, which is shown by diagonal arrows pointing upwards or downwards. Achievability depends on many different factors, and an upward-pointing arrow in the table does not mean that the objective will be achieved, but that the measure increases the likelihood of the objective being achieved. The direction of the arrows only applies under certain conditions which are further specified in the text (e.g. that primarily conifer branches/tops and stumps are extracted, that general environmental considerations are not adversely affected, that ash-recycling using high-quality ash is done where needed, provided that there is enough ash, and that extraction is only done on land with a high load-bearing capacity – see the text for further details). Slash can be extracted in thinning and in final felling. As consequences are slightly different if slash are extracted in both thinning and final felling, or only in final felling, both of these alternatives are shown in the table of effects on production conditions. The estimated optimum level of extraction for maximum energy production is marked with a grey field. The table present the different scenarios used at the workshop. However, at the workshop it was concluded that a possible harvesting volume is at 50% slash harvesting in combination with 20% stump harvesting, i.e. a little bit higher than the grey field in the table (see also Table 3).

Assortment	Harvesting scenario: Proportion (%) of fellings in the landscape in which additional biomass is harvested – Slash	Stump	Harvested proportion (%) of total available residues in the landscape – Slash	stump	Forest production Objective: Final cutting only	Final cutting and thinning	Environmental Quality Objectives: "Sustainable Forests""A Rich Diversity of Plant and Animal Life"	"A Non-Toxic Environment"	"Zero Eutrophication": Soil-water – Short-term	Soil-water – Long-term	Surface-water	"Natural Acidification Only": Soil, stand-level – Short-term	Soil, stand-level – Long-term	Soil-water, stand-level	Surface water – Headwater streams, shallow soils + NaCl	Surface water – Larger water bodies
Slash and stump	80	30	56	21	↘	↘	↘	→	→	→	→	↘	↘	↘	↘	→
	60	30	42	21	→	↘	↘	→	→	→	→	↘	↘	↘	↘	→
	40	30	28	21	→	↘	↘	→	→	→	→	→	→	→	→	→
	80	20	56	14	↘	↘	↘	→	→	→	→	↘	↘	↘	↘	→
	60	20	42	14	→	↘	→	→	→	→	→	↘	↘	↘	↘	→
(grey)	40	20	28	14	→	↘	→	→	→	→	→	→	→	→	→	→
	80	10	56	7	→	↘	↘	→	→	→	→	↘	↘	↘	↘	→
	60	10	42	7	→	↘	→	→	→	→	→	↘	↘	↘	↘	→
	40	10	28	7	→	↘	→	→	→	→	→	→	→	→	→	→
Slash only	80	0	56	0	↘	↘	↘	→	↗	→	→	↘	↘	↘	↘	→
	60	0	42	0	→	↘	→	→	↗	→	→	↘	↘	↘	↘	→
	40	0	28	0	→	↘	→	→	↗	→	→	→	→	→	→	→

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