Ecological Consequences of Increased Biomass Removal for Bioenergy from Boreal Forests

Nicholas Clarke
Norwegian Forest and Landscape Institute
Norway

1. Introduction

The increased use of renewable energy sources, including forest biomass, in energy consumption is a marked characteristic in many countries' current energy policies. Use of forest biomass for energy is supported as a sustainable form of energy that contributes to social welfare, local development and forest economy. Thus, in Europe there is a sharp increase in demand for wood as a source of renewable energy as well as for production of wood products. Forest inventories show that standing stock as well as annual growth would allow an increased use of the existing forest resource.

In conventional stem-only timber harvesting (SOH), where branches and tops are left in the forests, the organic material will decay on the site and nutrients are thus returned to the biogeochemical cycle. In whole-tree harvesting (WTH), branches and tops are removed, although in practice the amount removed is about 60-80% (Helmisaari et al., 2011). As a large part of the nutrients in trees are located in the foliage and branches, removing these will reduce the supply of nutrients and organic matter to the soil. In the longer term, this might increase the risk for future nutrient imbalances and reduced forest production (Egnell & Leijon 1999; Raulund-Rasmussen et al., 2008; Worrell & Hampson, 1997), as well as changes in species composition and biodiversity (Jonsell, 2007). In some countries, such as Finland, stumps may also be harvested, although this will not be considered here.

Forests provide a number of environmental services, such as water protection, carbon sequestration and biological diversity, which need to be maintained both during and after harvesting. Removal of forest residues after harvesting could increase the risk for adverse effects on these services. Thus, there is a potential for conflict between such goals as increased use of forest resources for bioenergy and rural employment on the one hand, and protection of ecosystem services together with long-term site sustainability on the other. In order to minimise the potential for conflict, legislation, certification systems and management guidelines have been developed. However, for these to be effective, there has to be a scientific basis, and there is at present insufficient knowledge about which factors determine the contrasting effects found in field experiments on increased biomass removal (see below), or of how variation in these controlling factors affects long-term site sustainability. This review will address the current state of knowledge regarding sustainable removal of branches and tops for bioenergy from boreal forest ecosystems.

2. Effects of harvesting intensity on soil and water

Nutrient depletion is the major environmental concern regarding WTH as compared with SOH, as this is relevant not only environmentally but also economically due to the risk for reduced growth in the next rotation. As stated above, a large portion of tree nutrients are in the foliage and branches, so removing these from the forest will also remove the nutrients. If these nutrients are not replaced, either by weathering, deposition or fertilisation, reduced growth in the next rotation may result. This risk will vary greatly, depending on site nutrient status, and a nutrient-rich site may tolerate a considerable nutrient removal. However, even on a nutrient-rich site, removal of nutrients without making sure they are replaced is inconsistent with the principles of sustainable forest management. Raulund-Rasmussen et al. (2008) suggested a nutrient balance approach for predicting sites at risk. This will require considerable knowledge of the various nutrient pools and fluxes (shown schematically in Fig. 1), which are sometimes difficult to obtain, leading to a large degree of uncertainty in nutrient balance calculations. A further approach suggested by Raulund-Rasmussen et al. (2008) was to classify forest soils into robust and sensitive types with respect to the risk for nutrient depletion (Table 1). Among relevant factors are temperature, soil depth, soil type (organic/mineral), soil texture, pH and mineralogy. In predicting site sensitivity, knowledge about similar sites is another useful tool. This knowledge can in many cases be obtained from literature studies, e.g. on harvesting experiments or fertilisation experiments.

To minimise the risk of nutrient depletion, it is important to develop methods for leaving the nutrient-rich foliage on site (Helmisaari et al., 2011). In forestry practice, piles of branches and tops are often left in the forest for periods of up to one year before removal, in order for as much as possible of the foliage to fall off (Fig. 2). This allows the return of the nutrients to the site.

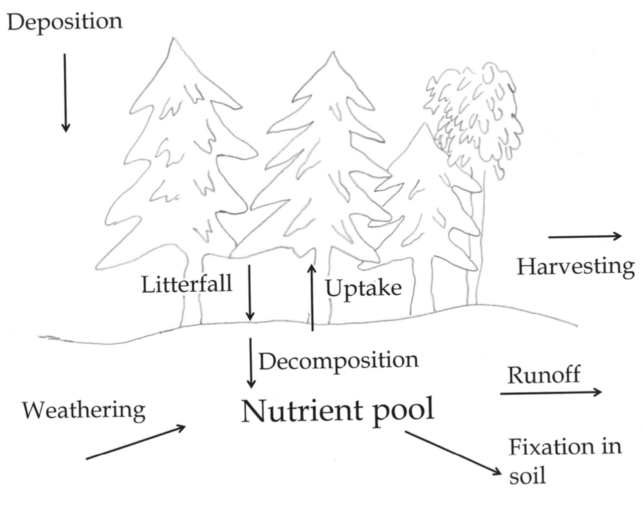

Fig. 1. Schematic overview of nutrient fluxes in the boreal forest ecosystem

Temperature	Depth	Type/texture		pH	Minerals	Sensitivity
<2°C	-	-	-	-	-	S
>2°C	<30 cm	-	-	-	-	S
>2°C	>30 cm	Organic	Fen	-	-	R/S
>2°C	>30 cm	Organic	Bog	-	-	S
>2°C	>30 cm	Mineral	Loamy	<4.8	-	S
>2°C	>30 cm	Mineral	Loamy	4.8-6	-	R
>2°C	>30 cm	Mineral	Loamy	>6	-	R
>2°C	>30 cm	Mineral	Sandy	<4.8	Quartz	S
>2°C	>30 cm	Mineral	Sandy	<4.8	Dark minerals	S
>2°C	>30 cm	Mineral	Sandy	4.8-6	Quartz	S
>2°C	>30 cm	Mineral	Sandy	4.8-6	Dark minerals	R
>2°C	>30 cm	Mineral	Sandy	>6		R

Table 1. Classification of soils into robust (R) and sensitive (S) types, based on Raulund-Rasmussen et al. (2008)

Fig. 2. Removal of a pile of branches and tops six months after harvesting, Gaupen, Norway (photo: Kjersti Holt Hanssen, Norwegian Forest and Landscape Institute)

There is some concern that piling of branches and tops might increase the risk for pest outbreaks, in contrast to direct removal of these residues after harvesting or chipping on-site. However, compared to SOH, piling, if carried out before insect colonisation, might even reduce the risk for outbreaks because larger amounts of wood (on the insides of the piles) would become less accessible to the pests (Schroeder, 2008). Piles of forest fuel from final cuttings are in some cases located close to stand edges of living trees, while whole trees from thinnings may be piled and stored in rows inside the stands; in these cases, there is a clear risk that bark beetles might attack nearby standing living trees (Schroeder 2008). However, it is not certain that the risk is great in practice. Recommendations include avoiding summer storage of large amounts of spruce with a diameter exceeding 10 cm close to mature living spruces, avoiding storage of spruce in thinned stands after warm and dry summers, and avoiding storage of both pine and spruce in defoliated forests (Schroeder 2008). National legislation regarding the amounts of coniferous wood that may be left or stored in the forest exists in many countries.

Returning wood ash to the forest has been suggested as a measure against nutrient loss, as all the major plant nutrients except nitrogen are found in wood ash. Wood ash input increases concentrations of base cations and reduces soil acidity (Arvidsson & Lundkvist, 2003; Brunner et al., 2004). Concentrations of potassium and magnesium in tree fine roots increase (Brunner et al., 2004). However, experiments with ash input on mineral soils have shown no significant increase (or decrease) in growth, probably due to nitrogen limitation (Karltun et al., 2008; Ozolinčius et al., 2007a). On peat soils, the situation is different: Swedish and Finnish experiments have shown an increase in tree growth after ash input (Karltun et al., 2008). There are concerns about increased concentrations of heavy metals after ash input (e.g. Reimann et al., 2008), especially in fungi and berries (Karltun et al., 2008). This will depend on the dose of ash added, and it is recommended to add a dose giving an amount of heavy metals no higher than the amount removed (Swedish Forest Agency, 2001). Effects on ground vegetation were limited when crushed hardened wood ash was used (Arvidsson et al., 2002). There may be a risk for damage to mosses and lichens (Ozolinčius et al., 2007b). Changes in mycorrhizal species composition have been observed (Karltun et al., 2008). The risk for negative effects appears to be low if the ash is treated before use, e.g. by hardening (Arvidsson et al., 2002) or added as granules (Callesen et al., 2007) or pellets (Rothpfeffer, 2007).

Soil organic matter (SOM) is an important reservoir for nutrients, especially nitrogen; its decomposition and mineralisation are important in nutrient cycling. In northern boreal forests, soil temperature and moisture are below optimal for decomposition, and changes in these after harvesting might be expected to increase decomposition and nutrient availability and leaching at least in the short term (Yin et al., 1989). However, increased soil moisture as a result of decreased evapotranspiration might lead to waterlogging and anaerobic conditions in the rooting zone that might inhibit decomposition (Prescott et al., 2000). In fact, the effect of harvesting on soil organic matter is variable. Decomposition rates of surface litter have been found to decrease after clear-cutting (Yanai et al., 2003), while accelerated mineralisation as a result of clear-cutting has been observed in Finland (Palviainen et al., 2004).

The effect of harvesting intensity on soil C and N has been found to vary greatly (Johnson and Curtis, 2001; Olsson et al., 1996a; Vesterdal et al., 2002). In their meta-analysis, Johnson and Curtis (2001) found different effects from different harvesting methods and tree species: SOH of coniferous species appeared to cause an increase in soil C while WTH caused a decrease. SOH of hardwoods, on the other hand, also appeared in most cases to lead to a decrease in soil C. A decrease in soil C was observed independent of harvest intensity for Norway spruce and Scots pine in Sweden (Olsson et al., 1996a). Harvest intensity may affect the decomposition of existing SOM as well as the build-up of new SOM from litter and forest residues.

At present, management recommendations for harvesting do not deal with optimisation of the carbon content of forest soils, although recommendations regarding erosion, soil compaction, drainage, and site preparation will clearly influence the carbon content. One reason for this is our incomplete understanding of the processes involved in carbon cycling in boreal forest ecosystems, and of which factors are most crucial for maximising carbon sequestration in these ecosystems.

Harvesting decreases evapotranspiration and thus increases runoff quantity. Haveraaen (1981) observed that clear-cutting might increase runoff by up to 40% in an area of eastern Norway with shallow soil. Harvesting also influenced water quality: nitrogen loss increased by up to six times (from 1.5 to 7-9 kg/ha), mostly (about 6 kg/ha) as nitrate. Corresponding increases were from 2 to 12-13 kg/ha for potassium, 18 to 24 kg/ha for sulphur in the form of sulphate, and from 16 to 35 kg/ha for chloride (Haveraaen, 1981). Removal of harvesting residues might possibly reduce runoff of these and other elements. Runoff water can become more acid after harvesting (Stupak et al., 2007).

Clear-cutting on Norway spruce-dominated drained peatlands has been shown to cause increased export of dissolved organic carbon (DOC) (Nieminen, 2004). Mineralisation of organic nitrogen followed by nitrification will increase nitrate concentrations. Because uptake is low, this nitrate will be largely leached from the system, together with base cations (Raulund-Rasmussen & Larsen, 1990). Nitrate in deposition will not be taken up to such a large extent as before harvesting, but will also be leached together with base cations. In Sweden, a clear nitrogen leaching gradient has been found on clear-cuts from the west to the east, following the deposition gradient but also influenced by higher runoff in the west (Akselsson et al., 2004). Increased export of all main forms of dissolved nitrogen (nitrate, ammonium and organic nitrogen) has been observed after harvesting (Haveraaen, 1981; Nieminen, 2004). However, small clear-cuts on a nitrogen-saturated site in Germany did not appear to increase the risk for nitrate contamination (Huber et al., 2004). P concentrations did not significantly increase, while P export increased only slightly after harvesting (Haveraaen, 1981; Nieminen, 2004). Base cation fluxes in runoff may increase after harvesting (Haveraaen, 1981; Hu, 2000), as increased decomposition of organic matter may lead to increased concentrations of base cations in runoff water. Piirainen et al. (2004) observed only slightly increased fluxes of P and base cations from below the B horizon after clear-cutting, despite increased fluxes from the O horizon.

Soil water chemistry in forest soils is affected by harvesting, with increased leaching of nutrients such as nitrogen and base cations after harvesting. For example, Hu (2000) found higher nitrate and potassium concentrations in soil water from mineral soils 2-3 years after harvesting and Piirainen et al. (2004) observed that the phosphorus flux under the organic layer increased three times and the base cation flux increased two times after SOH. This leaching is counteracted by growth, partly of ground vegetation (Fahey et al., 1991; Palviainen et al., 2005) and partly of new trees. Removal of forest residues influences soil water, as reduced concentrations of nitrate, ammonium and potassium have been observed (Staaf & Olsson, 1994). Where stumps had been removed, Staaf and Olsson found increased ammonium concentrations for two years, followed by two years of increased nitrate concentrations and acidity. These effects were only temporary: after four years there was no great difference between plots with stem-only harvesting, whole-tree harvesting, and whole-tree harvesting together with stump removal. As effects of harvesting on soil water chemistry change with time, it is important to have long-term experiments.

Significant forest resources are often located in more difficult situations, especially in mountain areas. Due to difficult access and the high cost of traditional (motor-manual) harvesting systems, these areas are currently underused. Today improved technical equipment as well as higher market prices make it possible to harvest also steeper slopes with partly- or fully-mechanized harvesting systems. Depending on the type of the technical system (wheeled or tracked harvesters, skidding/forwarding, cable systems etc.) and the design of the harvesting operation (distance and slope of the skid trails/roads) but also on soil quality and slope, various degrees of erosion and other physical damage to the soil can be observed after mechanized harvesting operations (Worrell & Hampson, 1997). Heavy erosion creates problems for soil, water and technical accessibility in the future. There is concern about the effect of increased sediment loads on water quality downstream of the harvested site: this might affect rural water treatment plants and fish reproduction (Nisbet, 2001). In addition, erosion causes loss of nutrients and organic matter from the forest ecosystem. Methods for reducing erosion risk are well-known, including for example building of culverts, bridges, and silt traps, and these methods have been incorporated in management guidelines in some countries (e.g. Forest Service, 2000; Forestry Commission, 2003).

3. Effects of harvesting intensity on biological diversity

Many organisms are dependent on logging residues as habitats or shelter, so removing this material for fuel will clearly affect these organisms' ability to survive. Species that depend on wood for their survival are termed saproxylic, and in northern Europe there exist several thousand such species, mainly fungi and insects. A further risk is that insects colonise wood bound for heating plants, and are thus trapped in wood that is burned. It is possible to make qualitative recommendations about which types of habitats or wood types that have the most threatened fauna and flora, based on information about landscape history and microhabitat associations (Jonsell, 2007). For example, in Sweden, based on studies of saproxylic beetles, it appears that coniferous wood can be harvested as forest fuel to a rather large extent, whereas deciduous tree species, and especially southern deciduous species and aspen, should be retained to a larger degree (Jonsell, 2007). In addition to saproxylic species, other organisms which feed on them, such as woodpeckers, are also likely to be affected.

Some studies have dealt with effects on ground vegetation. Vegetation retains nutrients in the ecosystem and can decrease nutrient leaching prior to stand re-establishment after clear-cutting (Palviainen et al., 2005). WTH and removal of logging residues leads to reduced amounts of woody debris in clear-cuts and changes in physical and other environmental conditions (Åström et al., 2005), including soil nutrient contents (Staaf & Olsson, 1994), microclimate (Åström et al., 2005), increased light supply and mechanical disturbance. These changes could lead to changed species composition, reduced biodiversity and reduced nutrient content in the humus layer (Olsson et al., 1996a, 1996b). Increased biomass removal may change the abundance of plant species with a key ecosystem role (Bergstedt & Milberg, 2001). Differences in ground vegetation related to felling (selective vs. clear-cutting) have been found as long as 60 -70 years after harvesting (Økland et al., 2003).

Reported effects of increased biomass removal on boreal forest vegetation differ (e.g. Åström et al., 2005; Olsson & Staaf, 1995). Fahey et al. (1991) found that grass biomass increased more rapidly after WTH compared with SOH and continued to make up a higher proportion of the biomass during the first four years after harvesting, while

Bergquist et al. (1999) found no effects of WTH on grasses. Åström et al. (2005) found that WTH reduced bryophyte cover by half (hepatics in particular were affected) and increased graminoid cover with 10% but found no significant effects on other vascular plants, whereas Olsson and Staaf (1995) reported lower cover of most vascular plants after WTH, while bryophytes were unaffected by the logging method. These contrasting results may be due to several factors, e.g. differences in environmental and climatic conditions at the study sites, sampling methods and statistical treatment (T. Økland, personal communication).

4. Effects of harvesting intensity on forest regeneration and productivity

The major concern about WTH from the point of view of the forestry industry has been that the removal of branches and foliage will lead to reduced productivity in the next rotations, as these parts contain a large share of the nutrients in the tree. This has generally (although not always) been found to be the case. In Fennoscandia, Jacobson et al. (2000) demonstrated growth decreases in the first 10 years after WTH in thinnings of Norway spruce and Scots pine stands when compared with conventional thinnings. The growth reduction could be counteracted by nitrogen fertilisation and they concluded that the reduction was due to reduced nitrogen supply. The growth reduction continued in a second ten-year period, but could also then be compensated by fertilisation (Helmisaari et al., 2011). Results from one of the sites included by Jacobson et al. (2000) and Helmisaari et al. (2011), Bergermoen in Norway, are given in Table 2. In the Table, it can be clearly seen that plots where whole-tree thinning had been carried out (Treatment 2) had lower production than plots where stem-only thinning had been carried out (Treatment 1), and that this reduced production could be counteracted using fertilisation (Treatments 3 and 5).

Revision year	1	2	3	4	5
1989	168	163	177	180	182
1994	209	196	216	221	225
1999	255	239	259	265	261
2005	312	293	308	320	313

Table 2. Total production (m^3/ha) by treatment and revision year in an experiment with stem-only vs. whole-tree thinning with and without fertilisation in a Norway spruce forest at Bergermoen, Norway. Thinning took place in 1984. The treatments are: 1) stem-only thinning (SOT), 2) whole-tree thinning (WTT), 3) WTT + NPK compensation fertilisation, 4) SOT + 150 kg N + 30 kg P/ha, and 5) WTT + 150 kg N + 30 kg P/ha. The data are available at http://www.skogforsk.no/feltforsok/Langfig.cfm?Fnr=1057 (in Norwegian)

Egnell and Valinger (2003) also found reduced growth in a Scots pine stand 24 years after WTH as well as branch and stem harvest (BSH). Comparable results have been found in the UK by Proe and Dutch (1994) in second generation Sitka spruce after clear-cutting including removal of residues. However, the effect of WTH seems to be site-dependent as well as species-dependent, as not all studies have shown an unambiguous nutrient decrease with subsequent growth reduction after whole-tree harvesting (Egnell & Leijon, 1999; Olsson et al., 1996a). Results from the North American Long-Term Soil Productivity study showed only a limited effect of WTH compared to SOH: although growth decreased, seedling survival was in fact improved five years after WTH (Fleming et al., 2006).

5. Legislation, certification and management recommendations

As mentioned above, the increased use of renewable energy sources, including forest biomass, is a marked characteristic in current energy policy. In forest policy, the use of forest biomass for energy is usually supported as a sustainable form of energy that contributes to social welfare, rural development and the forest economy. Energy legislation is used directly as a tool to promote renewable energy including forest and other biomass, whereas forest legislation rather works to ensure sustainably produced forest biomass for all uses (Stupak et al., 2007). However, increased use of forest biomass for energy might lead to conflict between different interests, all of which are politically important: on the one side, the need for a secure and renewable source of energy as well as rural employment, and on the other ecologically sound long-term timber production, biological diversity and other uses of the forest such as recreation. Trade-offs between these various interests will then be necessary, and increased knowledge is essential in order to optimise these trade-offs. Sustainability principles and criteria have therefore to be incorporated into policy frameworks and support schemes, as well as management guidelines. Many countries have produced national recommendations and guidelines for forest fuel extraction and/or wood ash recycling to encourage the extraction of forest fuels taking place in agreement with the principles of sustainable forest management. Certification is another approach: the main forest certification schemes are the Programme for the Endorsement of Forest Certification schemes (PEFC) and Forest Stewardship Council (FSC). In national PEFC and FSC standards, issues related to wood for energy are included under several criteria. Recommendations elaborated by governments or other groups of stakeholders could be used for further development of legislation, certification standards, and guidelines in relation to the sustainable use of forest biomass for energy. Recommendations vary according to subject, but on the whole, economic, ecological and social questions are treated for the whole forest fuel chain, from removal of biomass from the forest to recycling of wood ash to the forest (Stupak et al., 2007). Scientific results must be interpreted and transferred to operational criteria, indicators, recommendations and guidelines, with the final thresholds being set by politicians, certification bodies or other stakeholders (Stupak et al., 2007). This interpretation will necessarily include a large degree of uncertainty, so that continuous further development will be necessary as new knowledge is obtained.

6. Conclusions

Removal of forest residues for bioenergy after harvesting might increase the risk for adverse effects on the environmental services provided by forests, such as water protection, carbon sequestration and biological diversity. Forest legislation, certification systems, and management guidelines have been developed in order to reduce the risk for non-sustainable use of forest resources. However, not enough is known at present about which factors determine the contrasting effects found in field experiments, and more research is therefore needed, and further development of legislation, certification standards and management guidelines is likely to take place as new knowledge is obtained.

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8. References

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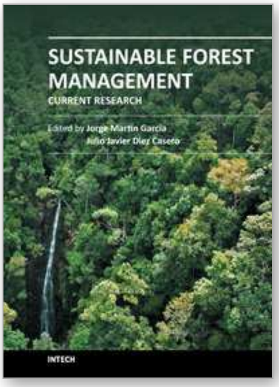

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