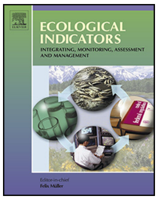
Ecological Indicators 65 (2016) 66–75

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Modelling impacts of forest bioenergy use on ecosystem sustainability: Lammi LTER region, southern Finland

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ARTICLE INFO

Article history:
Received 28 April 2015
Received in revised form 27 October 2015
Accepted 1 November 2015
Available online 13 December 2015

Keywords:
Bioenergy
Sustainability
Indicators
Ecosystem impacts
Modelling
Carbon
Nitrogen
Biodiversity

ABSTRACT

Increasing the use of forest biomass for energy production is an important mitigation strategy against climate change. Sustainable use of natural resources requires that these policies are evaluated, planned and implemented, taking into account the boundary conditions of the ecological systems affected. This paper describes the development and application of a quantitative modelling framework for evaluating integrated impacts of forest biomass removal scenarios on four key environmental sustainability/ecosystem service indicators: (i) carbon sequestration and balance, (ii) soil nutrient balances (base cations and nitrogen), (iii) nutrient leaching to surface waters (nitrogen and phosphorus), and (iv) dead wood biomass (used as proxy indicator for impacts on species diversity). The system is based on the use of spatial data sets, mass balance calculations, loading coefficients and dynamic modelling. The approach is demonstrated using data from an intensively studied region (Hämeenlinna municipality) encompassing the Lammi LTER (Long-Term Ecosystem Research) site in southern Finland. Forest biomass removal scenarios were derived from a management-oriented large-scale forestry model (MELA) based on sample plot and stand-level data from national forest inventories. These scenarios have been developed to guide future Finnish forest management with respect to bioenergy use. Using harvest residues for district heat production reduced fossil carbon emissions but also the carbon sink of forests in the case study area. Calculations of the net removal of base cations of the different scenarios ranged between −36 to −43 meq m^{-2} a^{-1}, indicating that the supply of base cations (soil weathering + deposition) would be enough to sustain also energy-wood harvesting. Greatly increased nutrient removal values and increasing nitrogen limitation problems were however predicted. Clear-cuttings and site preparation were predicted to increase the load of total nitrogen (4.0%) and total phosphorus (4.5%) to surface waters, compared with background leaching. The amount of dead wood has been identified as a key factor for forest species diversity in Finland. A scenario maximising harvest residues used for bioenergy production, would decrease stem dead wood biomass by about 40%, compared with a business-as-usual scenario. Clear trade-off situations could be observed in the case study area between maximising the use of energy-wood and minimising impacts on species diversity, soil carbon and nutrient stores, and nutrient leaching. The developed model system allows seeking for optimised solutions with respect to different management options and sustainability considerations.

1. Introduction

1.1. Increasing use of bioenergy from forests

The use of bioenergy is increasingly regarded as an important mitigation strategy against climate change. The European Union has set a mandatory target of 20% for the share of energy from renewable sources in the overall energy consumption by 2020 (EC, 2009). The annual demand for bioenergy is estimated to increase from the present 5.7 to 10 EJ by 2020 (Bentsen and Felby, 2012). According to the National Renewable Energy Action Plans (NREAPs) of the EU countries, the use of biomass for heating and cooling will double between 2005 and 2020 to account for 80% of the total renewable heating and cooling in the EU countries. Correspondingly, the use of biomass in electricity generation will triple during the same time period accounting for 19% of the total

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http://dx.doi.org/10.1016/j.ecolind.2015.11.032
1470-160X/

renewable electricity (Beurskens and Hekkenberg, 2011; Repo et al., 2014).

Consequently also in Finland, with its large forest resources (covering about 70% of the country) and highly developed industry, there is an increased interest in the use of forest harvesting residues for biofuel production. Forest biomass (non-merchantable timber) harvested for energy use includes living and dead branches, foliage, stem tops and off-cuts, stumps and roots, which are converted to chips in the forest, at the roadside or at the site of end-use. Finnish government policy aims to increase the use of renewable energy to 38% of energy consumption by 2020 (National Energy and Climate Strategy, 2013). Measures include an increase in the use of forest chips from 4.7 to about 13 million m^3 between 2008 and 2020 (Peltola, 2014). The governmental Foresight Study includes even higher targets (Foresight Report, 2009), with an increase in the use of wood energy from 19.3 TWh in 1997 to a maximum of 55.8 TWh in 2050.

Intensification of biomass removals from forests has raised concerns about the environmental effects on forest productivity, biodiversity, soil quality, and climate change mitigation potential (Aherne et al., 2012; Bouget et al., 2012; Lattimore et al., 2009; Repo et al., 2014; Verkerk et al., 2011; Walmsley and Godbold, 2010). The European Renewable Energy Directive (RED) defines sustainability criteria for biofuels and bioliquids (EC, 2009). The RED mandates that greenhouse gas (GHG) emission savings from the use of biofuel over the life-cycle shall be at least 60% compared to the use of fossil fuels from 2018 onwards. In addition, the raw material shall not be obtained from land with high biodiversity value or high carbon stock (EC, 2009).

These sustainability criteria and the concept of ecosystem services (ES) are closely linked. Ecosystem services are goods and services generated by the ecosystems, and of importance for human well-being. It is well known that various human activities contribute to changes in biodiversity with subsequent harmful effects on both ecosystem processes and ES (e.g. Barnosky et al., 2012), and these complex multi-layered relationships provide challenges for multidisciplinary science and policy (Mace et al., 2012; Steffen et al., 2015). Integrated assessment methodologies that include biophysical and socio-economic drivers of land use change and ES supply and demand are therefore called for (Bagstad et al., 2013; Crossman et al., 2013; Holmberg et al., 2015). Consequently, in addition to the above general sustainability criteria for bioenergy production (EC, 2009), landscape-scale integrative approaches evaluating impacts on multiple sustainability/ES indicators are clearly needed (Fu and Forsius, 2015; Iverson et al., 2014; Nelson et. al., 2009; Vihervaara et al., 2015). These indicators are also influenced by complex interactions of climate, deposition and environmental variation (Aherne et al., 2012; Akselsson et al., 2007; Forsius et al., 2013; Mace et al., 2012). A spatially explicit evaluation of such indicators can also couple biophysical estimates of service provision to an economic and monetary valuation (Fu et al., 2011; Nelson et al., 2009).

1.2. Sustainability indicators for forest biomass removal

In this paper, we develop and apply a quantitative modelling framework for evaluating integrated impacts of forest biomass removal scenarios on four key environmental sustainability/ES indicators: (i) carbon (C) sequestration and C balance, (ii) soil nutrient balances (base cations and nitrogen (N)), (iii) nutrient leaching to surface waters (N and phosphorus (P)), and (iv) dead wood biomass (proxy indicator for impacts on species diversity). The background and reasons for focusing the study on these indicators are given below.

The reductions in the C stocks of biomass and soil may offset some or all of the emission savings of bioenergy, and a key motivation for defining the sustainability criteria for biofuels in the EU is the effort to avoid bioenergy-related emissions from direct and indirect land use changes (COM, 2013; EC, 2009). This is because converting forests to energy crop cultivations or land clearing for delocalised food production often reduces C stocks of biomass, soil or both (e.g. Haberl, 2013; Searchinger et al., 2009). The emissions resulting from the reductions in the C stocks are not limited to land-use change but can occur within the same land use as a consequence of changed management, e.g. when harvesting of forest biomass is intensified. Forest harvest residues are commonly used to produce district heating in Finland, and the popularity of this practice is growing (Ylitalo, 2013). This form of bioenergy helps to reduce fossil C emissions but it also weakens the C sink of forests (Kallio et al., 2013; McKechnie et al., 2011; Repo et al., 2012; 2014; Sievänen et al., 2014). The effect on the net emissions is equal to the difference between these two changes.

Forest growth and harvesting have significant effect also on the acid–base status of forest soils owing to the excess accumulation of base cations compared with anions during tree growth (Olsson et al., 1993). Moreover, element concentrations in different tree compartments vary significantly, with much higher concentrations in needles, leaves and branches than in stem wood. Accordingly, alternative forest harvesting strategies have different impacts on soil and water quality (e.g. Aherne et al., 2012). Sustainable forest management practices should ensure that the long-term uptake of base cations by the vegetation does not exceed the supply by weathering and deposition (and potential applications of fertilizers). In the short term, imbalance is accommodated by the exchangeable cation pool; however, in the long term it will lead to a decrease in soil base saturation. Sustainability in terms of soil conditions can thus be defined as a situation where no long-term reduction in the base cation pool (base saturation) is allowed (Aherne et al., 2012; Akselsson et al., 2007). In addition to base cations, long-term sources of N such as deposition and N fixation (DeLuca et al., 2002) need to be quantified for sustainable forest management. Nitrogen is generally a growth-limiting factor in boreal ecosystems (e.g. Hyvönen et al., 2008), and although N mineralisation is likely to increase under a warmer climate (Forsius et al., 2013; Wright, 1998), the long-term supply is uncertain.

Harvest residues left on site in conventional stem-only harvesting are a potential source of nutrients to watercourses and removal may reduce nutrient load to surface waters. On the other hand, soil disturbance due to stump harvest may increase erosion and leaching of suspended solids and nutrients. The removal of harvest residues decreases the leaching of inorganic N compounds, P and potassium (K) as compared to no removal of harvest residues (Palviainen et al., 2010a; Wall, 2008). However, stump harvest can increase the leaching of N to watercourses (Eklöf et al., 2012; Palviainen et al., 2010b) due to a decrease in microbial immobilization of N. Energy-wood harvesting can thus have both increasing and decreasing impacts on nutrient leaching. The impacts are obviously also dependent on the extent of the harvesting areas. The changes in nutrient leaching are low, and generally, harvest residue removal and stump harvest seem not to differ substantially from conventional clear-cutting and site preparation in their effect on water quality. The impacts can, however, be estimated by comparing the leaching from unmanaged areas to the harvested ones in regions with similar landscape and climatic conditions.

Energy-wood harvesting has been identified as a new major risk of habitat loss and degradation for dead wood dependent saproxylic species (Bouget et al., 2012). Already for a long time the energy-wood harvesting has reduced the amounts of dead wood in managed forests to a great extent in Finland. This is much more than the present “retention forestry” (clear-cutting with retention trees and small-scale woodland key habitats) can be estimated to produce new dead wood in managed forests at the retention levels applied (data in Peltola, 2014). The decline of dead wood is one reason for the decline of one third of the threatened and near-threatened forest species (523 species of the total of 1590 species) in Finland (Rassi et al., 2010). Similarly, the decline of dead wood is one reason for the decline of 97% of the threatened and near-threatened forest habitat types (70 out of 72 types) in Finland (Raunio et al., 2008). Threatened species are often dependent on large-diameter dead wood (i.e. coarse woody debris) and thus, the use of large-sized timber for forest chips is most detrimental for the saproxylic species. In Finland, a great amount of forest chips are at present manufactured from large-diameter damaged or dried-out dead stems and off-cuts not serviceable as raw materials for forest industry. Without the demand for energy-wood, these would be left behind in the forest to decay. The amount of dead wood is thus a good proxy indicator for the impacts of forest bioenergy use on species diversity.

The key aims of this paper are:

- Describe the development of a quantitative modelling framework for evaluating the sustainability of increased use of forest bioenergy.
- Describe the background assumptions, methodology, data derivation and calculation of the selected sustainability indicators.
- Demonstrate the approach and methods using data from an intensively studied region encompassing the Lammi LTER (Long-Term Ecosystem Research) site in southern Finland.

Forest biomass removal scenarios have been derived from a management-oriented large-scale forestry model (MELA) based on sample plot and stand-level data from national forest inventories. These scenarios were developed to guide future Finnish forest management with respect to bioenergy use.

2. Material and methods

2.1. Study region

The study region Hämeenlinna municipality is located in the southern boreal taiga zone in southern Finland, with extensive coniferous forests (Fig. 1). The bedrock is primarily granodiorite and gneiss with some granite, with dominantly moraine soils and some organic soils. The total area of Hämeenlinna is 2031 km^2 of which forested land comprises 69.8%. Surface waters in the area (234 km^2) belong to the Kokemäenjoki river basin, with ten sub-catchments of the second level of the Finnish watershed division (Table 1). Hämeenlinna was chosen as study area for two main reasons: First, due to the fact that the Lammi LTER site is located in this region, a wealth of long-term ecological and environmental data is available. The core of Lammi LTER is the Lammi Biological Station (established 1953) of the University of Helsinki. The Lammi LTER area consists of several core sites/areas of which the Evo forest and lake area is the largest one and has a special value in terms of long term ecological studies (e.g. Rask et al., 2014). The Evo area is among the largest coniferous forest areas in southern Finland. Another important study area is Lake Pääjärvi and its surroundings. Lake Pääjärvi and its catchment have been studied since the early 1960s. Due to the availability of long-term intensive data records, instrumentation and experimental facilities at Lammi LTER, the site has also been much used for ecosystem model developments and applications (e.g. Forsius et al., 2010; 2013; Futter et al., 2009; Holmberg et al., 2015).

Table 1
Main characteristics of the study region Hämeenlinna municipality.

Location	61°00′ N, 024° 28′ E
Area (km^2)	2031
Forests (%)	69.8
Agricultural land (%)	12.6
Built area (%)	5.1
Wetlands (%)	1.0
Water (%)	11.5
Population (2015)	67 980
Mean air temperature (°C)	5.6
Annual precipitation (mm)	660

Secondly, due to the major national and international policy processes regarding climate change mitigation and increasing use of bioenergy, there is a strong interest also at the municipality level regarding carbon neutrality and sustainability concepts. The results of this study are thus of direct relevance also for local decision making and planning efforts, and the derived methodology can be used in other similar regions as well.

2.2. Forest bioenergy scenarios

In 2010, a total of 150 000 m^3 of energy-wood was harvested in the Hämeenlinna area according to the estimations made from the statistics of the Häme-Uusimaa forest centre. The harvested biomass in Hämeenlinna area totalled 442 kilotons, from which stem wood and energy-wood accounted for approximately 50% and 17%, respectively. The rest were harvest residues left to decompose in the forest.

Future projections of forest growth and harvesting until 2050 were obtained from the MELA model (Kärkkäinen et al., 2008). The realized harvest removal scenario compiled by the Natural Resources Institute Finland (former Finnish Forest Research Institute) was used as the baseline (business-as-usual) scenario for estimating the future harvesting levels in Hämeenlinna (Finnish Forest Research Institute, 2015). The realized harvest removal scenario outlines the development of forest resources if the current stem wood and energy-wood harvesting levels are carried out in the future. In this scenario, the net present value is maximized with a 4% discount rate subject to realized harvest removals (2008–2012) by timber assortments and realized energy-wood harvest (2009–2012).

Based on the realized harvest removal scenario, three scenarios for energy-wood usage were calculated for Hämeenlinna municipality. In scenario 1, harvest residues are not removed for energy production and Hämeenlinna is assumed to use coal for district heating (530 GWh). Harvest residues are left to decompose in the forest. In scenario 2, the use of energy-wood in district heat production is increased, and all available energy-wood is harvested and used for district heat production. In this scenario, about 62% of the required heat was produced from forest harvest residues and the rest from coal. The quantity of produced heat depended on the availability of forest harvest residues, which depended on the annual timber harvests (Finnish Forest Research Institute, 2015). In scenario 3, all available energy-wood is harvested, except stumps and roots, and used for district heat production. In this case, the proportion of stumps and roots from energy-wood is fairly small: 14, 3 and 5% in 2010s, 2020s and 2030s, respectively. The small proportion of stumps and roots is due to the economic optimization in the calculations of the Natural Resources Institute Finland. In the beginning of the time period the proportion of clearcuttings is high, but later on thinning (where stumps and roots cannot be harvested) becomes more frequent. In scenario 3, ca. 56% of the heat requirement was covered with forest harvest residues and the rest was produced from coal.

In all three scenarios, the cutting level is assumed to follow the realized harvest removal scenario, and the scenarios differ only with respect to the assumed use of the harvest residues. The three bioenergy scenarios can be summarised as follows:

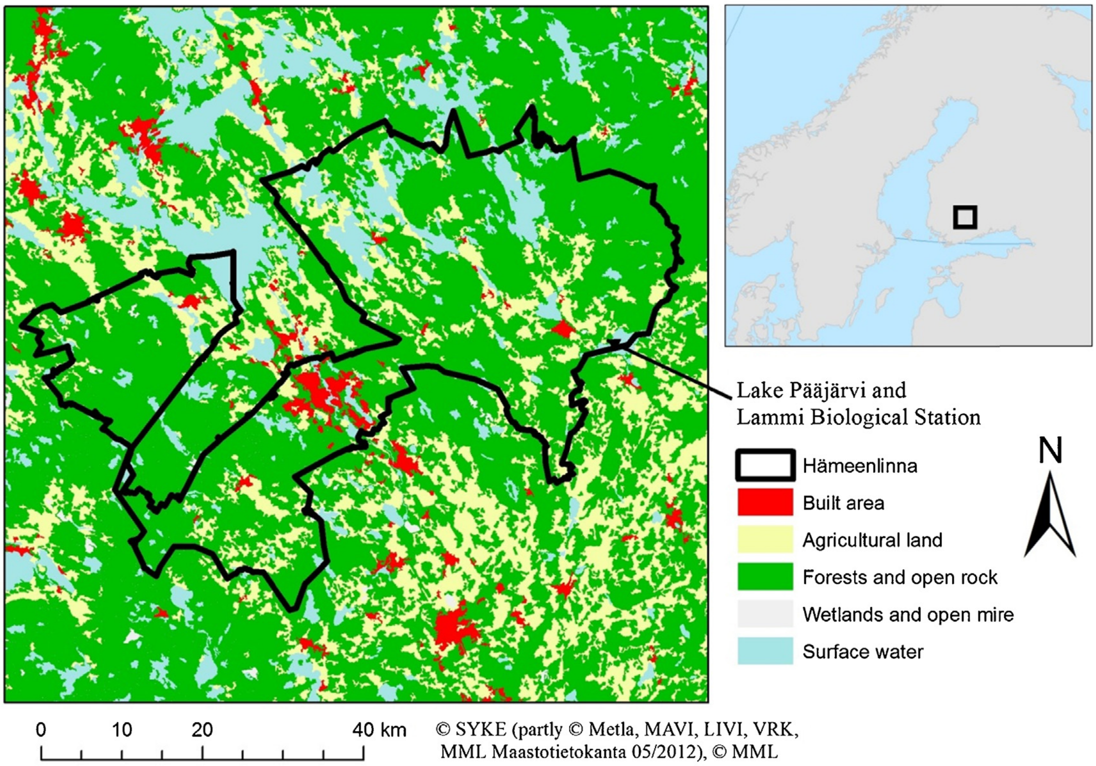

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Fig. 1. Location and main land use characteristics of the study region Hämeenlinna municipality.

- Scenario 1: No use of harvest residues for bioenergy production.
- Scenario 2: All harvest residues are extracted from the forest and used for bioenergy production.
- Scenario 3: Stumps and roots are not included in the harvest residues that are extracted from the forest and used for bioenergy production.

All biomass figures are dry mass.

2.3. Sustainability indicators

2.3.1. Carbon balance

The effects of forest-residue bioenergy on fossil C emissions and forest C sink in the municipality of Hämeenlinna was estimated between 2010 and 2040 using the three different forest bioenergy scenarios (see 2.2. above). The realized harvest removal scenario was used as a base assumption. A complete C budget of the forests was estimated using this scenario and methodologies described in Liski et al. (2002; 2006). These methods are essentially similar to those used in the Finnish national greenhouse gas inventory (Statistics Finland, 2012).

The soil C budget was estimated using the dynamic Yasso07 model (Tuomi et al., 2009; Tuomi et al., 2011a; Tuomi et al., 2011b). The Yasso07 model describes the litter decomposition and the soil C cycle based on the chemical quality of organic matter and climatic conditions (Tuomi et al., 2009). The decomposition of woody litter depends also on the physical size of the litter (Tuomi et al., 2011a). Estimates of annual litter production were calculated from the biomass estimates of the realized harvests (Liski et al., 2002, 2006; Statistics Finland, 2012). The C input to the soil consisted of the litter production of living trees, harvest residues and natural mortality. The chemical quality of organic matter was estimated based on earlier studies (Berg et al., 1991; Hakkila, 1989). Diameters of woody litter applied in the simulation were 2 cm for branches and 10 cm for stems. To start the simulation, the soil C stock was assumed to be in a steady state with constant litter input and climatic conditions. The model was run using an annual time-step.

2.3.2. Soil nutrient balances

The long term balance of base cations (Ca, Mg, K) and N was estimated by calculating the long term supply and removal of these compounds. Estimates of long-term average weathering rates in forest soils were taken from a national data base (Johansson and Tarvainen, 1997; Joki-Heiskala et al., 2003). These values had been derived for 1057 plots covering Finland, using the methodology of Olsson et al. (1993), based on total element contents and effective temperature sums. Long-term average base cation (BC) deposition values were also taken from a national data base, based on data from 38 stations measuring monthly bulk deposition in Finland (Aherne et al., 2008; 2012; Järvinen and Vänni, 1990). Values for both weathering rates and deposition (eq ha^{-1} a^{-1}) for Hämeenlinna were interpolated using inverse distance averaging of the four nearest data points. The values were calculated in equivalents (eq) to account for the charge of the different ions.

Data on the mass (kt a^{-1}) of the different tree compartments (stems and bark, foliage, live and dead branches stumps and roots) were available from the MELA model for each of the 15 Forest Centre in Finland, based on biomass equations by Marklund, 1988. Values for Hämeenlinna were obtained by scaling the Forest Centre results using forest area and volume. The temporal removal (harvest) of BC and N for each bioenergy scenario was estimated using the mass values and element concentrations in the different tree compartments. The element concentration data (ICP Integrated Monitoring, 2004) were based on a compilation of Nordic sources (e.g. Finér and Brække, 1991). The harvest residues were assumed to be removed immediately after harvest (i.e. the needles were not assumed to fall or decompose on the forest floor). The net removal of BC and N was then calculated as:

BC net removal = total removal – (weathering + deposition) (eq ha^{-1} a^{-1})

N net removal = total removal – deposition (kg ha^{-1} a^{-1})

2.3.3. *Nutrient leaching to surface waters*

The total N and total P loads on the watercourses caused by clear-cutting and site preparation were estimated using a calculation method based on the specific load values from different forest management practices and the area managed (Finér et al., 2010). The calculation method takes into account the fact that clear-cutting and site preparation have a long-term (10 years) impact. The specific load values used (Finér et al., 2010) are based on paired catchment studies, where two similar catchments are monitored during several years after which one of the catchments is treated and the other remains untreated. The monitoring period before treatment is called calibration period. The relationship between the catchments during the calibration period is used to predict the behaviour of the treated catchment during post-treated period as if it had not been treated. The treatment effect can be determined as the difference between the measured and predicted values. The specific load values used in the calculations (Finér et al., 2010) were determined with the approach of Laurén et al. (2009), which takes into account the uncertainty in the regression between the pre-treatment loads from the control and from the treatment catchments. Both specific load values and the area of clear-cuts were estimated for upland soils and peatland soils separately. The area of the clear-cuts in Hämeenlinna was estimated for different time periods from the data of MetINFO – Forest Information Services, where the future regional harvest possibilities of Finnish forests by forestry centres are presented. The background leaching was estimated with the same method (Finér et al., 2010) using average specific load values derived from 42 small pristine catchments in Finland (Kortelainen et al., 2006; Mattsson et al., 2003).

2.3.4. *Dead wood biomass*

As outlined in section 1.2, the decline of dead wood biomass is a major threat to many red-listed forest species. In order to estimate the change in the amount of dead wood (used here as proxy indicator for species diversity) caused by the different bioenergy scenarios, total biomass of dead wood was calculated by summing up the biomass of natural mortality, energy-wood yield and harvest residues for 2010–2040 based on the realized harvests scenario of the MELA-model. In these three categories of dead wood, the biomass was calculated for different tree compartments: stems, branches and leaves, stumps and roots. The changes in dead wood biomass were compared between the three bioenergy scenarios.

2.3.5. *Comparison of impacts*

In order to be able to compare the impacts of the different scenarios on the four sustainability indicators (all using different units), normalised values were calculated as percentual differences relative to scenario 1 (no use of harvest residues for bioenergy production). For each indicator, the difference between the resulting values of scenarios 2 and 3 to that of scenario 1, respectively, were divided by the value of scenario 1 and expressed as percentages.

3. Results and discussion

3.1. *Carbon balance*

Using harvest residues for district heat production reduced fossil C emissions but also the C sink of forests in the case study area, the municipality of Hämeenlinna, compared to no use of forest harvest residues (Fig. 2). It is noteworthy that the forests (trees + soil), remained a C sink despite of collecting the harvest residues (scenarios 2 and 3), but the C sink was weakened. At first, the C sink was reduced more than the emissions, and consequently the net emissions increased. However, the reduction effect on the C sink decreased over time while the quantity of the avoided fossil emissions remained the same. Consequently, the reduction in the net emissions increased with the continued bioenergy production (Fig. 2). After 30 years, this reduction represented already about two thirds of the cut in the gross emissions. These calculations illustrate the concept of C debt (Haberl, 2013), where increased harvest reduces C sequestration in the growing forest compared to a scenario with lower harvest levels.

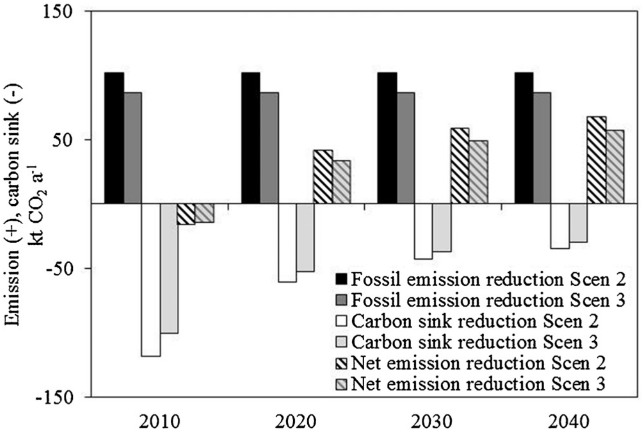

Fig. 2. Changes in fossil emissions, carbon sink and net emissions (kt CO$_2$ a^{-1}) in the municipality of Hämeenlinna resulting from energy use of forest harvest residues. Scenario 1 (no use of harvest residues) is used as the reference level. Using forest harvest residues for heat production reduced both fossil C emissions and the C sink of forests, and the change in the net emissions is equal to the difference between these two changes. The black and dark grey columns show the reductions in the emissions and the white and light grey columns the reductions in the forest C sink. Negative striped columns indicate an increase in the emissions and the positive columns a decrease in them.

Using or not using stumps for the bioenergy production had a relatively small effect on these results because the stumps represented only 16% of all harvest residues. Calculated per the amount of bioenergy obtained, the stumps had a longer-lasting effect on the forest C sink. This was because stumps decayed at a lower rate compared to the other harvest residues and would therefore store carbon for a longer time if left in forest. Bioenergy production from stumps has become a debated matter as a consequence of various environmental issues, such as adverse impacts on greenhouse gas balances and nutrient cycling (Kataja-aho et al., 2011; Melin et al., 2010; Walmsley and Godbold, 2010).

The calculations clearly indicate that ensuring the sustainability and potential climate impact of bioenergy from forest harvest residues requires accounting for changes in all C pools (Repo et al., 2014; Vanhala et al., 2013). The C balance of bioenergy may range from highly beneficial to strongly detrimental, depending on the plants grown, the land used (including its land-use history) as well as the fossil energy replaced (Haberl, 2013). Furthermore, in addition to acting as C reservoir, soil organic matter has numerous functions in amending soil structure, water regulation, nutrient cycling, site fertility and biological activity (e.g. Agostini et al., 2013). Carbon loss resulting from forest residue harvesting may pose a risk to these functions as well.

3.2. *Soil nutrient balances*

The nutrient removal due to harvesting was calculated using the element content of different tree compartments and the information from the MELA realized harvest scenario. In scenario 1, on average 223 kilotons of stem wood biomass per year will be removed during 2010–2040 in Hämeenlinna, which is about 25%

Table 2

Yearly average removal of biomass (kt a^{-1} dry mass), base cations (BC, keq a^{-1}) and nitrogen (N, t a^{-1}) from the Hämeenlinna area during the periods 2010–2040 and 2030–2040 according to the three bioenergy scenarios.

	Scenario 1	Scenario 2	Scenario 3
2010–2040			
Biomass (kt a^{-1})	223	300	295
BC (keq a^{-1})	16 395	26 024	25 489
N (t a^{-1})	219	418	415
2030–2040			
Biomass (kt a^{-1})	224	301	297
BC (keq a^{-1})	16 443	26 119	25 717
N (t a^{-1})	219	421	415

Table 3

Yearly average net removal of base cations (BC, meq m^{-2} a^{-1}) and nitrogen (N, kg ha^{-1} a^{-1}) from the Hämeenlinna area for the periods 2010–2040 and 2030–2040 according to the three bioenergy scenarios.

	Scenario 1	Scenario 2	Scenario 3
2010–2040			
BC (meq m^{-2} a^{-1})	−43	−36	−36
N (kg ha^{-1} a^{-1})	−1.47	0.04	−0.02
2030–2040			
BC (meq m^{-2} a^{-1})	−43	−36	−36
N (kg ha^{-1} a^{-1})	−1.47	0.06	0.02

less than in scenarios 2 and 3, where harvest residues are also removed (Table 2). In scenario 1, about 16 000 keq a^{-1} of BC and 219 tons of N will be removed with stem wood, which is about 50% less than in scenarios 2 and 3, where both stem wood and harvest residues are removed. The higher proportion of nutrients removed in scenarios 2 and 3 relative to the biomass removal is due to the fact that branches and foliage have higher nutrient concentrations than stem wood (Finér and Brække, 1991). Nutrient removal between scenarios 2 and 3 does not differ very much, due to the rather low proportion of roots and stumps in energy-wood according to the MELA realized harvests scenario results for the Hämeenlinna region. The results for the two different periods are also rather similar. In any case, removal of harvest residues is expected to greatly increase nutrient removal from these forest ecosystems for a long time into the future (Table 2).

Harvesting of biomass permanently removes nutrients from the forest ecosystems. From the sustainability point of view, the removal of nutrients of the different bioenergy scenarios should therefore also be compared with the long-term supply. The BC net removal (see section 2.2) of the different scenarios ranged between −36 to −43 meq m^2 a^{-1} (Table 3), indicating that the long-term supply of base cations (soil weathering + deposition) would be enough to sustain also energy-wood harvesting. It should, however, be recognized that these steady-state mass balance calculations do not consider the impacts of acidifying deposition and leaching processes on the long-term BC budget. Extracting stumps and roots for bioenergy may also accelerate nutrient leaching due to increased soil disturbance but experimental evidence of this is lacking. Accounting for these processes requires applications of dynamic hydro-geochemical models and site-specific model calibrations. Aherne et al. (2012) applied such a modelling framework (the MAGIC model) to 1066 lake catchments covering Finland, and used a similar approach as in the present paper to quantify removals of nutrients from harvesting scenarios. Aherne et al. (2012) concluded that only harvesting of above-ground woody biomass (stem-only or stem-and-branches harvesting scenarios) would be sustainable, i.e. not depleting the soil BC pools in the long term. They also concluded that additional inputs of N and K would be required to ensure sustained forest growth under intensive biomass harvesting. Repeated measurements on the impacts of stem-only and whole tree harvesting (WTH) in a fertile Norway spuce (*Picea abies* (L) *Karst.*) stand in southern Finland have also showed that the amounts of C, N and BaCl$_2$ extractable Ca and Mg, and cation exchange capacity and base saturation (%), were lower on the WTH plots (Kaarakka et al., 2014).

Nitrogen is generally a growth-limiting factor in boreal ecosystems (e.g. Hyvönen et al., 2008), and forest growth in Finland is mainly controlled by temperature and N availability. Consequently, fertilizer amendment (NPK) during forest establishment is a management practice (depending on site quality).Therefore, long-term sources of N such as deposition need to be quantified for sustainable forest management. In this context, a simple mass balance approach was employed to explore potential N limitations under each bioenergy scenario.

The calculations of net removal of N (i.e. removal minus deposition inputs) indicated that increased use of harvest residues (scenarios 2 and 3) would cause increasing N limitation problems also in the Hämeenlinna region (Table 3). Assuming scenario 2, N removal would exceed deposition inputs (net N removal 0.04–0.06 kg ha^{-1} a^{-1} for the two periods), and also scenario 3 would exceed this limit for the 2030–2040 period. As in the case with the BC net removal, these calculations do not consider leaching fluxes, which would push the system further towards N limitation.

In reality, the N budget of forest ecosystems is determined by a complex balance between deposition inputs, mineralisation of soil N pools, potential N fixation, fertilizer applications, vegetation uptake and leaching losses. Forests soils in Finland contain large N stores, on average 59 g m^{-2} for the humus layer and 111 g m^{-2} for the 0–20 cm mineral soil (Ilvesniemi et al., 2002). Site-specific modelling results have indicated that rising temperatures due to climate change could increase the decomposition of organic matter in the soil and release N that can be used by the vegetation. This could potentially increase the growth rate of pine trees and stem wood production by up to 40% in southern Finland (Forsius et al., 2013). The above calculations of steady-state net BC and N removal are simplifications, but they still illustrate the need to consider the importance of the removal of harvest residues in the overall BC and N budget of these systems. This conclusion is supported by the results of both the related modelling work (Aherne et al., 2012) and the empirical studies (Kaarakka et al., 2014) referred to above.

3.3. *Nutrient leaching to surface waters*

In 2010, nutrient load to surface waters caused by forest management practices (clear-cutting and site preparation, fertilization, ditch drainage) in the municipality of Hämeenlinna was approximately 11 and 0.6 tons of total N and total P, respectively. Most of the nutrient load was caused by clear-cutting and site preparation: 11 and 0.4 tons of total N and total P, respectively. According to the scenarios, the area of the clearcuttings will be smaller in the future, which would diminish the total N and total P load from clear-cutting and site preparation to 8 and 0.3 tons per year by the year 2040 (Fig. 3).

Specific load values for energy-wood harvesting are currently not available. Therefore, the impacts were estimated by comparing the leaching from unmanaged and managed (regeneration cuttings) areas.

The estimated average background leaching of total N and total P from forested areas is about 201 and 6.9 tons per year, respectively. Accordingly, the clear-cuttings and site preparation increase the load of total N and total P to surface waters by 4.0 and 4.5%, respectively. There is a clear need to get better empirical data on the impacts of increased biomass harvesting on the nutrient loadings in order to improve these estimates.

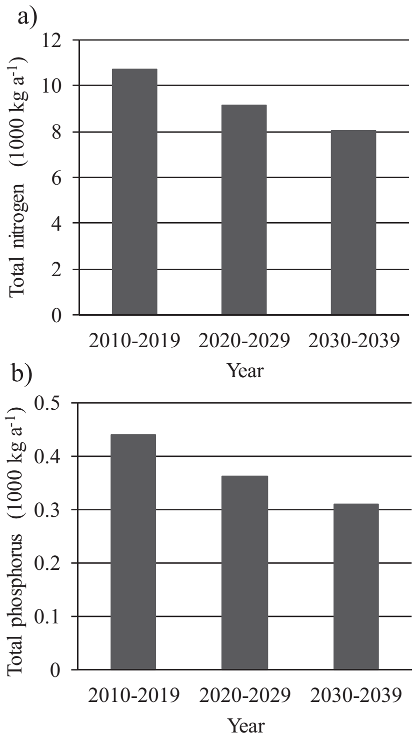

Fig. 3. Average annual total nitrogen (a) and total phosphorus load (b) to watercourses from clear-cutting and site preparation in the municipality of Hämeenlinna. Results for the periods 2010–2019, 2020–2029 and 2030–2039 are shown.

3.4. Dead wood biomass (impacts on species diversity)

The future of the forest species and the forest habitat types depends heavily on how the forests outside the reserve network are managed: these cover ca. 98% of the forest land of southern Finland. The share of semi-natural old forests (forests with age > 140 years and occurrence of forest damages relating to dead wood and thus, indicating naturalness, i.e. dead trees, fallen and broken trees, decayed trees, multiple symptoms in overmature senescent forests) is only about 1% in southern Finland (Virkkala et al., 2000) and, similarly, the amount of coarse woody debris is only a few percent (3.8 m^3 ha^{-1}, Peltola, 2014) of the estimated natural level (ca. 100 m^3 ha^{-1}, Siitonen, 2001) at present. The decline of natural forests and dead wood has led to the decline and loss of forest species, and to a large extinction debt of forest specialist species. It has been estimated that unless the quality of the forests and the amount of dead wood does not increase, approximately half of the species (∼1000 species) dependent on natural or semi-natural forests may be consigned to extinction (Hanski, 2005). The amount of dead wood is thus a good proxy indicator for forest species diversity in Finland.

The change in dead wood biomass of the different tree compartments for the three different scenarios in the Hämeenlinna case study area is shown in Table 4. For scenario 2 and the 2030–2040 period, the total biomass of dead trees would decrease from 323 to 249 kt a^{-1}, and the change in stem-wood biomass would form the largest fraction. Stem dead wood biomass is predicted to decrease by 39% in 2010–2040 and by 44% in 2030–2040 (Table 4, Fig. 4). As already noted above, the results between scenarios 2 and 3 are not very different, due to the rather low proportion of stumps and roots in energy-wood according to the MELA realized harvests scenario results. The biomass of branches, leaves, stumps and roots forms a large fraction of the deadwood biomass (Table 4). The results for the two periods 2010–2040 and 2030–2040 are not very different.

Table 4
Biomass of dead trees (kt a^{-1} dry mass) in Hämeenlinna, separately for stems, branches and leaves, stumps and roots, and total biomass for the periods 2010–2040 and 2030–2040, assuming the three different bioenergy scenarios. The results have been calculated based on the MELA model outputs.

	Scenario 1	Scenario 2	Scenario 3
2010–2040			
Stem biomass	107	65	65
Branch and leaves biomass	105	78	78
Stumps and roots biomass	120	114	120
Total biomass of dead trees	331	257	263
2030–2040			
Stem biomass	100	56	56
Branch and leaves biomass	107	78	78
Stumps and roots biomass	116	112	116
Total biomass of dead trees	323	249	263

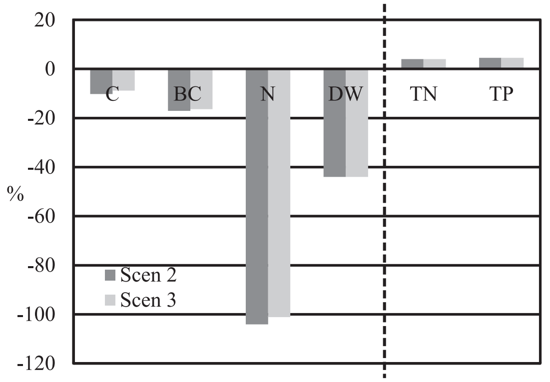

Fig. 4. Relative impacts (% change relative to Scenario 1) of cutting scenarios 2 and 3 on the different sustainability indicators for the period 2030–2040. Scenario 1 = no use of harvest residues for bioenergy production; Scenario 2 = all harvest residues used for bioenergy production; Scenario 3 = stumps and roots are not included in the harvest residues used for bioenergy production. C = C sink of forest soils, BC = net removal of base cations, N = net removal of N, DW = dead wood removal (species diversity proxy indicator), TN = loading of total N to watercourses, TP = loading of total P to watercourses. Note that the results for TN and TP were estimated by comparing the leaching from unmanaged and managed (regeneration cuttings) areas, and these results are therefore not directly comparable to the other indicators.

Cut stumps make up a considerable proportion, up to 80% of the total volume of coarse dead wood in managed forests, and the majority of this volume is formed in the regeneration cuttings (Berglund, 2012). There has been a huge increase in the use of stump and root wood as raw materials of forest chips in Finland. In 2000, the consumption was only 5000 m^3, while in 2013 the consumption was 1.2 million m^3. At the same time the consumption of large-sized timber as energy-wood has increased from 35 000 m^3 to 0.5 million m^3. Taken together, the usage of coarse dead wood as energy-wood has increased more than 40-fold, while the use of small-sized trees has increased eight-fold, from 0.8 to almost 7 million m^3 from 2000 to 2013 (Finnish Forest Research Institute, MetInfo).

Small-sized dead wood is a much more abundant resource than coarse dead wood in managed forests, and less than 20% of this consists of harvest residues in regeneration cutting areas (Berglund, 2012) that were earlier left behind in regeneration cutting and thinning areas to decay. Thus, in order to minimize impacts on species diversity, energy-wood harvesting could be targeted to small-sized conifer wood, the amounts of which have been increasing steadily in managed forest. The use of small-sized conifer wood does not seem to constitute an additional threat to the forest species according to present understanding (e.g. Berglund, 2012; Dahlberg et al., 2011a, 2011b).

According to the results of National Forest Inventories of Finland (NFI 11), the tree stock on open regeneration areas has decreased by one fifth (Peltola, 2014). This may indicate that the impairments of the forest certification criteria e.g. for retention trees and the increased energy-wood harvesting have lowered the amounts of living retention trees in regeneration areas. Similarly, the amounts of dead wood seem to have continued to decline in northern Finland.

The dead-wood budget of the managed forests has turned negative because the retention trees on regeneration areas do not suffice to compensate even the use of large-diameter dead wood for energy wood anymore (data in Peltola, 2014).

Clear-cutting and soil preparation already as such lead to heavy loss of downed logs, and this effect is reinforced by energy-wood harvesting because of additional increased destruction by heavy machinery used (Eräjää et al., 2010; Hautala et al., 2004; Rabinowitsch-Jokinen and Vanha-Majamaa, 2010). Adding to this unintentional reduction of dead wood in managed forest, also selective harvesting of dead trees for firewood has reduced the amounts of dead wood in the densely populated areas (Tikkanen et al., 2009).

One of the most cost-efficient means to increase the amounts of large-diameter dead wood in managed forests would be to retain the already-existing dead trees and to increase the amount of truly coarse living trees to be retained permanently in the regeneration areas and woodland key habitats, and refrain from thinnings or selective cuttings in the latter (Ranius and Kindvall, 2004; Tikkanen et al., 2012). Otherwise the production of new, large-sized dead trees in managed forests following regeneration cutting is slow (may take a century). If the decrease of dead wood in the managed forest continues, it is likely that the rate of the decline of species accelerates and further species become threatened.

3.5. Comparison of impacts and implications regarding ecosystem sustainability

The impacts of the bioenergy scenarios on the different sustainability indicators are compared in Fig. 4. The results of scenarios 2 and 3 have been normalised to the results of scenario 1 in order to show the relative impacts of increased use of harvest residues compared with “business-as-usual” harvesting. It should be recognised that the calculations regarding leaching losses of nutrients N and P have been based on different assumptions (see Section 2.3.3), and therefore these results are not directly comparable.

It can clearly be seen that in the present demonstration case for the municipality of Hämeenlinna, the largest relative impacts for the 2030–2040 period can be observed regarding the N and species diversity indicators (i.e. change in dead wood biomass). For scenario 2 (all harvest residues used for bioenergy production), the net removal of N would change by more than 100%. Also for the other indicators, increased negative impacts regarding ecosystem sustainability can be observed with increased use of harvest residues (note that the direction of change on what can be considered as “harmful” regarding ecosystem sustainability in Fig. 4 is dependent on the indicator: e.g. a decrease in the soil C sink and an increase in total N leaching are both negative effects in this respect). Due to the fact that the proportion of use of stumps and roots in scenario 3 is rather small in the Hämeenlinna region (caused by the assumptions in the MELA realized harvests scenario calculations, see Section 2.2), there is a rather small difference between the scenarios. This proportion is, however, predicted to be much higher in many other Finnish regions, and modelling of the sustainability impacts of the usage of stumps and roots is therefore a topic of general importance.

These calculations for Hämeenlinna presented in this paper should be regarded as examples, and they show the extremes of the different options regarding use of harvest residues for bioenergy production. In reality, varying forest management practices are used in the different forest management units, and there will never be a single strategy used over the entire landscape. It is still essential that reliable methods and data are available to evaluate the sustainability of the different management scenarios, so that the actual aim of the action is obtained (e.g. a positive C balance and avoided climate change effect, Repo et al., 2014), while minimizing impacts on other indicators (Fig. 4). The quantitative framework developed in this study allows seeking for such optimised solutions at various spatial scales. Clear trade-off situations can be observed between maximising the use of energy-wood and minimising, e.g., impacts on species diversity and nutrient removal also in the Hämeenlinna region.

The focus of this paper has been on developing the modelling framework for ecosystem sustainability evaluations, but different techniques are also available for the analysis of risks and spatial efficiency of different management options (e.g. Zhang et al., 2015). Moreover, it is a policy decision to assess the relative importance of the different sustainability indicators. Also for such situations, various methods are available to assist decision makers to make informed decisions based on multiple data sources and non-compatible data (e.g. MCDA, Mustajoki et al., 2004).

3.6. Uncertainties and future work

There are obviously many sources of uncertainties involved in the evaluations of complex ecological phenomena at large spatial scales for long time periods, and the model results (predictions) in the present study are subject to considerable uncertainty. Sources of uncertainty include characteristics of the spatial data, methods for spatial interpolation, assumptions behind the scenarios, inclusion of ecosystem processes, and the temporal drivers and the process rate parameters used to derive the results (Aherne et al., 2012; Beven, 1993; Holmberg et al., 2015). Feedback between availability of nutrients and the growth of forests has also not been accounted for. The potential impact of some of these uncertainties, like consideration of climate change impacts (Forsius et al., 2013), and deposition related processes (Aherne et al., 2012), have already been mentioned above. Increasing the spatial resolution, and focusing the work only on intensively studied ecosystem research plots/sites where detailed process data are available can reduce some on these sources of uncertainty (e.g. Rask et al., 2014). However, bioenergy policies are affecting entire forest districts and heterogeneous landscapes, and management decisions are also usually made for large spatial units. Therefore, there is an evident need for evaluations of ecosystem sustainability also at larger spatial scales, and methods to deal with the different sources of uncertainty have to be developed and applied and better spatial data sets collected and continuously updated.

Our aim is to increase the spatial resolution of the present model framework and to evaluate the impacts using actual decided cutting plans and more detailed forestry models for obtaining future scenarios. We are also working on including estimates of the uncertainties in the model outputs and improving the spatial databases for several ecosystem variables (e.g. soil weathering rates). Integrating biodiversity protection with the provision of ES is a key element for sustainable land use planning (Vihervaara et al., 2015), and it is therefore also planned to include other biodiversity indicators than the dead wood biomass in our model framework in the future. Spatial age-structure of forests, proportions of deciduous trees, species traits and trophic complexity, for instance, are essential biodiversity variables that may have impact on ecosystem functions and services, and that should be integrated in the model system. However, that requires use of novel data sources and Earth Observation outputs in addition to the approach used in this study.

4. Concluding remarks

Increasing the use of forest bioenergy is an important mitigation strategy against climate change. However, these policies need to be evaluated, planned and implemented taking into account the boundary conditions of the ecological systems affected. These boundary conditions include quantifying the real net C ecosystem budget and emission savings obtained, the long-term supply of nutrients available for sustained forest growth, and impacts on other relevant ecosystem compartments (e.g. nutrient leaching to surface waters and impacts on valuable species). A systems analysis approach is therefore needed to analyse these complex interactions.

The modelling framework developed and documented in the present study allows a quantitative analysis of the impacts of forest harvesting scenarios on several key ecosystem sustainability indicators. The demonstration case of the Hämeenlinna municipality shows how there can be conflicting goals between maximising the use of energy-wood and minimising impacts on species diversity, soil carbon and nutrient stores and nutrient leaching. The developed system allows seeking for optimised solutions with respect to different management options and sustainability considerations. Responsible and sustainable natural resources economy is a key policy goal of the Finnish government, and therefore such model systems are increasingly needed. However, the framework is complex and large uncertainties still remain regarding many components, including data sources, scenarios assumptions, simplifications of ecosystem processes, and process rate parameters. Continued work is therefore needed to improve these modelling and evaluation tools and to secure the collection of long-term detailed ecosystem and experimental data needed for the model developments and impact evaluations.

Acknowledgements

The work was supported by the European Commission through the FP7-projects OpenNESS (grant agreement no. 308428) and ExpeER (no. 262060), and LIFE-project MONIMET (no. LIFE12 ENV/FIN/000409). The study was also supported by Maj and Tor Nessling Foundation (grant no. 201500289). The support of the Academy of Finland is also acknowledged (decision numbers 256231 (CLIMES) and 271628 (LifeWatch)).

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