Assessing forest biomass use in south Sweden – development of methods for sustainability analysis

Johnny de Jong, Cecilia Akselsson, Per-Erik Karlsson, Tommi Suominen, Gediminas Jasinevičius

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Abstract

It is of large importance that harvesting of forest for bioenergy purposes is sustainable from environmental, social and economic perspectives. The biofuel market requires a sustainable use of biomass and it is important to be able to demonstrate the potential sustainability impacts of different harvesting alternatives. A synthesis must be based on present knowledge on how harvesting affect different environmental variables, as well as social and economic factors, but we also need methods to balance different sustainability components in order to compare with societal goals. In this project, we have used a decision-making tool, ToSIA, developed for the forest sector in order to analyze alternative situations throughout the forest value chain. The overall aim of the project was to develop a systematic, pedagogic and transparent methodology for the assessment of sustainability, which could be a useful tool for the Energy Agency in future syntheses projects in which different scenarios for bioenergy harvesting can be compared.

We have chosen to limit the study to the geographical area to Kronoberg County (south Sweden), and the bioenergy assortment slash from final cutting and thinning. In the model, we use a number of indicators for environmental, social and economic sustainability. Three different scenarios with varying levels of harvest residue removals have been tested, resulting in different indicator values. The environmental indicators that we have used are biodiversity, soil chemistry and greenhouse gas emissions (GHG, presented as carbon stock change in the forest ecosystem and substitution). The social indicator is employment, and the economic indicator is the gross value added (GVA).

The decision-making tool that we have used, ToSIA, describes the flow of carbon through different processes, starting with all forestland in Kronoberg County. One part of the forest area will be set aside for conservation purposes, and the remaining will be used for forestry by yearly fractions of clearcutting, thinning and pre-commercial thinning. After clear-cut and thinning, some slash continues as bioenergy to local district heating plants or larger combined heat and power (CHP) plants. Within each process, the absolute value of each indicator is calculated by multiplying the carbon flow through the process with a relative indicator value. There were also indicator values used that were independent of the carbon flow through the process.

How to select the optimal scenario from a sustainability perspective depends on your values. We analysed this by using a Multi Criteria Analysis (MCA) in which we did choose two different ways of prioritizing. First, we analyse each sustainability component one by one in which each component is given 100 % priority. Environment is however divided into two components, GHG and other environmental factors, since these two might be in conflict with each other. Second, we performed MCA based of stakeholder's interest, and in this case we used imaginary persons with different priorities: economy and energy (case 1) and conservation (case 2) to demonstrate how MCA may be used.

The decision-making tool that we tested is very simplified and consequently the results from the MCA is relatively predictable, for example a large harvesting volume of slash is good for social and economic values, as well as for GHG, but bad for other environmental

components. However, the more sustainability indicators added into the model, the more complex it will become, and the result will be more complicated to predict. For example a large harvesting volume is not necessarily bad for biodiversity, it depends on what kind of substrate, how and when it is harvested and where the harvesting occur. The strength with this type of model is that it is easy to continue to add more indicators to get closer to a more realistic situation. The model could then be used for a real MCA, in which for example different stakeholders could meet and valuate different indicators. It would then be possible to for example suggest an optimal harvesting volume for a certain geographical region.

Sammanfattning

Det är av stor betydelse att uttaget av skogsbränsle från skogen är hållbart ur naturvårds, socialt och ekonomiskt perspektiv. På biobränslemarknaden ställs ofta krav på ett hållbart uttag och vi måste tydligt kunna demonstrera vilka konsekvenser uttaget får. En syntes måste baseras på kunskapsläget, dvs. hur uttaget påverkar olika miljövariabler, samt sociala och ekonomiska faktorer, men man måste också ha en metodik för att sammanväga dessa faktorer och kunna stämma av mot samhällets uppsatta mål för att kunna ta beslut om önskvärd utveckling. I det här projektet har vi använt ett beslutsverktyg, ToSIA, som har utvecklats för skogssektorn för att kunna analysera alternativa situationer inom hela den skogliga värdekedjan. Det övergripande syftet med projektet har varit att ta fram en systematisk, pedagogisk och transparant metod för bedömning av hållbarhet, som kan bli ett effektivt sätt för Energimyndigheten att genomföra synteser vad gäller olika scenarier för skogsbränsle.

Vi har valt att begränsa oss geografiskt till Kronobergs län, och olika volymer för det skogsbränsle som plockas ut i form av grenar och toppar (grot) från föryngringsavverkning och gallring. I modellen undersöker vi effekter av olika alternativ på olika indikatorer som är fördelade efter miljö-, social- och ekonomisk hållbarhet. Vi har använt tre olika scenarier med varierande uttagsnivåer av grot som har resulterat i olika värden av de undersökta indikatorerna. De miljöindikatorer som har använts är biodiversitet, markkemi och växthusgasemission (GHG, redovisat separat för förändringar av kolförråden i skogsekosystemen respektive substitutionseffekter). Den sociala indikatorn som beaktats är arbetstillfällen, och den ekonomiska är bruttofördelningsvärde (på engelska gross value added, förkortat GVA).

Det beslutsverktyg som vi har använt, ToSIA, beskriver hur kolflödet rör sig genom olika processer. Vi börjar med all skogsmark i Kronoberg. En del av detta avsätts en viss areal för naturvård, medan resten går vidare till återkommande föryngringsavverkning, gallring och röjning. Efter föryngringsavverkning och gallring går en del vidare som grot till förbränningsanläggningar. För varje process beräknas ett värde på indikatorn beroende på hur stort flödet är och hur kolet fördelas för olika transporter.

Vilket scenario som är bäst ur ett hållbarhetsperspektiv beror på vilka värderingar man ansätter. Detta har analyserat i en multikriterieanalys (MCA) där vi valt två olika sätt att prioritera. Vi har dels visat ett resultat där vi valt ut en hållbarhetsaspekt i taget och prioriterat den till 100 %. Miljö har vi dock delat upp i två delar, GHG och övriga faktorer, eftersom de delvis står i konflikt med varandra. Vi har också genomfört MCA utifrån olika intressegruppers tänkbara prioriteringar. Vi har då satt vikter för olika aspekter, tänkta att representera personer med olika prioriteringar, nämligen ekonomi och energiproduktion (fall 1) respektive miljö (fall 2), för att visa hur MCA kan användas.

Det beslutsverktyg som vi har testat är väldigt förenklat och resultaten från MCA blir därmed ganska förutsägbara, t.ex. att ett stort grotuttag är bra för sociala och ekonomiska värden, samt för GHG, men dåligt för biodiversitet. Vidare får ett stort uttag av barrgrot inte så stor negativ betydelse för biodiversitet, medan även ett litet uttag av lövgrot får stor

negativ inverkan. Ju mer hållbarhetsindikatorer som läggs in i modellen desto mer komplex blir den och resultatet blir inte alltid så lätt att förutse, dvs. det behöver inte vara självklart att ett stort uttag är dåligt för biodiversitet eftersom det beror på vad som tas ut, var man gör det och hur man gör det. Styrkan med beslutsverktyget är att man enkelt kan fortsätta att lägga till indikatorer tills man får något som blir relevant för den verkliga situationen. Modellen skulle sedan kunna användas för en MCA där olika intressegrupper värderar indikatorerna, och där man kan laborera fram ett uttag av grot från skogsavverkningar som ger mesta möjliga nytta till minsta möjliga skada.

Introduction

European Union (EU) set targets on GHG emission reduction, renewable energy and energy efficiency. Until 2030 EU committed to reduce domestic GHG by at least 40 percent (from 1990 levels), to increase share for renewable energy by at least 27 percent and to improve energy efficiency by at least 27 percent (EU 2014). Moreover, EU adopted a bioeconomy strategy for Europe. Bioeconomy development targeting European forest-based sector as a source of renewable resources. Biomass will be of crucial importance in energy supply (EU 2012). The climate mitigation targets and bioeconomy development will most likely effect the use of forest resources within the EU. Sweden is a leading country in achieving and exceeding GHG emission reduction targets. Currently in Sweden over 50 percent of energy is from renewable sources (figure 1) mainly from wood and other biofuels. The latest study by Rockström et al. (2017) drew a roadmap for de-carbonization to keep global warming below 2 degrees Celsius at the end of this century. The roadmap showed that to be able to stabilize global warming, the world needs to reach net zero emissions by 2050. The key actions will be increased usage of renewables and reduced usage of fossil-based materials. In this respect, forests will play an important role, because forests are significantly affecting the global carbon cycle by absorbing carbon from the atmosphere.

In Sweden forests covers over 28.3 mill. ha, of which 4.7 mill. ha are unproductive forests and 0.9 mill. ha are exempt from forest management due to environmental protection (SKOGSDATA, 2017). Currently the growing stock in Swedish forests today is 80 percent higher compared to 1920 and fellings are lower than growth. As a result, accumulation of biomass of 22.6 mill. m^3 annually was observed in the period of 2000 – 2010 (Swedish Statistical Yearbook of Forestry, 2014). The historical trends of increasing increment, fellings and standing volume are predicted to continue at a similar rate at least until 2110 (SKOGSDATA, 2016).

Substituting fossil –based energy production with renewable energy is seen as one of the ways that can contribute to climate change mitigation. Today, the main sources for bioenergy in Sweden are byproducts from the forest industry. However, in the Nordic countries, where intensive utilisation of forests for wood is standard practice, the use of harvest residues for bioenergy production has been one of the most straight-forward ways of increasing bioenergy production, typically in small local district heating plants or larger combined heat and power (CHP) plants. In addition to the environmental effects, bioenergy from forest resources has impact on employment and local value added to rural communities. One of the topics of concern regarding the increased wood extraction, including harvest residues, has been the increase in removal of nutrients from the forest (de Jong et al. 2017, Werhahn-Mees 2010) and impact on biodiversity (de Jong & Dahlberg 2017, Santaniello et al. 2016, 2017).

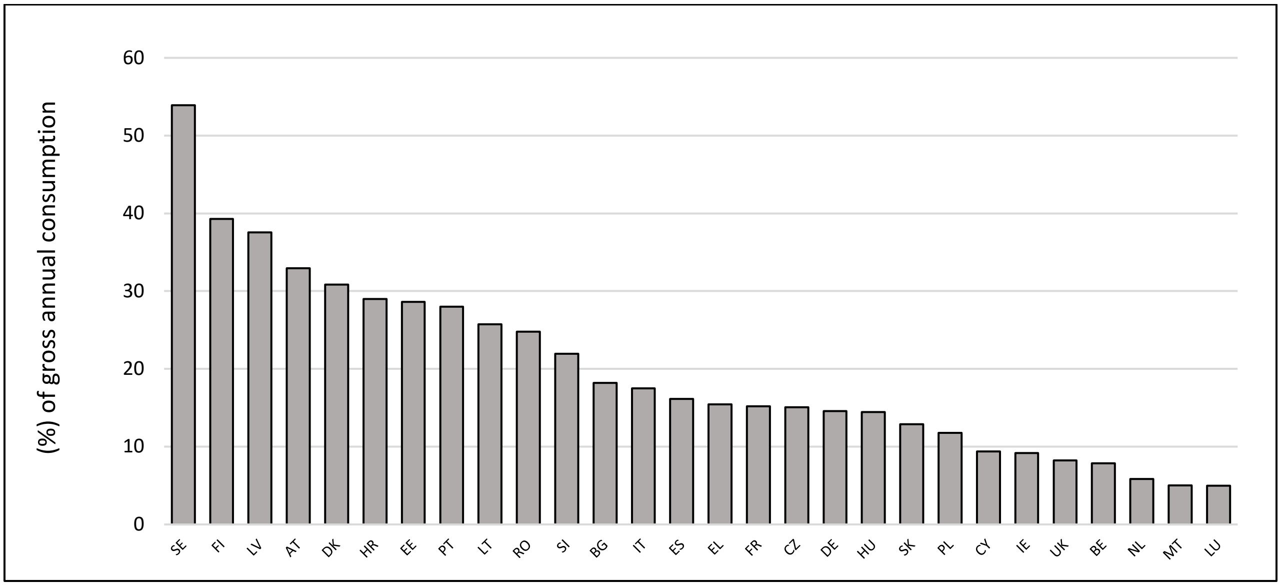

Figure 1. Overall share of energy from renewable sources in EU-28, year 2015 (Source, EUROSTAT 2018)

The objective of this study was to test the Tool for Sustainability Impact Assessment (ToSIA) (Päivinen et al 2012, Lindner et al. 2010) in a Swedish case study. The authors have a keen interest to expand the performed assessment from a local/provincial scale to the national scale, and in that sense this study serves as a pilot study to the envisaged geographical expansion.

ToSIA has previously been applied to case studies in Eastern Finland, with conditions similar to Sweden (den Herder et al. 2012 & 2017, Haatanen et al. 2014, Suominen et al. 2017). In Sweden, ToSIA has been previously applied to analyse the trade-offs between forestry and reindeer husbandry (Berg et al. 2016). Lindner et al. (2012) have presented a case study where a part of Swedish forest use has been described on a national/Nordic level. However, application of ToSIA in Sweden for a pure bioenergy case study has been absent, until now.

Our case study focuses on a CHP plant and the value chain supplying its wood-fuel in the Kronoberg area in the province of Småland, Sweden. The alternatives being evaluated are focusing on increasing the amount of harvest residues collected for energy production. We investigate different harvesting scenarios and its impact on environmental, social and economic factors, and demonstrate how this tools might be used on a larger scale.

The forests in the county province of Kronoberg cover approximately 70% of the total area and 78% of the land area (CAB, 2007). The county has 187 156 inhabitants (22/km2). County gross regional product was 267 000 kr per capita (Sweden 285 000). Unemployment (2006, aged 16-64, including policy measures) was 5%. The number of persons employed (2005) by wood industry was approximately 10% and by pulp and paper, 2%. There were 118 nature reserves in the county (2.6% of the area, 1.4% of the productive forest area). The county received financing supporting rural area development, 10Mkr/yr.

The forests in the county of Kronoberg receive relatively high air pollution loads and the Environmental Quality Standards are not met regarding acidification and eutrophication.

The forest industry is very important and other forest ecosystem services are important as well, e.g. tourism, hunting, fishing etc. >80% of the forest area is owned by ~14 000 private forest owners

Methods

Assessment tool

To estimate environmental and socio-economic impacts of alternative intensities of harvest residues use in Kronoberg we employed the Tool for Sustainability Impact Assessment (ToSIA). The Tool has been developed for assessing the sustainability impacts of changes (e.g., increased utilization of harvest) using indicators of environmental, social, and economic sustainability. This process-based tool focuses on differences in material flows and indicator values by comparing alternative options. ToSIA has been developed as a holistic framework for sustainability impact assessment that allows for tracking material from forest establishment until the production of final products. The system boundaries of applications can be adjusted depending on the study objectives (Lindner et al. 2010, Päivinen et al. 2010). In this study we applied ToSIA for tracking harvest residues flows from forest standing stocks, though different harvest operations and road transport until the end of energy production. Material flows are defined as chains of production processes, so called Forest Wood Chains (e.g., harvesting, collecting harvest residues, chipping, transport and combustion), which are linked with products (e.g., electric power and heat). Sustainability is assessed for all the different processes along the alternative chains by analyzing environmental and socio-economic sustainability indicators. The software calculates sustainability values by multiplying relative indicator values (indicator value expressed per unit of material flow) with the material flow along the process-based value chains.

Forest Wood Chains

In order to examine the effects of increased harvest residues extraction and utilization we built wood value chain and assessed the effects of different utilization alternatives. Our value chain included processes starting from the forest standing stocks, thought harvest processes and road transport until the production of power and heat in combined heat and power plant in Kronoberg (Figure 2). We developed this chain for the Kronoberg province only; however, value chains could be developed for all Sweden or even up-scaled to the European level. We did not include import and export across the border of the Kronoberg County.

Data on processes and material flows were collected from various sources; statistics, reports and stakeholders, e.g. forest management companies, transport providers and power producers (Table 1-3).

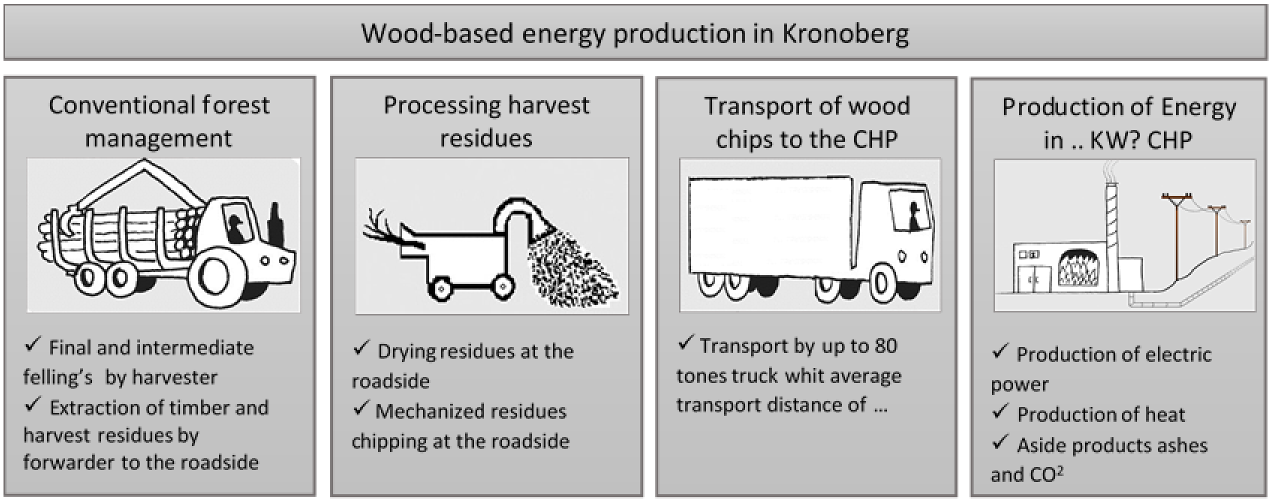

Figure 2. Simplified illustration of energy production value chain in Kronoberg.

Topology

The ToSIA model value chain created for this project starts from the conventional forest management in Kronoberg until combustion of harvest residues at CHP plant in Växjö (Figure 3, Table 1-3), meaning that all processes that might have an effect on socio-economic and environmental values, related with energy production from harvest residues, were included in the chain.

The material flows between forest resource management and consecutive processes along the value chain are of different mass, size, but all products contains a percentage of carbon. To ensure that all information is comparable and consistent, the mass in tons of carbon (base unit) was used as the information carrier along the value chain. Each individual product was automatically converted from original mass to mass of contained pure carbon.

The value chain topology is grouped by processes and divided into three modules: M2 - forest management (the yellow boxes in Figure 3), M3 - forest operations (purple boxes) and M4 – forest industry (the green box). Processes and products are described further below.

M2 - Forest management

The first process "Conventional forest management in Kronoberg" has seven output products: trees for final felling, for thinning and remaining trees, divided into coniferous and deciduous trees, and trees in protected forests (Table 1). The parts going to final felling and thinning are input products in the final felling and thinning processes in M3, whereas the remaining trees and trees in protected forests are input products in the process "Remaining forest after management".

The carbon flows from the processes "Leaving coniferous residues in the forest", "Leaving deciduous residues in the forest", "Forest growth in Kronoberg" and "Remaining forest after management" to the process "Remaining forest after management" are currently not coupled to relative indicator values, but they are included for future developments. By using these processes, it might be possible to complete calculations of forest ecosystem carbon stock changes coupled to the forest value chain.

Table 1. Processes, input and output products in module 2 (M2). The topology is visualized in Figure 3.

Process	Input product	Output product
Conventional forest management in Kronoberg	Standing stock in Kronoberg	Conifers for final felling Conifers for thinning Remaining conifers Deciduous trees for final felling Deciduous trees for thinning Remaining deciduous trees Trees in protected forests
Leaving coniferous residues in the forest	Coniferous residues in forest	Coniferous residues in forest
Leaving deciduous residues in the forest	Deciduous residues in forest	Deciduous residues in forest
Forest growth in Kronoberg	Annual increment in Kronoberg	Annual increment in Kronoberg
Remaining forest after management	Remaining conifers Remaining deciduous trees Coniferous residues in forest Deciduous residues in forest Trees in protected forest Annual increment in Kronoberg	Standing stock in Kronoberg+1

M3 - Forest operations

The processes “Final felling with harvester” and “Thinning with harvester” get their input from outputs of the process “Standing stock in Kronoberg”, as described above. The outputs are large-dimensioned timber (only for final felling), small-dimensioned timber and residues in forest, divided into coniferous and deciduous (Table 2).

The large- and small-dimensioned timber goes to the processes “Extraction of harvested large-dimensioned timber to roadside” and “Extraction of harvested small-dimensioned timber to roadside”. The four products, large- and small-dimensioned timber at roadside, divided into coniferous and deciduous, are not handled further in this project, but can be used in future developments.

The coniferous and deciduous residues are handled in the two processes “Extraction of coniferous residues with forwarder to roadside” and “Extraction of deciduous residues with forwarder to roadside”, giving the two output products “Coniferous residues at roadside” and “Deciduous residues at roadside”. They are inputs to the process “Drying residues at roadside” and are there lumped together, to the output product “Dried residues at roadside”. The dried residues goes further to the process “Chipping residues are roadside” and then to the process “Transport of dried chips to CHP plant”, where it becomes an input product to the Process “Combustion at CHP plant” in M4.

Table 2. Processes, input and output products in module 3 (M3). The topology is visualized in Figure 3.

Process	**Input product**	**Output product**
Final felling with harvester	Conifers for final felling Deciduous trees for final felling	Coniferous residues in forest Large dimensioned coniferous timber in forest Small dimensioned coniferous timber in forest Deciduous residues in forest Large dimensioned deciduous timber in forest Small dimensioned deciduous timber in forest
Thinning with harvester	Conifers for thinning Deciduous trees for thinning	Coniferous residues in forest Small dimensioned coniferous timber in forest Deciduous residues in forest Small dimensioned deciduous timber in forest
Extraction of harvested large-dimensioned timber to roadside	Large dimensioned coniferous timber in forest Large dimensioned deciduous timber in forest	Large dimensioned coniferous timber at roadside Large dimensioned deciduous timber at roadside
Extraction of harvested small-dimensioned timber to roadside	Small dimensioned coniferous timber in forest Small dimensioned deciduous timber in forest	Small dimensioned coniferous timber at roadside Small dimensioned deciduous timber at roadside
Extraction of coniferous residues with forwarder to roadside	Coniferous residues in forest	Coniferous residues at roadside
Extraction of deciduous residues with forwarder to roadside	Deciduous residues in forest	Deciduous residues at roadside
Drying residues at roadside	Coniferous residues in forest Deciduous residues in forest	Dried residues at roadside
Chipping residues at roadside	Dried residues at roadside	Dried chips at roadside
Transport of dried chips to CHP plant	Dried chips at roadside	Chips at plant

Table 3. The process and input and output products in module 4 (M4). The topology is visualized in Figure 3.

Process	Input product	Output product
Combustion at CHP plant	Chips at plant	Heat at the plant Power produced at the plant Ash

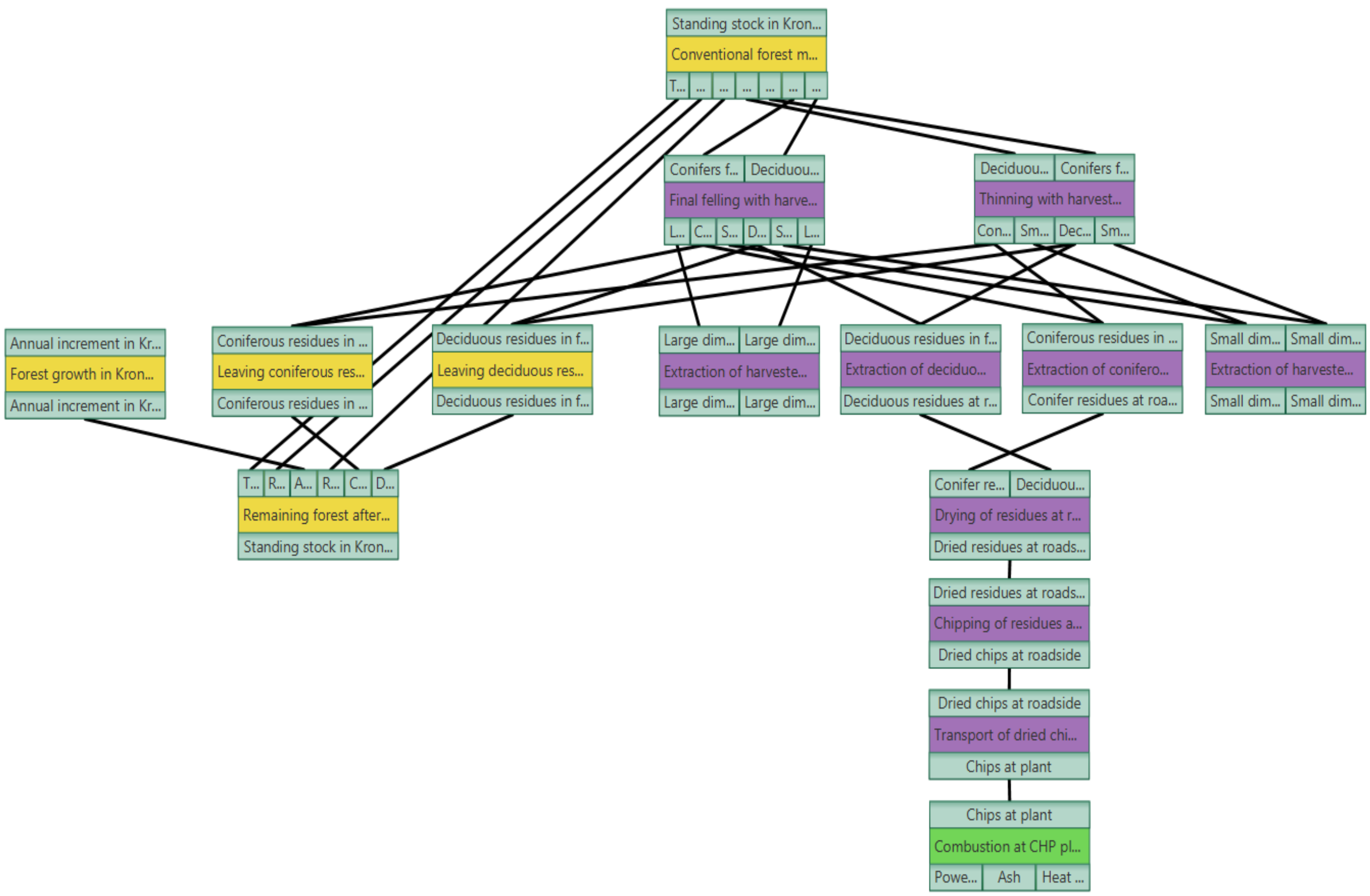

Figure 3. The forest value chain topology in ToSIA. The topology is divided into three modules: M2 - forest management (the yellow boxes), M3 - forest operations (purple boxes) and M4 – forest industry (the green box). Detailed information about processes, input products and output products are given in Table 1-3.

M4 - Forest industry

The module M4 - Forest industry, has only one process, "Combustion at CHP plant" (Table 3), because only this process was relevant for this study, however in principle model could analyse processes beyond combustion. The output products from combustion process are: "Heat at the plant", "Power produced at the plant" and "Ash".

Scenarios

To assess sustainability impacts of alternative harvest residues use, we developed one reference and two alternative scenarios (Table 4). The alternatives focused on increased harvest residues extraction and use in Kronoberg that were expected to enhance socio-economic performance and renewable energy production from the wood-based biomass. The alternatives differed in residues extraction levels.

Table 4. Assumed harvest residues utilization alternatives in Kronoberg. The reference scenario is close to the present situation, while the two different alternatives reflect increased harvest residue extraction ambitions. Another possible 0-scenario is no harvesting at all. However, that scenario was considered to be unlikely and for that reason not analyzed.

Scenario	Description
Reference	Extraction of coniferous (25 % of the total volume) harvest residues. No extraction of deciduous harvest residues.
1	Extraction of coniferous (75 % of the total volume) harvest residues. No extraction of deciduous harvest residues.
2	Extraction of both deciduous (75 % of the total volume) and coniferous (75 % of the total volume) slash.

Indicators

In ToSIA, the calculated absolute process indicator values are determined based on the material flow through the specific process multiplied with the relative indicator value per process unit (Table 5). Care needs to be taken to avoid "double accounting" along the forest value chain. All indicator values have the timescale of one year, if relevant.

In the following, we include only descriptions of indicators that will differ between the different scenarios (Table 5). Thus, gross value added for e.g. the initial process "Conventional forest management in Kronoberg" is not described here. The indicators are divided into economic and social indicators, and environmental indicators.

Table 5. Indicators used in different modules

Indicator group	Indicator	Module
Economic		
Gross Value added	1.1 Gross Value added	M3,M4
Environmental		
Forest biodiversity	25.2.3 Volume of fine coniferous debree	M2
	25.2.4 Volume of fine deciduous debree	M2
Soil condition and soil quality	23.1.5 Base saturation	M2
Energy generation and use	18.1.1.2 On-site heat generation from renewables - other wood biomass	M4
	18.1.2.2 On-site electricity generation from renewables - other wood biomass	M4
	18.2.2.2 Energy use – Direct fuel use – fossil fuel	M3,M4
GHG emission and C stock	19.1.1 Greenhouse gas emissions from machinery	M3
	19.2 Carbon stock	M2
	19.3 Substitution effect	M4
Water, air and soil pollution	24.2.2 Non-greenhouse gas emissions into air – NOx	M3,M4
Social		
Employment	10.1 Employment - absolute number	M2,M3,M4

Economic and social indicators

The details for the calculations of GVA and employment for the different processes are outlined in Appendix 1.

Only two indicators were included as economic and social indicators, gross value added and employment. Gross value added, GVA, was defined by Eurostat (2018) as the value of all newly generated goods and services less the value of all goods and services consumed as intermediate consumption. The depreciation of fixed assets was not taken into account. GVA was expressed as EUR per process unit. Only prices of inputs and outputs used to produce the specified outputs of a given process were included, to e.g. avoid including transportation if modeled independently in subsequent processes. This implicitly defines the system boundary.

In detail, GVA was calculated as:

GVA at factor cost = GVA at basic prices – taxes on production + subsidies on production if applicable.

Gross value added at factor cost was derived from Gross Value Added at basic prices by subtracting indirect taxes and adding subsidies on producer's production. From the point of view of the producer, purchaser's prices for inputs and basic prices for outputs represented the prices actually paid and received.

Gross value added was an unduplicated measure of output in which the values of the goods and services used as intermediate inputs were eliminated from the value of output. The production process itself was described by a vector of the quantities of goods and services consumed or produced in which inputs carry a negative sign. By associating a price vector with this quantity vector, gross value added was obtained as the inner product of two vectors.

The employment indicator was simply the number of employees per year from processes in the value chains in full time equivalent.

Environmental indicators

Biodiversity

Indicators for biodiversity were applied only for the process "Conventional forest management in Kronoberg". Important biodiversity factors includes volume of coarse woody debris, proportion of deciduous trees, forests structure, area of set-asides etc. However, these factors are not affected by slash harvesting, but how forestry in general is organized. Instead, in this study we focus on the volume of fine coniferous debris (indicator 25.2.3), and volume of fine deciduous debris (indicator 25.2.4), which are affected by slash harvesting (Table 5). The volume of fine woody debris is a combination of natural created, and woody debris created after logging. The natural created woody debris was set to 1.1 mill. m^3. After logging 0,423 mill. m^3 of coniferous slash, and 0,024 m^3 deciduous slash was created. Besides this slash was crested after thinning, 0,315 mill. m^3 coniferous wood and 0,132 mill. m^3 deciduous wood. The calculations were based on data from the Swedish national forest inventory (https://www.slu.se/en/Collaborative-Centres-and-Projects/the-swedish-national-forest-inventory/). Thus, the total amount of slash is 1,994 mill. m^3 of which 0,894 mill. m^3 is created by logging and affected by different harvesting scenarios.

Soil condition and soil quality

Indicators for soil conditions and soil quality were applied only for the process "Conventional forest management in Kronoberg". It includes one indicator, "23.1.5 base saturation" (Table 5). Base saturation were set as absolute numbers for the three scenarios. In the reference scenario it was set to 12.7%, which is the average (0-5 cm in the mineral soil) from four sites in the county of Kronoberg from the SWETHRO network (Pihl Karlsson et al., 2011). The base saturation in scenario 1 and 2 was set to 11.5%, based on measured reductions after whole-tree harvesting from Brandtberg and Olsson (2012).

Energy generation and use

Energy generation and use included three indicators: 18.1.1.2 On-site heat generation from renewables - other wood biomass, 18.1.2.2 On-site electricity generation from renewables - other wood biomass and 18.2.2.2 Energy use – Direct fuel use – fossil fuel (Table 5).

Process Final fellings and thinnings

The fossil fuel use was estimated to 8.1 kWh/m^3 for final fellings and to 15.7 kWh/ m^3 for thinnings. This was based on Brunberg, 2013.

Process Extraction of residues with forwarder to roadside

The fossil fuel use was estimated to 14 kWh/m^3. This was based on a publication by SCB, 2007. It was estimated that the extraction of harvest residues 50 m^3/ha.

Process Chipping of residues at roadside

The fossil fuel use was estimated to 19 kWh/ ton. This was based on Suominen et al., 2017.

Process Transport of dried chips from roadside to CHP plant

The fossil fuel use was estimated to 23.4 kWh/ ton. This was based on Suominen et al., 2017.

Process Combustion at CHP plant

On-site heat generation from renewables - other wood biomass

This indicator was set to 8100 MJ/ton. This was calculated based on data on the energy content (kWh/m^3) and dry density of chips (ton/m^3). The energy content of chips with a moisture content of 35-40% is around 900 kWh/m^3 (www.bioenergiportalen.se; www.novator.se). 1 kWh is 3.6 MJ, thus 900 kWh/m^3 corresponds to 3240 MJ/m^3. The density of chips is around 0.4 ton/m^3 (www.novator.se) and indicator for heat generation can thus be calculated to 8100 MJ/ton.

On-site electricity generation from renewables - other wood biomass

The indicator was set to 2250 kWh/ton, based on the energy content (900kWh/m^3) and the density (0.4 ton/m^3) from above.

Energy use – Direct fuel use – fossil fuel

The indicator was estimated to 200 kWh/ton. In 2013 the amount of added fuel to Växjö Energi AB, VEAB, was 750 260 MWh (VEAB, 2014). 8% of this oil or peat, i.e. 600 20 MWh. The added fuel, minus the part from fossil fuel, 690 240 MWh, can be recalculated to m^3 using the energy content 900 kWh/m^3 from above, resulting in 766 933 m^3. Then the amount of energy from fossil fuel per m^3 of forest fuel can be calculated to 0.078 MWh/m^3. Using the density 0.4 ton/m^3, this can be recalculated to 0.20 MWh/ton, or 200 kWh/ton.

GHG emission and C stock

GHG emission and C stock included three indicators: “ 19.1.1 Greenhouse gas emissions from machinery”, “19.2 Carbon stock” and “19.3 Substitution effect” (Table 5).

Greenhouse gas emissions from machinery

Final fellings

For final fellings, the fossil fuel use was estimated to 2.16 kg $CO2_e/m^3$. For thinnings, the corresponding values were 3.81 kg $CO2_e/m^3$. These values were based on Suominen et al., 2017.

Extraction of residues with forwarder to roadside

The fossil fuel use was estimated to 2.16 kg $CO2_e/m^3$. These value was based on Suominen et al., 2017.

Chipping of residues at roadside

The fossil fuel use was estimated to 5.03 kg $CO2_e$/ton. This value was based on Suominen et al., 2017.

Transport of dried chips from roadside to CHP plant

The fossil fuel use was estimated to 5.67 kg $CO2_e$/ton. This value was based on Suominen et al., 2017.

Carbon stocks

The indicator carbon stocks was applied only for the process "Conventional forest management in Kronoberg". Carbon stocks in woody living biomass above ground were first estimated for the reference scenario, from standing volume, all forest land in Kronoberg, with IPCC default method. The value estimated was 135639 kg CO_2-e/ ha. Carbon stock in woody living biomass below ground was estimated as 25% of the value above ground.

For the scenarios 1 and 2, the above values for the reference scenario was reduced 5%.

Substitution

Substitution effects indicator calculation: Use of wood for energy was associated with lower CO_2 emissions compared with other materials like coal (Sathre and O'Connor, 2010). Material substitution effect appeared when wood products replaced more energy-intense materials and could contribute to climate change mitigation (Gustavsson et al., 2006; Eriksson et al., 2012). The meta-analysis by Sathre and O'Connor (2010) based on 21 studies identified the average displacement factors of wood products substituted in place of non-wood materials. The average displacement factor when wood was used for material and it was found to be 2.1 and 0.7 when wood was used for energy. This meant that for each ton of carbon in wood products substituted in place of non-wood products on average GHG emission reduction was from 0.7 to 2.1 tons of carbon. In order to estimate substitution effect of residues use we applied average displacement factors estimated by Sathre and O'Connor (2010, Table 6). It should be noted that in our value chain only substitution effects for energy use was relevant.

Table 6. Rage of substitution displacement factors (GHG emission reduction in tons of C per ton of carbon in wood products). In this project, we used middle displacement factor for energy.   For comparison reasons displacement factors for material use are also presented.

Use of wood	Low	Middle	High
For material	0.8	2.1	4.6
For energy	0.5	**0.7**	1.0

Water, air and soil pollution

This included one indicator: “24.2.2 Non-greenhouse gas emissions into air – NOx”.
This indicator was represented in the modules M3 and M4

Non-greenhouse gas emissions into air – NOx

Final fellings and thinnings.

NO_x emissions were estimated to 0.0049 and 0.0091 kg NO_x/m^3 for final fellings and thinnings, respectively. These values were calculated from Svenska MiljöEmissionsData (SMED), submission 2018 (Jerksjö, personal communication, 2017). It was assumed 50% productivity for thinnings as compared to final harvests.

Extraction of residues with forwarder to roadside

NO_x emissions were estimated to 0.0049 kg NO_x/m^3. Also these values were calculated from SMED, submission 2018. (Jerksjö, personal communication, 2017).

Chipping of residues at roadside

NO_x emissions were estimated to 0.38 kg NO_x/ton. Estimated from the diesel consumption given by Suominen et al., 2017.

Transport of dried chips from roadside to CHP plant

NO_x emissions were estimated to 0.0049 kg NO_x/ton. This was based on calculations made by Mohammad-Reza Yahya, IVL Swedish environmental Research Institute. It was assumed a “Dragbil med släp”, load 60 t, transport distance 100 km.

Combustion at CHP plant

In the process “Combustion at CHP plant”, the NOx emissions were estimated to 189.1 kg/ton. This was based on data about NOx emissions, 91 kg/MWh for heat production and 49 kg/MWh for electricity production in 2013 (VEAB, 2014). The total amount of kg NOx emissions was estimated by multiplying these numbers with produced heat (611 359 MWh) and produced electricity (151 336 MWH) for 2013, from the same source. The total amount of NOx was thus estimated to 63 049 133 kg. Similarly as above, the amount off added fuel, 750 260 MWh, was recalculated to m^3 using the energy content 900 kWh/m^3, and further to ton, using the density 0.4 ton/m^3. By dividing the amount of NOx emission with tons of forest fuel, the indicator was calculated to 189.1 kg/ton.

Shares

A product share is used to divide the material flow (in carbon) of each process into the input or output products. Input products for each process in a chain receive material from matching output products of previous processes. One link between two following processes is defined by output product of the source process and the input product of the target process.

In the following, calculations for shares for the output products of the different processes are briefly described. More detailed descriptions can be found in Appendix 2. The shares were identical for the reference scenario and scenarios 1 and 2.

Process "Conventional forest management in Kronoberg"

Share for trees in protected areas

The share for trees in protected areas in Kronoberg for the years 2010 and 2020 were derived from SKA15 (Skogsstyrelsen 2015), results, scenario 90 % harvests, Table 7. Areas of different protected forests were multiplied with area standing stock, across all tree species. The total standing stocks in Kronoberg county was 98.2 M m^3 ob.

Table 7. Calculated values for standing stocks of different tree species in protected areas in Kronoberg county. All forest owners included. Source: Table 1.1 in SKA15, results (Skogsstyrelsen 2015), scenario 90% harvests,. Unit M m^3 ob.

Standing stocks* , divided into different trees species and land use			
Land use	Tree species	2010	2020
Total protected	conifers % of tot standing stocks	9.57	10.65
Total protected	deciduous % of tot standing stocks	3.46	4.00
Total protected	All tree species, % av tot standing stocks	**13.03**	**14.65**

*Total standing stocks in Kronoberg county 98.2 M m3 ob

Share for coniferous and deciduous trees for annual final fellings

The conifer standing stocks for annual final fellings were derived from SKA15 (Skogsstyrelsen 2015), results, scenario 90% harvests (Table 8).

Table 8. Coniferous and deciduous standing stocks assigened for annual final fellings in Kronoberg, Source: Table 4.1 in SKA15 (Skogsstyrelsen 2015), results, scenario 90% harvests. Unit M m^3 ob yr^{-1}.

Tree species	**2010**	**2020**
conifers % of tot standing stocks*	1.55	1.33
deciduous % of tot standing stocks*	0.08	0.12

*Tot standing stocks in Kronobergs county 98.2 M m3 ob

Share for coniferous and deciduous trees for annual thinning

The conifer standing stocks for thinning were derived from SKA15 (Skogsstyrelsen 2015), results, scenario 90% harvests (Table 9).

Table 9. Coniferous and deciduous standing stocks assigned for annual thinning in Kronoberg, Source: Table 5.1 in SKA15 (Skogsstyrelsen 2015), results, scenario 90% harvests. Unit M m^3 ob yr^{-1}.

Tree species	2010-	2020-
conifers % of tot standing stocksförråd*	1.16	1.01
deciduous % of tot standing stocks*	0.48	0.38

* Tot standing stocks in Kronobergs county 98.2 M m3 ob

Remaining standing stocks in productive forests after fellings, excluding growth

Remaining coniferous and deciduous standing stocks in productive forests after fellings, excluding growth, were calculated as:

(Current standing stocks, all forest land) – (Coniferous and deciduous standing stocks assigned for annual final fellings) - (Coniferous and deciduous standing stocks assigned for annual thinning) – (trees in protected areas)

This estimate did not include the increase in standing stocks due to the annual growth. Growth was treated as a separate process, but not included in the assessments with indicator values (Table 10).

Table 10. Remaining coniferous and deciduous standing stocks in total forest land Kronoberg after fellings, unit M m^3ob yr^{-1}. The increase in standing stocks due to the annual growth was not included.

Tree species	2010	2020
conifers % of tot standing stocks*	69.09	68.03
Deciduous % of tot standing stocks*	14.61	14.48

*Tot standing stocks in Kronobergs county 98.2 M m3 ob

An overview of all values used for shares of the output products for process the process “Conventional forest management in Kronoberg” is shown in Table 11.

Table 11. An overview of suggested share values for the process Conventional forest management in Kronoberg.

Output product name	Share
Trees in protected forests	0.13030
Conifers for thinning	0.01160
Conifers for final felling	0.01550
Remaining conifers	0.69090
Deciduous trees for thinning	0.00480
Deciduous trees for final felling	0.00083
Remaining deciduous trees	0.14610

Process “Final felling with harvester”

A major problem with calculating the shares for the output products of the processes “Final felling with harvester” and Process “Thinning with harvester (CTL)” was that biomass from coniferous and deciduous trees were merged into single processes for final fellings and thinnings, respectively (Figure 3). As a result, we could not distinguish between these origins. 95% of the biomass as input to process “Final fellings” was coniferous and 5% deciduous.

It was assumed that of the standing stocks above-ground biomass that were subject to final felling, 5% ended up as tops and 10% as branches. However, it was also needed to distinguish between small dimensional and large dimensional timber. As a first approximation, the distribution between pulp- and saw wood for all harvests in Kronoberg, was taken from SKA-15 scenario 90% harvests (Table 12, Skogsstyrelsen 2015).

As an average, it was assumed that 70% of the final harvest round wood ended up as saw wood (large dimensional) and 30% as pulpwood (small dimensional).

For deciduous trees, it was assumed that 100% ended up as pulpwood (small dimensional).

Table 12. Annual gross harvests divided into pulp- and saw wood for all harvests in Kronoberg county, taken from table 3.2 in SKA-15 scenario 90% harvests (Skogsstyrelsen 2015).

Trädslag	Sortiment	Period 2010- 1000 m3fub/year	Period 2010- Share of total
Tall	Saw wood	448.7	0.71
Tall	Pulp wood	183.2	0.29
Gran	Saw wood	991.4	0.64
Gran	Pulp wood	547.9	0.36
Löv	Pulp wood	405.2	1.00

The following calculations were made for different output shares from the process "Final harvest":

Share output "Deciduous residues in forest": Share = 0.0075 (=0.15*0.05)

Share output "Coniferous residues in forest": Share = 0.1425 (=0.15*0.95)

Share output "Small dimensioned coniferous timber in forest": Share = 0.2375 (=0.25*0.95)

Share output "Small dimensioned deciduous timber in forest": Share = 0.0125 (=0.25*0.05)

Share output "Large dimensioned coniferous timber in forest": Share = 0.57 (=0.60*0.95)

Share output "Large dimensioned deciduous timber in forest": Share = 0.03 (=0.60*0.05)

Process "Thinning with harvester (CTL)"

The standing stocks aimed for thinning had to be divided between stemwood and harvest residues. According to Peterson (1999) the living and dead branches consituted the following fractions of the total dry weight above "stubbskär": 0.32 for Norway spruce, 0.21 for Scots pine och 0.22 for birch. These values were derived from measurements made within the forests of Sveaskog from a large number of sites across Sweden.

Petersson et al (2012) published a diagram over the different fractions of biomass of Scots pine of different ages. The share of branches to the total biomass decrease with age. We had to assume a certain age at thinning and final harvests, respectively, as thinning, 35 year, final harvests, >60 years.

Based on the information above it was assumed that of the standing stocks above-ground biomass that were subject to thinning, 10% ended up as tops and 15% as branches. The corresponding values at final harvests were 5% tops and 10% branches.

However, it was also needed to take into account that 70.7% of the biomass as input to process 22 was coniferous and 29.3% deciduous. Hence, the results of the calculations were :

Share “Deciduous residues in forest”: Share = 0.07 (=0.25*0.293)

Share “Coniferous residues in forest”: Share = 0.18 (=0.25*0.707)

Share “Small dimensioned coniferous timber in forest”: Share = 0.53 (=0.75*0.707)

Share “Small dimensioned deciduous timber in forest”: Share = 0.22 (=0.75*0.293)

Remaining processes

For all the remaining precesses, there were only one output product.

Multi Criteria Analysis

To asses sustainability, an integrative approach is needed that takes in account economic, environmental and social aspects of sustainability (Gasparatos et al. 2008). The method of multi-criteria analysis (MCA) is seen as framework for sustainability impact assessment that can facilitate transparent decision-making processes in the forest and other sectors (Wolfslehner et al. 2012). Integrative environmental impact assessment based on MCA can bridge the gap between theories and practice (Lee 2006).

In ToSIA sustainability indicators (economic, environmental and social) are integrated and were applied for this study to estimate potential environmental impacts and interpret the results. This illustrate how MCA could be integrated and used.

To test and demonstrate the MCA tool in ToSIA, the indicators were divided into different groups, for which different weights were tested. In ToSIA, the default grouping for result presentation includes three indicator groups; economic, social and environmental indicators, but since there is an obvious risk of conflict between environmental indicators related to climate and other environmental indicators, a further division was considered to be necessary. Thus, four groups were defined:

1. Economic indicators
2. Social indicators
3. GHG and C indicators (part of the environmental indicators)
4. Biodiversity indicators (part of the environmental indicators)

Two approaches were used in the weighing between different indicator groups:

1. One at a time of the four indicator groups were given the highest weight (100%) whereas the other ones were given the lowest weight (0%). This simple method was used to get an overview of how ToSIA MCA works, without introducing too much complexity.

2. Two sets of weights were applied, one an imaginary person who prioritizes economy and energy generation and one from another imaginary person who instead prioritizes environmental aspects in order to show a comparison between two very different views, more realistic than in approach 1. These two cases were compared with a case where all indicators were given the same weight.

The weights for approach 2 are listed in Table 13. The same weights were given in all modules.

Table 13. Weights in the three cases in approach 2.

Group of indicators, as grouped in ToSia	Case 1, Energy	Case 2, NGO	Case 3, Equal weights
Forest biodiversity	30%	90%	50%
Soil condition and soil quality	30%	90%	50%
Gross value added	90%	10%	50%
Energy generation and use	90%	60%	50%
GHG emissions and carbon stock	60%	90%	50%
Water, air and soil pollution	30%	90%	50%
Employment	10%	30%	50%

Results

Differences between scenarios – the flows through the model

The flows in the model (Figure 3) from the source (e.g. “Conventional forest management”) via the product (e.g. “conifers for final felling”) to the target (e.g. “final felling with harvester”) were presented in Appendix 3. Some of the main differences in produced products between the reference, scenario 1 and scenario 2 are presented in table 14a. The amount of chips at plant increased considerably from the reference to scenario 1, and from scenario 1 to scenario 2. The amount of deciduous thin woody debris (TWD) and residues remaining in the forest decreased to some extent in scenario 1 compared with the reference, however in scenario 2 the decrease was more obvious. The total amount of coniferous residues decreased substantially in scenario 1 and scenario 2 compared with the reference.

Differences between scenarios – the indicators

The indicators demonstrated clearly the differences between the scenarios (Table 14b). The heat generation, and electricity generation from renewables increased and a number of indicators followed, e.g. the energy use and the gross value added and the employment. The greenhouse gas emissions increased due to higher production but the avoided CO_2 emissions due to substitution also increased. On the other hand the forest ecosystem carbon stock decreased as well as the volume of fine woody debris.

Table 14a. The flow of some products in different scenarios. A total list is presented in appendix 3.

Product	Unit	Scenarios Reference	Scenario 1	Scenario 2
Chips at plant	ktonnes	60	180	224
Deciduous residues remaining in forest	$1000m^3$	300	286	69
Coniferous residues remaining in forest	$1000m^3$	949	285	285
Deciduous residues at roadside	$1000m^3$	0	0	108
Coniferous residues at roadside	$1000m^3$	150	451	451

Table 14b. The indicator results in different scenarios..

Indicator	Scenario Reference value	Scenario 1	Scenario 2
1.1 - Gross value added (at factor cost)	4 315 227	12 983 032	16 107 590
10.1 - Employment - absolute number	1 243	1 604	1 742
18.1.1.2 - On-site heat generation from renewables - other wood biomass	485 463 011	1 460 591 104	1 812 103 833
18.1.2.2 - On-site electricity generation from renewables - other wood biomass	134 850 836	405 719 751	503 362 176
18.2.2.2 - Energy use - Direct fuel use - fossil fuel	55 224 020	86 684 522	98 719 710
19.1.1 Greenhouse gas emissions from machinery	10 794 293	12 516 557	13 311 800
19.1.2 Greenhouse gas emissions from wood combustion	95 893 928	288 511 823	357 946 436
19.2.1 - Carbon stock in woody living biomass (above ground)	95 489 859 065	90 498 240 486	90 498 240 486

19.2.2 - Carbon stock in woody living biomass (below ground)	26 932 928 865	25 524 946 664	25 524 946 664
19.2.3 - Carbon stock in woody dead wood	30 605 696 983	29 005 621 209	29 005 621 209
19.2.4 - Carbon stock in soils of forest	227 157 575 292	215 283 513 112	215 283 513 112
19.2 - Carbon stock	349 580 363 222	331 306 700 262	331 306 700 262
19.3 - Substitution effect	73 418 789	220 891 865	274 052 740
22.1 - Forest and Other Wooded Land Area	704 000	704 000	704 000
22.4.1 - Balance of increments and fellings: Net annual increment	4 012 800	3 806 549	3 806 549
22.4.2 - Balance of increments and fellings: Volume of felled trees	3 168 000	3 160 419	3 160 419
24.2.2 - Non-greenhouse gas emissions into air - NOx	11 379 987	34 191 692	42 415 231
25.2.1 - Volume of standing deadwood	6 265 600	6 250 606	6 250 606
25.2.3 - Volume of fine coniferous debris	474 475	142 358	142 358
25.2.4 - Volume of fine deciduous debris	150 249	142 752	34 260

Multi-Criteria analysis

Approach 1 – 100% priority on one of the indicator groups

Economic indicators

The only economic indicator, Gross value added, was in this case given the weight 100%, whereas all other indicators were given the value 0%. Gross value added was an indicator only for process M3 and M4, and thus there was no effect on process M2. The results clearly showed that with these weights, Scenario 2 was the best choice and the reference scenario was the worst choice both in M3 and M4 (Figure 5).

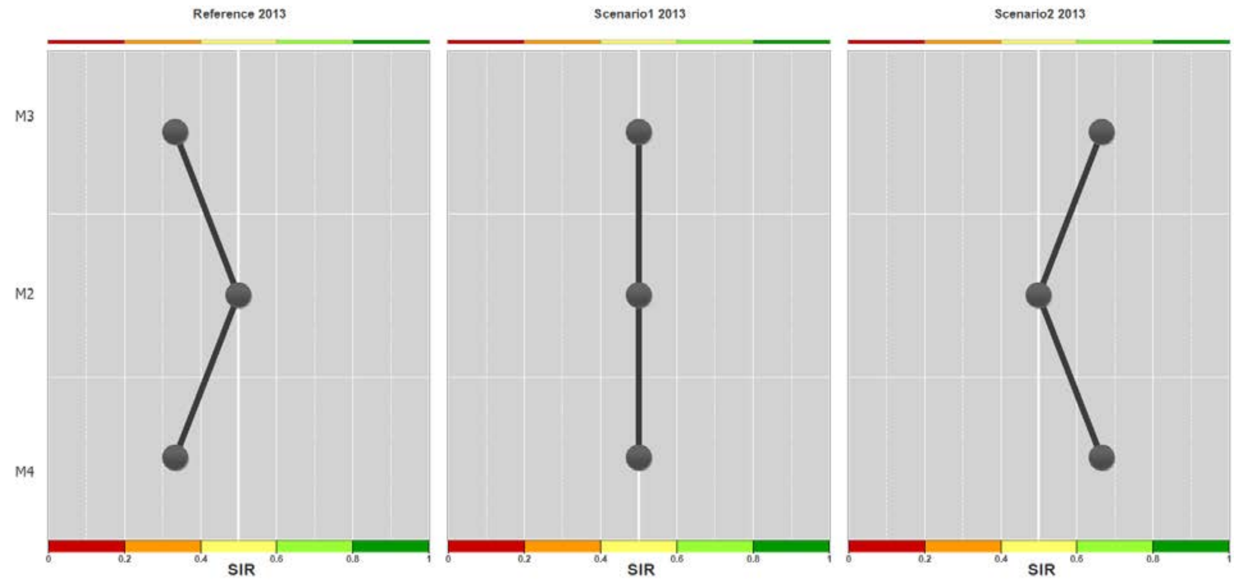

Figure 5. MCA results for the case where the economic indicators were given 100% weight and the other indicators were given 0%. On the y-axis the results for different processes are shown, and on the x-axis a sustainability index is shown.

Social indicators

In this case the only social indicator, Employment, was given the weight 100%, whereas all other indicators were given the value 0%. Employment was an indicator of all modules, but in M2 there was no difference between the scenarios, since the employment was given per hectare forest, and there was difference in hectares of forest between the scenarios. The results were similar to the case where the economic indicators were given 100% weight (Figure 6).

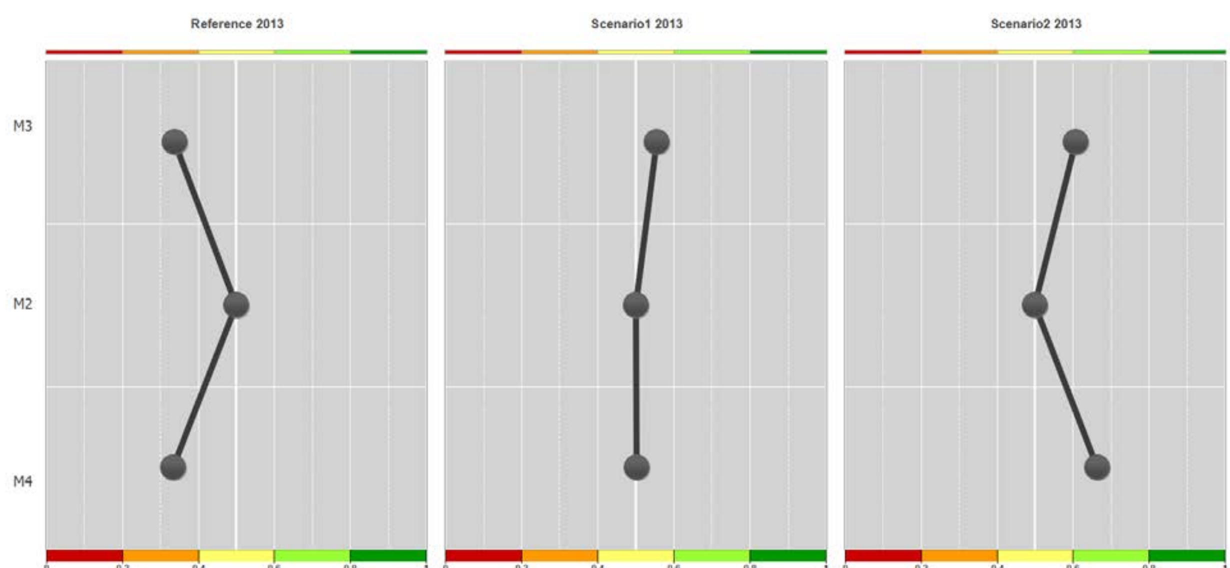

Figure 6. MCA results for the case where the social indicators were given 100% weight and the other indicators were given 0%.

GHG emissions and carbon stock

In this case the indicators related to GHG emissions and carbon stock were given the weight 100%, whereas all other indicators were given the value 0%.

In M2 the indicator “Carbon stock” was included. The carbon stock was affected negatively by the removal of forest fuel, and therefore the reference scenarios was the best option from this perspective.

In M3, the indicators “Energy use – Direct fuel use – fossil fuel” and “GHG emissions from machinery” were included. The situation became worse with more harvesting of residues, as can be seen in Figure 7. This was due to the increased need of energy and machinery at higher harvesting levels.

In M4, the indicators “On-site heat generation from renewables - other wood biomass”, “On-site electricity generation from renewables - other wood biomass” and “Substitution effect” and “Energy use – Direct fuel use – fossil fuel” were included. However, since the two indicators “On-site heat generation from renewables - other wood biomass” and “On-site electricity generation from renewables - other wood biomass” covered the same effect as “Substitution effect”, those two indicators were given 0% weight, to avoid double counting. In M4, the situation became better the more residues that were harvested, which can be explained by more generated heat and electricity, and an improved substitution effect. The increased need of energy use counteracted a bit, but the net effect was still substantially positive (Figure 7).

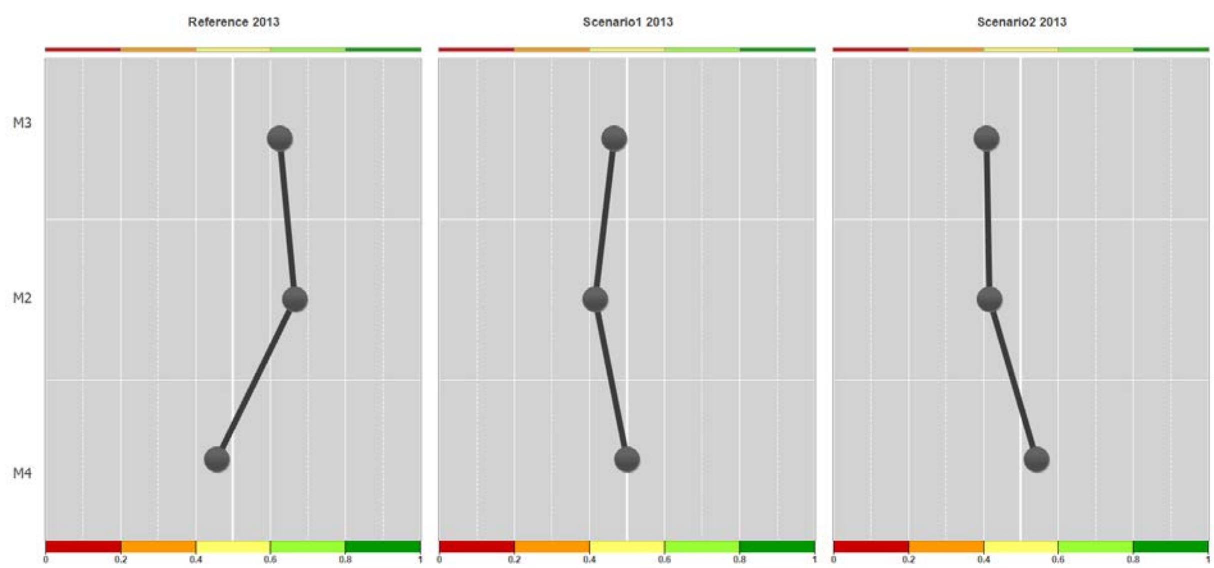

Figure 7. MCA results for the case where the GHG emissions and carbon stock were given 100% weight and the other indicators were given 0%.

Biodiversity
Biodiversity was represented by two indicators: “Volume of coniferous fine debree” and “Volume of deciduous fine debree”. In this case both those indicators were given a weight of 100%, whereas all other indicators were given the value 0%. The biodiversity indicators were only represented in M2. The biodiversity indicator was affected negatively by forest fuel removal. The effect of removal of only coniferous forest fuel was small, whereas the effect of removal of also deciduous forest fuel was larger (Figure 8).

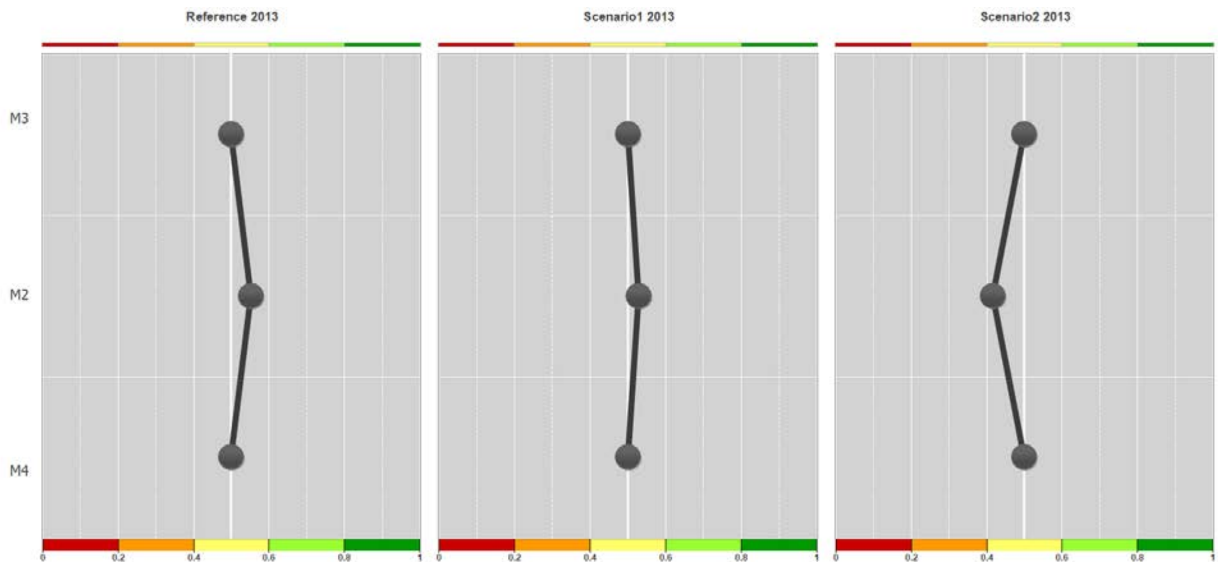

Figure 8. MCA results for the case where the biodiversity indicators were given 100% weight and the other indicators were given 0% (grey dots).

Comparison between all cases
In Figure 9 all cases were compared. It can be noted that according to the economic and employment case scenario 2 was regarded as advantageous whereas the reference scenario was the worst, whereas for biodiversity it was the other way around. For GHG emissions and carbon stock the results were different for the different modules. In M2 (forest management) and M3 (forest operations), the forest fuel harvesting resulted in a negative effect, whereas in M4 (forest industry) the effect was positive.

In Table 15, the preferences for the three modules were weighted, giving one preference value for each scenario in each case. This showed that the weighted preference was higher in scenario 1 and 2 compared to the reference scenario in the economic and social cases, but that it was the other way around in the GHG and carbon stock and biodiversity cases. However, the weights of the different modules were the default ones. Increasing the weight of forest industry would give different results.

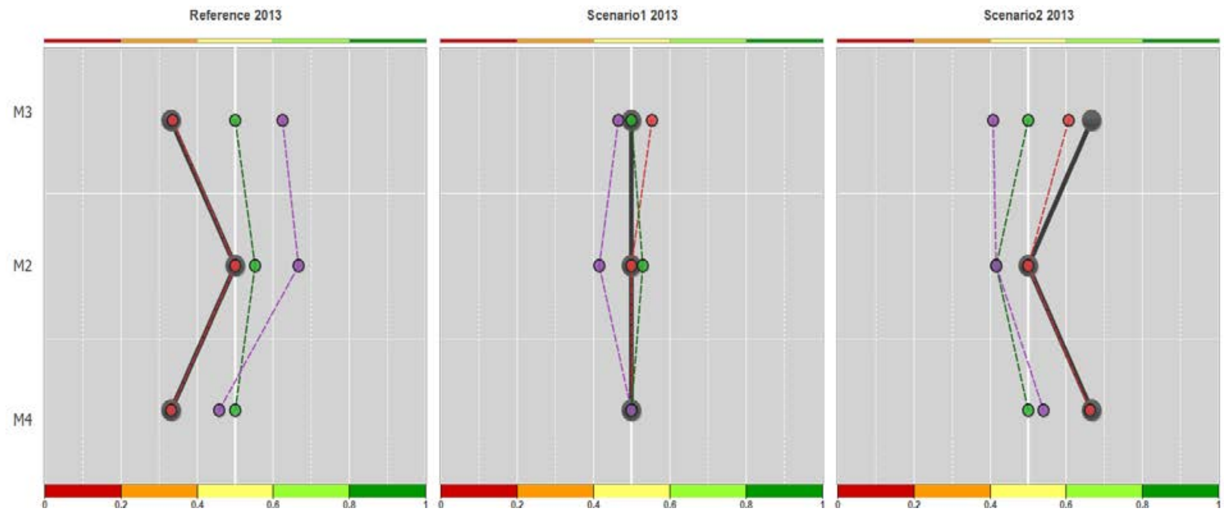

Figure 9. MCA results for all five cases: The economy case (grey dots), the employment case (red dots), the GHG emissions and carbon stock case (purple dots) and the biodiversity case (green dots).

Table 15. Synthesized preference values for the three different scenarios, in different cases (with different indicator groups prioritized). A value of 1 means full preference, whereas a value of 0 means no preference.

Prioritized indicator group	Reference	Scenario 1	Scenario 2
Economic	0.38	0.50	0.62
Social	0.38	0.52	0.60
GHG and carbon stock	0.58	0.46	0.46
Biodiversity	0.52	0.51	0.46

Approach 2 – Imaginary stakeholders

The results showed that if the same weights were given to all indicators, then the reference scenario had the highest preference and scenario 2 the lowest in M2, whereas it was the other way around in M4. In M3 there was no difference between the scenarios. The energy case gave very similar results. The NGO case gave results in the same direction for M2, but the difference between scenarios was bigger. In this case also M3 had the highest preference in the reference scenario and the lowest in scenario 2. In M4, scenario 1 had slightly higher preference than the reference scenario, but scenario 2 had lower preference, which could be explained by the biodiversity indicator.

The synthesized preference values showed that the reference scenario was the most favorable one using the NGO set of weights, whereas scenario 2 was the least favorable (Table 16). In the energy case the difference in synthesized preferences was small; the preference was slightly higher for the reference scenario than for scenario 1 and 2. As described above and in Figure 10, the modules M2 and M4 gave results in different directions, resulting in very similar synthesized preferences for the different scenarios.

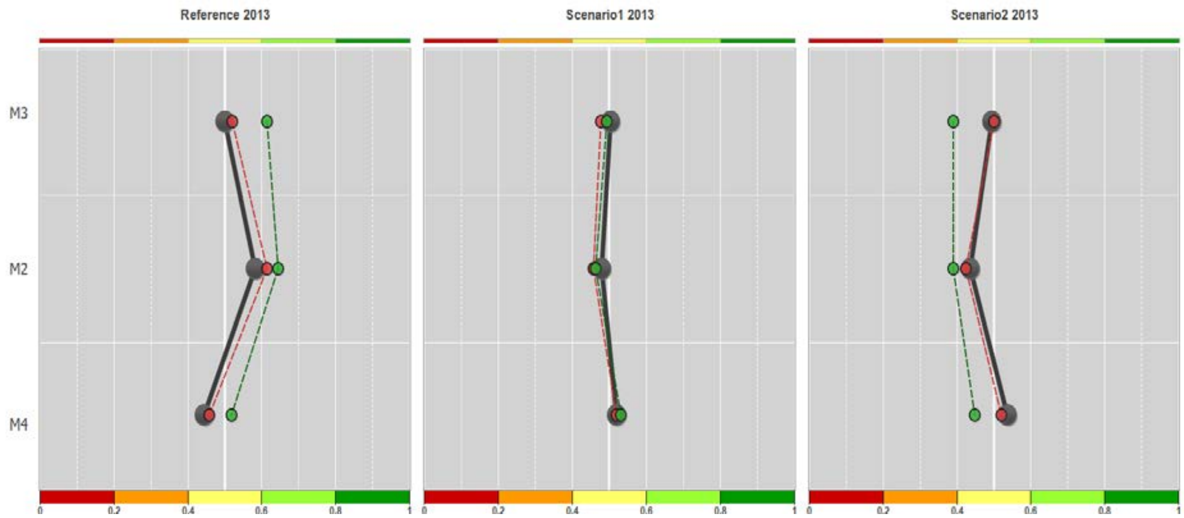

Figure 10. MCA results for all five cases: The equal weights case (grey dots), the energy case (red dots) and the NGO case (green dots).

Table 16. Synthesized preference values for the three different scenarios, in the three cases of Approach 2. A value of 1 means full preference, whereas a value of 0 means no preference.

Prioritized indicator group	Reference	Scenario 1	Scenario 2
Energy	0.52	0.49	0.49
NGO	0.59	0.50	0.41
Equal weights	0.50	0.50	0.50

Discussion

Former syntheses of effects of forest fuel harvesting within the Forest Fuel Programme have focused on effects on environmental objectives and biomass production, whereas economic and social effects have not been taken into account (de Jong et al., 2017). With the ToSIA concept, environmental as well as economic and social values can be included, and different weights can be given to different aspects using multicriteria analysis (MCA). The tool is promising and intuitive, but to fully test the applicability the "imaginary persons" should be replaced by real persons, representing different interests. That was beyond the scope of this project.

ToSIA model chains, like the one in this project, give an output of the economic, social and environmental indicators that have been defined. Thus, different types of effects of the defined scenarios can easily be presented and discussed. However, in our case social value is limited to employment and economic value is limited to GVA. We are aware of that these two sustainability components much be developed further to be able to get more realistic results and to compare different scenarios. The main advantage by using ToSIA is that the model chain approach ensures that the same input data and indicators are used for all scenarios.

The MCA can be used as a pedagogic tool in stakeholder groups, to show how different preferences can affect the "preferred scenario". It also highlights differences between different parts of the model chain, in our case between the forest, the energy plant and the transport in between. The transparency of the MCA results is, however, limited. Therefore, the actual indicator results from ToSIA should be used as the input to actual policy recommendations, rather than the MCA results.

Harvesting of slash and other wood for bioenergy is not the only factor affecting sustainability components. How ordinary forestry for timber and pulp production is organized have big impact and might affect sustainability in any direction. For example, a high output of bioenergy-wood can be compensated by more efficient conservation considerations in ordinary forestry, or by more nature reserves or habitat restoration. For a realistic model the whole forestry chain including restoration and compensation alternatives must be regarded.

The overarching aim of this project was to bring forward a method for future syntheses of effects from forest fuel harvesting in Sweden, where economic, social and environmental indicators are taken into account. We believe that ToSIA could be used for this, but it would require a different approach than in this project, where the problems with data collection and technical ToSIA issues are solved.

Conclusions

ToSIA is a powerful tool to create models describing different parts of the biomass chain. The combination of indicators can be used to inform stakeholders about economic, social and environmental effects of different scenarios, as a basis for policy decisions. The MCA can be highly useful in stakeholder groups, as a pedagogic tool to highlight how different preferences can affect the results.

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