TRADE-OFF ANALYSIS OF FOREST ECOSYSTEM SERVICES – A MODELLING APPROACH

Xi Pang

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Ten years ago, I was a master student living in a student accommodation area in northern Stockholm which was surrounded by big areas of natural forest. There was a pair of very big trees (perhaps more than 200 years old), a stout pine and a plump oak, standing beside each other—with her branches, the oak embracing the pine, and they were just standing there like that, forever…

To those wonderful years at Kungshamra
ACKNOWLEDGEMENTS

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Finally, I dedicate this thesis to my parents, for your sacrifice and fighting against the tough life to bring us up. Thanks to my brother Pang Jun, for the love and emotional support, you are my best friend. Thanks all those that make my life path cross with yours for some wonderful periods in Sweden.
ABSTRACT

Forest is a resource that is increasingly utilized for multiple purposes. The balance between energy demands and the long-term capacity of ecosystems to support biodiversity and other ecosystem services is crucial. The aim of this project was to increase the knowledge on and to develop methods and tools for trade-offs and synergies analysis among forest ecosystem services based on different forest management policies.

Paper I provides an overview of existing models for integrated energy-environment assessment. A literature review was conducted on assessment models and their ability to integrate energy with environmental aspects. Missing environmental aspects concern land use, landscapes and biodiversity. In Paper II a modelling framework was set up to link a landscape simulator with a habitat network model for integrated assessment of bioenergy feedstock and biodiversity related impacts in Kronoberg County. In Paper III we continued with the same management scenarios, while the analysis was expanded to five ecosystem services by developing the Landscape simulation and Ecological Assessment (LEcA) tool: industrial wood, bioenergy, forest carbon stock, recreation areas and habitat networks. In Paper IV we present two heuristic methods for spatial optimization – simulated annealing (SA) and genetic algorithm (GA) – to find optimal solutions for allocating harvest activities, in order to minimize the impacts on habitat networks. In Paper V, as response to the findings in Paper I, we linked the energy model MESSAGE with our LEcA tool for forest bioenergy demand assessment while applying environmental and transport restrictions, in a study of Lithuania.

We found trade-offs between industrial wood production and bioenergy on one side, and recreation values, biodiversity, and to some extent carbon storage on the other side. The LEcA tool integrated forest simulation and management with assessment of ecosystem services, which is promising for integrated sustainability assessment of forest management policies.

Key words: Forest bioenergy feedstock, Landscape simulation, Forest simulation, Ecosystem services modelling, Integrated sustainability assessment, Spatial optimization, Optimization heuristics
SAMMANFATTNING

Skog betraktas alltmer i perspektivet av den mångfald av resurser som den tillhandahåller, utifrån flera hållbarhetsperspektiv så som klimatperspektiv, ekosystemtjänster och biologisk mångfald. Balansen mellan efterfrågan på skogens resurser så som timmer, massaved och energiråvara å ena sidan, och dess funktioner för andra ekosystemtjänster och biologisk mångfald å andra sidan, blir därför allt viktigare i policy och planering. Syftet med denna avhandling är att utveckla beslutstöd för att integrera viktiga hållbarhetsaspekter i policy för och planering av skogens användning och skötsel, där flera olika viktiga ekosystemtjänster kan integreras i en samlad hållbarhetsbedömning.


Resultaten visade att avvägningar behöver göras mellan produktion av timmer, massaved och utvinning av skogsbiomassa för bioenergi å ena sidan, och rekreativt, habitatnätverk som stöd för biodiversitet, och i viss mån kolindring å andra sidan. LEcA-verktyget integrerar simulering av skogens tillväxt och skötsel med bedömning av ekosystemtjänster och har därigenom stor potential för integrerad hållbarhetsbedömning av alternativa strategier för skogsskötsel på landskapsnivå.
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LIST OF APPENDED PAPERS

This thesis is based on the following papers which are referred to in the text by their Roman numerals. Papers included in the thesis:


The thesis author was responsible for collecting the data and writing the paper. Associate Professor Ulla Mörtberg initiated the theme of the paper and was responsible for outlining the paper. Nils Brown contributed with comments and information on LCA.


The thesis author was responsible for the habitat modelling and paper writing. Associate Professor Ulla Mörtberg participated in the habitat modelling, as well as in outlining and writing the paper. Dr. Eva-Maria Nordström and Dr. Hannes Böttcher provided advice and comments on the paper. Professor Ola Sallnäs and Dr. Renats Trubins were responsible for the development and running of the LandSim model for simulating forest growth and management, in cooperation with the two first authors for adapting to the habitat modelling.


The thesis author was responsible for the modelling of ecosystem services and for writing the paper. Dr. Eva-Maria Nordström participated in paper writing and provided advice and comments on the paper. Dr. Hannes Böttcher participated in the modelling and outlining. Dr. Renats Trubins was responsible for running the LandSim model and participated in writing. Associate Professor Ulla Mörtberg contributed in writing the paper as well as formulating the research questions.


The thesis author was responsible for programming and modelling, as well as paper writing. Associate Professor Ulla Mörtberg participated in paper writing and provided advice and comments.

The thesis author was responsible for programming and modelling, as well as paper writing. Dr. Renats Trubins was responsible for running the LandSim model. Associate Professor Ulla Mörtberg participated in paper writing, modelling and provided advice and comments. Professor Gintautas Mozgeris and Dr. Gintaras Kulbokas provided data on the study area. Professor Arvydas Galinis and Dr. Vidas Lekavicius were responsible for the running of the MESSAGE model for energy demand projection. All co-authors participated in paper writing.

Flowchart: overview of the study and the relation between the papers.
## List of Abbreviations

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<th>Abbreviation</th>
<th>Explanation</th>
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<tr>
<td>AGB</td>
<td>Above ground biomass</td>
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<tr>
<td>BGB</td>
<td>Below ground biomass</td>
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<tr>
<td>CAB</td>
<td>County Administrative Boards</td>
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<td>CBD</td>
<td>Convention on Biological Diversity</td>
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<td>CCF</td>
<td>Continuous Cover Forestry</td>
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<td>CHP</td>
<td>Combined Heat and Power plant</td>
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<td>EAF</td>
<td>Even-Aged Forestry</td>
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<td>ECA</td>
<td>Equivalent Connected Area</td>
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<td>EC</td>
<td>European Commission</td>
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<td>EEA</td>
<td>European Environment Agency</td>
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<td>ES</td>
<td>Ecosystem Services</td>
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<td>FORMAS</td>
<td>Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning</td>
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<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
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<td>GHG</td>
<td>Green House Gas</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>OECD</td>
<td>The Organisation for Economic Co-operation and Development</td>
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<tr>
<td>REEEM</td>
<td>The Horizon 2020 research project “Role of technologies in an energy efficient economy – model based analysis policy measures and transformation pathways to a sustainable energy system”</td>
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<tr>
<td>SA</td>
<td>Simulated Annealing</td>
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<tr>
<td>SEA</td>
<td>Swedish Energy Agency (as author in references)</td>
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<tr>
<td>SEA</td>
<td>Strategic Environmental Assessment</td>
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<tr>
<td>SEPA</td>
<td>Swedish Environmental Protection Agency</td>
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<tr>
<td>SLU</td>
<td>Swedish University of Agricultural Sciences</td>
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<tr>
<td>SNBH</td>
<td>The Swedish National Board of Housing Building and Planning</td>
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<tr>
<td>SOU</td>
<td>Statens Offentliga Utredningar (Swedish Government Official Reports)</td>
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<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
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Introduction

Forests play an important role for climate change mitigation by providing bioenergy feedstock to substitute fossil fuels, as well as carbon storage to counteract greenhouse gas emissions, while they are also important for other ecosystem services and biodiversity. The United Nations Sustainable Development Goal 7 - Affordable and Clean Energy - aims to ensure access to affordable, reliable, sustainable and modern energy for all, which is also one of the targets to substantially increase the share of renewable energy in the global energy mix. Still, the other United Nations Sustainable Development Goals need to be reached simultaneously, such as Climate Action and Life on Land, which is why an integrated approach to sustainability is called for. To limit the increase in temperature to well below 2 degrees Celsius according to the Paris Agreement (UNFCCC, 2015), emissions of greenhouse gases worldwide need to be halved by 2050 and to be close to zero by 2100 (IPCC, 2014). Sweden is a country with relatively good preconditions for both switching to renewable energy sources (water, wind and forest biomass) and for climate change mitigation through carbon sequestration in forests and substitution of fossil-based materials by forest products. In Sweden, the Parliament has declared that the vehicle fleet should be independent of fossil fuels by 2030 (IEA, 2014) and adopted a vision for Sweden of zero net emissions of greenhouse gases by 2050 (Sweden, 2014).

By the year 2016, around 32.5% of the final energy consumption in Sweden comes from fossil fuels, which equals to 122 TWh (SEA, 2015). A bigger share (37%) of the domestic energy consumption came from bioenergy in 2016 (SEA, 2017). Hydropower and nuclear power are two other sources that can be seen as carbon neutral and that also have a large share of the energy generation in Sweden (SEA, 2017). However, the opportunities for expanding these two sources are limited (SEPA, 2009, SOU, 2014). These factors, together with the climate-related goals, may lead to an increased demand for forest bioenergy feedstock in Sweden (e.g. Börjesson et al., 2017), and may induce substantial changes in the forests.

According to the Swedish environmental quality objective “Reduced climate impact”, and “Sustainable Forests”, climate-related goals should be achieved without jeopardizing other goals of sustainable development; and the value of forests for biological production must be protected, at the same time as biodiversity, cultural heritage and recreational values are safeguarded (Govt. prop. 1997/98:145 and 2004/05:150). However, according to (SEPA, 2015) these environmental quality objectives may not be achieved by 2020 under current development and policies. On EU level, the EU Renewable Energy Directive (2009/28/EC) aims to promote renewable energy sources and to reduce greenhouse gas emissions in a sustainable way, avoiding negative effects on ecosystem services and biodiversity (EC, 2001, 2010). Thus, to integrate multiple ecosystem services and biodiversity in
assessments of policies and plans for increasing use of forest biomass as a renewable energy source is crucial.

Today, forest in Sweden is mainly used for industrial wood production (sawlog and pulpwood). Biomass for bioenergy is extracted as harvest residues, and as a by-product of industrial wood production such as black liquor, wood chips, sawdust and bark. In practice, only a part of the total harvest residues is extracted. For instance, comparing actually extracted amounts in 2015 (SEA, 2016), only 24% of the estimated potential 2010-2019 (SFA, 2015) was used, and stumps were only harvested on experimental scale (Melin, 2014). An increased demand for bioenergy would probably begin with increasing the extraction of harvest residues, possibly also stumps. At higher levels of demand, the bioenergy sector might have to compete with other forest related industries for raw material, such as round wood and sawn wood industries, the wood board industry as well as with pulp and paper producers (Carlsson, 2012; Jonsson, 2012, 2013; Lauri et al., 2014).

Due to the simplification of forest structure and the loss of old trees and dead wood, industrial forestry has been identified as a major cause of depletion of forest biodiversity (Berg et al., 1994; EEA, 2010; Puettmann et al., 2009; Thompson et al., 2011), even if plans and actions are carried out to protect biodiversity (Eriksson et al., 2015). New forest management practices may be needed to meet the increased demand in Sweden (Larsson et al., 2009; Lidskog et al., 2013). Intensified forestry could increase the biomass production through applying shorter rotation times, planting of monocultures of native or introduced tree species, and using forest fertilizers. This may have negative impacts on biodiversity by reducing habitat size and connectivity in forest landscapes (Hanski, 2011; Larsson et al., 2009; Ranius and Roberge, 2011). Further impacts may result from increased extraction of forest residues for bioenergy (e.g. de Jong and Dahlberg, 2017; Hedin et al., 2008).

Forests provide a multitude of ecosystem services beside industrial wood, bioenergy and habitat supporting biodiversity; such as cultural ecosystem services including recreation, aesthetics and cultural heritage (Fredman and Tyrväinen, 2010; Milligan and Bingley, 2007; Sonntag-Öström et al., 2014). Forests also play an important role in carbon storage for mitigating climate change (Canadell and Raupach, 2008; Pan et al., 2011). The supply of ecosystem services and the balance between them will depend on forest management regimes on both stand and landscape scales. Thus, the trade-offs between forest biomass production and other ecosystem services can be foreseen to be a major challenge for energy and climate policies as well as for those supporting biodiversity and ecosystem services.

Forest management regimes

Forests subject to industrial forestry are normally managed by final felling and re-plantation, i.e. even-aged forest management (EAF).
EAF has been viewed as having the greatest negative impacts on biodiversity and the environment (e.g. McDermott et al., 2010), which to a high degree is considered to be related to the simplification of forest structure and composition (Smith et al., 1997; Lindenmayer and Franklin, 2002; Puettmann et al., 2009; Thompson et al., 2011).

Seeing the negative environmental impacts of EAF, the forestry policy changed during the 1980s and 1990s, and legislation and forest-management guidelines in Sweden, Finland and Norway were revised to incorporate environmental concerns into harvest operations (Gustafsson et al., 2012). According to the new forestry policy in Sweden, production and environmental objectives should have equal weights in the management of the forest (Prop. 1992/93:226; SFS 1979:429). Retention forestry (Figure 1) was a new forestry concept of planning, managing and harvesting forests with primary focus on the type and quantity of forest structures that are left behind after harvest which intended to integrate the conservation of biodiversity (Franklin et al., 1997 et al, 2012). It is a modified form of clear-cutting by retaining import elements, such as standing dead trees and patches with valuable habitats, during harvest (Simonsson et al., 2014). Production forests in Sweden started to be managed under retention forestry since it was introduced during the 1980s; it is now applied in harvest operations on all production forests in the country (Gustafsson et al., 2012).

One important function of retention forestry is to enrich structural diversity in the developing stand by e.g. increasing the amount of old living trees and also dead wood (Franklin et al., 1997, Kruys et al., 2013). According to Kruys et al. (2013), in 2007 in Sweden, dead wood that is left in young forest (0-10 years old) is about 8 m³ per ha. In older forest with age classes of 61-100 years it is about 10 m³ per ha, and 15 m³ per ha in forest more than 100 years old, while the number for the forest between 11-60 years old is less than 4 m³ per ha. Retained living old trees decreased since the 1950s until the 1980s when they started to increase. In 2007 the number of living old trees reached the level of 1950s with 15 trees per hectare (Kruys et al., 2013). Although retention forestry practices have become consolidated, the discussion about the practical implementation of retaining living old trees is still going on.
Figure 1: Example of retention forestry in boreal Sweden (Simonsson et al., 2014, with permission).

Other ways of forestry have been discussed; compensating negative ecological impacts by increasing the fraction of protected areas as well as areas with multi-purpose forest management (e.g. Hunter and Calhoun, 1996; Messier et al., 2009). Multi-purpose management can be EAF with retention, as mentioned, or continuous cover forest management (CCF) which involves selective harvesting methods (Forestry Commission, 1998; Pommerening and Murphy, 2004; Yorke, 1998). The sustainability of CCF compared to EAF, has been addressed by Kuuluvainen et al. (2012) and Nordström et al. (2013) with varying results. From an ecological perspective, CCF may better promote ecological objectives because it can support species that depend on forest continuity, but the ecological performance of such forestry methods on wider spatial and temporal scales remains poorly examined (Jonsson et al., 2005; Kuuluvainen et al., 2012).

Although plans and actions are proposed to protect biodiversity, intensified forestry partly triggered by bioenergy production still may impose a serious threat to biodiversity due to the expansion of intensive silviculture.

Development of landscape simulation

In order to address questions concerning land zoning and forest management, models that can simulate forest development on
landscape scale and its consequences on several ecosystem services are necessary. Most of the existing landscape development models can be divided into two categories: 1) models for forest management planning support, and 2) models of land use change. Examples of the first category that also address biodiversity issues are reported in Chumachenko et al. (2003); Gustafson et al. (2006); and Wikström et al. (2011), which in general do not have the possibility to address whole landscapes but only forest stands and tend to have large data requirements (except for Gustafson et al. 2006 which model is instead very coarse when it comes to forest growth). Examples of the second category are Deal and Pallathucheril (2009); Eastman (2012); and Hepinstall-Cymerman et al. (2009). These models usually have a coarser representation of forest dynamics and include fewer or no parameters related to forest management.

For assessment of biodiversity impacts, several ecological assessment models and approaches exist, addressing impacts on habitat quality, quantity and connectivity for prioritised biodiversity components (e.g. Gontier et al., 2006). Among those, models that analyse habitat networks based on graph theory have been developed, that can address habitat quantity and connectivity in a pragmatic way (Dale and Fortin, 2010; Saura and Rubio, 2010; Saura et al., 2011; Urban et al., 2009; Zetterberg et al., 2010). These have been used for addressing, among other, forest management planning (Saura et al., 2011).

There are trade-offs to be assessed between co-related forest ecosystem services since there might be conflicts among them. However, such trade-offs are seldom analysed in energy assessments (Pang et al., 2014), and trade-offs between services are still poorly understood (Filyushkina et al., 2016). Currently, most trade-off analyses on forest ecosystem services are focused on the conflict between bioenergy extraction and carbon stock (Bottalico et al., 2016; Hoel and Sletten, 2016). Many studies provide biophysical mapping of ecosystem services, but with no projections of possible future trends. In a few studies, development of multiple ecosystem services and trade-offs among them have been projected over time (Forsius et al., 2015; Verkerk et al., 2014). However, some ecosystem services have a spatial component and have to be considered in a landscape context, such as the spatial distribution of habitat for species and of recreation areas for people. Most assessments of ecosystem services conducted so far have not included such spatial aspects, so a critical issue is thus to develop models that enable projections of the development of different ecosystem services on landscape level as a function of the forest management.

Thus, there is a need for cross-disciplinary cooperation as well as for methods and tools that can link energy and climate issues with environmental impacts of renewable energy options. This calls for the development of more comprehensive decision support tools for assessing future energy scenarios, integrating main policy concerns when assessing renewable energy options. To
simultaneously assess the provision of biomass, carbon storage, and spatially explicit habitat networks supporting recreation as well as biodiversity, will enable analysis of scenarios for land zoning and forest management in policy and planning, for integrated assessment of their sustainability.

**Aim and objectives**

The aim of this study was to develop methods for integrated sustainability assessment of alternative management regimes in forest landscapes, for long-term provisioning of various ecosystem services, considering climate and other environmental and societal goals. Two scenarios based on different management strategies were simulated for Kronoberg County, a study area in southern Sweden, using the recently developed LandSim model which is a spatially explicit model for long term projection of forest development (Pang et al., 2017). Building on previous studies, this paper connects existing models for projection of industrial wood production, bioenergy feedstock and carbon stock with spatially explicit methods for recreation area assessment and habitat network assessment to analyse trade-offs and synergies among five ecosystem services: provision of industrial wood and bioenergy feedstock, forest carbon storage, recreation areas and habitat networks for selected focal species. We integrated methods and models in a Landscape simulation and Ecological Assessment (LEcA) tool in order to project the corresponding changes of the ecosystem services under alternative forest management scenarios over a 100 years’ period. The LEcA tool thus aims to provide decision support to stakeholders for integrated sustainability assessment of policy and planning alternatives.

The specific targets were to:

- Investigate how current broadly used energy models deal with environmental impacts and what environmental issues are addressed (Paper I).

- Integrating ecological model with industrial wood and bioenergy feedstock production potential to assess forest biomass extraction impacts on habitat networks, in a study of Kronoberg County, Sweden (Paper II).

- Trade-off analysis among five forest ecosystem services, in a study of Kronoberg County, Sweden (Paper III).

- Develop spatial optimization methods for incorporating habitat networks in forest management planning (Paper IV).

- Linking an energy system planning model with forest simulation and an integrated model for assessment of forest bioenergy feedstock supply while applying environmental and transport restrictions, using the LEcA tool, in a study of Lithuania (Paper V).
Methodology

The methodology consisted of a literature review in order to summarise current research on forest management regimes and their impacts on the environment, as well as models and tools for integrated sustainability assessment of renewable energy options. In addition, analyses of different ecosystem services, including industrial wood production, bioenergy potential, carbon storage, recreation potential and biodiversity-related impacts were performed. This was done through the simulation of forest and landscape development under different forest management scenarios. Based upon this, the consequences for the selected ecosystem services were estimated, and among these, habitat networks supporting selected biodiversity components were analysed and optimised. In this way, trade-offs and synergies among the ecosystem services could be analysed and assessed.

Literature reviews

A literature review was performed in order to compile a State-of-the-Art on bioenergy, forestry, environmental impacts of forest management regimes, as well as integrated sustainability assessment of renewable energy options, which included energy related modelling tools.

In order to get an overview of energy related models and their potential for integrated assessment the research was carried out in three steps (Paper I). First, a literature review was conducted concerning modelling tools that are potentially useful for addressing energy policy and its environmental impacts in an integrated assessment. The questions posed in this review were:

- Which aspects have been addressed in energy models?
- Which aspects have been involved in models addressing biodiversity and ecosystem services related to land use?
- Are there any potential linkages between energy models and ecological assessment?

Second, a survey on energy related publications and their research scopes was performed through searches in the scientific literature database Scopus. In order to achieve a broad overview of publications on energy-related analysis within both energy and environmental areas, we started by using all journal sources in Scopus and applying “energy model” as the keyword and “energy” and “environmental science” as research area limitation. Then, we narrowed down the sources to two selected journals, “Energy” and “Energy Policy”, which focus on energy-related publications, to specifically address the environmental-related research within energy analysis. For the analysis, the specific issues for strategic environmental assessment (SEA) defined in the EU SEA Directive 2001/42/EC were used as a checklist. The questions addressed in the second step were:
• How many energy-related publications in the whole database concerned climate change, land use, landscape and biodiversity, respectively?

• How are these specific issues for environmental assessment addressed in two energy-related journals?

Third, EU’s most comprehensive energy plan, the EU Energy Roadmap 2050 and its related impact analysis reports were reviewed to determine which environmental impacts were considered. The following questions were addressed during the review:

• What impacts were considered in the analyses of the EU Energy Road Map 2050?

• What models were used for the impact analysis?

• What impacts that are covered by the SEA framework were not included or appropriately addressed in the EU Energy Road Map 2050?

**Landscape development in Kronoberg County**

To develop methods for assessing the sustainability of forest management options, Kronoberg County was selected as study area (Figure 2). It covers 9,424 km², of which 66% of the total area is covered with forest (78% of the land area), compared to the whole country of Sweden where around 52% of the total area (70% of the land area) is forest (County Administrative Boards, CAB, 2006; Statistics Sweden, 2013). Kronoberg County is situated in the hemi-boreal zone in southern Sweden and is dominated by coniferous forest, often mixed with deciduous trees. The land use in the County is dominated by forestry and agriculture with relatively small urban and industrial areas, and the share of privately owned forest land is high, around 80% (SFA, 2013). Therefore, forest management is of high interest in the region.

Certain issues with forest-related environmental aspects seemed to be problematic within the County. For instance, significant forest areas with high biodiversity values and red-listed species in the County were not protected. According to the Swedish Red List 2010, the proportion locally extinct of the red-listed species in Kronoberg County is 16.5 %, which is among the highest of the counties in Sweden (Gärdenfors, 2010). In relation to this, it has been pointed out that new planning and decision support tools and instruments may be needed to reach the sustainability objectives (SEPA, 2014).
Trade-off analysis of forest ecosystem services – A modelling approach

Figure 2: The study area embraced Kronoberg County (spatial data © Lantmäteriet [I:2014/00591]).

For the modelling, forest data on timber volume by tree species, age and height was used (SLU, 2013). This data is based on a conjunct processing of satellite imagery (Landsat TM and Spot) and field data from the Swedish National Forest Inventory (Reese et al., 2003). Land cover and topographic data were obtained from (Lantmäteriet, 2013a, Lantmäteriet, 2013b). Data on protected areas and areas of national interest for nature conservation, cultural and recreational values (SNBH, 2013, SEPA, 2006) were retrieved from (CAB, 2013). Data on areas of high biodiversity value, defined as part of a green infrastructure on national level but not necessarily protected, was retrieved from (SEPA, 2012).

In order to simultaneously explore effects of different land zoning policies and related forest management regimes on bioenergy and prioritised biodiversity components, the landscape simulation model LandSim was developed to simulate possible future development scenarios of the study area and its forest (Papers II and III). The first scenario, “EAF-tot”, was based on EAF, where the forest was divided into management stands, based on the properties of the forest and of the site. Each stand was managed according to a cycle of clear-cutting, regeneration, cleaning, thinning, and again clear-cutting and so on. In the EAF-tot scenario, EAF was applied to all forest areas that were not formally protected (3 % of the productive forest land). For the EAF-tot scenario, a sub-scenario was developed, EAF-tot/r, with 5 % retention, which means that 5 % of the area set out for final felling in each time step was not felled, but retained. These areas were selected randomly.

The second scenario, “CCF-int”, was based on the land zoning principle that 30 % of the landscape should be dedicated to protected areas and to low-intensive, multi-purpose CCF forestry, while the remaining landscape should be subject to more intensive forestry for increasing bioenergy feedstock, using 10 years shorter rotation time. We made three assumptions for the area under CCF,
concerning possibly suitable habitat: a) that 100 % of the areas with this treatment was suitable habitat for the selected model species, i.e. had old trees; b) that 50 % of the area with this treatment was suitable habitat, and c) that 25 % of the area with this treatment was suitable habitat.

In Paper IV, a small area in Kronoberg County was used as a study area (the red square in Figure 3). The pixels of the study area were aggregated from 25 x 25 meters into 1 x 1 km “stands” for the theoretical study of spatial optimization methods.

**Figure 3: Location of the study area of Paper IV within Kronoberg County**

**Scenarios for Lithuania**

For linking the energy planning model MESSAGE with the ecosystem service assessment models, the study area of Lithuania was used (Figure 4). The country is covered with forest to 33.5 % and the dominating tree species are pine (33.2%), birch (21.1%) and spruce (19.7%). A business-as-usual forest scenario for forest management was created, based on forestry conditions and development in Lithuania during the period since year 2000. This has been a rather stable period in terms of legal, institutional and technological forestry environment. Major transformations which took place after the restoration of independence in 1991 had already been completed, including the adoption of a new forest law with strengthening a segregated forest management approach based on four functional forest groups, turning towards market economy, modernization of forestry technologies, and liberalization of international trade and acceptance of international environmental standards.

The forest management strategies of the country includes four categories: 1) no active forest management is assumed in strict reserves; 2) special purpose forests encompass ecosystem protection and recreational use with severe forest management restrictions; 3) protective forests are aimed at protection of soil or water, with some additional management restrictions compared to...
commercial forests; while 4) timber production is prioritized in commercial forests (Lithuanian statistical yearbook of forestry, 2016).

![Figure 4: The study area of Lithuania, illustrating different forest management strategies that are applied in the country, see text for explanation. Coordinate system LKS_1994_Lithuania_TM, spatial data State Forest Survey Service (2016).](image)

Through the energy model MESSAGE (IAEA, 2007), two bioenergy demand scenarios were developed. They were based on not only the price and availability of biomass but also on the requirements for the share of renewable energy sources in the final energy demands. Environmental restrictions were applied. Extractable logging residues were considered to be those that could be extracted while minimizing soil-related damages on forest ecosystems according to (State_Forest_Service, 2010). These environmental restrictions involve:

1) Poor soils, where the objective is to maintain the natural fertility;
2) For soil with a slope of more than 15 degrees, remaining cutting residues are supposed to make such soil stable;
3) For eroded soils, the aim is to minimize the erosion process;
4) For moist soil, the objective is to minimize the damage on soil;
5) For organic soil, extraction is not allowed due to both damage avoidance and maintaining the property.

Transport restrictions were taken into consideration in this study, so even if economically, 1 km extraction distance to collection spots has been suggested, more forest biomass would be required, then from a political point of view, 3 km would be the choice.
Transport distances from collection points to combined heat and power (CHP) plants that were assumed were therefore 30 km along roads and 1 km from collection points.

**Landscape simulations with LandSim**

LandSim can simulate the development of the forest in the landscape in terms of forest growth and management, the latter in terms of thinning, clear-cutting and no action. The simulations of both study areas were run for 25 x 25 m rasters, in 5 year time steps over a 100 years period.

For the study of Kronoberg County, the consequences of the two management regimes were described for four different variables:

- Site productivity (4 classes),
- Dominating tree species (8 classes),
- Forest age (33 classes),
- Timber volume (10 classes).

For the study of Lithuania, the state of each pixel coinciding with forest land was described by six variables:

- Mean age (33 classes),
- Standing volume (13 classes).
- Dominant tree species (8 classes),
- Site productivity (2 classes),
- Ownership (2 classes),
- Forest group (4 classes).

From the output of the simulations by LandSim in each time step and scenario, industrial wood harvest was directly derived, while estimations were made of potential bioenergy feedstock, carbon storage, and the spatially explicit recreation areas and habitat network indicators for model species tied to old forest.

**Estimation of bioenergy feedstock**

From the harvested volumes, the potential bioenergy feedstock was estimated, in Papers II and III by predicting the expansion from stem volume into dry weight of each tree component, which was then summed up. For this purpose, Eq. 1 was fitted using linear regression and was applied for the bioenergy feedstock of the different tree species:

\[
W_i = (a_i + b_i e^{-0.01t})V
\]

where \(W_i\) is the dry weight of tree component \(i\), while \(t\) is stand age and \(V\) is the stem volume. The coefficients \(a_i\) and \(b_i\) are shown in Table 1. The variable \(e^{-0.01t}\) is a time-dependent term (related to tree age). The functions for predicting the expansion from stem
volume into dry weight for each tree component were derived from (Lehtonen et al., 2004).

**Table 1: Parameters for dry weight calculation (Lehtonen et al., 2004).**

<table>
<thead>
<tr>
<th>Tree components (i)</th>
<th>Pine stands</th>
<th>Spruce stands</th>
<th>Broadleaved stands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>a</td>
</tr>
<tr>
<td>Foliage</td>
<td>0.0177</td>
<td>0.0499</td>
<td>0.0388</td>
</tr>
<tr>
<td>Branches</td>
<td>0.0706</td>
<td>0.0212</td>
<td>0.0905</td>
</tr>
<tr>
<td>Branches, dead</td>
<td>0.0010</td>
<td>0.0059</td>
<td>0.0088</td>
</tr>
<tr>
<td>Bark</td>
<td>0.0254</td>
<td>0.0221</td>
<td>0.0353</td>
</tr>
<tr>
<td>Stump</td>
<td>0.0472</td>
<td>-0.0039</td>
<td>0.0488</td>
</tr>
</tbody>
</table>

In Paper V, the bioenergy feedstock was estimated by summing up the available firewood, industrial wood waste and extractable residues without negative influence on forest ecosystem (Table 2), according to the Lithuanian State Forest Service (2010).

**Table 2: Parameters for biomass estimations for Lithuania.**

<table>
<thead>
<tr>
<th>% based on harvested stem volume</th>
<th>Pine</th>
<th>Spruce</th>
<th>Birch</th>
<th>Aspen</th>
<th>Black alder</th>
<th>Grey alder</th>
<th>Oak</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firewood</td>
<td>2%</td>
<td>2%</td>
<td>4%</td>
<td>29%</td>
<td>17%</td>
<td>17%</td>
<td>10%</td>
<td>8%</td>
</tr>
<tr>
<td>Industrial waste</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Residues</td>
<td>0-21%</td>
<td>0-21%</td>
<td>0-15%</td>
<td>0-15%</td>
<td>0-15%</td>
<td>0-14%</td>
<td>0-17%</td>
<td>0-16%</td>
</tr>
</tbody>
</table>

**Estimation of carbon storage**

In order to estimate the function of the forest as a carbon sink in Papers II and III, the biomass expansion factors were used to estimate the carbon content of a whole tree using stem volume as input data (Penman et al., 2003). Lehtonen et al. (2004) provided biomass expansion factors that are dependent on stand age and tree species as a basis for this quantification. In the current study, we estimated carbon stocks, C, from stem volume, V, multiplied by BEF (Tables 3) at age $i$ for species $j$, and used the IPCC default carbon conversion factor 0.5 (Penman et al., 2003) (Equation 2):

$$C = \sum_{i=1}^{n} \sum_{j=1}^{n} 0.5 \times BEF_{i,j} \times V$$  \hspace{1cm} \text{Eq. 2}
Table 3: Biomass expansion factors (Lehtonen et al., 2004).

<table>
<thead>
<tr>
<th>Age</th>
<th>Pine</th>
<th>Spruce</th>
<th>Mixed conifers</th>
<th>Mixed conifers and broadleaves</th>
<th>Broadleaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-19</td>
<td>0.697</td>
<td>0.862</td>
<td>0.780</td>
<td>0.744</td>
<td>0.707</td>
</tr>
<tr>
<td>20-29</td>
<td>0.705</td>
<td>0.860</td>
<td>0.783</td>
<td>0.750</td>
<td>0.716</td>
</tr>
<tr>
<td>30-39</td>
<td>0.710</td>
<td>0.841</td>
<td>0.776</td>
<td>0.748</td>
<td>0.720</td>
</tr>
<tr>
<td>40-49</td>
<td>0.702</td>
<td>0.820</td>
<td>0.761</td>
<td>0.742</td>
<td>0.723</td>
</tr>
<tr>
<td>50-59</td>
<td>0.701</td>
<td>0.816</td>
<td>0.759</td>
<td>0.738</td>
<td>0.718</td>
</tr>
<tr>
<td>60-69</td>
<td>0.710</td>
<td>0.791</td>
<td>0.751</td>
<td>0.736</td>
<td>0.720</td>
</tr>
<tr>
<td>70-79</td>
<td>0.708</td>
<td>0.784</td>
<td>0.746</td>
<td>0.727</td>
<td>0.709</td>
</tr>
<tr>
<td>80-89</td>
<td>0.707</td>
<td>0.777</td>
<td>0.742</td>
<td>0.725</td>
<td>0.709</td>
</tr>
<tr>
<td>90-99</td>
<td>0.704</td>
<td>0.782</td>
<td>0.743</td>
<td>0.725</td>
<td>0.707</td>
</tr>
<tr>
<td>100-119</td>
<td>0.703</td>
<td>0.784</td>
<td>0.744</td>
<td>0.726</td>
<td>0.707</td>
</tr>
<tr>
<td>120-139</td>
<td>0.698</td>
<td>0.782</td>
<td>0.740</td>
<td>0.724</td>
<td>0.707</td>
</tr>
<tr>
<td>140-</td>
<td>0.690</td>
<td>0.788</td>
<td>0.739</td>
<td>0.723</td>
<td>0.707</td>
</tr>
</tbody>
</table>

Estimation of recreational area

The total potential recreation area was used as an indicator to estimate the supply of recreational ecosystem services and its changes in different scenarios, quantitatively and spatially, in Papers II and III. Mature forest was used as an indicator for high recreation values, both to coniferous forest (Sonntag-Öström et al., 2014) and broadleaves (Mattsson and Li, 1994); (Norman et al., 2010b). Based on the survey by Hörnsten and Fredman (2000) the distance of 2 km between forest and residential areas was used as buffer distance for identifying suitable recreational areas. In the current study, forest more than 70 years old and accessible within 300 meters distance along each side of small roads were also viewed as valuable recreation areas. Land cover data on residential areas (Lantmäteriet, 2013b) and the road system (Lantmäteriet, 2013a), together with data on tree age from (Reese et al., 2003) and from the output of LandSim, were used to find potential recreation areas, $A(k)$, summarized as the total recreation area, $A(total)$ (Equation 3).

$$A(total) = \sum_{k=0}^{n} A(k)$$

Eq. 3

Habitat network assessment

In Papers II and III, two model species, the three-toed woodpecker (Picoides tridactylus) that is tied to spruce-dominated coniferous old forest, and the middle spotted woodpecker
Trade-off analysis of forest ecosystem services – A modelling approach

(Dendrocopos medius) that is tied to southern broadleaved old forest, were selected for the assessment. Suitable habitat for each model species across the study area was derived and a habitat network analysis was performed for the two scenarios.

In order to assess quantitatively the habitat and connectivity for certain species within a certain landscape and time, a habitat network analysis method based on graph theory was used (Saura and Rubio, 2010, Pascual-Hortal and Saura, 2006). A graph is a set of nodes (patches) and links (connections), while loss of nodes and/or links may or may not cause a graph component (connected habitat) disconnection. In the current study, the Equivalent Connected Area (ECA) index was used since it takes into account both the amount of habitat within habitat patches and the connectivity among them. ECA builds on the probability of connectivity and relates the connectivity changes to the amount of available habitat (Saura et al., 2010). It is defined as the size of a single habitat patch, maximally connected, that would provide the same value of the probability of connectivity as the actual habitat pattern in the landscape (Saura et al., 2010). It was calculated as in Eq. 4:

\[ ECA = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j p_{ij}^*} \]  \hspace{1cm} (Eq. 4)

where \( a_i \) and \( a_j \) are the area of the habitat patches \( i \) and \( j \), and \( p_{ij}^* \) is the maximum product probability of all the possible paths between patches \( i \) and \( j \). ECA has an area unit which makes it relatively easy to interpret, since it represents changes in the available habitat area. ECA was calculated for the model species in each scenario and time step.

Spatial optimization for incorporating habitat networks in forest planning

Different spatial location of harvesting operations may result in different impacts on forest habitat networks. To minimize the impacts, spatial optimization can be used for allocating harvest activities. Since the spatial dimension makes this difficult to be solved by ordinary optimization techniques, two heuristic methods for spatial optimization - simulated annealing (SA) and genetic algorithm (GA) – were applied in Paper IV for the spatial optimization through a theoretical study.

The objective was to maximize the habitat network, by using a modified version of the ECA indicator (Saura et al., 2010). The middle spotted woodpecker (Dendrocopos medius) was used as model species to parameterise the model. The modified ECA* was formulated as in Equation 5. However, the harvest demand and the demand on total suitable habitat area left behind must simultaneously be fulfilled. They were set as two constraints in the mathematical formula (Equations 6 and 7). In the study we assumed that thinning would result in loss of 50% of the habitat resource for the model species. The final optimal solution was a
trinary vector of $x$ with elements representing the activity for each stand.

The objective function (Equations 5 and 9) was to maximize available habitat within the habitat network, i.e. maximizing the $ECA^*$, where $a_i$ and $a_j$ were the size of the habitat patches $i$ and $j$, and $p_{ij}$ was the probability of linkage of all the possible paths between patches $i$ and $j$. Instead of using “maximum product probability of linkage between patches”, as described in (Saura et al., 2010), we calculated the probability of linkage between each pair of patches to estimate the habitat connectivity. A and B in Equations 6 and 7 were prerequisites for the harvest demand and total suitable habitat area limitations. Each stand had a different volume value of $v_i$. The number of variables, $n$, was the number of total stands. The harvest activity for stand $i$, $x_i$, was set to be either 0 – no activity; 1 – thinning; or 2 – clear-cutting (Equation 8). The mathematical formulation of the model was as follows:

$$\text{Max } ECA^* = \sum_{i=1}^{n} \sum_{j=1}^{n} a_i x_i a_j x_j p_{ij} \quad \text{Eq. 5}$$

Subject to:

$$\text{Harvest: } \sum_{i=1}^{n} v_i x_i \geq A \quad \text{Eq. 6}$$

$$\text{TotSuit: } \sum_{i=1}^{n} a_i x_i \geq B \quad \text{Eq. 7}$$

$$x_i = \{0, 1, 2\} \quad \text{Eq. 8}$$

The coding and processing were performed in MatLab (MathWorks, 2016). The structure of the above formulation was adjusted for running GA in MatLab. For SA, the constraints must be combined with the objective as a penalty function. The objective function for SA was as follows:

$$\text{Max } Z = \sum_{i=1}^{n} \sum_{j=1}^{n} a_i x_i a_j x_j p_{ij} + M_1 \cdot f(\text{Harvest}, A) + M_2 \cdot f(\text{TotSuit}, B) \quad \text{Eq. 9}$$

Where $Z$ represents the penalty function value and $M_1$ and $M_2$ are the penalty parameters. If the constraints were not satisfied, the objective function will be punished to have a big minus value so that it would not be possible to be selected as an optimum. In this study, we tried with two sets of constant penalty parameters (Set 1: $M_1 = 300$, $M_2 = 200$; Set 2: $M_1 = 100$, $M_2 = 100000$) while keeping the other parameters the same.
The process of SA started with a random solution and then a comparison with the neighbourhood, and continued with iterations by accepting new better solutions that were verified by the objective function until it could not find even better solutions. It attempts to avoid getting trapped in local optima through generally two ways in MatLab. One is by restarting a new set of iterations (reannealing) after accepting certain new solutions. The other is by accepting a worse solution with a certain probability, and the probability will decrease along the optimization process (as a “temperature cooling schedule” for metal annealing) (Pukkala and Kurttila, 2005). Parameters that need to be specified when using SA are annealing parameters, bounds of variables, initial temperature and starting point, data type and stopping criteria.

An important concept of GA is population; since unlike traditional search methods, GA relies on a group of candidate solutions (Sastry et al., 2014). GA starts with a group of initial solutions (initial population), which then are processed by selecting elite solutions and better solutions, which are evaluated by the objective function and constraints. Elite solutions will be kept for the next iteration, while better solutions will be used for crossover (parent chromosomes) and mutation (random change in genes). These operations result in new better solutions (offspring) and continue with following iterations (new generations). Keeping elite solutions, crossover and mutation are aiming at both finding better solutions and reducing the risk of being trapped in local optima.

**Linking an energy planning model with an ecosystem services assessment model**

The LEcA tool (Papers III and V) consists of three modules embedded in a GIS framework (Figure 4); the LandSim model that can simulate forest growth and management; the storage and yield calculator, that estimates the provision of industrial wood and bioenergy, and carbon storage; and the habitat assessment tool, used for localising and quantifying habitat with high value for forest biodiversity as well as for recreation.

A crucial linkage between forest biomass consumption and ecosystem services provision is forest management. In this study we used a rule based approach based on possible adjustment of forest management for increased biomass supply ranked according to the readiness of their implementation. We focused primarily on logging residues and sawmilling residues in addition to the firewood consumed by individual households. Stump wood and industrial wood were only considered as alternative sources when the above sources were exhausted. The searches for a suitable forest management configuration started from an initial configuration representing current forest management practices and proceed by testing the possible adjustment for increased supply until the demand is met or the list of possibilities is exhausted. In all cases the total harvest amount was constrained to a non-declining level.
Figure 5: Overview of the LEcA tool (Papers III and V), including LandSim, the storage and yield calculator, and the habitat assessment tool. Five forest ecosystem services can be assessed together: industrial wood, bioenergy, carbon storage, recreation value and habitat for prioritized biodiversity components.
Results and discussion

**Bioenergy for energy consumption — the case of Sweden**

Renewable energy sources are projected in the EU Energy Roadmap_high renewables scenario to be accounting for 75% of the total energy consumption in 2050 (EC, 2011a).

Sweden has fairly low emissions of carbon dioxide due to the big input from hydropower and nuclear power for most of the electricity generation. These two energy sources together accounted for 27% of energy consumption in 2016 (Figure 6). However, in relation to the lessons from nuclear power incidents and disasters, today’s Swedish energy policy restricts the expansion of nuclear power and plans exist for phasing it out (SEPA, 2011). For hydropower, much of the economically viable hydropower in Sweden has already been developed, while most of the unexploited larger rivers and streams in Sweden are protected by law (SEPA, 2009). Hydropower comes with several environmental impacts and potential goal conflicts, which have recently been investigated (SOU, 2014) and is under debate. This may imply a trend towards reduced hydropower production in Sweden (Renöfält et al., 2010).

![Final domestic energy use in 2016 Sweden](image)

*Figure 6: Final domestic energy use in 2016 Sweden (Hektor et al., 2014), data from SEA (2017).*

In view of these restrictions, the increasing energy demand together with the goal to limit the increase in temperature to 2 °C, much emphasis seems to turn to increasing the use of bioenergy, e.g. the strategy for a bio-based economy (EC, 2012, FORMAS, 2012). Today, around 32% of the final energy consumption in Sweden still depends on fossil fuels. To fulfil the aim of zero GHG emissions by 2050, at least 122 TWh would need to be replaced by fossil-free energy sources (SEA, 2015). In 2016, bioenergy became the biggest energy source which accounted for 37% of all Sweden’s domestic energy consumption (Figure 6). Bioenergy from forest is playing an important and increasing role...
(de Jong et al., 2014b), and today about 85% of all bioenergy in Sweden comes from forest (IEA, 2014).

However, several studies question the carbon-neutral performance of forest biomass, since burning forest biomass will contribute to GHG emission for years until re-generated trees grow back (Zanchi et al., 2014, Bracmort, 2013). But it is still taken as a good way to manage climate change (EC, 2011a). In 1991, Sweden introduced a tax on carbon dioxide emissions from fossil fuels but bioenergy was exempted from the tax and even encouraged by the Parliament with grants (Riksrevisionen, 2011). The biggest expansion of bioenergy utilization happened in the district heating sector also strongly stimulated by the Electricity Certification System (SEA, 2009). The increasing use of bioenergy has also reached the industrial and transport sectors. Bioenergy use in industry increased from 21% in 1970 to 38% in 2013 (SEA, 2015). In the transport sector, the government has launched several incentives to encourage biofuel-powered vehicles, such as, the congestion tax from 2007, while flexible-fuel vehicles were exempted from the tax in Stockholm (Eliasson, 2014). From 2009, environmental friendly vehicles are exempted from motor vehicle tax for a period of five years (OECD, 2014). Biofuel use in the transport sector has increased to 8.4 TWh in 2013 which account for 10% of total energy use in the transport sector (SEA, 2015). As a result of bioenergy expansion in all these sectors, bioenergy consumption has kept increasing significantly and has been the biggest energy supplier for the whole country since 2013 (SEA, 2015, Hektor et al., 2014).

Forest management history in Sweden

In 2015 Sweden’s total land area was 40.8 million hectares, of which 28.2 million hectares were covered by forest and 23.4 million hectares were covered by productive forest (SLU, 2016). The use and management of forest has a long history in Sweden, with substantial differences between the north and the south parts.

Northern Sweden

The Sami people in northern Sweden had adapted to the environment thousands of years ago through seasonal movements due to resource availability, and reindeer herding (Andersson et al., 2005). During the 17th and 18th centuries, new national regulations aimed to cultivate the “wilderness” and to promote colonization in northern Sweden. New settlers who came from the south established in these areas.

After farming was introduced, intensive reindeer herding, milking and bark harvesting ceased between the end of the 19th century and beginning of the 20th century (Andersson et al., 2005). In the early 1890s the colonization process accelerated due to the increasing demand for forestry labour such as using the watercourses for floating timber, especially when state-owned forest companies began to employ woodsmen working all year round from the 1950s (Andersson et al., 2005). Along with the
colonization and forest industrialization came changes of the ecosystems in the area. Low altitude areas became more intensively used, and deforestation increased due to firewood collection and timber felling for construction (Andersson et al., 2005).

Prior to the 19th century, natural forest was spatially extensive in northern Sweden (Östlund and Roturier, 2011), natural forest being defined as naturally regenerated forest composed of indigenous tree species (FAO, 2001). A major part of the forest landscape was less used due to the very low population density. Trees were modified with the aim of using tree products like bark and wood, for marking paths and boundaries, and to produce tar and potash. At that time nature fire was the main force for forest regeneration (Östlund and Roturier, 2011). The dominance of this natural disturbance regime lasted until the early logging carried out by the sawmill industry in the 19th century, which was seen by (Östlund and Roturier, 2011) as a “mining” process since the loggers only targeted the most valuable and large diameter pines. From the beginning of the 20th century, spruce and smaller trees were also used for pulpwood (Östlund and Roturier, 2011).

Forest management gradually started to transform the forests to become high-yielding. Clear-cutting was introduced by the end of the 19th century in northern Sweden and after that alternated with selective cutting (Lundmark et al., 2013). Regeneration after logging was not implemented due much due to the economic recession and high cost. When the economy market recovered before World War II, once again, clear-cutting became possible (Lundmark et al., 2013). The strong expansion of industries at the beginning of the 1940s greatly stimulated the market for all kinds of timber. From the beginning of the 1940s, clear-cutting rapidly became the predominant forest management method and has dominated thereafter. In order to use forests in the most economical way, and in the 1950’s, a circular was issued by the National Forest Service which stated that the forests should be restored and that cleared areas should be reforested (Lundmark et al., 2013). Herbicides were used to remove regenerated deciduous trees during the 1960s and 1970s (Andersson and Östlund, 2004, Östlund, 1993, Östlund et al., 1997). Primary nature conifer forests were gradually replaced by even-aged stands.

**Middle Sweden**

A similar forest history took place in the middle of Sweden, when large scale logging was introduced in the late 1800s. The forest commons sold logging contracts including large timber trees at public auctions. This resulted in an almost total loss of large old trees in some areas (Linder and Östlund, 1998). Natural regeneration without any soil treatment was the most common technique until the 1940s when draining of wetlands and nitrogen fertilization was introduced to increase stand productivity (Linder and Östlund, 1998). Dead trees were removed from the forests since they were seen as a source of dispersal of fungi and insects which might attack healthy trees. Furthermore, in the 1960s and
1970s, broadleaved trees in young stands were killed by spraying herbicides (Linder and Östlund, 1998). The forest standing volume was drastically reduced by the initial large cuttings in the late 1800s. The number of large trees also decreased, so that the density of large diameter trees in the late 20th century only accounted for 10 to 20% of that in the 1880s (Linder and Östlund, 1998). Earlier, large numbers of dead standing trees were a characteristic of the natural boreal forests in Sweden. For instance, (Kohh, 1975) showed that there may have been 11-13 m³/ha snags in the forests of the middle of Sweden in the 1880s, while this number changed to be 8.3 in 1922 and 0.8 in 1952. These differences between natural forest, extensively managed forest and intensively managed forest have great implications on the state of today’s forest, not at least on forest biodiversity.

**Southern Sweden**

Long before the forest in northern and middle Sweden had changed, forests in southern Sweden had already started the transformation. Beech seem to have been the most common tree species and covered large areas of south-western Sweden until the early eighteenth century (Björse and Bradshaw, 1998, Brunet et al., 2012). In 1893, Danish and German foresters introduced dense, even-aged and single-layered beech stands to Sweden which could be harvested and regenerated at the stand age of 100-140 years (Brunet et al., 2012). From the mid-eighteenth century the beech forest declined substantially due to the introduction of coniferous forest. The largest historical loss of beech forest happened between 1960 and 1975, and it was replaced by Norway spruce. One reason was that Norway spruce was easy to manage and was believed to provide a higher future income than beech. Another reason was that beech wood lost its importance as a heating source during the first decades of the 20th century when coal gradually took its place (Brunet et al., 2012). In recent years, though, a severe storm damaged many spruce stands in 1999 and marked the end of Norway spruce dominance at Skabersjö. The most recent major increase in forest area occurred between 1990 and 1995 when subsidies were available for the afforestation of agricultural areas as part of the preparation for Sweden to join the European Union. A majority of the plantations in this area were broadleaved forest, particularly oaks (Brunet et al., 2012).

**Development after World War II**

In the 1950s forest fertilization was advocated as a means to increase the yields (Lindkvist et al., 2011). According to (Lindkvist et al., 2011), the reason for the great interest in forest fertilization was that forest was seen as a bottleneck in the production process when facing the huge demand for timber for the reconstruction of Europe after World War II. In this context, nitrogen-based fertilizers were scientifically proved to increase the tree growth in an economically feasible way.
In the early 1960s, a debate about the use of chemicals started. Many were worried that fertilization threatened forest birds, while others complained about the pollution of surface and ground water. For example, in the summer of 1971 in Värmland County people were outraged over the poisoning of three cows (Lindkvist et al., 2011).

Negative environmental impacts of the new forest management have mainly been attributed to the “high efficiency” of the applied EAF management regime. In EAF, forests are managed according to stand age and age class intervals are determined by the average rotation time for the stands. For an average rotation time of more than 140 years, 50-year age class intervals were used; otherwise 20-year age class intervals were used (Hellberg et al., 2009). The intensive forest management was aiming at high timber production but it had negative impacts for biological diversity. With relatively short rotation periods and even-aged management, old, dying and dead trees which were seen as not qualified for timber production were cleared away. However, old trees are essential for maintaining biological diversity.

In the middle of the 1990’s, as mentioned in the Introduction, the forest policy changed so that production and environmental goals were given equal priority. In relation to this, as mentioned, legislation and forest management guidelines were revised to incorporate environmental concerns into forestry (Govt. prop. 1992/93:226; SFS 1979:429). More recently, growing climate concerns and ideas of a biobased economy put increasing demands for forest bioenergy and material purposes (FORMAS, 2012; EC, 2012), which will lead to increasing demands on the forest.

**Sustainable forests**

Climate change mitigation began to emerge as a major concern of Swedish environmental policy by the late 1980s, and policies concerning climate issues were specially treated. Among the 16 environmental quality objectives adopted by the Swedish Government (Govt. prop. 1997/98:145 and 2004/05:150), that should guide policy and planning, one is called “Reduced Climate Impact”. It is described as:

“In accordance with the UN Framework Convention on Climate Change, concentrations of greenhouse gases in the atmosphere must be stabilized at a level that will prevent dangerous anthropogenic interference with the climate system. This goal must be achieved in such a way and at such a pace that biological diversity is preserved, food production is assured and other goals of sustainable development are not jeopardized. Sweden, together with other countries, must assume responsibility for achieving this global objective.”

(Govt. prop. 1997/98:145 and 2004/05:150)

The history of Swedish forestry shows that from selective cutting of big trees, to clear cutting and then to EAF, forest management has mainly been driven by economic concerns (Andersson and Östlund, 2004; Andersson et al., 2005; Brunet et al., 2012; Östlund, 1993; Östlund and Roturier, 2011; Östlund et al., 1997).
Environment impacts were seldom studied and hardly played any role in decision making in earlier phases, but over the last decades, environmental concerns have been increasing. The Swedish environmental policy has shifted from a “do least harm” emphasis on eliminating threats to human health and to fauna and flora concerns, into a “do most good” emphasis and to protect the environment in terms of what we wish to achieve (SEPA, 2011, SEPA, 2012). As mentioned, by the end of the 1990s Sweden developed the environmental quality objectives. Firstly, in 1997 the government determined fifteen general objectives (Govt. prop. 1997/98:145); and several years later one more objective, concerning biodiversity, was added (Govt. prop. 2004/05:150) (SEPA, 2012).

Over half of Sweden is covered by forests which have multiple functions, including the provision of timber, pulp and biomass for bioenergy, as well as other ecosystem services such as outdoor recreation, cultural heritage, and provision of habitat for a variety of animal and plant species. The environmental quality objective “Sustainable Forests” is described as:

“The value of forests and forest land for biological production must be protected, at the same time as biological diversity and cultural heritage and recreational assets are safeguarded.” (Govt. prop. 1997/98:145 and 2004/05:150)

The environmental quality objective Sustainable Forests has several specific aims, so that the physical, chemical, hydrological and biological qualities and processes of forest land are to be maintained and the ecosystem services of forests should be preserved. Natural and cultural heritage values should be conserved and forest values for outdoor recreations should be maintained. Biodiversity is to be preserved as well, including habitats and their connectivity in all natural geographical regions, and viable populations of forest species are to be sustained, including threatened species. It should be noted that these ecosystem services and functions may not always be compatible with one another, and in the use of the forest, there is a risk for goal conflicts (SEPA, 2012).

The state of the forest environment is mainly affected by the intensity of forestry and the methods used (SEPA, 2015). Several negative environmental impacts of the forest management can be attributed to the on-going large-scale application of EAF management in industrial forestry, such as the increasing demand for forest biomass for bioenergy. An intensified forestry could implicate the use of shorter rotation times, fertilization, exotic fast-growing species and more frequent running of heavy machinery in the forest.

Large-scale use of short rotation times will affect the amount of mature and old forest and dead wood in the landscape, which are important for biodiversity. Forest residues such as branches, tops and stumps, especially of certain broadleaved tree species, may constitute habitat for different species and their extraction would
therefore also impact on biodiversity (de Jong et al., 2014b). Large extractions of nutrient-rich biomass could lead to acidification and spreading of toxic substances, while the use of forest fertilization could cause increased eutrophication. In addition, intensification of the forestry could affect cultural ecosystem services. These and other environmental impacts of forestry need to be taken into account simultaneously for a sustainable use of forests.

To preserve forest environments for multiple ecosystem services and biodiversity conservation, and thereby reach the objective of “sustainable forests”, several measures are needed. Even if the area covered by old forest and protected forest is increasing, the conservation status of many forest species is inadequate and many of these are threatened. The quality and scope of measures to counter loss of habitat and fragmentation must increase, so that biodiversity values are sustained on a landscape scale. Initiatives are taking place to improve environmental considerations in connection with felling. A comprehensive review of instruments is required, as is continued protection and increased application of forestry methods without clear-felling (SEPA 2015). Nature reserves and other forms of protection are essential, combined with voluntary set-asides of forest by landowners (SEPA, 2012). Forest areas may also need to be restored and managed in ways that enhance their multiple values. For instance, forests with large numbers of visitors, such as in peri-urban areas, may need to be managed properly to make them more attractive and accessible (SEPA, 2012). All in all, to achieve a balance between conserving and developing biodiversity and a range of ecosystem services, while still remaining competitive as timber and energy resource providers, is going to be a big challenge for forest planning and management in the future.

**Forest ecosystem services**

Forests provide a multitude of ecosystem services including the provision of industrial wood, bioenergy and habitat supporting biodiversity, recreation, carbon storage and so on. In Sweden, the goal to replace fossil fuels may lead to an increasing demand for bioenergy feedstock. This could induce substantial changes in the current management and use of forests. As pointed out by (Jasanoff and Jasonoff, 2003), new technologies bring unquestioned benefits but they also generate new uncertainties, failures and unforeseen consequences. The history of Swedish forestry shows that forest management and new techniques were for a long time driven mainly by economic concerns. In the 1990’s came changes in forest policy and legislation so that production and environmental goals were given equal priority, and lately climate change mitigation has become a major concern. All in all, forest management need to take a range of ecosystem services and biodiversity into account for reaching a sustainable development.
Forest industrial wood production

Today, forest management in Sweden is focused on production of industrial wood (sawlogs and pulpwood). In 2015, the industrial roundwood production from Sweden is 67.3 million m$^3$ which is among the highest in EC countries (Eurostat, 2017). Sweden is the world’s 3$^{rd}$ largest exporter of pulp, paper and sawn timber. In 2016, 80% of the total products were exported. The export value was about 125 billion SEK. Around 70,000 employees were working in forestry in 2016 (Industries, 2017).

Forest bioenergy

Energy consumption has shifted from fossil fuel to renewables, especially biomass due to climate change mitigation. To limit the increase in temperature to well below 2 degrees Celsius according to the Paris Agreement (UNFCCC, 2015), emissions of greenhouse gases (GHG) worldwide need to be halved by 2050 and to be close to zero by 2100 (IPCC, 2014), which puts high expectations on renewable energy sources. According to the EU Directive on Renewable Energy 2009/28/EC (EU, 2009), 20% of the energy consumption in the European Union should come from renewable energy sources by the year 2020. All EU countries must also ensure that at least 10% of their transport fuels come from renewable sources by 2020. Furthermore, in the EU Energy Roadmap 2050, renewables would be dominating among energy sources for the EU countries in the future, according to the scenario analyses (EC, 2011a).

In the past decades, policies for climate change mitigation as well as for other environmental issues have been formulated in Sweden, such as promoting the development of renewable energy sources in order to replace fossil fuels. Moreover, the Swedish government proclaimed a target of 49% renewable energy sources to be reached by 2020 (EU, 2009), while in the Swedish National Renewable Energy Action Plan, the ambitions concerning renewable energy sources were raised to 50% of the final energy consumption (Government_Offices, 2010). According to the plan, biomass will contribute 59.2% of the total renewable energy consumption in 2020 which equals to 30% of the final energy consumption. In addition, the Swedish Parliament has declared that the vehicle fleet should be independent of fossil fuels by 2030 (IEA, 2014) and adopted a vision for Sweden of zero net emissions of greenhouse gases by 2050 (Ministry_of_the_Environment_Sweden, 2014).

Forest carbon storage

Carbon storage in forest biomass is an essential attribute of forest ecosystems, and forests play an important role in carbon storage for mitigating climate change (Pan et al., 2011, Canadell and Raupach, 2008).

However, changes in forest cover have been net sources instead of as sinks of carbon dioxide to the atmosphere globally (Brown,
Changes in the amount of forest carbon storage can result from a variety of human and natural influences. Depending on different forest management practices, such as clear-cut harvesting, regeneration, the net carbon storage will be dynamically increase or decrease.

The measuring of carbon in forests is required by the UNFCCC, and landuse changes and forestry are sectors within which national inventories of sources and sinks of CO2 should be performed (Brown, 2002). For carbon storage in forest biomass, the calculations are normally divided into five components: aboveground biomass, belowground (root) biomass, dead woody biomass, and forest floor litter and soil organic carbon (Nave et al., 2010, Brown, 2002). In this thesis, we focused on storage in the whole tree (aboveground and belowground biomass).

**Forest recreation**

Forests provide a multitude of ecosystem services beside industrial wood, bioenergy and habitat supporting biodiversity; such as cultural ecosystem services including recreation, aesthetics and cultural heritage (Sonntag-Öström et al., 2014, Fredman and Tyrväinen, 2010, Milligan and Bingley, 2007). Outdoor and leisure activities in forest could be hunting and fishing, bird-watching, picnicking, berry and mushroom picking, and camping as well as activities such as orientation, running, walking, biking, riding and skiing.

Hansen and Malmaeus (2016) showed that doing activities in nature could improve human health (Norman et al., 2010a, Hansen and Malmaeus, 2016). According to these authors, it helps to reduce the risk of depression and release anxiety, while the chance to avoid getting infections will also be increased. The study is also showing that walking in forests can help to decrease pulse and blood pressure; and, according to the authors, the amount of stress hormones in the blood declines considerably (Norling and Larsson, 2004). Other studies show that walking in urban areas may have beneficial effects on the blood pressure (Hansen and Malmaeus, 2016, Hartig, 2003).

Recreation has been well recognised as one of the most important forest ecosystem services. So it is very important to take into account the recreation value when designing forest management plans. Changes in forest characteristics may affect the recreational value of a forest (Ode and Miller, 2011, Filyushkina et al., 2017). (Filyushkina et al., 2017) found that mixed tree species and stands with trees of varying height are preferred. In addition, variation between stands was found to contribute positively to the recreation value. (Lupp et al., 2016) asked forest visitors about their most favorite thing about the forest. Most interviewees mentioned the natural features and the diversity of the forest are the most attractiveness of forests for recreation, while noise was disliked the most. Gamfeldt et al. (2013) reported that tree species richness in production forests has positive relationships with multiple ecosystem services including recreational value. According
to several studies (Sonntag-Oström et al., 2014; Mattsson and Li, 1994; Norman et al., 2010b), mature forest seems to be linked to high recreation values.

**Forest biodiversity**

Bioenergy from forest biomass mainly consists of residues from timber harvesting, in the form of tops, branches, stumps and small stems. The forest is normally managed by clear-cutting and re-plantation, which can be called even-aged forestry (EAF). Of forest management regimes, even-aged forestry has been viewed as having the most negative impacts on biodiversity and the environment (e.g. McDermott et al., 2010). The habitat degradation that results from this type of industrial forestry is to a high degree related to the simplification of forest structure and composition that is part of the ordinary forest management (Smith et al., 1997), which impact on biodiversity and ecosystem services (e.g. (Lindenmayer and Franklin, 2002); (Puettmann et al., 2009a); (Thompson et al., 2011).

The negative impact of current forest management regimes on biodiversity has been highlighted by the Convention on Biological Diversity (CBD, 2010), and is also highly relevant from a European perspective, including the EU Habitats and Birds Directives (Directive 79/409/EEC and 92/43/EEC). Among European forest types, old growth natural and semi-natural forests are seen as the most valuable in terms of storing biodiversity, while unsustainable forest management and fragmentation are among the major threats to Europe's forest biodiversity. Thus, due to a long history of industrial forestry for timber and pulp production in Sweden and large parts of northern Europe, production forests have become more even-aged and much less structurally diverse than natural forests. Amounts of dead wood, old trees and other properties of importance to biodiversity are much lower compared with natural forest landscapes (Peterken, 1996, Fridman and Walheim, 2000, Josefsson and Östlund, 2011). Additional impacts may emerge from the extraction of branches, tops and stumps especially from broadleaved tree species, which may increase the threat of extinction of some red-listed wood-living species (e.g. (Hedin et al., 2008); (Jonsell, 2007); (de Jong et al., 2014a). As a consequence, the intensive forest management has caused decreased habitat quality, quantity and connectivity and a loss in biodiversity (e.g. (Berg et al., 1994a); (Siitonen, 2001); (Grove, 2002); (Niemelä et al., 2007). Therefore, from a biodiversity perspective, land zoning strategies in forestry may be an important complement to protected areas.

Intensive forestry aims at enhancing provisioning ecosystem services to increase the production of woody biomass. This can involve, to different extents, use of fertilisers, improved genetic material, introduction of exotic tree species, use of fast-growing deciduous trees and shorter rotation times (Lidskog et al., 2013a). These practices are currently not allowed on a large scale by Swedish legislation, but their possibilities for increased wood
production and associated environmental risks were investigated by (Larsson et al., 2009a), commissioned by the Swedish Government. According to this and several other authors, intensive forestry could result in further simplification of managed stands and high risk of reducing other ecosystem services (Gustafsson et al., 2012a); (Smith et al., 1997); (Thompson et al., 2011). Also impacts on biodiversity could be anticipated, since important ecological properties of the forest such as the volume of dead wood, that provides habitat for many species, and the connectivity on stand and landscape level, would be negatively affected by intensified forestry (e.g. Ranius and Roberge, 2011).

**Trade-off analysis**

Despite the already intensive forest management for timber and pulp extraction, the incentives for increasing green electricity and biofuels may lead to even more intensified forest management. An increasing demand for forest biomass may call for new forest management practices to increase the supply in Sweden (Larsson et al., 2009b, Lidskog et al., 2013b). Intensified forestry could increase the biomass production through planting of monocultures of native or introduced tree species, forest fertilization and application of shorter rotation times. This may, if not wisely planned, have detrimental impacts on other ecosystem services, among those carbon storage, recreation values, and habitat supporting biodiversity. So, there are trade-offs to be made between all these ecosystem services since it may not be possible to increase the supply of one ecosystem service without affecting some other ecosystem service negatively.

For instance, industrial forestry has been identified as a major cause of depletion of forest biodiversity, mainly due to the simplification of forest structure and the loss of old trees and dead wood (Berg et al., 1994b, Puettmann et al., 2009b, EEA, 2010b, Thompson et al., 2011), even if plans and actions are carried out to protect biodiversity (Eriksson et al., 2015). Intensified forestry resulting from increasing demand for industrial wood and bioenergy feedstock is expected to have negative impacts on biodiversity by reducing habitat size and connectivity in forest landscapes (Larsson et al., 2009b, Ranius and Roberge, 2011, Hanski, 2011). Further impacts (positive and negative) may result from increased extraction of forest residues for bioenergy (de Jong and Dahlberg, 2017, Hedin et al., 2008). Still, unsustainable forest management and fragmentation are among the major threats to Europe's forest biodiversity (EEA, 2010a).

Even if such trade-offs are seldom analysed in energy assessments (Pang et al., 2014), assessment of ecosystem services is currently a rapidly growing area of research. Depending on the ecosystem service in focus and the geographical scale, different models and techniques have been used. Many assessment initiatives have been large scale, e.g. global (the Millennium Ecosystem Assessment; (MEA, 2005) or European (the RUBICODE project; (Vandewalle et al., 2009), and may provide important information for policy
and decision making on international level, but there is a need for studies that can support decision making on national, regional and local level (Burkhard et al., 2010).

Although the research on forest ecosystem services have kept growing, the trade-offs between services are still poorly understood (Filyushkina et al., 2016). Currently, most trade-off analysis on forest ecosystem services are focused on comparison of two ecosystem services, such as the conflict between bioenergy extraction and carbon stock (Bottalico et al., 2016, Hoel and Sletten, 2016). Many studies provide biophysical mapping of ecosystem services, i.e. descriptions of the present state, but with no projections of possible future trends or with projections based on historical trends or simplified assumptions on future development. In a few studies, development of multiple ecosystem services and trade-offs among them have been projected over time (Forsius et al., 2015, Verkerk et al., 2014). However, some ecosystem services have a spatial component and have to be considered in a landscape context, such as the spatial distribution of habitat for species and of recreation areas for people. Most assessments of ecosystem services conducted so far have not included such spatial aspects, so a critical issue is thus to develop models that enable projections of the development of different ecosystem services on landscape level as a function of the forest management.

A range of policy analysis tools exist for analysing the energy system, linking energy supply and/or demand, some to economy and some to certain environmental impacts, particularly regarding air quality and climate change (EC, 2011a, Fragkos et al., 2013, Klimont et al., 2013, Reis et al., 2012, Wagner et al., 2013), as well as to resource use and emissions (Felten et al., 2013, Stow et al., 2012). However, existing analytical tools within the energy sector mainly deal with environmental impacts related to emissions, while tools for analysing impacts on ecosystems and landscapes are largely missing (Finnveden et al., 2003). At the same time, tools that address biodiversity, ecosystems and landscapes relative to e.g. land use change are common, with a great potential for analysing such interactions (Alkemade et al., 2009, Gontier et al., 2006, González del Campo, 2012, Mörtberg et al., 2007, Segan et al., 2011, Zetterberg et al., 2010). Such models have a spatial dimension and can therefore localise and quantify impacts of land use change, imposed by e.g. renewable energy plantations and infrastructure, on biodiversity and ecosystems on landscape and regional levels. Linking such models will make it possible to bridge energy-environmental assessment gaps concerning renewables.

**Energy models and environmental assessment (Paper I)**

The literature review of Paper I embraced available methods and tools for integrated assessment of renewable energy options, as summarised here.
**Missing links between energy models and environmental assessment**

Energy models, that are designed for analysing the energy system with links to energy supply and/or demand, some to economy and/or certain environmental impacts, especially concerning air quality and climate change evaluation (Fragkos et al., 2013; Wagner et al., 2013); were found widely used as decision support tools. For instance, TIMES is an economy related energy model which is used for scenario analysis of local, national or regional energy systems (Loulou and Labriet, 2007), while GAINS is an emission related energy model (EC, 2011b). In the EU Energy Roadmap 2050, the Global Biomass Optimization Model (GLOBIOM) was used together with the G4M model for analysis of wood demand, emissions from forest and agricultural land and land use changes (EC, 2011b). The General equilibrium model (GEM-E3) has been used by EU for social impact analysis, such as employment (EC, 2011b).

Several models for landscape simulation have been developed, for forests across landscapes and consequences on different sustainability issues, such as (de Bruijn et al., 2014; Garman, 2004; Hernandez et al., 2014; Mehta et al., 2004; Chumachenko et al., 2003; Gustafson et al., 2006, Haatanen et al., 2014; Lindner et al., 2010; Wikström et al., 2011). Other types of models relate to whole landscapes development and the ecological consequences, such as (Deal and Pallathucheril, 2009; Eastman, 2012; Hepinstall-Cymerman et al., 2009; Walz, 2015).

Furthermore, ecological assessment models that have a spatial dimension can localize and quantify impacts of land use change on biodiversity and ecosystems, such as (Gontier et al., 2006; Mörtberg et al., 2007; Zetterberg et al., 2010; Alkemade et al., 2009; Moilanen, 2007; Segan et al., 2011). In addition, models that analyse ecological networks based on graph theory can address quantitatively habitat networks (Saura et al., 2011; Saura and Rubio, 2010; Zetterberg et al., 2010; Urban et al., 2009; Dale and Fortin, 2010). These have been used for addressing forest management planning (Saura et al., 2011) and integrated sustainability assessment.

**Overview of energy related models**

The survey on publications on energy models in the Scopus database (Paper I) showed that energy related models were very much focusing on climate change issues compared with other environmental issues (Figure 7). The links with biodiversity and landscapes were more scarce.
The results of the survey on journal papers are illustrated in Figure 8. Energy model based research papers related to biodiversity were very few and seemed to have just started in recent years.

When combining the results of the reviews it was found that climate factors were the main focus of the models. Looking into a single model, it could be seen that most of the now-existing energy models for policy assessment are not designed for integrated analysis and mostly focus on economy and GHG emission topics. Landscapes and biodiversity issues were largely neglected while integrating land use issues was a minor but growing field.

Models for energy system analysis and models for ecological systems analysis were found rather isolated from each other and not very well integrated. Thus, to achieve a comprehensive policy assessment, model integration which can fully cover crucial environmental factors, especially biodiversity, landscapes and related land use issues, are required.
Trade-off analysis among ecosystem services (Papers II and III)

In response to the gap between energy policies and related energy assessment models, and tools for addressing forest ecosystem services, Papers II and Paper III aimed at developing relevant tools for integrated sustainability assessment including an array of ecosystem services across landscapes.

Bioenergy feedstock

According to the forest growth simulations and estimation of their consequences, the bioenergy feedstock was projected to develop as in Figure 9 (Paper II) in the County of Kronoberg. In the CCF-int scenario, the production would be considerably lower than that of the EAF-tot scenario.

\[\text{Figure 9: Bioenergy feedstock in the EAF-tot and the CCF-int scenarios 2010-2110.}\]

Impacts on habitat networks

The ECA of coniferous forest habitats in the CCF-int scenario was higher than those in the EAF-tot scenarios (Figure 10). There would ideally be more and more old trees being left under the CCF scenario due to the restrictions on clear-cuts within these areas, which result in that the ECA index kept growing with time, until 27% of the landscape was under CCF management. For the assumption of “all area under CCF is suitable as habitat”, which means that old trees are left throughout, the ECA is much higher than using other CCF scenario assumptions such as “50% of the forest managed with CCF is suitable as habitat”. The ECA was
even lower with the assumption that “25% of the forest under CCF management is suitable as habitat”.

The forest management under EAF followed the circle of clear-cutting, regeneration, cleaning, thinning, and again clear-cutting; and therefore, areas with suitable habitat would not increase but shrink considerably during the simulation period. It seemed to be slightly better if the forest was harvested with 5% retention (EAF-tot/r). However, since there was a random component in the spatial allocation of retention areas, these results are highly uncertain. It would be big difference if the retention areas would be arranged to support existing habitat patches compared to if they were scattered throughout the landscape.

The size of the indicator species’ home range seemed to make a difference for the resulting ECA. As shown in Figure 10, when there was a high total amount of habitat resources, species which had a larger home range seemed to have higher ECA. By contrast, with limited habitat resources, species with smaller home ranges seemed to easier find available habitat (measured as ECA). However, since there was a random component in the spatial allocation of suitable habitat, further uncertainty analyses would be necessary in order to draw conclusions about this.

Southern broadleaved forest is more scarce in the landscape today, compared with coniferous forest. The relatively smaller total habitat amount and lower connectivity had the consequence that the ECAs were much smaller (Figure 11). The results tell a similar story as the development of coniferous habitats, when it comes to home range size.

**Figure 10:** ECA of coniferous forest habitats in the EAF-tot and CCF-int scenarios (2010-2110).

Southern broadleaved forest is more scarce in the landscape today, compared with coniferous forest. The relatively smaller total habitat amount and lower connectivity had the consequence that the ECAs were much smaller (Figure 11). The results tell a similar story as the development of coniferous habitats, when it comes to home range size.
The results showed that when applying the CCF-int scenario, the forest bioenergy feedstock will probably be about 30% lower than that of the EAF-tot scenario, but the habitat networks for both model species would be improved significantly. This would be especially so if the CCF is applied so that old trees with dead wood are retained throughout the landscape, thus constituting suitable habitat. If only a minor part of the area under CCF is suitable habitat, such as 25%, the advantage of the CCF-int scenario for the habitat networks seems to be much smaller and the spatial allocation of the suitable habitat will be more crucial.

When joining the bioenergy feedstock and ECA result data together, one can see the trade-offs between bioenergy and habitat networks in the two scenarios (Figures 12a and 12b). When forests are managed intensively as in the EAF-tot scenario, bioenergy yield can be much higher with the trade-off of less ECA of habitat networks, comparing with if the forests are managed as in the CCF-int scenario.
Trade-off analysis among five ecosystem services

The projections for the five ecosystem services (Paper III) were compared with the situation for year 2010, the base year for the assessment, and the increase or decrease in percentages are shown in Figure 13. In the EAF-tot scenario, the output from the forest resource was dominated by industrial wood, bioenergy feedstock production and, to some extent, carbon stock. Available habitat of the habitat networks, as measured by ECA (Paper II, illustrated by
Figures 10, 11 and 12), was predicted to follow a negative trend and would most probably be very low following this development (Figure 12a). In the CCF-int scenario, the production of timber, pulpwood and bioenergy feedstock were not as high as in the EAF-tot scenario, but the other ecosystem services assessed showed positive development over time and there seems to be a synergy between these services. Especially for habitat networks, the increase was large from 2050 and onwards compared with the base year 2010 (Figure 12b).

Figure 13a: Trade-offs and synergies in the EAF-tot scenario 2010-2110 (% of year 2010 values).

Figure 13b: Trade-offs and synergies in the CCF-int scenario 2010-2110 (% of year 2010 values).
Spatial optimization (Paper IV)

In this paper we present two heuristic methods for spatial optimization, simulated annealing (SA) and genetic algorithm (GA), through a case study. The optima found through each of the two heuristic techniques were compared, together with the performance of the associated computing processes. The results showed that both methods functioned well for the optimization analysis, but GA performed better in both finding the best fitness and the model-run time for this case study. For spatial planning problems that aim to take both habitat size and connectivity into account, it could be beneficial to use GA which performs more efficiently using group solution comparisons, rather than the pairwise comparisons used by SA. The use of these optimization techniques could be an effective means for integrating landscape-level biodiversity targets and thus achieving a more sustainable forest management.

Table 5: Best optimum from using SA and GA together with the average run time of the simulation.

<table>
<thead>
<tr>
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<th>Best optimum</th>
<th>Average execution time</th>
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<tbody>
<tr>
<td>SA</td>
<td><img src="image" alt="SA Image" /></td>
<td>2237 seconds</td>
</tr>
<tr>
<td></td>
<td>0: no activity (65 cells)</td>
<td></td>
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<tr>
<td></td>
<td>1: thinning (19 cells)</td>
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<tr>
<td></td>
<td>2: clear-cutting (36 cells)</td>
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<td></td>
<td>MaxECA' = 17.7 km²</td>
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<tr>
<td></td>
<td>Harvest = 29263 m³</td>
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<tr>
<td></td>
<td>TotSuit = 88 km²</td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td><img src="image" alt="GA Image" /></td>
<td>49 seconds</td>
</tr>
<tr>
<td></td>
<td>0: no activity (73 cells)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1: thinning (9 cells)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2: clear-cutting (38 cells)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MaxECA' = 18.1 km²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harvest = 29115 m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TotSuit = 78 km²</td>
<td></td>
</tr>
</tbody>
</table>

Heuristic methods, including SA and GA, are not designed for finding the absolute best optimum but to find a better solution, so it is important to run the model many times and check the best
result. We did 20 model runs with each of the heuristic techniques. By using GA, the model found a best optimum of 18.1 km² (MaxECA*). The value was higher than the best optimum of 17.7 km² that was found by SA. When it comes to execution time, GA showed to be much more efficient and faster to find optima, while SA may take rather long time for each model run (Table 5). Further analyses will be needed, but the results are promising for using spatial optimisation as a tool for scenario testing of habitat networks in integrated sustainability assessment of policy and planning alternatives.

**Linking the energy model MESSAGE with the LEcA tool (Paper V)**

The MESSAGE model (IAEA, 2007) estimates the forest biomass supply that will be needed for bioenergy purposes in the two scenarios for Lithuania, Biomass Low and Biomass High (Figure 14). Both scenarios represent the possible Lithuanian energy sector development which correlates well with the current European Union energy policy, and the country’s energy is oriented towards the widest possible integration into the international energy markets and the optimal use of the country’s energy infrastructure. The differences between the scenarios are in wood biomass price projections and assumed wood biomass availability for centralized energy production purposes.

![Figure 14: Energy demands (results from MESSAGE).](image)

**Environmental restrictions concerning soils**

There are environmental restrictions on forest residues extraction in Lithuania, aiming to minimize soil-related damages on forest ecosystems. For poor soil, the objective is to maintain the natural fertility. For soil with slope more than 15 degrees, remaining cutting residues are supposed to make such soil stable. For eroded soils, the aim is to minimize the erosion process. For moist soil, the objective is to minimize the damage to the soil. For organic soil, extraction is not allowed due to both damage avoidance and maintaining the property (Lithuanian State Forest Service, 2010).
Transport restrictions

There are also limitations on extraction distances to the demand nodes. Economically, 1 km extraction distance to collection spot is suggested. If more forest biomass is required, then from a political point of view, 3 km could be possible. The distance from the collection spot to a CHP plant or equivalent could be 10-30 km. In this study, we created a buffer zone area of 30 km to CHPs and 1 km extraction distance representing the transportation restrictions (Figure 15). It was used as the mask for residues extraction.

Figure 15: Forest residues extraction areas around CHP plants and alike, with transportation restrictions. Coordinate system LKS_1994_Lithuania_TM, spatial data State Forest Survey Service (2016).

Forest bioenergy demand vs supply

We made two assumptions in this scenario. Logging residues and stumps were considered as fully used for bioenergy, although in reality stumps are not in use in Lithuania. In Assumption Set 1, 10% of the harvested volume was accounted as biomass from industrial waste, and in Assumption Set 2, it was 15%. For firewood biomass, in Assumption Set 1, around 6% of the harvested volume was accounted, and it was 25% for Assumption Set 2. The proportions for Assumption Set 1 were based on “schoolbook” example, while the proportions for Assumption Set 2 were calculated after consulting the empirical data from forest statistics for Lithuania (State Forest Service, 2016).

When comparing the bioenergy feedstock supply estimated with the LEcA tool, with the demand as expressed in the energy scenarios Biomass Low and Biomass High, it can be seen that the predicted demand would not be fulfilled by the supply using a
business-as-usual forest management strategy (Figure 16). Also when the extraction options were exhausted, apart from using industrial wood, the demand would not be met.

With environmental restrictions related to soils and Assumption Set 1, 76% of the demand projected by the Biomass Low scenario would be met. When the transport restriction was applied, 43% of the demand could be fulfilled. Likewise, for the Biomass High scenario, 60% of the demand projected by the MESSAGE model would be met. If the transport restriction was applied, 34% of the demand could be fulfilled.

When applying environmental restrictions related to soils and Assumption Set 2, 121% of the demand projected by the Biomass Low scenario would be met. With transport restrictions, 88% of the demand could be fulfilled. Likewise, for the Biomass High scenario, 96% of the demand projected by the MESSAGE model would be met. With transport restriction, 70% of the demand could be fulfilled. If stumps were not considered, the number will be even lower, respectively (see Table 6, based on the results shown in Figures 16 and 17).

**Table 6: Comparison of the LEcA results with the MESSAGE projections. TR means transport restrictions.**

<table>
<thead>
<tr>
<th>Forest bioenergy feedstock available with environmental restrictions</th>
<th>Assumption set 1</th>
<th>Assumption set 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bio_High</td>
<td>Bio_Low</td>
</tr>
<tr>
<td>Full use of biomass feedstock:</td>
<td>60%</td>
<td>76%</td>
</tr>
<tr>
<td>Without stumps:</td>
<td>39%</td>
<td>50%</td>
</tr>
<tr>
<td>Full use with TR:</td>
<td>34%</td>
<td>43%</td>
</tr>
<tr>
<td>With TR without stumps:</td>
<td>28%</td>
<td>36%</td>
</tr>
</tbody>
</table>
Figure 16: Comparison of the demand for forest bioenergy feedstock according to the MESSAGE scenarios, versus the supply according to the LEcA tool simulation and estimations. Two Assumption Sets were applied for estimating the share of industrial waste and firewood. However, the residues were the same in both Assumption Sets.
Final discussion

The increasing demand for biomass for bioenergy and other purposes in Sweden need careful and multi-disciplinary sustainability assessment. Despite the already intensive forest management for the supply of domestically produced bioenergy, the increasing demand may imply new forest management practices to increase the feedstock supply for producing more bioenergy in Sweden. However, forest bioenergy comes with environmental impacts and related potential goal conflicts that need to be taken into account in policy and planning (de Jong et al., 2014b). All the papers (I-V) of this thesis addressed the need for integrated sustainability assessment of forest and energy policy options, while developing relevant methods for the task. Points of the final discussion embrace the habitat network modelling, the spatial optimization and the integrated sustainability assessment modelling.

**Habitat network modelling**

For the habitat network modelling, habitat patches were represented as a set of nodes with different size, while habitat connections were represented as links with different connection probabilities (Figure 18).

![Figure 17: Forest residues available with and without transport restriction.](image)
The ECA index that was used for the habitat network assessment is based on graph theory and is defined as the size of a single habitat patch that would provide the same value of the probability of connectivity as the actual habitat pattern in the landscape (Saura et al., 2010b). In this way, the impacts of habitat patch size together with connectivity can be quantified, and the higher the values of the ECA index, the more robust would the habitat network be.

The idea of habitat networks being described by habitat patches of certain sizes, and connectivity between those, is of course highly simplified. For instance, the habitat patches were defined from classified raster data with limited information about habitat quality. Factors that would not be well represented by this model include for instance soil quality, climatic conditions and changes, heterogeneity within patches and among different trees, natural disturbances, human interventions, etc. However, for modelling purposes, a set of assumptions were made:

1. The soil quality would be similar across the study area,
2. The climate would be uniform across the study area,
3. Trees in the same stand would initially be homogeneous in all properties,
4. No natural disturbances would take place within the study area, and
5. No anthropogenic disturbances (other than forest management) would take place within the study area.

Factors such as soil fertility, local climate and wetness may though impact on tree growth and availability of organic resources for different species. Such factors could be better integrated in further development of the model, following improved overall knowledge of habitat demands as well as available data. On a detailed scale, trees in the same stand may have different properties, and in particular, improved data on important habitat features such as amount of old trees and dead wood, moisture and fertility gradients, as well as their relation to the long-term persistence of populations of different species on a landscape level, would be highly useful. In addition, the harvesting or not harvesting of residues in the form of tops, branches and stumps could also be spatially modelled as a part of relevant habitat networks.

When it comes to natural disturbances, for instance fire or snowstorm and their impacts on forest habitats, have been widely

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**Figure 18: A model of the ECA index, representing a habitat network.**
studied (Thom and Seidl, 2015, Börger and Nudds, 2014, Nguon and Kulakowski, 2013). From the point of view of natural disturbances, the risk for destruction of habitat networks may even be lower when two geographically isolated habitat networks are promoted, compared to one highly connected with a higher overall ECA. In this context, the idea of a higher ECA always representing a more robust habitat network can be questioned. Still, natural disturbances were not taken into account in the habitat network modelling, since those would be very difficult to predict.

Other types of disturbances come from direct human activities, which also impact on the habitat networks. One dominating human activity is forest management, which was accounted for in the landscape scale simulations of forest growth and management. In addition, the recreation area indicator, which would need further developed in itself, may also represent possible disturbances that may affect the habitat suitability for sensitive species.

Thus, a consequence of the applied assumptions is that several properties that matters in real forest habitat networks will not be represented in the applied modelling. So, Equation 4 is realistic only if the real world would have the same properties as illustrated by Figure 18. However, the applied models still give a good overview of important impacts of forest harvesting patterns on habitat network changes. To pursue a very detailed representation of habitat may not always be desired, since it may render models that are too data-demanding and complicated to be used for integrated sustainability assessment.

Another interesting property of habitat networks is it’s relation to the total habitat amount in the landscape. As shown already by Andrén (1994) when the total amount of habitat in the landscape declines to below 25-30%, the habitat fragmentation start increasing drastically if a random distribution is applied. This is in line with the results of Paper II, where the assumption that even if the areas with CCF forest management is relatively well concentrated in the landscape, the ECA of the habitat networks would be considerably lower at 25% suitable habitat of the areas where CCF is applied, compared to 50% and 100%. Insights gained from the modelling exercise would be that 1) the way CCF is applied will matter, i.e. whether and to which extent mature and old trees with dead wood are kept, and 2) the less total habitat amount in the landscape, the more important is the spatial configuration of habitat, i.e. whether it is scattered or not in the landscape.

Furthermore, the choice of indicative species should be expanded to embrace a suite of relevant biodiversity components, sensitive to the studied forest management scenarios applied. In addition, more knowledge on species’ demands on their landscapes is needed, not only the range of parameters for habitat quality, quantity and connectivity for modelling their habitat networks, but
also thresholds for the persistence of populations in the landscape (e.g. Mörtberg et al. 2012). In this way, impacts on habitat networks supporting important biodiversity components could be well represented in policy and planning.

**Spatial optimization**

Involving habitat networks into forest management is an important issue for forest biodiversity on landscape scale and the two heuristic techniques SA and GA can help with non-linear spatial optimization for the planning of sustainable forest management. In this case study, GA showed better performance than SA. Yet it might be misleading to say that GA definitely outperforms SA in this field of problems, because the performance is very much related to how the parameters are set for each of the algorithms. An effective cooling schedule of SA is essential to reduce the amount of time required for finding an optimal solution (Cardoso et al., 1994, Cohn and Fielding, 1999, Fox, 1993, Nourani and Andresen, 1998, Henderson et al., 2003, Romeo and Sangiovanni-Vincentelli, 1991). Parameters that may affect the results of GA include population parameters, reproduction parameters, constraints parameters and stopping criteria (Sastry et al., 2014).

However the comparison and application of the two techniques in forest management planning need to be further explored. With the help of parallel computing, more detailed spatial optimization over larger areas will be possible. This will enhance the possibilities to plan for supporting habitat networks with high connectivity (measured as ECA), in each time step of the scenarios assessed. An additional, related question concerns land ownership when it comes to spatial optimization of habitat networks, and if and how optimised forest management planning can be applied in a real world situation. This question was out of scope of this thesis, but is well worth exploring.

**Integrated sustainability assessment of forest management options**

There are of course shortcomings in the landscape simulations, bioenergy feedstock estimations and habitat network assessments which need to be improved. In addition, to arrive at an integrated sustainability assessment, other forest ecosystem services should be involved besides those addressed here.

The growth-model in the present application of LandSim was probably overestimating the increment in the area and the management programs used were probably not fully realistic. For instance, tree retention on smaller scale was not represented in the model. However, very few of the optional models (e.g. Chumachenko et al.; Gustafson et al. 2006; Wikström et al. 2011), if any, could work on an area-covering basis over such large areas, using probability-based forest growth and management information, and adapted to ecosystem services assessment. Since our system was based on the kNN/SMD data set, it could be used for arbitrary areas in Sweden.
In addition, there are limitations in the applied biomass expansion functions which might affect the bioenergy feedstock calculations. For instance, the functions for predicting the expansion from stem volume into dry weight of each tree component by (Lehtonen et al., 2004) were developed using data from pine and spruce stands in Finland between 10 and 150 years of age with stem wood volumes less than 250 m$^3$/ha, and from broadleaved stands between 10 and 100 years of age and with stem wood volume less than 200 m$^3$/ha. Therefore, there might be a bias to the biomass estimation in younger trees and in areas which have higher stem wood volume.

Furthermore, the applied modelling framework did not yet account for the more detailed implications that the particular bioenergy-purpose biomass extraction, the forest residues, would have on ecological networks and forest biodiversity (e.g. de Jong et al. 2017). In order to improve biodiversity assessments, it would be interesting to integrate quantification and localisation of the forest residues, either harvested or left in the forest, as parts of habitat networks. Another important step would be to quantify the amount of dead wood that is generated by different management regimes. It is possible that, for instance, CCF can be developed in different directions, taking more or less account of this and other factors that are important for biodiversity conservation.

A strong side of our approach was that we could indeed illustrate the trade-offs between the different dimensions focused by various potential interest groups. This study applied a quantitative prediction tool for biodiversity assessment in terms of habitat network changes on a landscape level. The linking of this tool with scenario simulations can thereby be considered to fill a gap as pointed out by Gontier et al. (2006) that the biodiversity assessment remained on a descriptive level due to lack of quantitative ready-to-use methodologies. Thus, the LEcA tool enables a multi-disciplinary assessment, and can be further developed in several ways. A range of habitat networks can be applied, including combinations of forest and other habitat types, representing a wider array of relevant biodiversity components. Likewise, several parameters for better representing recreation values can be applied, such as forest volume combined with tree species, proximity to water, and other. Both habitat networks and recreation areas can be spatially optimised for efficient landscape level planning. In this way, the LEcA tool has great potential for integrated sustainability assessment of forest bioenergy and forest management policies.

**Concluding remarks and future research**

The thesis shows a theoretical approach for how to link forest development with the change of habitat networks and other ecosystem services. From the results one can see that different forest management strategies would have different impacts on long-term potential biomass extraction and ecosystem services; and that the impacts change over time. The LEcA tool has great
potential for evaluation of impacts of different alternative policies and plans for land zoning and forest management regimes on bioenergy supply and other ecosystem services. It can help to find the best solutions among alternatives by comparing different strategies, but may in its current state not be efficient to find a best design only from theoretical ideas. The design problem can be addressed through optimisation, which can be useful for forest planning. It can also be concluded that the impact analysis of forest management planning on biodiversity was restricted by the development of fundamental knowledge such as model species selection, definitions of habitat suitability and home range size, as well as thresholds for species’ persistence in the landscape. Along with improvements in related research, in the future, more precise and well-informed methods which can deal with complicated multi-objective forest planning can be expected.

The multiple functions of forests’ provision of different ecosystem services rather than only biomass production is getting more and more attention. The pressure on management plans to meet various economical, ecological, social and environmental requirements is increasing. Since different ecosystem services may compete with or complement each other, it is hard to foresee the trade-offs and synergies. Another uncertainty concerns the spatial dimension of the forest planning. Where, when and how much to harvest has great impact on the shape and connectivity of wildlife habitats. A problem is that different land-owners may have different size and amount of valuable habitat on their land. If they take responsibility for their part, the economic draw-backs may be substantial and most probably unequally shared between land-owners. Apart from that, technology has developed to optimize the spatial planning of forestry, such as mathematical optimization techniques, simulation techniques and meta-heuristic techniques, but they all have advantages and disadvantages. A flexible and efficient method is still missing. The complexity of integrating the multiple objectives of forestry in land zoning and planning of forest management makes it a difficult issue for decision-makers.

To achieve a sustainable forest management as well as meeting climate and energy goals, the ecosystem services and biodiversity values of a forest should be fully considered and equally treated. From our research, concurrent energy-related models seem very well developed regarding the economic benefits and climate change mitigation factors. As forests are viewed as one of the renewable energy resources to replace fossil fuels, the possible threats to biodiversity, recreation and other ecosystem services are largely neglected by the currently used energy-related models. We attempted in our research to show that models for evaluating different ecosystem services can be linked together to do comprehensive and integrated analyses for sustainable land zoning strategies and planning of forest management.

The LEcA tool and the linking of the MESSAGE energy model allow for new insights concerning implications of the EU renewable energy policies in different scenarios:
• Spatial analysis using GIS as part of the LEcA tool enable detailed national and landscape level sustainability assessments
• Forest growth and management can be simulated in a way that allows ecosystem services to be assessed
• Demand for forest biomass as bioenergy feedstock can steer the forest management
• Multiple ecosystem services provided by the forest can be analysed and assessed together
• The results can be fed back to energy policy making as well as planning

Addressing main sustainability challenges and renewable energy targets, insights could be gained on trade-offs and synergies between ecosystem services, in integrated sustainability assessment of forest bioenergy options.

Future efforts will be put on large scale repetitions of random runs as well as spatial optimization by using parallel computing with help of super computers. For recreational evaluation, distance to facilities and population parameters will be taken into consideration.

For habitat network assessment, different specific indicator species and ranges of related parameters will be used and combined, regarding to different forest characters, for a more integrated forest biodiversity analysis. For linking with energy models, impact analysis on other ecosystem services will be added.
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