

Dissertationes Forestales 197

**Assessing impacts of intensified biomass removal and
biodiversity protection on European forests**

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Academic dissertation

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ABSTRACT

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Forests provide many benefits to society and it is important to understand if, and how, policies affect the provisioning of ecosystem services. The objective of this dissertation was to analyze and evaluate impacts of intensified biomass production and biodiversity protection on ecosystem services provided by European forests.

Article I assessed to what extent forests are protected and how felling restrictions affect the potential annual wood supply. Felling restrictions applied to currently protected forest areas reduce the long-term potential supply of wood by 35 million m³ yr⁻¹. Despite these restrictions, wood harvesting is allowed to a fair extent in these protected forests.

Articles II-V assessed the future woody biomass potentials and impacts of different scenarios on forests using the European Forest Information SCENario model (EFISCEN). In article II, the realisable woody biomass potential was estimated at 741 million m³ yr⁻¹ in 2010, including woody biomass from stems, residues, stumps and other biomass, ranging from 620 to 891 million m³ yr⁻¹ in 2030. Mobilising these potentials would imply drastic changes in the management of European forests.

According to articles III-V intensified biomass removals could involve trade-offs with other forest ecosystem services. Carbon storage in forest biomass, as well as the amount of deadwood, was projected to decline due to measures to intensify the use of forests. An economic valuation showed that intensifying biomass removals could lead to a net economic benefit measured by the aggregated value of five ecosystem services, as compared to projections without measures to intensify use of forest biomass. Larger social benefits could potentially be obtained if biodiversity protection is enhanced in European forests.

The results presented in this dissertation illustrate that careful planning is required to accommodate the need for protection of biodiversity, the expected growing demand for wood, as well as the provisioning of forest ecosystem services.

Keywords: ecosystem services, EFISCEN, scenario analysis

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Finally the moment is there that the preface of my dissertation can be written. This means that the work on my dissertation is soon completed, which is a liberating thought!

This academic dissertation is the result of work carried out during several years in various projects in which I have been involved as part of my work at the European Forest Institute (EFI). I would like to thank EFI and especially my supervisor Marcus Lindner for providing me the opportunity to work on these projects. I also would like to thank him for all the support he provided throughout the years. It has been a real pleasure to work with him. I also would like to thank all (current and former) colleagues in Joensuu and Barcelona that have made EFI an interesting place to work for almost 10 years now.

During my work on this dissertation I regularly met with my supervisor Timo Pukkala to discuss the progress on my dissertation. During these discussions I was always very optimistic that my dissertation would soon be completed, but it always took a bit longer. I would like to thank him for his patience and for all his smart comments on the manuscripts that I presented to him.

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Barcelona, 3 March 2015

LIST OF ORIGINAL ARTICLES

This doctoral thesis synthesizes the following five articles, which are referred to in the text by the Roman numerals I-V. The articles are reprinted here with the kind permission of the publishers.

- I Verkerk P.J., Zanchi G., Lindner M. (2014) Trade-offs between forest protection and wood supply in Europe. *Environmental Management* 53, 1085-1094.
<http://dx.doi.org/10.1007/s00267-014-0265-3>
- II Verkerk P.J., Anttila P., Eggers J., Lindner M., Asikainen A. (2011) The realisable potential supply of woody biomass from forests in the European Union. *Forest Ecology and Management* 261: 2007-2015.
<http://dx.doi.org/10.1016/j.foreco.2011.02.027>
- III Böttcher H., Verkerk P.J., Gusti M., Havlik P., Grassi G. (2012). Projection of the future EU forest CO₂ sink as affected by recent bioenergy policies using two advanced forest management models. *GCB Bioenergy* 4 (6): 773-783.
<http://dx.doi.org/10.1111/j.1757-1707.2011.01152.x>
- IV Verkerk P.J., Lindner M., Zanchi G., Zudin S. (2011) Assessing impacts of intensified biomass removal on deadwood in European forests. *Ecological Indicators* 11: 27-35.
<http://dx.doi.org/10.1016/j.ecolind.2009.04.004>
- V Verkerk P.J., Mavsar R., Giergiczny M., Lindner M., Edwards D., Schelhaas M.J. (2014) Assessing impacts of intensified biomass production and biodiversity protection on ecosystem services provided by European forests. *Ecosystem Services* 9, 155-165.
<http://dx.doi.org/10.1016/j.ecoser.2014.06.004>

Pieter Johannes Verkerk was primarily responsible for the study design, execution, analysis and writing of articles I, II, IV and V. The co-authors contributed to the development of the methods, they collected and processed data and/or they commented on the manuscripts of the articles. Article III was primarily led by Dr. Hannes Böttcher with major contributions by Pieter Johannes Verkerk to the study design, execution, analysis and writing of the article.

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ABBREVIATIONS

C	Carbon
CBD	Convention on Biological Diversity
CO ₂	Carbon dioxide
EC	European Commission
EU	European Union
EFI-GTM	European Forest Institute - Global Trade Model
EFISCEN	European Forest SCENario model
FAO	Food and Agriculture Organization of the United Nations
G4M	Global Forest Model
MCPFE	Ministerial Conference on the Protection of Forests in Europe
ob	Over bark
ub	Under bark
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change

COUNTRY NAMES

AT	Austria
BE	Belgium
BG	Bulgaria
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxembourg
LV	Latvia
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
UK	United Kingdom

1 INTRODUCTION

1.1 European forest resources

Land use is of great importance to humans as it provides critical natural resources, including food and fibre (Foley et al. 2005). Through changes in land use and harvest of biomass, humans currently appropriate about 30% of the potential, global net primary production annually (Haberl et al. 2007). Intensive land use practices have caused and are causing losses in biodiversity, for example through loss and degradation of habitats, pollution and overexploitation (Butchart et al. 2010; Pimm et al. 2014). Intensive land use practices are, however, not a recent phenomenon. Expansion of agricultural land combined with fuelwood harvesting have been linked to deforestation in many parts of the world over the last hundreds to thousands of years (Williams 2000).

Land use is particularly intensive in Europe (Haberl et al. 2007) and historical land use practices have also resulted in major losses of forest cover in this part of the world during the last centuries to millennia (Bradshaw 2004; Kaplan et al. 2009). Trends in forest cover change have reversed in Europe, however, and the forest area has been expanding during the 20th and 21st century (Kuusela 1994; Rudel et al. 2005; Gold et al. 2006; Rautiainen et al. 2010; Forest Europe et al. 2011; Fuchs et al. 2013).

Besides change in the extent of forest in Europe, the structure of these forest resources has also been changing (Figure 1). The growing stock and increment rates have been increasing almost continuously over the last decades (Kuusela 1994; Gold et al. 2006; Rautiainen et al. 2010; Forest Europe et al. 2011), although the increment rates have started to decrease during the last few years (Nabuurs et al. 2013), which is supported by several other studies that observed climate change induced growth decreases across various sites in Europe (see review by Lindner et al. 2014). In 2010, European forest resources (45 countries in total, excluding the Russian Federation) covered 211 million ha, which, on average, corresponds to 32% of the land area, with an average growing stock of 156 m³ ha⁻¹. It should be noted, however, that the resources vary greatly across European countries with forest cover ranging from 0 to 73% of the land area and average growing stocks ranging up to 346 m³ ha⁻¹ (Forest Europe et al. 2011).

European forests are managed for a range of purposes. Wood production is an important function and wood removals from all European forests (excluding the Russian Federation) were about 468 million m³ in 2010 (Forest Europe et al. 2011). The rate of wood removals has been increasing over the last decades (Figure 1), but at a slower pace when compared to the increase in increment rates. Currently, the harvest intensity is about 62% of the net annual increment (Forest Europe et al. 2011), but with large variation across European regions (Levers et al. 2014). Some European regions are managed with the main aim to produce wood, while other regions have objectives other besides wood production (Hengeveld et al. 2012). The management regimes that are applied across European forests range from small-scale, individual tree harvests in Central Europe to more large-scale clear-cut systems in Northern Europe.

The increasing growing stock and increment rates, combined with a less strong increase in the rate of wood removals, caused European forests to have been acting as a carbon sink for decades, i.e. they have removed more carbon from the atmosphere through photosynthesis than the amount that was released back to the atmosphere through decomposition and burning (Goodale et al. 2002; Nabuurs et al. 2003b; Nabuurs et al.

2013). Factors contributing to increasing increment rates are being debated and include improved accuracy of forest inventories, nitrogen deposition, increased atmospheric carbon dioxide (CO₂) concentrations, changes in climate, cessation of grazing and litter raking, ageing of the forest resources and changes in, or lack of, forest management (Nabuurs et al. 2003b; Gold et al. 2006; Ciaia et al. 2008; Luyssaert et al. 2010; Bellassen et al. 2011; de Vries and Posch 2011). The effects of age, as well as the single effect of increased atmospheric CO₂ concentrations have been disputed (Körner et al. 2005; Vilén et al. 2012; Erb et al. 2013). The results of monitoring and modelling studies now suggest that the main drivers are forest management (Vilén et al. 2012; Erb et al. 2013) and nitrogen deposition (de Vries et al. 2009; de Vries et al. 2014; Fernandez-Martinez et al. 2014), as well as the combined effect of nitrogen deposition, increased atmospheric CO₂ concentrations and climate change (Pretzsch et al. 2014).

Besides affecting growing stock accumulation and carbon sequestration, forest management also affects species richness in European forests (Paillet et al. 2010). Past intensive management practices have altered forest biodiversity across European forested landscapes (Siitonen 2001; Wallenius et al. 2010; Brukas et al. 2013). To reverse biodiversity loss, protected areas have been established over a long time (Reid and Miller 1989) and the area of forests protected for biodiversity has increased during the last decades (Forest Europe et al. 2011; Figure 1).

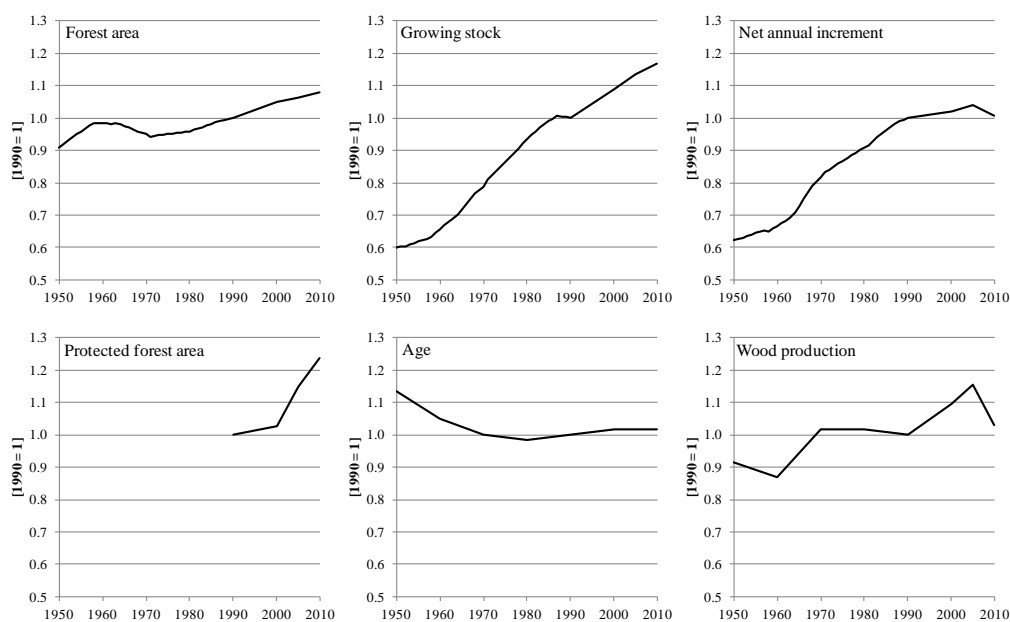


Figure 1: Changes in area, growing stock per hectare, net annual increment per hectare, protected forest area, age and annual wood removals per hectare in European forests. Data are indexed to the year 1990 (i.e. 1990=1) (Kuusela 1994; Gold 2003; Forest Europe et al. 2011; Vilén et al. 2012).

1.2 Demands on European forests

Forests have been for a long time primarily used as a source of wood and fuel. The demand for wood in Europe for material use has increased steadily in the 20th century, driven to a large extent by population growth (Hurmekoski and Hetemäki 2013; Hurmekoski et al. 2014). The demand for wood for material use is expected to increase over the next decades in Europe (UNECE-FAO 2011), although doubts have been expressed concerning the extent that this will really happen due to observed structural changes in wood markets (Hurmekoski and Hetemäki 2013; Hurmekoski et al. 2014).

In addition to providing wood for material use, forests have also long provided wood for fuel. Although the importance of wood as fuel has dramatically decreased due to the availability of fossil fuels, forests are, however, regaining their importance as a source of fuel. Many European countries have committed themselves to international climate agreements to reduce emissions of CO₂ and other greenhouse gases by ratifying the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol. Forests can play an important role in mitigating climate change since carbon sequestration in biomass and soil can offset greenhouse gas emissions. Furthermore, wood could be used to substitute fossil fuels or energy intensive products (Canadell and Raupach, 2008). Policies have been developed to increase the share of renewable energy in energy consumption (e.g. Renewable Energy Directive 2009/28/EC). Forests are considered an important resource to meet these renewable energy targets, because forests are arguably not managed to their full extent (fellings are well below the annual increment in many countries, which suggests that wood removal could be increased) and may represent a cheaper resource than other resource options.

Forests are also important for biodiversity. Many European countries committed themselves to the conservation of biological diversity and the sustainable use of its components by ratifying the United Nations Convention on Biological Diversity (CBD), as well as related policies (e.g. the EU biodiversity strategy to 2020 COM/2011/0244). The ratification of the UNFCCC and CBD are two important conventions relevant for the management of (European) forest resources. However, there are many other benefits that forests provide to society (Millennium Ecosystem Assessment 2005; de Groot et al. 2010) and demand for many such benefits – or ecosystem services – is increasing.

The above-mentioned conventions place potentially competing demands on forests. For example, increased bio-energy production could also have negative effects on biodiversity (Huston and Marland 2003), whereas enhanced biodiversity protection may decrease wood supply (Linden and Uusivuori 2002; Bolkesjø et al. 2005; Leppänen et al. 2005; Kallio et al. 2006; Hänninen and Kallio 2007). It is likely that while the provisioning of some services can be combined in the same forest, trade-offs may occur between the provisioning of other services (cf. Sarr and Puettmann 2008). Understanding trade-offs and defining optimal strategies to achieve different policy goals is a key challenge for scientists, decision makers and forest managers (McShane et al. 2011). Forest management plays a crucial role here as management options can affect the provisioning of different ecosystem services, for example through choice of tree species (Gamfeldt et al. 2013), harvest regimes (Ribe 1989; Gundersen and Frivold 2008), or wood removal rates (Hood et al. 2002; Eggers et al. 2008).

1.3 Impact assessment

To avoid or mitigate unintended policy outcomes, proposals for policies in the European Union (EU) need to be evaluated with regards to their economic, environmental and social

impacts inside and outside the EU (Tscherning et al. 2008). To respond to this requirement, tools are needed and being developed to conduct integrated sustainability impact assessments of policies before they are implemented (e.g. Ness et al. 2007; Helming et al. 2011; Lindner et al. 2012; Päivinen et al. 2012). Such tools often rely on scenarios to assess impacts of policies or management actions. Impacts can be assessed by comparing the outcome of a scenario with the intended policy against the outcome of a scenario without the intended policy. Another feature of many of these tools is that they often rely on indicators to assess policy impacts.

Different model approaches have been developed within forestry that can be used to assess future forest growth. Forest growth and yield models focus in particular on addressing management effects (Pretzsch et al. 2008). Within Europe, many growth and yield models have been developed over the last decades (see e.g. <http://www.efiatlantic.efi.int/portal/databases/formodels/> or www.forestdss.org/), but they mostly focus on tree or stand level. To assess impacts of policies, models are needed that address forest resources at a larger scale, but few models exist that address growth and yield at such scales. Two models are currently applied for forest resource assessments at the European level: the European Forest Information SCENario model (EFISCEN) (e.g. Sallnäs 1990; Nabuurs et al. 2003a; Nabuurs et al. 2007; Eggers et al. 2008; UNECE-FAO 2011; Hanewinkel et al. 2013) and the Global Forest Model (G4M) (Kindermann et al. 2008; Kindermann et al. 2013). Several other growth and yield type of models are currently being developed for resource assessments at the European level (e.g. Pilli et al. 2013; Mubareka et al. 2014).

Forest simulation models typically provide multiple outputs or indicators. Outputs from such models can be used to assess how indicators change with time and how they are affected by policy or management changes. This can be done for each indicator individually or by integrating multiple indicators in an index. To evaluate alternative policy options and to identify favourable and unfavourable outcomes, indicator impacts can be combined with information on preferences. Numerous methods exist to address preferences in impact assessments, but common methods include cost-benefit analysis and multi-criteria analysis (Ness et al. 2007). The former method is an economic decision-making approach, using economic values as a basis for the comparison of different options. While several methods exist to estimate economic values in (environmental) impact assessments (e.g. hedonic pricing, travel costs, choice modelling), contingent valuation has become a widely used tool in cost-benefit analyses to elicit stated preferences on environmental matters (Spash et al. 2005). The use of economic values for environmental impacts or services has been criticised, as there is doubt whether markets really reflect social preferences (Joubert et al. 1997; Spash et al. 2005). For example, a person's preference could be affected by budget constraints and would not state his or her real preference (Joubert et al. 1997). Despite the criticism, economic valuation is considered an important method to incorporate ecosystem services into decision making (Mooney et al. 2005; Bateman et al. 2013), because the use of economic values has the advantage that the outcomes of a cost-benefit analysis are compatible with the market mechanism and that they are comprehensible to decision makers (Diakoulaki and Karangelis 2007). Multi-criteria analysis is an alternative, popular method to support decision making, which relies on weights (Kangas et al. 2001; Wolfslehner and Seidl 2010). It also assists in structuring a decision making process, it can help when stakeholders in the process have different and/or competing interests and it can include both quantitative and qualitative criteria. Both methods potentially lead to the same evaluation outcome in case economic values in a cost-benefit analysis properly reflect the preferences (weights) in a multi-criteria analysis (Diakoulaki and Karangelis 2007).

1.4 Objectives

While there is pressure to protect forests to prevent further loss of biodiversity, there are also policies being developed that may lead to a greater demand for wood or biomass from forests. Policy options that address these topics may affect each other, as well as other ecosystem services provided by forests. In this dissertation, an approach is presented that assesses the impacts of forest policy and management scenarios addressing intensified biomass production and biodiversity protection on each other and on a number of ecosystem services provided by European forests. Such an approach is needed because existing European-wide assessments have only addressed single or few ecosystem services at a time (e.g. Nabuurs et al. 2001a; Karjalainen et al. 2003; Nabuurs et al. 2007; Eggers et al. 2008; Kindermann et al. 2013). Furthermore, assessment studies that included multiple ecosystem services have relied mainly on land cover information to quantify ecosystem services provisioning (Bennett et al. 2009; Seppelt et al. 2011), but it is also important to consider (forest) management when assessing ecosystem services. Finally, several studies have linked model simulations with economics to optimise stand- or forest -level management (Seidl et al. 2007; Palahí et al. 2009; Miina et al. 2010; Başkent et al. 2011; Pukkala 2011; Pukkala et al. 2011; de-Miguel et al. 2014; Pukkala 2014), but there are no studies that linked model simulations with an economic valuation to evaluate impacts of alternative policy options on ecosystem services provided by European forests.

The main aim of this dissertation was to analyze and evaluate impacts of intensified biomass production and biodiversity protection on ecosystem services as provided by European forests. Specifically, the objectives were to:

1. Assess to what extent forests are currently protected and how felling restrictions in forests protected for biodiversity affect the current potential wood supply from forests (article I);
2. Assess the realisable woody biomass potential from forests (article II);
3. Develop methods to assess impacts of forest management and policy scenarios using large-scale forest resource modelling (articles III and IV); and to:
4. Assess and evaluate impacts of intensified woody biomass removals and biodiversity protection on selected ecosystem services provided by forests (articles III-V).

Impacts of intensified biomass removal and biodiversity protection on European forest resources were studied in the five articles that comprise this dissertation. Article I assessed to what extent forests are currently protected and how felling restrictions affect the potential annual wood supply within Europe. Articles II-V assessed future biomass potentials and impacts of different scenarios on forest resources, by applying the EFISCEN forest resource model. In article II, the model was applied to assess the realisable woody biomass potentials from European forests. In articles III-V, the model was applied to study impacts of policy and management scenarios related to intensified production of biomass and biodiversity protection using indicators for various forest ecosystem services.

2 MATERIALS AND METHODS

2.1 Study area and system boundaries

The study area in articles I-V is briefly described in Table 1. To facilitate comparison of results from all articles, this synthesis covers 24 European countries (Figure 2), comprising the European Union member states, excluding Croatia, Cyprus, Greece and Malta. No correction was made for differences in e.g. forest area between the original articles (Table 1). Therefore there are small deviations in the results presented in the synthesis of this dissertation as compared to the original results presented in articles I, II and V. This dissertation and all articles focused only on impacts on forests within the study area; impacts occurring when processing wood, impacts of material and energy substitution, as well as impacts outside (European) forests are excluded from the analysis, but the implications of these system boundaries are discussed.

Table 1: Description of the original study area in articles I-V

Article	Extent (million ha)	Number of countries	Countries	Forest type
I	33	29	European Union (excl. Croatia), Norway, Switzerland	Protected forests ¹
II	126	27	European Union (excl. Croatia)	Forest area available for wood supply ²
III	132	24	European Union (excl. Croatia, Cyprus, Greece and Malta)	Forest remaining forest ³
IV	123	24	European Union (excl. Croatia, Cyprus, Greece and Malta)	Forest area available for wood supply ²
V	132	26	European Union (excl. Croatia, Cyprus, Greece and Malta), Norway, Switzerland	Forest area available for wood supply ²

¹ Forests that have been protected based on the existence of a legal basis, a long term commitment (minimum 20 years) and an explicit designation for the protection of biodiversity and landscapes (Parviainen et al. 2010).

² Forests where any legal, economic, or specific environmental restrictions do not have a significant impact on the supply of wood (MCPFE 2007).

³ Forest area reported by EU Member States as part of their greenhouse gas emission reports to UNFCCC.



Figure 2: Overview of the 24 countries forming the study area of this synthesis. The grouping of countries in European regions was adapted from Forest Europe et al. (2011).

2.2 Current restrictions on fellings in forests protected for biodiversity

In article I, restrictions on fellings within protected areas were estimated and combined with statistics on the extent of protected forest areas and their increment rates to estimate the long-term wood volumes unavailable annually due to protection of forests in Europe. Firstly, data on the extent of forests protected for biodiversity in 2005 were collected from Forest Europe et al. (2011) as the main data source for the analysis. Forests protected to preserve landscapes and specific natural elements are not considered in this dissertation, but are included in the analysis presented in article I. Data on protected forests were compiled by national correspondents following guidelines on protected forest and other wooded land in Europe (Parviainen et al. 2010). According to these guidelines, only protected forests with a legal basis, a long term commitment, and an explicit designation are included. Data on protected areas are also available from other sources, but were not used because they were incomplete or because they follow classification systems that are not specifically designed for forests (Parviainen and Frank 2003; Frank et al. 2007; Parviainen et al. 2010).

Secondly, the volume of wood that could be harvested from these protected areas was assessed by estimating the theoretical potentials for wood fellings. The theoretical felling potential reflects the maximum amount of stem volume that could potentially be harvested each year, while disregarding all forms of protection or limitations to mobilise the resources. Following the principles of sustainable forest management (Forest Europe et al. 2011), as well as guidelines for large-scale wood or biomass assessments (Vis and Dees 2011), the net annual increment was used to estimate the maximum theoretical felling potential. Net annual increment for the total forest area - including protected forests - was

taken from UNECE-FAO (2000). More recent estimates of the net annual increment (for example from Forest Europe et al. 2011) refer only to the productive forest area available for wood supply and were therefore not used.

Thirdly, restrictions on fellings in protected areas were estimated. Data on such felling restrictions were collected from summary tables compiled between 2002 and 2005 by national experts within the COST action E27 study on protected forests in Europe (European Forest Institute 2007; Frank et al. 2007). These tables included multiple characteristics for a wide range of different protection types. Felling restrictions were provided in the tables by the national experts as scores. In article I, these scores were converted into felling restrictions expressed as a percentage reduction in wood supply. Based on the restriction levels for each individual protected forest type in the dataset, average restrictions were calculated for each country, using the forested area within the protected forest type as a weight. For countries without data on felling restrictions the felling restrictions from neighbouring countries were used.

Fourthly and finally, the data collected in the first three steps were multiplied with each other to estimate the potential annual wood volume unavailable due to forests protected for biodiversity.

2.3 Future forest resource development

2.3.1 Model description

To project future forest resource development in articles II-V, the EFISCEN model (version 3.1) was used. EFISCEN is a large-scale forest scenario model that projects forest resource development at regional to European scale, based on national forest inventory data on the forest area available for wood supply, average growing stock and net annual increment. The model is described briefly below, relying heavily on model descriptions from articles II-V. A detailed model description is given by Schelhaas et al. (2007).

In EFISCEN, the state of the forest is described by distributing forest area over matrices consisting of age- and volume-classes. Separate matrices are created for different regions, owners, site-classes and species, depending on the level of detail provided in the forest inventory data for each country. The initial distribution of area over matrices represents the state of the forest as derived from the national forest inventory data. During simulations, area is transferred between matrix cells and these transitions are determined by natural processes (e.g., growth and mortality) and influenced by management regimes (thinning, final felling, choice of tree species in regeneration,) and changes in forest area. Growth dynamics are simulated by shifting area proportions between matrix cells. In each 5-year time step, the area in each matrix cell moves up one age-class to simulate ageing. Part of the area of a cell also moves to a higher volume-class, thereby simulating volume increment. Growth dynamics are estimated by the model's growth functions, which are derived from inventory data or yield tables. Harvest regimes are specified at two levels in the model. First, a basic management regime defines the period during which thinnings can take place and a minimum age for final fellings. These regimes can be regarded as constraints on the total harvest level. Second, the demand for wood is specified for thinnings and for final felling separately and EFISCEN will harvest the requested wood volume if available. During thinnings and final fellings, logging residues are produced, which can either be left in the forest to decompose or be extracted, e.g. to produce energy.

EFISCEN provides information on (future) forest resource structure (tree species, area, age-class structure, stem wood volume, increment, mortality), as well as wood removals

and logging residues and stumps from thinning and final fellings for every five-year time-step. With the help of biomass expansion factors, stemwood volume is converted into whole-tree biomass and subsequently to whole-tree carbon stocks. The soil module YASSO (Liski et al. 2005) is linked to EFISCEN and can be used to provide information on forest soil carbon stocks.

2.3.2 Model extension

The EFISCEN model was extended in article IV to assess deadwood dynamics. This was achieved by quantifying natural mortality, as well as developing a procedure to track and quantify the amount of deadwood. Mortality was defined as death of trees through ageing, suppression and/or disturbances. Mortality occurs in the model on areas that have not been recently thinned or have not been clear-felled in the same time-step. This is to prevent double counting as managed forests thinnings and final fellings counteract mortality (Cooper 1983) and because upon (large-scale) disturbances, fresh deadwood is often recovered and included in wood removal statistics (Schelhaas 2002). Mortality was implemented in the model by transferring a given area one volume-class down as determined by the specified mortality rate and management intensity.

Upon tree death, standing deadwood is formed, which eventually falls down and forms downed deadwood. A negative exponential curve was applied to describe the rate at which standing deadwood falls down (Storaunet and Rolstad 2004). The amount of standing deadwood is calculated from the initial volume, the input from mortality and the volume falling down. The standing deadwood pool was initialized as equilibrium between the input from mortality of the first time-step and the fall rate. No loss in mass due to decomposition was assumed while standing (Krankina and Harmon 1995; Mäkinen et al. 2006).

After falling down, standing deadwood becomes downed deadwood. YASSO was used to describe the physical fractionation and decomposition of downed deadwood on mass basis. Downed deadwood enters YASSO in its coarse woody litter compartment and is transferred to different compartments based on chemical quality of the deadwood. The amount of downed deadwood is estimated as the balance between input of standing deadwood and loss of mass to the atmosphere through decomposition of downed deadwood estimated with the model. The initial amount of downed deadwood is estimated by running YASSO to the equilibrium with the input from standing deadwood of the first time-step.

Stem residues form the third type of deadwood. Stem parts that are left behind in the forest after thinning or final fellings become residues. The input of stem residues is determined by the proportion of felled stemwood that is removed from the forest and management intensity. Decomposition of residues was modelled by YASSO similar to the decomposition of downed deadwood. Litter and residues from branches and roots were not assessed as they were not considered to form deadwood.

2.3.3 Model input data

National forest inventory data on area, growing stock and net annual increment are used to initialize the EFISCEN model. EFISCEN was initialized in article IV with data collected by Schelhaas et al. (2006). National forest inventory data were updated for Austria, Belgium, Czech Republic, Denmark, Finland, Germany, Hungary, Ireland, Italy, Latvia, Netherlands and Sweden for article II and Italy was again updated for articles III and V.

To incorporate mortality and deadwood in articles IV and V, mortality functions were estimated and EFISCEN's growth functions were converted into gross annual increment functions. This conversion was done using increment correction factors. If either the

mortality rate or the increment correction factor was estimated, then the other was calibrated through the balance of gross increment, net increment and mortality. Mortality data were collected from forest inventories in Austria, Germany and Sweden. For other countries, country-specific correction factors for broadleaved and coniferous species separately were calculated from UNECE-FAO (2000) as the ratio between reported gross and net annual increment. To further model deadwood, fall rates of standing deadwood were collected from literature for various tree species in Northern Europe as well as for two tree species in Central Europe. For the remaining countries and tree species likely fall rates were concluded from known fall rates of other countries. The estimated or assumed stem fall rates did not include loss of volume due to disintegration of standing deadwood (i.e. reduction in height of dead stems). To correct for this we assumed that volume fall rates were twice the fall rates for deadwood stems.

General forest management parameters on age-limits for thinnings and final fellings were based on a compilation of conventional forest management according to handbooks (cf. Nabuurs et al. 2007) and were updated in articles II, III and V by consulting national correspondents. The proportion of volume from thinning or final fellings being removed from the forest was calculated on a country level, distinguishing between coniferous and broadleaved species (UNECE-FAO, 2000).

2.4 Realisable potential supply of woody biomass

2.4.1 Theoretical woody biomass potential

The realisable potential supply of woody biomass was estimated in article II for stemwood; branches and harvest losses ('residues'); stumps and coarse roots ('stumps'); and woody biomass from early or energy thinnings in young forests ('other biomass'). As a first step, the theoretical potential of forest biomass supply in Europe was estimated, i.e. the overall, maximum amount of forest biomass that could be harvested annually within fundamental bio-physical limits (Vis and Dees 2011), taking into account increment, the age-structure and stocking level of the forests. To assess the theoretical potential, EFISCEN was applied to iteratively assess the theoretical harvest potential of stemwood for the period 2010-2030 for every five-year time-step. This potential was estimated by first assessing the maximum volume of stemwood that could be harvested annually during 50-year periods. From this maximum harvest level an average (maximum) harvest level was calculated. EFISCEN was then rerun to check whether this harvest level was feasible in the time step for which the theoretical potential was estimated. If it was not feasible, the harvest level was iteratively reduced by 2.5% until harvest was feasible. This procedure provided estimations of the stemwood potentials, as well as the associated potential from logging residues and stumps, from thinning and final fellings separately.

2.4.2 Constraints on woody biomass supply

Theoretical forest biomass potentials estimated by EFISCEN are higher than what can be supplied from the forest due to environmental, social, technical, and economic constraints on wood supply. In a second step, such constraints were quantified and combined with the theoretical potential to estimate the realisable woody biomass supply. To do this, important constraints on biomass supply were identified from literature, national biomass harvesting

guidelines and recommendations with regards to supply of woody biomass. The following constraints were included in the analysis:

- Site productivity (limits residue extraction on poor soils);
- Soil and water protection (limits residue extraction to prevent erosion, soil compaction and water pollution);
- Biodiversity protection (reduces stemwood and residue extraction to prevent loss of biodiversity);
- Recovery rate (limits residue extraction level based on slope and machinery);
- Soil bearing capacity (limits mechanised harvesting of biomass on certain soil types);
- Ownership structure (reduces stemwood and residue extraction based on forest holding size of privately owned forests).

Each of these constraints was quantified separately for all types of woody biomass (i.e. stemwood, residues, stumps and other biomass) and by type of felling activity (i.e. early thinning, thinnings and final felling) for three mobilisation scenarios. These scenarios were defined as follows:

- The high mobilisation scenario has a strong focus on the use of wood for producing energy and for other uses. Recommendations on wood mobilisation are successfully translated into measures that lead to an increased mobilisation of wood. This means that new (public and private) forest owner associations or co-operations are established throughout Europe. Together with existing associations, these new associations lead to improved access of wood to markets. Strong mechanization is taking place across Europe and existing technologies are effectively shared between countries through improved information exchange. Biomass harvesting guidelines become less restricting, because technologies are developed that are less harmful for the environment. Furthermore, possible negative environmental effects of intensified use of forest resources are considered less important than the negative effects of alternative sources of energy or alternative building materials. Application of fertilizer is permitted to limit detrimental effects of logging residue and stump extraction on the soil.
- The medium mobilisation scenario builds on the idea that recommendations are not all fully implemented or do not have the desired effect. New forest owner associations or co-operations are established throughout Europe, but this does not lead to significant changes in the availability of wood from private forest owners. Biomass harvesting guidelines that have been developed in several countries are considered adequate and similar guidelines are implemented in other countries. Mechanization of harvesting is taking place, leading to a further shift of motor-manual harvesting to mechanized harvesting. Application of fertilizer is permitted to a certain extent to limit detrimental effects of logging residue and stump extraction on the soil.
- In the low mobilisation scenario, the use of wood for producing energy and for other uses is subject to strong environmental concerns. Possible negative environmental effects of intensified use of wood are considered very important and lead to strict biomass harvesting guidelines. Application of fertilizer to limit detrimental effects of logging residue and stump extraction on the soil is not permitted. Forests are set aside to protect biodiversity with strong limitations on harvest possibilities in these areas. Furthermore, forest owners have a negative attitude towards intensifying the use of their forests. Mechanization of harvesting is taking place, leading to a shift of motor-

manual harvesting to mechanized harvesting, but with little effect on the intensity of resource use.

The environmental and technical constraints were implicitly quantified for stemwood by considering only the forest area available for wood supply. The quantification of the constraints, according to the three mobilisation scenarios, for the other types of biomass is described in the supplementary material of article II and is not repeated here. Spatially explicit data were collected in raster format (1x1 km resolution) for each environmental and technical constraint. The different raster layers were combined by determining the minimum permitted extraction rate for each raster cell and then aggregated to calculate the average restriction per EFISCEN region and country according to each mobilisation scenario and biomass type. For all types of biomass, the effect of private ownership structure on wood mobilisation was estimated by linking size-classes of privately-owned forest holdings with maximum extraction rates per size-class at the national level. Finally, the realisable biomass potential from European forests was estimated by combining the theoretical forest biomass potential at the regional level with the average reduction factor for each region for environmental and technical constraints and for the constraint related to forest holding size.

2.5 Impacts of intensified biomass removal and enhanced biodiversity protection

2.5.1 Impact scenarios

Impacts of intensified removal of woody biomass, as well as enhanced forest protection were assessed in articles III-V in separate scenarios. The scenarios are described in Table 2.

Table 2: Description of the scenarios in articles III-V

Article	Name	Description
III	Baseline scenario	Scenario describing the development of the EU energy demand under trends and policies implemented until April 2009. It includes current trends on population and economic development including the 2008 economic downturn and takes into account bioenergy markets. Economic decisions are driven by market forces and technology progress in the framework of concrete national and EU policies and measures implemented until April 2009. It includes several energy efficiency measures, but excludes the most recent renewable energy targets (Renewables Directive 2009/28/EC). The total roundwood demand from European forests was estimated by the Global Biosphere Management Model (GLOBIOM).
III	Reference scenario	Scenario based on the baseline scenario from article III, including policies adopted between April and December 2009 and assuming that national targets for renewable energy under the Renewables Energy Directive 2009/28/EC and the GHG Effort Sharing Decision 2009/406/EC are achieved in 2020. The total roundwood demand from European forests was estimated by GLOBIOM.
IV	Baseline scenario	Scenario in which no changes in policies or management strategies were assumed throughout the simulation. Future wood demand is based on historical development of the European forest sector and forecasts of

		<p>economical growth (Kangas and Baudin 2003; Schelhaas et al. 2006). Wood demand increased moderately in most countries between 2000 and 2030 and stem residues were not removed.</p>
IV	Bio-energy scenario	<p>Scenario in which stem residues were extracted and final fellings were increased to the maximum potential (where possible) from 2010 onwards. The maximum felling potential was determined for different species based on the rotation length, the mean annual net increment over the rotation period and the actual growing stock volume in each five-year time step (EEA 2006). The amount of residues from stems that are generated during harvest operations was estimated by running EFISCEN with the estimated thinning and final fellings levels. Residues from branches were not assessed as they were not considered to form deadwood. Constraints were applied to address environmental criteria that limit the amount of residues that could be extracted. The criteria included slope, elevation, soil water regime, base saturation in top- and subsoil and soil type (EEA 2006).</p>
V	Reference scenario	<p>Scenario which assumes no changes in current policies or management strategies. The future demand for domestically harvested roundwood was taken from the B2 reference future as projected by the global forest sector model EFI-GTM (UNECE-FAO 2011). The share of logging residues (all countries) and stumps (in Finland, Sweden and the United Kingdom only) that are extracted during harvest operations (thinning and final fellings) was assumed to increase linearly until 2020, according to the constraint quantification in medium mobilisation scenario in article II and remain constant thereafter.</p>
V	Wood energy scenario	<p>Scenario which considers that the national renewable energy targets for 2020 (e.g. Renewable Energy Directive 2009/28/EC) are achieved, and that the trend continues to 2030. The future demand for domestically harvested roundwood was taken from the wood energy scenario as projected by the EFI-GTM model (UNECE-FAO 2011), leading to a larger demand for wood as compared to the article V reference scenario. The share of logging residues and stumps (both in all countries) that are extracted during harvest operations (thinning and final fellings) was assumed to linearly increase until 2020 to the level of the high mobilisation scenario as presented in article II. Other parameters were kept the same as in the article V reference scenario;</p>
V	Biodiversity scenario	<p>Scenario in which 5% of the forest area available for wood supply was set aside for biodiversity protection. Fellings in these protected areas were restricted based on the restrictions from article I. Less intensive management was assumed in the unprotected area by focusing more on small-scale interventions (thinning and group-wise harvest) and shifting gradually to more broadleaved dominated area (Nabuurs et al. 2001b). This was implemented by (i) applying longer rotation lengths, (ii) increasing the share of wood from thinnings, and (iii) regenerating upon final harvest 50% of area that was dominated by conifers with broadleaves. The future demand for wood was the same as for the article V reference scenario and was prioritized on the unprotected area. Extraction of logging residues and stumps was not permitted anywhere.</p>

The reference year was 2005 in articles III and IV and 2010 in article V. Wood demand up until the reference year in each article was based on historical roundwood production converted to overbark volumes and which was used as wood demand until the year 2005 or 2010. The forest area was kept constant in all projections, except for the projections in article III, in which the forest area decreased slightly due to deforestation, as projected by the G4M model. No climate change was assumed in articles III and IV. Climate and environmental change effects on productivity were incorporated in article V by scaling the growth functions in EFISCEN (Schelhaas et al. 2010).

2.5.2 Biophysical impacts

Impacts of intensified removal of woody biomass (articles III-V), as well as enhanced forest protection (article V) were assessed in separate scenarios for five ecosystem services (Table 3). These ecosystem services were selected as they could be estimated using the EFISCEN model outputs and they cover different types of ecosystem services.

To quantify the biophysical impacts on the indicators in Table 3, EFISCEN outputs on roundwood production, logging residue and stump biomass production, deadwood and carbon sequestration were used. Recreational attractiveness was estimated in article V as an expert-based index (on a scale of 1-10) representing the preference value of different forest stands for recreation, based on surveys for four European regions, involving 46 experts (10 to 14 experts from different countries within each region (Edwards et al. 2012)). Calculations were made for each country by multiplying (i) the area in different age-classes as projected by EFISCEN, with (ii) age-class and species-group specific recreational scores for different management regimes across Europe (Edwards et al. 2012).

Table 3: Overview of the forest ecosystem services included in articles III-V. The classification follows de Groot et al. (2010).

Type of service	Biophysical indicator	Article(s)
Provisioning services	Roundwood production (industrial- and fuelwood)	III, IV & V
	Residue and stump biomass production	V
Regulating services	Carbon sequestration (i.e. net annual uptake of carbon in forest biomass from the atmosphere)	III & V
Habitat services	Deadwood	IV & V
Cultural and amenity services	Recreational attractiveness	V

2.5.3 Economic impacts

The biophysical impacts, as quantified in article V, were complemented with an assessment of economic impacts. Economic values for each ecosystem service were estimated as follows:

- For roundwood, the average roundwood price (euro m⁻³ overbark) in each country was estimated from data on total volume (converted to overbark volumes) and market value of roundwood produced in 2010 (Forest Europe et al. 2011);
- The price of harvest residues (euro GJ⁻¹) was estimated for 12 countries (Alakangas et al. 2007) and the average of these 12 countries was applied to the countries where no data were available. Values in GJ were converted to tonnes dry matter using a net calorific value of 18.5 GJ ton⁻¹ dry matter (Alakangas et al. 2007);
- The value of carbon sequestration was based on the social carbon cost. The median social carbon cost (at 3% discount rate, estimated from 232 published estimates) of 14.67 euro ton⁻¹ C (4 euro ton⁻¹ CO₂) as reported by (Tol 2012) was used;
- The valuation of recreation was based on the willingness-to-pay estimates for recreation in protected and unprotected forests as estimated by Giergiczny et al. (2008). These values were derived from (1) a meta-regression analysis on 253 estimates from 49 studies in 8 countries across Europe to estimate what factors affect the willingness to pay for recreation, (2) the mean recreational value of forests in the United Kingdom provided by the Forestry Commission estate according to a questionnaire involving over 15,000 visitors, and (iii) using the results of the meta-analysis to transfer the mean recreational value of forests in the United Kingdom to other European countries.

The estimated economic values are shown in Table 4. The impacts on deadwood (or biodiversity) were not included in the economic assessment due to lack of European-wide data. The prices of roundwood and residues include costs related to harvesting and management. To exclude these costs, an internal rate of return of 2.8% (Ylitalo 2012) was used, i.e. a net benefit was used of 2.8% of the prices for roundwood and residue and stump biomass, shown in Table 4.

Table 4: Mean values (in 2010 euro values) for different forest ecosystem services included in article V (Alakangas et al. 2007; Giergiczy et al. 2008; Forest Europe et al. 2011).

Country	Roundwood	Residue and stump biomass	Recreation unprotected area	Recreation protected area
	euro m ⁻³	euro GJ ⁻¹	euro ha ⁻¹ yr ⁻¹	euro ha ⁻¹ yr ⁻¹
Austria	53.58	5.46	10.31	21.23
Belgium	30.09	4.27	30.56	62.96
Bulgaria	29.07	1.71	4.06	8.37
Czech Republic	38.03	2.41	9.96	20.52
Denmark	37.52	4.88	15.88	32.71
Estonia	39.53	2.64	2.19	4.52
Finland	35.16	3.90	1.75	3.60
France	43.40	5.67	11.18	23.03
Germany	50.38	2.97	19.19	39.54
Hungary	33.18	3.81	7.64	15.75
Ireland	40.99	4.22	8.66	17.84
Italy	51.90	3.94	15.51	31.95
Latvia	34.17	2.46	2.46	5.07
Lithuania	28.82	2.27	3.96	8.16
Luxembourg	23.55	4.65	22.00	45.32
Netherlands	22.37	2.67	38.55	79.42
Poland	29.28	2.33	7.49	15.42
Portugal	27.13	2.57	7.91	16.30
Romania	29.07	1.94	5.45	11.23
Slovenia	42.85	3.24	6.32	13.03
Slovakia	35.39	2.57	8.52	17.54
Spain	42.26	3.62	7.67	15.79
Sweden	31.53	4.43	2.26	4.66
United Kingdom	28.16	4.06	31.86	65.63

3 RESULTS

3.1 Felling restrictions in forest protected for biodiversity

In 2005 about 16 million ha of forests within the study area were protected with biodiversity as the main objective. This corresponded to about 11% of the forest area in the 24 countries included in this synthesis. The extent to which individual countries have protected their forests varied between 0 and 35%. The potential wood volume that could annually be felled was about $4.5 \text{ m}^3 \text{ ob ha}^{-1} \text{ yr}^{-1}$ and ranged from $2.2\text{-}8.4 \text{ m}^3 \text{ ob ha}^{-1} \text{ yr}^{-1}$ between countries. Felling restrictions within the protected areas do not restrict fellings completely. It was estimated in article I that felling restrictions in forests protected for biodiversity reduced fellings within these areas by 51% (range between countries: 34-85%). This means that 49% of the wood volume in these protected forests could still be potentially felled. Consequently, 35 million $\text{m}^3 \text{ ob yr}^{-1}$ is in effect protected from felling activities (Figure 3).

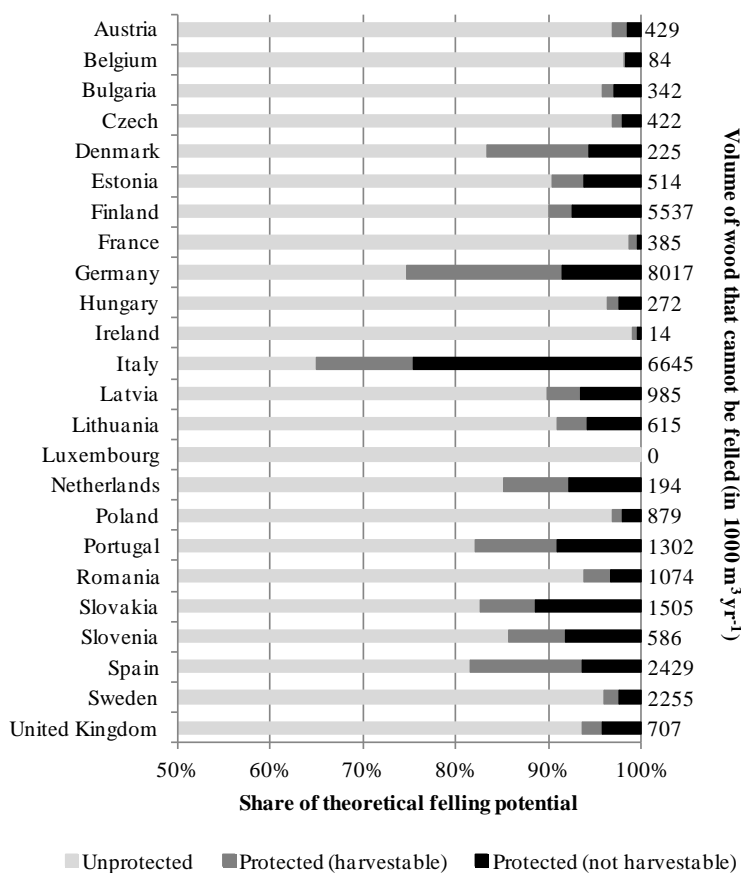


Figure 3: Share of protected forest in 2005 with biodiversity as primary objective and the effective reduction in wood that can be potentially felled according to article I.

3.2 Realisable potential supply of woody biomass

The theoretical potential supply of woody biomass from European forests within the study area was estimated at 1,271 million m³ ob yr⁻¹ in 2010 in article II. The theoretical potential was estimated to be rather stable over time (-1.8% change between 2010 and 2030). Environmental, technical and social constraints reduce the amount of woody biomass to 741 ob million m³ yr⁻¹, or 58% of the theoretical potential in 2010 (Table 5). This potential is primarily composed of stemwood (84%), followed by residues (14%). Stumps and other biomass have a small share each. In 2030, the woody biomass potential was estimated to range between 620 and 891 million m³ ob yr⁻¹ summed over all 24 countries, according to the low and high mobilisations scenarios, respectively. This range is to large extent determined by the degree to which residues, stumps and other biomass are extracted in the mobilisation scenarios.

The realisable potential supply of woody biomass from forests was estimated per unit of land to make the estimates comparable between countries (Figure 4). The potential supply of woody biomass from forests per unit of land is generally highest in Central and Northern Europe. This is explained by high forest productivity (mainly Central Europe) and/or high forest cover ratios (mainly Northern Europe). Conversely, the potential supply of woody biomass per unit of land are generally low in Southern European countries due to lower productivity of the forest resources, as well as in countries that have only a low share of forest cover (e.g. Denmark, Ireland, the Netherlands, and United Kingdom).

Table 5: Potential supply of woody biomass from European forests for different mobilisation scenarios in 2010 and 2030 according to article II. Potentials are given in million m³ ob yr⁻¹. Values in brackets are percentage changes in 2030 as compared to 2010.

Compartment	Current (2010)	High (2030)	Low (2030)
Stem	619	625 (+1%)	555 (-10%)
Residues	100	150 (+49%)	55 (-45%)
Stump	10	101 (+948)	0 (-100%)
Other	12	15 (+27%)	10 (-15%)
Total	741	891 (+20%)	620 (-16%)

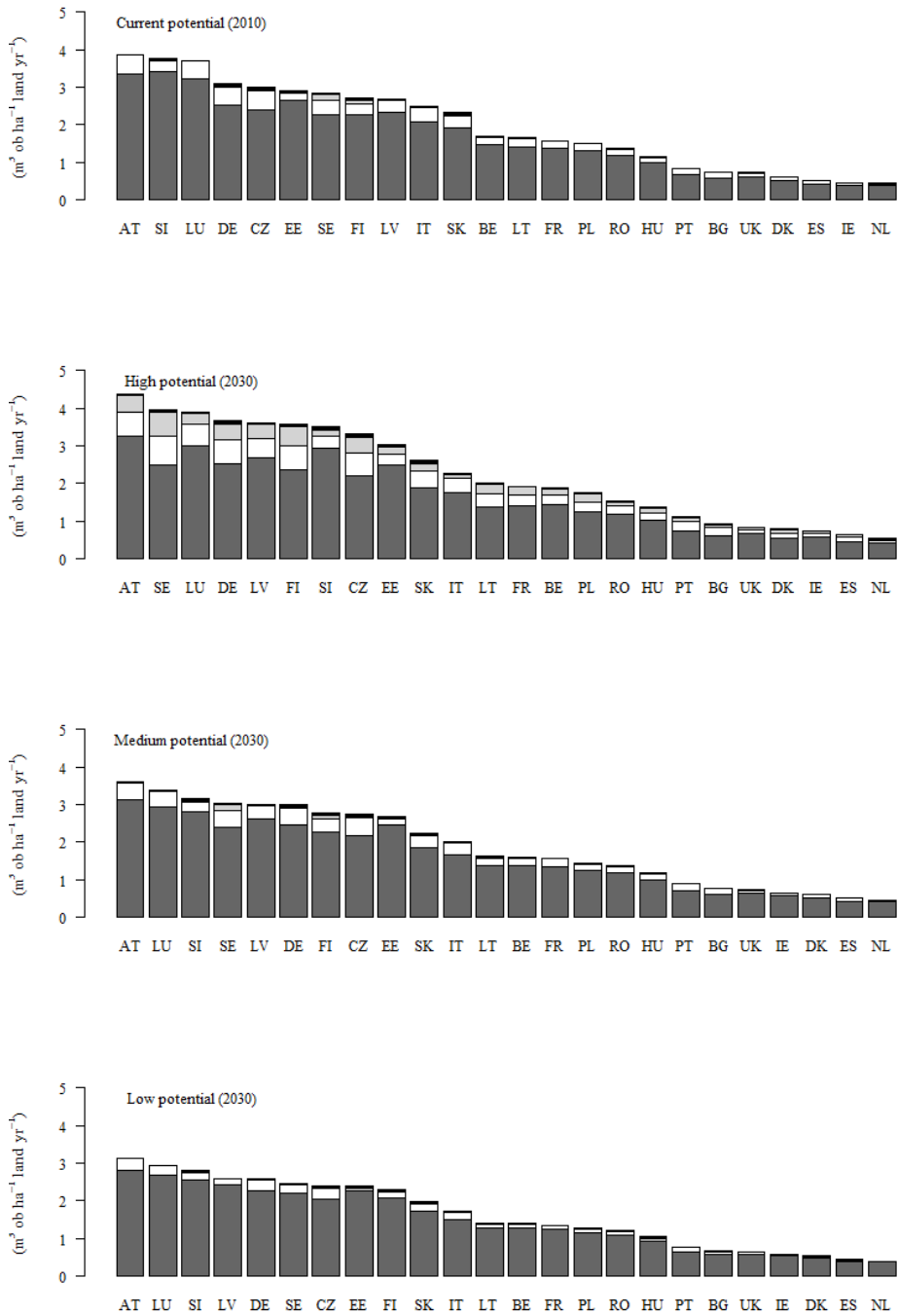


Figure 4: Potential supply of woody biomass from European forests in 2010 and for the three mobilisation scenarios in 2030 as estimated in article II.

3.3 Impacts of intensified biomass removal and enhanced biodiversity protection

3.3.1 Biophysical impacts

Roundwood production

Roundwood production was quantified in articles III-V for seven scenarios (Figure 5). An initial difference of roughly 51-86 million m^3 ob yr^{-1} is shown for the projections from article IV as compared to articles V and III, resp. Also the *biodiversity scenario* (article V) showed there was already less wood production in 2010 compared to the other scenarios. Despite initial differences, six scenarios projected an increase in roundwood production between 2010 and 2030 (median: +14%; range between scenarios: 0 to +42%) with roundwood production increasing only modestly according to article III. Roundwood production was projected to increase in most parts of Europe, but the ranking of European regions according to the percentage increase differed between scenarios and articles.

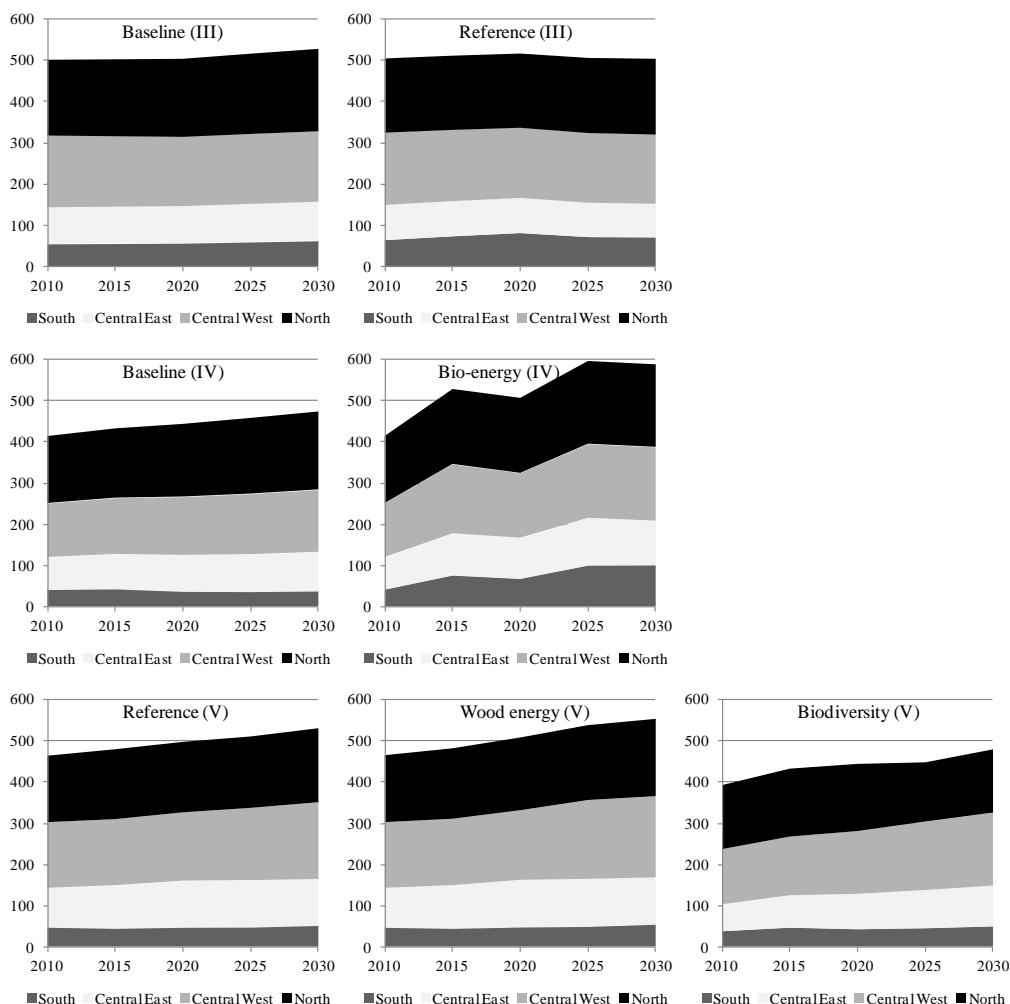


Figure 5: Projected roundwood production (million m^3 ob yr^{-1}) in four European regions according to articles III-V.

Residue and stump biomass production

The extraction of woody biomass from residues and stumps was quantified in article V (Figure 6). Extraction of residue and stump biomass was projected to increase between 2010 and 2030 in both the *reference* and the *wood energy scenarios*. For both scenarios, the largest (absolute) increases were projected for the northern and central western parts of Europe, mainly due to the large volumes of wood that are harvested and the dependency of stump removals on the amount of stemwood removals. Residue and stump extraction was abolished in the *biodiversity scenario* after 2010.

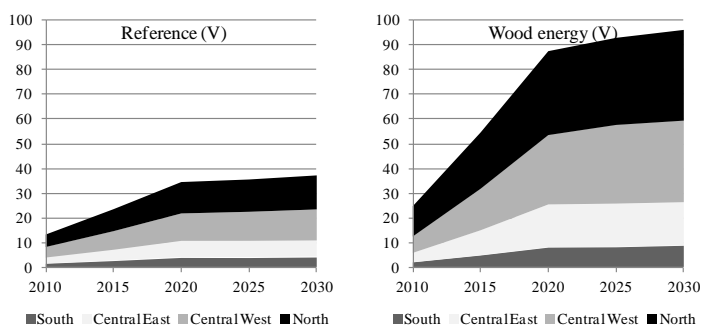


Figure 6: Projected residue and stump biomass production (Tg dry matter yr⁻¹) in four European regions according to article V.

Carbon sequestration

Carbon sequestration in forest biomass was quantified in articles III and V for five scenarios in total. Differences are shown for the initial levels of carbon sequestration, which is affected by the initial differences in roundwood production. Nevertheless, all scenarios indicated that European forests still act as a sink of carbon (Figure 7). However, the size of the sink was projected to decline in all five scenarios. Without major changes in policy objectives, the sink was projected to decline by 15 (*reference scenario* in article V) to 24% (*baseline scenario* in article III) in 2030 as compared to 2010. The response to additional policy measures that enhance use of wood for energy ranges from a modest decline (-6%; *reference scenario* of article III) to a stronger decline (-22%; *wood energy scenario* of article V). The estimated carbon sequestration for the *biodiversity scenario* (article V) was much larger compared to all other scenarios over the whole 20-year period. To a large extent, these differences between scenarios follow the patterns in wood production, as shown in Figure 4.

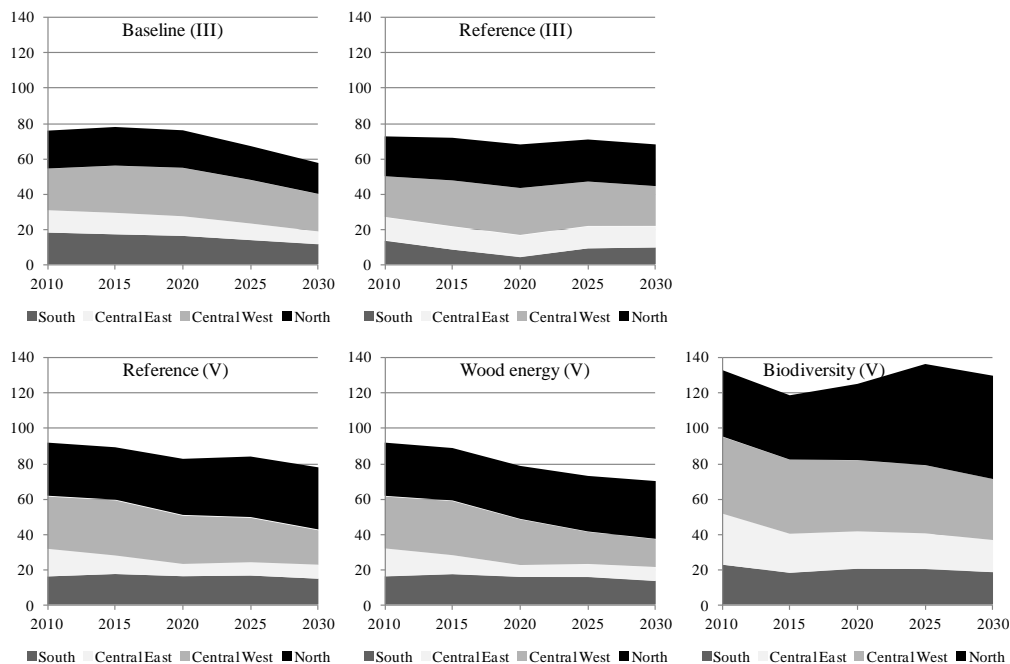


Figure 7: Projected carbon sequestration (Tg C yr⁻¹) in forest biomass in four European regions according to articles III and V.

Deadwood

The amount of deadwood was quantified for five scenarios in total in articles IV and V (Figure 8). Differences are shown for the initial levels of deadwood between the scenarios, which is affected by the initial differences in roundwood production. According to model projections the amount of deadwood in European forests ranged from 1,534 to 1,621 Tg in 2010. The amount of deadwood increased over the 20-year period in the *baseline scenario* (+5%; article IV) and the *biodiversity scenario* (+3%; article V) and decreased in all other scenarios. Extraction of residues and stump biomass reduced the amount of deadwood in forests according to both the *bio-energy scenario* (-6%; article IV) and the *wood energy scenario* (-7%; article V). Deadwood increased in some countries despite the extraction of residues and stumps, which can be explained by increased additional input of stem residues resulting from additional fellings. The additional input of residues compensated in some countries for the reduction in deadwood due to more intensive removal of biomass.

In addition to the amount of deadwood, the type of deadwood was quantified as well in article IV (Figure 9). According to the projections, stem residues constituted about 64% of all deadwood in 2010 and standing and downed deadwood represented 9 and 27%, respectively. In the *baseline scenario*, there was an average increase of stem residues (+7%) between 2010 and 2030, as well as an overall increase in standing (+4%) and downed deadwood (+2%). Intensification of forest biomass removal affected the different types of deadwood. According to the *bio-energy scenario*, the amount of stem residues reduced most strongly between 2010 and 2030 (-9%), but remained the most common type of deadwood. The average amount of standing deadwood reduced as well (-6%), but the amount of downed deadwood remained more or less constant over the 20-year period.

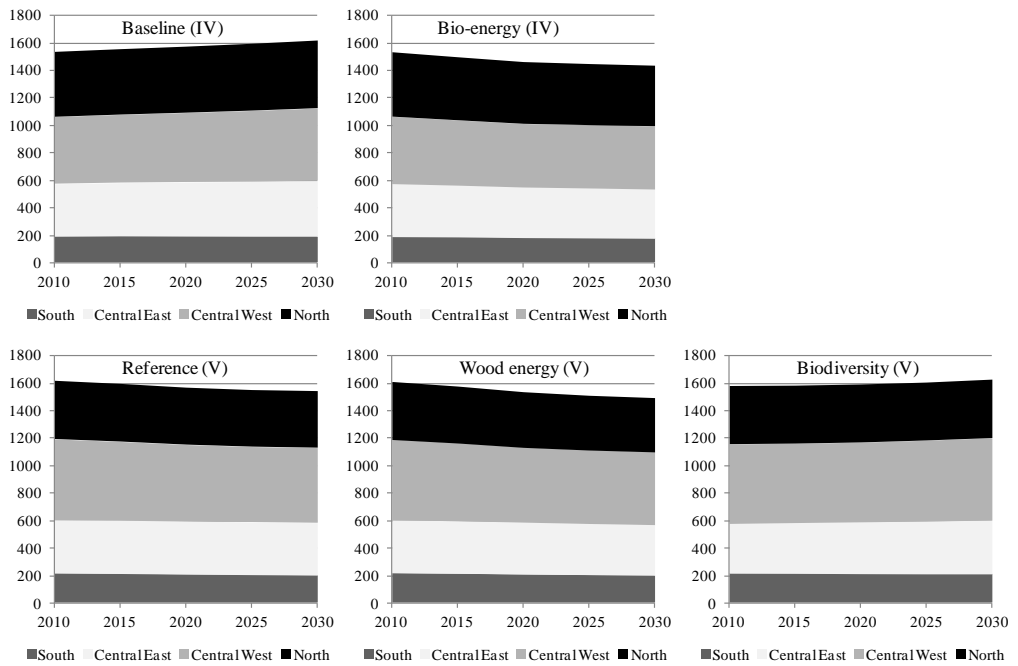


Figure 8: Projected development of total deadwood (Tg dry matter) in four European regions according to articles IV and V.

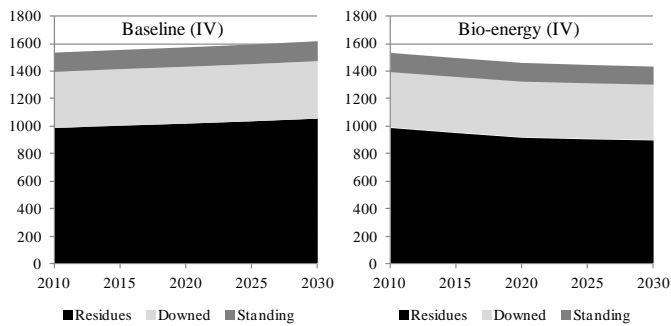


Figure 9: Projected development of different deadwood types (Tg dry matter) according to article IV.

Recreational attractiveness

Recreational attractiveness was quantified in article V (results not shown). Recreational attractiveness did not change at the European level according to the *reference scenario* (+0.1%) and the *wood energy scenario* (-0.4%). Results of the biodiversity scenario indicated a slightly larger recreational attractiveness by 0.5 points (+9.4%).

3.3.2 Economic impacts

The economic impacts of three different scenarios were estimated in article V by combining biophysical impacts with economic values (Figure 10). The *reference scenario* was ranked lowest resulting in a net loss of 0.69 euro ha⁻¹ yr⁻¹ in 2030 as compared to the situation in 2010. An intensification of wood and biomass production (i.e. the *wood energy scenario*) led to a net loss of 0.49 euro ha⁻¹ yr⁻¹. The biodiversity ranked highest with an estimated benefit of 4.84 euro ha⁻¹ yr⁻¹. This ranking of scenarios depended on the type of ecosystem services that were considered; the *wood energy scenario* would yield the highest economic gains if only marketed ecosystem services were considered. However, when non-marketed services are also considered, the *biodiversity scenario* yielded the largest gains.

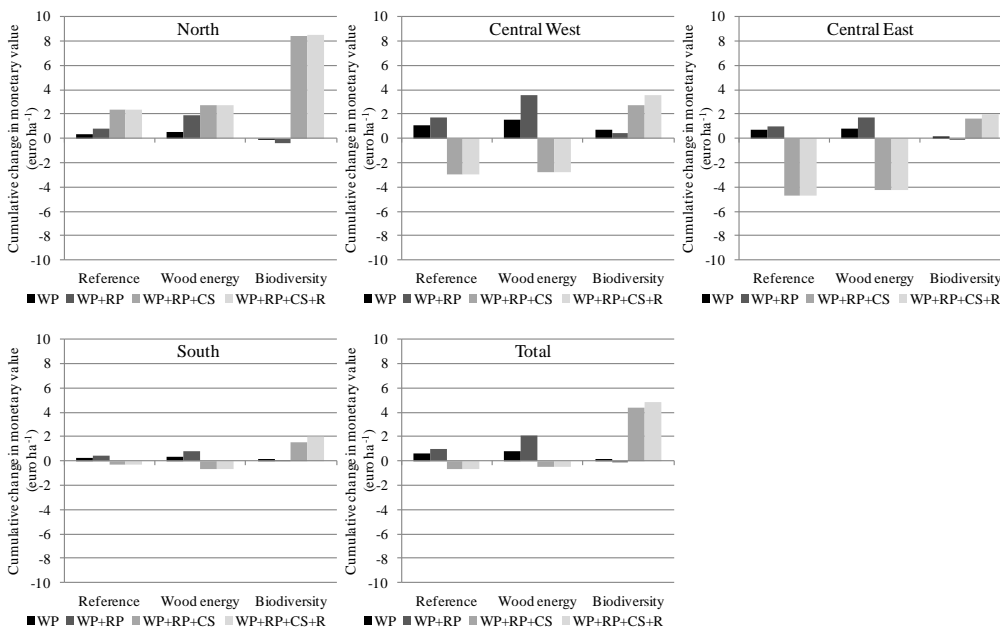


Figure 10: Cumulative economic impacts (euro ha⁻¹ yr⁻¹; 2010 euro values) on forest ecosystem service provisioning in 2030 as compared to 2010 for the reference, wood energy and biodiversity scenarios as estimated in article V. Explanation of abbreviations: WP: roundwood production; RP: residue and stump biomass production; CS: carbon storage; R: recreation.

4 DISCUSSION

4.1 Intensified biomass removal

Policies are currently being developed that aim at preventing further loss of biodiversity, as well as policies that may lead to a larger demand for wood or biomass from forests. Such policies may affect each other, as well as other ecosystem services provided by forests. In this synthesis, methods are presented that have been applied to assess the impacts of scenarios addressing intensified biomass production and biodiversity protection on a number of ecosystem services provided by European forests. This synthesis relies to a large extent on projections by applying the EFISCEN model for different scenarios. These scenarios were constructed to analyse what could happen if certain policy or management measures would be taken, but they are not predictions of what will happen in the future.

According to article II, the current realisable potential biomass supply from European forests was 741 million $\text{m}^3 \text{ ob yr}^{-1}$ in 2010 (of which 619 $\text{m}^3 \text{ ob yr}^{-1}$ in the form of roundwood) and could range from 620 to 891 million $\text{m}^3 \text{ ob yr}^{-1}$ in 2030. According to statistics, 405 million $\text{m}^3 \text{ ub yr}^{-1}$ was removed in 2010 in the EU in the form of roundwood (Forest Europe et al. 2011). Available information on removal of residues indicated that 20 million $\text{m}^3 \text{ yr}^{-1}$ was removed in the form of logging residues in 2005 (Steierer 2010), although data on removal of residues are not available for all countries. Altogether, these data suggest that there is significant potential to increase wood supply from European forests. To mobilise this potential, a significant increase in harvest level is required compared to the current situation. This implies quite drastic changes in forest management across Europe. Even in the low mobilisation scenario, potential removal rates are estimated to exceed current harvest levels and there would be more intensive forest management compared to current practices. In the high mobilisation scenario, biomass from stumps played an important role. However, stump harvesting is increasingly disputed (Walmsley and Godbold 2010) and it is not certain that the high mobilisation rate would be accepted by society.

Besides societal acceptance, the willingness of forest owners to supply biomass also needs to be considered. In article II, this was taken into account (in absence of European-wide empirical data) by assuming that maximum biomass extraction rates increased with forest holding size. Blennow et al. (2014) criticized this relationship and hence the estimated potentials; the authors conducted 800 interviews in Germany, Portugal and Sweden and found *“that European private forest owners’ readiness to increase the supply of woody biomass for energy is substantially lower”* than estimated in article II. However, Blennow et al. (2014) focused only on stemwood and did not ask whether owners are willing to mobilise residues and/or stumps from their forests, which represent an important part of the potentials estimated in article II. Furthermore, Blennow et al. (2014) asked forest owners about their attitude towards supplying woody biomass for energy generation, but did not ask them to think whether they are willing to supply it in case the demand from other wood markets would decline (cf. Hurmekoski and Hetemäki 2013). The attitude of forest owners to supply wood or biomass to meet future demands is an important factor to consider and owners may not be so eager to change established practices. Their attitude to mobilising more wood, however, remains unclear.

Although guidelines on biomass production have been taken into account when quantifying biomass potentials in article II, intensification of biomass production from European forests for renewable energy could increase the pressure on forest biodiversity (Jonsell 2008; Bouget et al. 2012; Lamers et al. 2013). Results of article IV indicate that the

amount of deadwood in European forests could increase in the next decades without taking any specific biodiversity measures due to ageing and additional inputs of stem residues from increasing felling levels. However, intensification of biomass removal could fully counteract this development at European level and reduce the amount of deadwood in 2030 below the levels that were estimated for 2005. Without additional management measures to protect deadwood, intensification of biomass removal could thus negatively affect deadwood-dependent species, which constitute an important part of biodiversity in European forests. Intensified biomass removal may also, however, have positive effects on light-demanding species in European forests and/or species associated with (neglected) coppice forests (Fuller 2013).

According to articles III and V, intensification of biomass production from European forests also affected the forest carbon sink. EFISCEN projected a decline in the observed sink of carbon (Figure 1) in managed forests of EU. The decreasing trend was mainly attributed to forest ageing and especially intensified biomass removals to meet renewable energy targets. This indicates that if use of wood for energy (as well as material use) is to be a climate effective strategy, these emissions from forests need to be accounted for.

When combining all impacts in an economic assessment in article V, intensified biomass removal was estimated to result in an economic loss across Europe, except in Northern Europe. This loss would be mainly due to decreased carbon sequestration rates in forest biomass. However, the economic loss may be smaller as compared to projections without specific measures to intensify use of forest biomass. Furthermore, intensified use of forest biomass could reduce emissions from fossil fuel burning or from the use of more energy intensive materials (Sathre and O'Connor 2010). Such substitution effects were not considered as they do not occur in forests, but they are relevant when quantifying all impacts of the investigated scenarios.

4.2 Biodiversity protection

Currently, about 16 million ha of European forests are protected with biodiversity as the main objective within the study area of this synthesis. Article I showed that felling restrictions imposed in these protected areas effectively reduce the long-term potential supply of wood from European forests by 35 million m³ ob annually (51% reduction of the long-term, annual supply within protected areas, or 5% reduction of the long-term, annual supply of the total forest area). Yet, fellings in these protected areas were found to be permitted to a fair extent. Given that (i) management intensity may increase to meet future materials and energy needs in forests that are available for supplying wood (UNECE-FAO 2011), which (ii) may increase pressure on biodiversity outside protected areas (article IV), the question could be raised whether biodiversity is sufficiently protected both inside and outside designated areas.

In article V, enlarging the area of protected forests, combined with biodiversity-oriented management practices was found to improve the provisioning of biodiversity, carbon storage and recreation, but it negatively affected wood, residue and stump biomass production. Overall, increased biodiversity protection provided larger economic benefits to society as compared to a situation without such measures.

4.3 Intensified biomass removal and biodiversity protection

Intensified biomass removal and biodiversity protection are both addressed through international conventions and, depending on their implementation, place competing demands on forests. Increased biomass removal for bio-energy production was found to negatively affect deadwood, as well as several non-provisioning ecosystem services within the study area. If attempts are to be made to avoid such impacts, for example by restricting intensification of biomass removals, it should be taken into account that such restrictions should not result in more greenhouse gas emissions through the use of other fuels or building materials (i.e. substitution), or through international trade and displacement of impacts to other parts of the world (Creutzig et al. 2014). Enhanced biodiversity protection, on the other hand, may decrease wood supply, but may positively affect other ecosystem services. The outcome of the economic assessment (article V) suggests that a strategy focusing on biodiversity protection would result in larger benefits to society than a strategy focusing on intensifying biomass removal. However, costs or benefits outside the study area were not assessed. Kallio et al. (2006) showed that if the protected area in the European Union, Norway and Switzerland were to be enlarged such that 5% of the growing stock would be protected, this would lead to a decreased harvest of roundwood of 3.1% in the area and to a 3.8% increase in harvest of roundwood in European Russia. This indicates that protection within Europe could lead to increased harvests in other parts of the world through international trade. Such displacement of impacts may have negative impacts on biodiversity outside Europe (Mayer et al. 2005). These findings indicate that the trade-offs between different ecosystem services through use of domestic resources need to be weighed against impacts that are occurring abroad.

It is also important to consider that the impacts of forest policy and management scenarios were only evaluated for a limited set of ecosystem services. An analysis of impacts should be further elaborated by including ecosystem services that were not considered in this dissertation, as well as other sustainability impacts that may occur, for example when processing wood (Lindner et al. 2012). Planning is needed to cope with these competing demands on forest resources, keeping in mind the global context. Such planning requires identifying (i) where biodiversity protection should be prioritized, (ii) where wood production could be maximized, but also (iii) where both biodiversity and wood production could be combined through integrated forest management.

4.4 Comparison with other data

In this dissertation, methods were developed and applied to assess impacts of intensified woody biomass removals on selected ecosystem services provided by forests. An attempt was made to compare the calculation results with other studies where possible. Article I quantified the effect of forest protection on European wood supply. Schmack et al. (2012) conducted a similar analysis for Germany. Stronger felling restrictions and substantially larger volumes of wood being unavailable were estimated in article I for Germany. Schmack et al. analysed site- and tree species specific restrictions and focused on Natura2000 sites, protected according to the Habitats Directive of the European Union (Council Directive 92/43/EEC). Due to data availability, a simpler approach was applied in article I in which only national level data from international statistics were used. Variations

in the extent of protected forest areas, as well as estimated restrictions imposed on these areas, may explain the differences.

In articles II-V, EFISCEN was used. The model has been validated for Finland and Switzerland using long-term forest inventory data (Nabuurs et al. 2000; Thürig and Schelhaas 2006). These validation studies found that the model was capable of reliably projecting the development of forest resources for periods up to 50–60 years. While the model has been validated in terms of its estimates of forest resource structure, its estimates of various ecosystem services have not been validated in a strict sense. In article II, an attempt was made to compare the estimated woody biomass potentials to other studies reviewed by Rettenmeier et al. (2010). It was found that the estimated potentials for 2010 compared rather well with other studies and that the low and high mobilisation scenarios more or less represented the minimum and maximum range reported by other studies.

In article III, EFISCEN was applied together with the G4M model. These two models were harmonized as well as possible in their major assumptions on input data (forest area, age-structure, harvested wood) and both projected a decline compared to the observed sink of carbon in managed forests of EU, but the rates differed. The decline was estimated to be about 25% according to EFISCEN and 40% according to G4M, in 2030 relative to 2010. These differences could be explained by differences in data despite harmonization efforts. Furthermore, management actions are implemented differently in the two models; EFISCEN determines rotation lengths based on management guidelines combined with the demand for wood from domestic resources, while G4M applies an optimization procedure aiming at satisfying the demand for wood from domestic sources and taking into account growth conditions. Also the distribution of harvest over thinning and final fellings is different between the models. The projections by both models have also been compared with data from greenhouse gas inventories that European countries submit annually to the UNFCCC (Groen et al. 2013). Differences exist between estimates of EFISCEN and G4M on the one hand and national estimates on the other hand. No single factor was identified that explained these differences, but variables such as biomass expansion factors, harvest volumes and the way harvest losses are treated were considered to explain differences observed for individual countries.

In article IV, EFISCEN results were compared with reported deadwood amounts according to national or international statistics. For countries for which proper data on mortality and/or fall rates were available, EFISCEN projected standing deadwood rather well. For countries in which less detailed data on mortality and fall rates were available larger differences were found, but EFISCEN results were generally comparable with reported deadwood amounts.

4.5 Uncertainties

The approaches that were developed and applied in articles I-V were all data-based approaches and the results are thus dependent on the availability and quality of data across Europe. In some cases, simple approaches had to be applied and rough assumptions had to be made. This introduces uncertainties in the estimates presented in this dissertation.

To assess the annual felling potential from protected areas in article I, the net annual increment was used of all forests in a country. These data were used in absence of detailed resource information on the location, structure and growth of protected forests. Protected areas are, however, often located on sites with lower productivity, at higher elevation, on

steeper slopes and at greater distance from roads and cities (Joppa and Pfaff 2009; Boncina 2011). Growth rates of protected forests may thus deviate from the average national-level net annual increment. Furthermore, the use of net annual increment as a measure for the felling potential assumes an equal distribution of area over age-classes. This does not hold for most of Europe's forests, as there is generally a larger share of young forests (Vilén et al. 2012). Hence, the use of the net annual increment in article I may lead to an overestimate of the wood volumes unavailable due to forest protection.

In articles II-V, EFISCEN was used to project resource development. There are uncertainties associated with these projections due to (the combined effect of) the structure of the model, quality of data that were used and/or scenarios that were analysed. With regards to the structure of the model, the main weakness of EFISCEN is that the model is designed for managed, even-aged forests; projections for unmanaged, uneven-aged, or shelterwood forests should therefore be considered less reliable.

Despite the use of the same model in articles III-V, differences could be observed in the results presented in this synthesis. These differences are due to differences in input data (forest inventory data, historical wood production statistics), as well as the scenarios that were analysed. For projection of future resource development, wood demand is one of the main drivers in the model. The demand for wood differed between the scenarios in articles III-V already under reference conditions (Figure 5), resulting in different harvest levels and different impacts on ecosystem services. These differences can be explained by differences in the construction of the scenarios; in article IV, the demand for wood was linked to estimates of economic growth, while articles III and V also included the effects of global trade with the help of the forest sector models GLOBIOM and EFI-GTM, respectively. The use of different forest sector models, as well as different assumptions on economic growth, leads to differences in estimated future wood demand. Uncertainty about the development of the forest sector leads to uncertainty about the future development of forest resources, and vice versa.

Besides wood demand, climate change is a factor becoming increasingly important for European forest resources (Eggers et al. 2008; de Vries and Posch 2011). While the regional patterns of climate change impacts on European forests are increasingly better understood (Lindner et al. 2010; Lindner et al. 2014) the exact impacts of climate change on e.g. growth rates are still not well understood and depend on future global development (Reyer et al. 2014). Changes in growth rates have been included in article V only and explain to some extent differences in article V, as compared to articles III and IV. Besides growth changes, climate change has also been linked to recent and future increases in forest disturbances from fires, storm and insect outbreaks (Seidl et al. 2014). The potential impact of disturbances have not been considered in the results presented in this dissertation. Increases in damage from forest fire could reduce harvest potentials, whereas increases in storm events could lead to sudden availability of large amounts of wood and disrupt timber markets in the short-term and may affect the future availability of wood in the long-term. Similarly, disturbances may also affect the amount and type of deadwood that is formed in European forests, as well as other ecosystem services provided by forests (Seidl et al. 2014).

To summarize, challenges remain in assessing future forest resource development as well as the impacts of different forest-related policies and their related forest management, but these challenges should not be an impediment to develop and improve assessments of the kind presented in this dissertation. The analyses presented here provide a basis for informed decision-making and help to point out gaps in existing knowledge about European

forest resources. The analyses could be improved through the use of additional and better quality data on European forests, but also through the use of more sophisticated forest resource models that are better able to address forest resource development, taking into account the broad range of current and future forest management practices and impacts of climate change across Europe.

5 CONCLUSIONS

Forests provide many benefits to society and it is important to understand if, and how, changing forest policies may affect the provisioning of ecosystem services. This dissertation synthesizes articles I-V in which an analysis and evaluation is presented of the impacts of intensified biomass production and biodiversity protection on the ecosystem services of European forests.

Protected forests covered 11% of forests within the 24 European countries included in this synthesis in 2005. Felling restrictions applied in these protected areas reduce the long-term potential supply of wood from European forests by 35 million $\text{m}^3 \text{ ob yr}^{-1}$. In all European forests that are available for wood supply, the realistic harvest potential was estimated at 741 million $\text{m}^3 \text{ ob yr}^{-1}$ in 2010, including woody biomass from stems, residues, stumps and other biomass. Projections of future realisable biomass potentials indicate a range from 620 to 891 million $\text{m}^3 \text{ ob yr}^{-1}$ in 2030, depending on the extent to which measures are taken to restrict or enhance the mobilisation of wood for producing energy or materials as compared to current guidelines. While these projections indicate that it is possible to increase the availability of forest biomass significantly beyond the current level of resource utilization, implementing these ambitious scenarios would imply quite drastic changes in the current management of European forests.

Increases in resource utilization in terms of woody biomass removals will involve trade-offs with other ecosystem services provided by forests. For example, the carbon sink and the amount of deadwood are projected to decline in scenarios that include policy measures to intensify the use of existing forests to produce more woody biomass as compared to projections without such measures. Results of an economic valuation show that intensifying biomass removals could lead to a net economic benefit measured by the aggregated value of five ecosystem services, as compared to projections without measures to intensify use of forest biomass. Larger social benefits could potentially be obtained if biodiversity protection is enhanced in European forests.

It should be noted that the assessments presented in this dissertation are not predictions of what will happen in the future. Rather, they are projections of what could happen. The projections depend heavily on the availability and quality of data across Europe, as well as the assumptions made in the scenarios that were presented. Important assumptions relate to the system boundaries considered, e.g. impacts inside and outside Europe due to international trade or the effects of substituting more emission-intensive materials.

The approach presented in this dissertation offers a means to assess the development of several ecosystem services in large-scale forest resource assessments. Previous assessments focused more on the (future) structure of Europe's forest resources or addressed few ecosystem services at a time, but the work presented in this dissertation focuses on multiple benefits that these resources provide to human society and how they are affected by different forest-related policies that are being considered. Results of the assessment presented here could be used as support to guide forest related policy development and implementation as they provide consistent information across Europe.

The results presented here illustrate the need for careful planning to accommodate both the need for protection of biodiversity, the expected growing demand for wood as well as the provisioning of other services by forests. Such planning requires identifying (i) where biodiversity protection should be prioritized, (ii) where wood production could be maximized, but also (iii) where both biodiversity and wood production could be combined through integrated forest management.

REFERENCES

Alakangas E., Heikkinen A., Lensu T., Vesterinen P. (2007). Biomass fuel trade in Europe. Summary Report VTTR0350807. VTT Technical Research Centre of Finland, Jyväskylä.

Başkent E., Keleş S., Kadioğulları A., Bingöl Ö. (2011). Quantifying the Effects of Forest Management Strategies on the Production of Forest Values: Timber, Carbon, Oxygen, Water, and Soil. *Environmental Modeling and Assessment* 16, 145-152.
<http://dx.doi.org/10.1007/s10666-010-9238-y>

Bateman I. J., Harwood A. R., Mace G. M., Watson R. T., Abson D. J., Andrews B., Binner A., Crowe A., Day B. H., Dugdale S., Fezzi C., Foden J., Hadley D., Haines-Young R., Hulme M., Kontoleon A., Lovett A. A., Munday P., Pascual U., Paterson J., Perino G., Sen A., Siriwardena G., van Soest D., Termansen M. (2013). Bringing ecosystem services into economic decision-making: land use in the United Kingdom. *Science* 341, 45-50.
<http://dx.doi.org/10.1126/science.1234379>

Bellassen V., Viovy N., Luysaert S., Le Maire G., Schelhaas M.-J., Ciais P. (2011). Reconstruction and attribution of the carbon sink of European forests between 1950 and 2000. *Global Change Biology* 17, 3274-3292.
<http://dx.doi.org/10.1111/j.1365-2486.2011.02476.x>

Bennett E. M., Peterson G. D., Gordon L. J. (2009). Understanding relationships among multiple ecosystem services. *Ecology Letters* 12, 1394-1404.
<http://dx.doi.org/10.1111/j.1461-0248.2009.01387.x>

Blennow K., Persson E., Lindner M., Faias S. P., Hanewinkel M. (2014). Forest owner motivations and attitudes towards supplying biomass for energy in Europe. *Biomass and Bioenergy* 67, 223-230.
<http://dx.doi.org/10.1016/j.biombioe.2014.05.002>

Bolkesjø T. F., Tromborg E., Solberg B. (2005). Increasing Forest Conservation in Norway: Consequences for Timber and Forest Products Markets. *Environmental and Resource Economics* 31, 95-115.
<http://dx.doi.org/10.1007/s10640-004-8248-0>

Boncina A. (2011). Conceptual approaches to integrate nature conservation into forest management: a Central European perspective. *International Forestry Review* 13, 13-22.
<http://dx.doi.org/10.1505/ifor.13.1.13>

Bouget C., Lassauce A., Jonsell M. (2012). Effects of fuelwood harvesting on biodiversity - a review focused on the situation in Europe. *Canadian Journal of Forest Research* 42, 1421-1432.
<http://dx.doi.org/10.1139/x2012-078>

Bradshaw R. H. W. (2004). Past anthropogenic influence on European forests and some possible genetic consequences. *Forest Ecology and Management* 197, 203-212.
<http://dx.doi.org/10.1016/j.foreco.2004.05.025>

Brukas V., Felton A., Lindbladh M., Sallnäs O. (2013). Linking forest management, policy and biodiversity indicators – A comparison of Lithuania and Southern Sweden. *Forest Ecology and Management* 291, 181-189.
<http://dx.doi.org/10.1016/j.foreco.2012.11.034>

Butchart S. H. M., Walpole M., Collen B., van Strien A., Scharlemann J. P. W., Almond R. E. A., Baillie J. E. M., Bomhard B., Brown C., Bruno J., Carpenter K. E., Carr G. M., Chanson J., Chenery

A. M., Csirke J., Davidson N. C., Dentener F., Foster M., Galli A., Galloway J. N., Genovesi P., Gregory R. D., Hockings M., Kapos V., Lamarque J.-F., Leverington F., Loh J., McGeoch M. A., McRae L., Minasyan A., Morcillo M. H., Oldfield T. E. E., Pauly D., Quader S., Revenga C., Sauer J. R., Skolnik B., Spear D., Stanwell-Smith D., Stuart S. N., Symes A., Tierney M., Tyrrell T. D., Vié J.-C., Watson R. (2010). Global biodiversity: indicators of recent declines. *Science* 328, 1164-1168.
<http://dx.doi.org/10.1126/science.1187512>

Ciais P., Schelhaas M. J., Zaehle S., Piao S. L., Cescatti A., Liski J., Luysaert S., Le-Maire G., Schulze E. D., Bouriaud O., Freibauer A., Valentini R., Nabuurs G. J. (2008). Carbon accumulation in European forests. *Nature Geoscience* 1, 425-429.
<http://dx.doi.org/10.1038/ngeo233>

Cooper C. F. (1983). Carbon storage in managed forests. *Canadian Journal of Forest Research* 13, 155-166.
<http://dx.doi.org/10.1139/x83-022>

Creutzig F., Ravindranath N. H., Berndes G., Bolwig S., Bright R., Cherubini F., Chum H., Corbera E., Delucchi M., Faaij A., Fargione J., Haberl H., Heath G., Lucon O., Plevin R., Popp A., Robledo-Abad C., Rose S., Smith P., Stromman A., Suh S., Masera O. (2014). Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*.
<http://dx.doi.org/10.1111/gcbb.12205>

de-Miguel S., Pukkala T., Yeşil A. (2014). Integrating pine honeydew honey production into forest management optimization. *European Journal of Forest Research* 133, 423-432.
<http://dx.doi.org/10.1007/s10342-013-0774-2>

de Groot R., Fisher B., Christie M., Aronson J., Braat L., Gowdy J., Haines-Young R., Maltby E., Neuville A., Polasky S., Portela R., Ring I. (2010). Chapter 1. Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation. In: P. Kumar (Ed.), *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. Earthscan, London, Washington, pp. 9-40.

de Vries W., Dobbertin M. H., Solberg S., van Dobben H. F., Schaub M. (2014). Impacts of acid deposition, ozone exposure and weather conditions on forest ecosystems in Europe: an overview. *Plant and Soil* 380, 1-45.
<http://dx.doi.org/10.1007/s11104-014-2056-2>

de Vries W., Posch M. (2011). Modelling the impact of nitrogen deposition, climate change and nutrient limitations on tree carbon sequestration in Europe for the period 1900-2050. *Environmental Pollution* 159, 2289-2299.
<http://dx.doi.org/10.1016/j.envpol.2010.11.023>

de Vries W., Solberg S., Dobbertin M., Sterba H., Laubhann D., van Oijen M., Evans C., Gundersen P., Kros J., Wamelink G. W. W., Reinds G. J., Sutton M. A. (2009). The impact of nitrogen deposition on carbon sequestration by European forests and heathlands. *Forest Ecology and Management* 258, 1814-1823.
<http://dx.doi.org/10.1016/j.foreco.2009.02.034>

Diakoulaki D., Karangelis F. (2007). Multi-criteria decision analysis and cost-benefit analysis of alternative scenarios for the power generation sector in Greece. *Renewable and Sustainable Energy Reviews* 11, 716-727.
<http://dx.doi.org/10.1016/j.rser.2005.06.007>

Edwards D. M., Jay M., Jensen F. S., Lucas B., Marzano M., Montagné C., Peace A., Weiss G. (2012). Public Preferences Across Europe for Different Forest Stand Types as Sites for Recreation. *Ecology and Society* 17.

<http://dx.doi.org/10.5751/es-04520-170127>

EEA (2006). How much bioenergy can Europe produce without harming the environment? EEA report no. 7/2006. European Environment Agency, Copenhagen.

Eggers J., Lindner M., Zudin S., Zaehle S., Liski J. (2008). Impact of changing wood demand, climate and land use on European forest resources and carbon stocks during the 21st century. *Global Change Biology* 14, 1-16.

<http://dx.doi.org/10.1111/j.1365-2486.2008.01653.x>

Erb K.-H., Kastner T., Luyssaert S., Houghton R. A., Kuemmerle T., Olofsson P., Haberl H. (2013). Bias in the attribution of forest carbon sinks. *Nature Climate Change* 3, 854-856.

<http://dx.doi.org/10.1038/nclimate2004>

European Forest Institute (2007). COST E27. PFA tables. http://www.efi.int/portal/project/cost_e27/results/pfa_tables/ [accessed 22 January 2008]. European Forest Institute, Joensuu.

Fernandez-Martinez M., Vicca S., Janssens I. A., Sardans J., Luyssaert S., Campioli M., Chapin Iii F. S., Ciais P., Malhi Y., Obersteiner M., Papale D., Piao S. L., Reichstein M., Roda F., Penuelas J. (2014). Nutrient availability as the key regulator of global forest carbon balance. *Nature Climate Change* 4, 471-476.

<http://dx.doi.org/10.1038/nclimate2177>

Foley J. A., DeFries R., Asner G. P., Barford C., Bonan G., Carpenter S. R., Chapin F. S., Coe M. T., Daily G. C., Gibbs H. K., Helkowski J. H., Holloway T., Howard E. A., Kucharik C. J., Monfreda C., Patz J. A., Prentice I. C., Ramankutty N., Snyder P. K. (2005). Global consequences of land use. *Science* 309, 570-574.

<http://dx.doi.org/10.1126/science.1111772>

Forest Europe, UNECE, FAO (2011). State of Europe's forests 2011. Status and trends in sustainable forest management in Europe. Ministerial Conference on the Protection of Forests in Europe. Forest Europe liaison unit Oslo, Ås.

Frank G., Parviainen J., Vandekerckhove K., Latham J., Schuck A., Little D. (Eds.) (2007). COST Action E27 Protected forest areas in Europe-analysis and harmonisation (PROFOR): results, conclusions and recommendations. Federal research and training centre for forests, natural hazards and landscape (BFW), Vienna.

Fuchs R., Herold M., Verburg P. H., Clevers J. G. P. W. (2013). A high-resolution and harmonized model approach for reconstructing and analysing historic land changes in Europe. *Biogeosciences* 10, 1543-1559.

<http://dx.doi.org/10.5194/bg-10-1543-2013>

Fuller R. J. (2013). Searching for biodiversity gains through woodfuel and forest management. *Journal of Applied Ecology* 50, 1295-1300.

<http://dx.doi.org/10.1111/1365-2664.12152>

Gamfeldt L., Snäll T., Bagchi R., Jonsson M., Gustafsson L., Kjellander P., Ruiz-Jaen M. C., Froberg M., Stendahl J., Philipson C. D., Mikusinski G., Andersson E., Westerlund B., Andren H., Moberg F., Moen J., Bengtsson J. (2013). Higher levels of multiple ecosystem services are found in forests with more tree species. *Nature Communications* 4, 1340.

<http://dx.doi.org/10.1038/ncomms2328>

Giergiczny M., Mavsar R., Wenchao Z. (2008). Report documenting the results of the meta-data analysis linking the monetary values with the physical characteristics of forests. Fondazione Eni Enrico Mattei, Milano.

Gold S. (2003). The development of European forest resources, 1950 to 2000: a better information base. Geneva timber and forest discussion paper 31. UNECE/FAO, Geneva.

Gold S., Korotkov A., Sasse V. (2006). The development of European forest resources, 1950 to 2000. *Forest Policy and Economics* 8, 183-192.
<http://dx.doi.org/10.1016/j.forpol.2004.07.002>

Goodale C. L., Apps M. J., Birdsey R., Field C. B., Heath L. S., Houghton R. A., Jenkins J. C., Kohlmaier G. H., Kurz W., Liu S., Nabuurs G.-J., Nilsson S., Shvidenko A. Z. (2002). Forest carbon sinks in the Northern hemisphere. *Ecological Applications* 12, 891-899.
[http://dx.doi.org/10.1890/1051-0761\(2002\)012\[0891:FCSITN\]2.0.CO;2](http://dx.doi.org/10.1890/1051-0761(2002)012[0891:FCSITN]2.0.CO;2)

Groen T. A., Verkerk P. J., Böttcher H., Grassi G., Cienciala E., Black K. G., Fortin M., Köthke M., Lehtonen A., Nabuurs G.-J., Petrova L., Blujdea V. (2013). What causes differences between national estimates of forest management carbon emissions and removals compared to estimates of large-scale models? *Environmental Science & Policy* 33, 222-232.
<http://dx.doi.org/10.1016/j.envsci.2013.06.005>

Gundersen V. S., Frivold L. H. (2008). Public preferences for forest structures: A review of quantitative surveys from Finland, Norway and Sweden. *Urban Forestry and Urban Greening* 7, 241-258.
<http://dx.doi.org/10.1016/j.ufug.2008.05.001>

Haberl H., Erb K. H., Krausmann F., Gaube V., Bondeau A., Plutzer C., Gingrich S., Lucht W., Fischer-Kowalski M. (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences* 104, 12942-12947.
<http://dx.doi.org/10.1073/pnas.0704243104>

Hanewinkel M., Cullmann D. A., Schelhaas M.-J., Nabuurs G.-J., Zimmermann N. E. (2013). Climate change may cause severe loss in the economic value of European forest land. *Nature Climate Change* 3, 203-207.
<http://dx.doi.org/10.1038/nclimate1687>

Hänninen R., Kallio A. M. I. (2007). Economic impacts on the forest sector of increasing forest biodiversity conservation in Finland. *Silva Fennica* 41, 507-523.
<http://dx.doi.org/10.14214/sf.286>

Helming K., Diehl K., Bach H., Dilly O., König B., Kuhlman T., Pérez-Soba M., Sieber S., Tabbush P., Tscherning K., Wascher D., Wiggering H. (2011). Ex Ante Impact Assessment of Policies Affecting Land Use, Part A: Analytical Framework. *Ecology and Society* 16.
<http://www.ecologyandsociety.org/vol16/iss1/art29/>

Hengeveld G. M., Nabuurs G.-J., Didion M., van den Wyngaert I., Clercx A. P. P. M., Schelhaas M.-J. (2012). A forest management map of European Forests. *Ecology and Society* 17.
<http://dx.doi.org/10.5751/es-05149-170453>

Hood S. M., Zedaker S. M., Aust W. M., Smith D. W. (2002). Universal Soil Loss Equation (USLE)-predicted soil loss for harvesting regimes in appalachian hardwoods. *Northern Journal of Applied Forestry* 19, 53-58.

Hurmekoski E., Hetemäki L. (2013). Studying the future of the forest sector: Review and implications for long-term outlook studies. *Forest Policy and Economics* 34, 17-29.
<http://dx.doi.org/10.1016/j.forpol.2013.05.005>

Hurmekoski E., Hetemäki L., Linden M. (2014). Factors affecting sawnwood consumption in Europe. *Forest Policy and Economics*.
<http://dx.doi.org/10.1016/j.forpol.2014.07.008>

Huston M. A., Marland G. (2003). Carbon management and biodiversity. *Journal of Environmental Management* 67, 77-86.
[http://dx.doi.org/10.1016/S0301-4797\(02\)00190-1](http://dx.doi.org/10.1016/S0301-4797(02)00190-1)

Jonsell M. (2008). The effects of forest biomass harvesting on biodiversity. In: D. Röser, A. Asikainen, K. Raulund-Rasmussen, I. Stupak (Eds.), *Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic region*. Springer, Dordrecht, pp. 129-154.

Joppa L. N., Pfaff A. (2009). High and Far: Biases in the Location of Protected Areas. *PLoS ONE* 4, e8273.
<http://dx.doi.org/10.1371/journal.pone.0008273>

Joubert A. R., Leiman A., de Klerk H. M., Katua S., Aggenbach J. C. (1997). Fynbos (fine bush) vegetation and the supply of water: a comparison of multi-criteria decision analysis and cost-benefit analysis. *Ecological Economics* 22, 123-140.
[http://dx.doi.org/10.1016/S0921-8009\(97\)00573-9](http://dx.doi.org/10.1016/S0921-8009(97)00573-9)

Kallio A. M. I., Moiseyev A., Solberg B. (2006). Economic impacts of increased forest conservation in Europe: a forest sector model analysis. *Environmental Science & Policy* 9, 457-465.
<http://dx.doi.org/10.1016/j.envsci.2006.03.002>

Kangas J., Kangas A., Leskinen P., Pykäläinen J. (2001). MCDM methods in strategic planning of forestry on state-owned lands in Finland: applications and experiences. *Journal of Multi-Criteria Decision Analysis* 10, 257-271.
<http://dx.doi.org/10.1002/mcda.306>

Kangas K., Baudin A. (2003). Modelling and projections of forest products demand, supply and trade in Europe. A study prepared for the European Forest Sector Outlook Study (EFSOS). Geneva timber and forest discussion paper 30. ECE/TIM/DP/30. UNECE/FAO, Timber Section., Genva, New York.

Kaplan J. O., Krumhardt K. M., Zimmermann N. (2009). The prehistoric and preindustrial deforestation of Europe. *Quaternary Science Reviews* 28, 3016-3034.
<http://dx.doi.org/10.1016/j.quascirev.2009.09.028>

Karjalainen T., Pussinen A., Liski J., Nabuurs G. J., Eggers T., Lapveteläinen T., Kaipainen T. (2003). Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget. *Forest Policy and Economics* 5, 141-155.
[http://dx.doi.org/10.1016/S1389-9341\(03\)00021-2](http://dx.doi.org/10.1016/S1389-9341(03)00021-2)

Kindermann G., Obersteiner M., Sohngen B., Sathaye J., Andrasko K., Rametsteiner E., Schlamadinger B., Wunder S., Beach R. (2008). Global cost estimates of reducing carbon emissions through avoided deforestation. *Proceedings of the National Academy of Sciences* 105, 10302-10307.
<http://dx.doi.org/10.1073/pnas.0710616105>

Kindermann G., Schorghuber S., Linkosalo T., Sanchez A., Rammer W., Seidl R., Lexer M. (2013). Potential stocks and increments of woody biomass in the European Union under different management and climate scenarios. *Carbon Balance and Management* 8, 2.
<http://dx.doi.org/10.1186/1750-0680-8-2>

Körner C., Asshoff R., Bignucolo O., Hättenschwiler S., Keel S. G., Peláez-Riedl S., Pepin S., Siegwolf R. T. W., Zotz G. (2005). Carbon flux and growth in mature deciduous forest trees exposed to elevated CO₂. *Science* 309, 1360-1362.
<http://dx.doi.org/10.1126/science.1113977>

Krankina O. N., Harmon M. E. (1995). Dynamics of the Dead Wood Carbon Pool in Northwestern Russian Boreal Forests. *Water Air and Soil Pollution* 82, 227-238.

Kuusela K. (1994). Forest resources in Europe. European Forest Institute research report 1. Cambridge University Press, Cambridge.

Lamers P., Thiffault E., Paré D., Junginger M. (2013). Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. *Biomass and Bioenergy* 55, 212-226.
<http://dx.doi.org/10.1016/j.biombioe.2013.02.002>

Leppänen J., Linden M., Uusivuori J., Pajujoja H. (2005). The private cost and timber market implications of increasing strict forest conservation in Finland. *Forest Policy and Economics* 7, 71-83.
[http://dx.doi.org/10.1016/S1389-9341\(03\)00012-1](http://dx.doi.org/10.1016/S1389-9341(03)00012-1)

Levers C., Verkerk P. J., Müller D., Verburg P. H., Butsic V., Leitão P. J., Lindner M., Kuemmerle T. (2014). Drivers of forest harvesting intensity patterns in Europe. *Forest Ecology and Management* 315, 160-172.
<http://dx.doi.org/10.1016/j.foreco.2013.12.030>

Linden M., Uusivuori J. (2002). Econometric analysis of forest conservation: the Finnish experience. *Environment and development economics* 7, 281-297.
<http://dx.doi.org/10.1017/S1355770X02000189>

Lindner M., Fitzgerald J. B., Zimmermann N. E., Reyer C., Delzon S., van der Maaten E., Schelhaas M.-J., Lasch P., Eggers J., van der Maaten-Theunissen M., Suckow F., Psomas A., Poulter B., Hanewinkel M. (2014). Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *Journal of Environmental Management* 146, 69-83.
<http://dx.doi.org/10.1016/j.jenvman.2014.07.030>

Lindner M., Maroschek M., Netherer S., Kremer A., Barbati A., Garcia-Gonzalo J., Seidl R., Delzon S., Corona P., Kolström M., Lexer M. J., Marchetti M. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management* 259, 698-709.
<http://dx.doi.org/10.1016/j.foreco.2009.09.023>

Lindner M., Werhahn-Mees W., Suominen T., Vötter D., Zudin S., Pekkanen M., Päivinen R., Roubalova M., Kneblík P., Brüchert F., Valinger E., Guinard L., Pizzirani S. (2012). Conducting sustainability impact assessments of forestry-wood chains: examples of ToSIA applications. *European Journal of Forest Research* 131, 21-34.
<http://dx.doi.org/10.1007/s10342-011-0483-7>

Liski J., Palosuo T., Peltoniemi M., Sievanen R. (2005). Carbon and decomposition model Yasso for forest soils. *Ecological Modelling* 189, 168-182.
<http://dx.doi.org/10.1016/j.ecolmodel.2005.03.005>

Luyssaert S., Ciais P., Piao S. L., Schulze E. D., Jung M., Zaehle S., Schelhaas M. J., Reichstein M., Churkina G., Papale D., Abril G., Beer C., Grace J., Loustau D., Matteucci G., Magnani F., Nabuurs

G. J., Verbeeck H., Sulkava M., Van Der Werf G. R., Janssens I. A., members of the C-I. S. T. (2010). The European carbon balance. Part 3: forests. *Global Change Biology* 16, 1429-1450.
<http://dx.doi.org/10.1111/j.1365-2486.2009.02056.x>

Mäkinen H., Hynynen J., Siitonen J., Sievänen R. (2006). Predicting the decomposition of Scots pine, Norway spruce and birch stems in Finland. *Ecological Applications* 16, 1865-1879.
[http://dx.doi.org/10.1890/1051-0761\(2006\)016\[1865:PTDOSP\]2.0.CO;2](http://dx.doi.org/10.1890/1051-0761(2006)016[1865:PTDOSP]2.0.CO;2)

Mayer A. L., Kauppi P. E., Angelstam P. K., Zhang Y., Tikka P. M. (2005). Importing timber, exporting ecological impact. *Science* 308, 359-360.
<http://dx.doi.org/10.1126/science.1109476>

MCPFE (2007). State of Europe's forests 2007. The MCPFE report on sustainable forest management in Europe. MCPFE Liaison Unit Warsaw, UNECE and FAO, Warsaw.

McShane T. O., Hirsch P. D., Trung T. C., Songorwa A. N., Kinzig A., Monteferri B., Mutekanga D., Thang H. V., Dammert J. L., Pulgar-Vidal M., Welch-Devine M., Peter Brosius J., Coppolillo P., O'Connor S. (2011). Hard choices: Making trade-offs between biodiversity conservation and human well-being. *Biological Conservation* 144, 966-972.
<http://dx.doi.org/10.1016/j.biocon.2010.04.038>

Miina J., Pukkala T., Hotanen J.-P., Salo K. (2010). Optimizing the joint production of timber and bilberries. *Forest Ecology and Management* 259, 2065-2071.
<http://dx.doi.org/10.1016/j.foreco.2010.02.017>

Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being: current state & trends assessment*. Volume 1. Island Press, Washington.

Mooney H., Cropper A., Reid W. (2005). Confronting the human dilemma. *Nature* 434, 561-562.
<http://dx.doi.org/10.1038/434561a>

Mubareka S., Jonsson R., Rinaldi F., Fiorese G., San-Miguel-Ayanz J., Sallnäs O., Baranzelli C., Pilli R., Lavalley C., Kitous A. (2014). An Integrated Modelling Framework for the Forest-based Bioeconomy. *Earthzine*.
<http://dx.doi.org/10.1101/011932>

Nabuurs G.-J., Lindner M., Verkerk P. J., Gunia K., Deda P., Michalak R., Grassi G. (2013). First signs of carbon sink saturation in European forest biomass. *Nature Climate Change* 3, 792-796.
<http://dx.doi.org/10.1038/nclimate1853>

Nabuurs G.-J., Schelhaas M.-J., Pussinen A. (2000). Validation of the European Forest Information Scenario Model (EFISCEN) and a projection of Finnish forests. *Silva Fennica* 34, 167-179.
<http://dx.doi.org/10.14214/sf.638>

Nabuurs G., Pussinen A., van Brusselen J., Schelhaas M. (2007). Future harvesting pressure on European forests. *European Journal of Forest Research* 126, 391-400.
<http://dx.doi.org/0.1007/s10342-006-0158-y>

Nabuurs G. J., Päivinen R., Pussinen A., Schelhaas M. J. (2003a). *Development of European forests until 2050 - a projection of forests and forest management in thirty countries*. Brill, Leiden, Boston, Köln.

Nabuurs G. J., Paivinen R., Schanz H. (2001a). Sustainable management regimes for Europe's forests - a projection with EFISCEN until 2050. *Forest Policy and Economics* 3, 155-173.
[http://dx.doi.org/10.1016/S1389-9341\(01\)00058-2](http://dx.doi.org/10.1016/S1389-9341(01)00058-2)

Nabuurs G. J., Päivinen R., Schelhaas M. J., Pussinen A., Verkaik E., Lioubimow A., Mohren F. (2001b). Nature-oriented forest management in Europe: Modeling the long-term effects. *Journal of Forestry* 99, 28-34.

Nabuurs G. J., Schelhaas M. J., Mohrens G. M. J., Field C. B. (2003b). Temporal evolution of the European forest sector carbon sink from 1950 to 1999. *Global Change Biology* 9, 152-160.
<http://dx.doi.org/10.1046/j.1365-2486.2003.00570.x>

Ness B., Urbel-Piirsalu E., Anderberg S., Olsson L. (2007). Categorising tools for sustainability assessment. *Ecological Economics* 60, 498-508.
<http://dx.doi.org/10.1016/j.ecolecon.2006.07.023>

Paillet Y., Bergès L., Hjältén J., Ódor P., Avon C., Bernhardt-Römermann M., Bijlsma R.-J., De Bruyn L. U. C., Fuhr M., Grandin U. L. F., Kanka R., Lundin L., Luque S., Magura T., Matesanz S., Mészáros I., Sebastià M. T., Schmidt W., Standovár T., Tóthmérész B., Uotila A., Valladares F., Vellak K. A. I., Virtanen R. (2010). Biodiversity Differences between Managed and Unmanaged Forests: Meta-Analysis of Species Richness in Europe. *Conservation Biology* 24, 101-112.
<http://dx.doi.org/10.1111/j.1523-1739.2009.01399.x>

Päivinen R., Lindner M., Rosen K., Lexer M. J. (2012). A concept for assessing sustainability impacts of forestry-wood chains. *European Journal of Forest Research* 131, 7-19.
<http://dx.doi.org/10.1007/s10342-010-0446-4>

Palahí M., Pukkala T., Bonet J. A., Colinas C., Fischer C. R., Martínez de Aragón J. R. (2009). Effect of the inclusion of mushroom values on the optimal management of even-aged pine stands of Catalonia. *Forest Science* 55, 503-511.

Parviainen J., Frank G. (2003). Protected forests in Europe approaches - harmonising the definitions for international comparison and forest policy making. *Journal of Environmental Management* 67, 27-36.
[http://dx.doi.org/10.1016/S0301-4797\(02\)00185-8](http://dx.doi.org/10.1016/S0301-4797(02)00185-8)

Parviainen J., Frank G., Bücking W., Schuck A., Vandekerckhove K. (2010). Information document on data collection and compiling the statistics on protected and protective forest and other wooded land for pan-European reporting. United Nations, Geneva.

Pilli R., Grassi G., Kurz W. A., Smyth C. E., Blujdea V. (2013). Application of the CBM-CFS3 model to estimate Italy's forest carbon budget, 1995–2020. *Ecological Modelling* 266, 144-171.
<http://dx.doi.org/10.1016/j.ecolmodel.2013.07.007>

Pimm S. L., Jenkins C. N., Abell R., Brooks T. M., Gittleman J. L., Joppa L. N., Raven P. H., Roberts C. M., Sexton J. O. (2014). The biodiversity of species and their rates of extinction, distribution, and protection. *Science* 344.
<http://dx.doi.org/10.1126/science.1246752>

Pretsch H., Biber P., Schütze G., Uhl E., Rötzer T. (2014). Forest stand growth dynamics in Central Europe have accelerated since 1870. *Nature Communications* 5.
<http://dx.doi.org/10.1038/ncomms5967>

Pretsch H., Grote R., Reineking B., Rötzer T., Seifert S. (2008). Models for forest ecosystem management: a European perspective. *Annals of Botany* 101, 1065-1087.
<http://dx.doi.org/10.1093/aob/mcm246>

Pukkala T. (2011). Optimizing forest management in Finland with carbon subsidies and taxes. *Forest Policy and Economics* 13, 425-434.
<http://dx.doi.org/10.1016/j.forpol.2011.06.004>

Pukkala T. (2014). Does biofuel harvesting and continuous cover management increase carbon sequestration? *Forest Policy and Economics* 43, 41-50.

<http://dx.doi.org/10.1016/j.forpol.2014.03.004>

Pukkala T., Lähde E., Laiho O., Salo K., Hotanen J.-P. (2011). A multifunctional comparison of even-aged and uneven-aged forest management in a boreal region. *Canadian Journal of Forest Research* 41, 851-862.

<http://dx.doi.org/10.1139/x11-009>

Rautiainen A., Saikku L., Kauppi P. E. (2010). Carbon gains and recovery from degradation of forest biomass in European Union during 1990-2005. *Forest Ecology and Management* 259, 1232-1238.

<http://dx.doi.org/10.1016/j.foreco.2009.07.043>

Reid W. V., Miller K. R. (1989). *Keeping options alive: the scientific basis for conserving biodiversity*. World Resources Institute, Washington.

Rettenmaier N., Schorb A., Köppen S., Berndes G., Christou M., Dees M., Domac J., Eleftheriadis I., Goltsev V., Kajba D., Kunikowski G., Lakida P., Lehtonen A., Lindner M., Pekkanen M., Röder J., Torén J., Vasylyshyn R., Veijonen K., Vesterinen P., Wirsenius S., Zhelyezna T. A., Zibtsev S. (2010). *Status of Biomass Resource Assessments, version 3 (deliverable D3.6)*. Biomass Energy Europe project. Institute for Energy and Environmental Research, Heidelberg.

Reyer C., Lasch-Born P., Suckow F., Gutsch M., Murawski A., Pilz T. (2014). Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. *Annals of Forest Science* 71, 211-225.

<http://dx.doi.org/10.1007/s13595-013-0306-8>

Ribe R. G. (1989). The aesthetics of forestry: What has empirical preference research taught us? *Environmental Management* 13, 55-74.

<http://dx.doi.org/10.1007/BF01867587>

Rudel T. K., Coomes O. T., Moran E., Achard F., Angelsen A., Xu J., Lambin E. (2005). Forest transitions: towards a global understanding of land use change. *Global Environmental Change* 15, 23-31.

<http://dx.doi.org/10.1016/j.gloenvcha.2004.11.001>

Sallnäs O. (1990). A matrix model of the Swedish forest. *Studia Forestalia Suecica* 183, 23.

Sarr D. A., Puettmann K. J. (2008). Forest management, restoration and designer ecosystems: integrating strategies for a crowded planet. *Ecoscience* 15, 17-26.

[http://dx.doi.org/10.2980/1195-6860\(2008\)15\[17:FMRAD\]2.0.CO;2](http://dx.doi.org/10.2980/1195-6860(2008)15[17:FMRAD]2.0.CO;2)

Sathre R., O'Connor J. (2010). Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy* 13, 104-114.

<http://dx.doi.org/10.1016/j.envsci.2009.12.005>

Schelhaas M.-J., Eggers J., Lindner M., Nabuurs G. J., Päivinen R., Schuck A., Verkerk P. J., Werf D. C. v. d., Zudin S. (2007). *Model documentation for the European Forest Information Scenario model (EFISCEN 3.1.3)*. Alterra report 1559 and EFI technical report 26. Alterra and European Forest Institute, Wageningen and Joensuu.

Schelhaas M. J., Brusselen J. v., Pussinen A., Pesonen E., Schuck A., Nabuurs G. J., Sasse V. (2006). *Outlook for the development of European forest resources. A study prepared for the European forest sector outlook study (EFSOS)*. Geneva timber and forest discussion paper 41. ECE/TIM/DP/41. UNECE/FAO, Timber Section., Geneva, New York.

Schelhaas M. J., Hengeveld G., Moriondo M., Reinds G. J., Kundzewicz Z. W., ter Maat H., Bindi M. (2010). Assessing risk and adaptation options to fires and windstorms in European forestry. *Mitigation and Adaptation Strategies for Global Change* 15, 681-701.
<http://dx.doi.org/10.1007/s11027-010-9243-0>

Schelhaas M. J., Nabuurs, G.J., Sonntag, M. and Pussinen, A. (2002). Adding natural disturbances to a large-scale scenario model and a case-study for Switzerland. *Forest Ecology and Management* 167, 13-26.
[http://dx.doi.org/10.1016/S0378-1127\(01\)00685-5](http://dx.doi.org/10.1016/S0378-1127(01)00685-5)

Schmack S., Aichholz R., Hartebrodt C. (2012). Modellgestützte Bewertung naturschutzfachlicher Restriktionen. *AFZ-Der Wald* 20.

Seidl R., Rammer W., Jäger D., Currie W. S., Lexer M. J. (2007). Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. *Forest Ecology and Management* 248, 64-79.
<http://dx.doi.org/10.1016/j.foreco.2007.02.035>

Seidl R., Schelhaas M.-J., Rammer W., Verkerk P. J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. *Nature Climate Change* 4, 806-810.
<http://dx.doi.org/10.1038/nclimate2318>

Seppelt R., Dormann C. F., Eppink F. V., Lautenbach S., Schmidt S. (2011). A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. *Journal of Applied Ecology* 48, 630-636.
<http://dx.doi.org/10.1111/j.1365-2664.2010.01952.x>

Siitonen J. (2001). Forest management, coarse woody debris and saproxylic organisms: Fennoscandian boreal forests as an example. *Ecological bulletins* 49, 11-41.
<http://www.jstor.org/stable/20113262>

Spash C. L., Stagl S., Getzner M. (2005). Exploring alternatives for environmental evaluation. In: M. Getzner, C. L. Spash, S. Stagl (Eds.), *Alternatives for environmental evaluation*. Routledge, London and New York, pp. 1-20.

Storaunet K. O., Rolstad J. (2004). How long do Norway spruce snags stand? Evaluating four estimation methods. *Canadian Journal of Forest Research* 34, 376-383.
<http://dx.doi.org/10.1139/x03-248>

Thürig E., Schelhaas M.-J. (2006). Evaluation of a large-scale forest scenario model in heterogeneous forests: a case study for Switzerland. *Canadian Journal of Forest Research* 36, 671-683.
<http://dx.doi.org/10.1139/x05-283>

Tol R. S. J. (2012). A cost-benefit analysis of the EU 20/20/2020 package. *Energy Policy* 49, 288-295.
<http://dx.doi.org/10.1016/j.enpol.2012.06.018>

Tscherning K., König B., Schöber B., Helming K., Sieber S. (2008). Ex-ante Impact Assessments (IA) in the European Commission – an overview. In: K. Helming, M. Pérez-Soba, P. Tabbush (Eds.), *Sustainability impact assessment of land use changes*. Springer, Berlin, pp. 17-33.

UNECE-FAO (2000). *Forest Resources of Europe, CIS, North America, Australia, Japan and New Zealand*. Contribution to the Global Forest Resources Assessment 2000. UN, New York and Geneva.

UNECE-FAO (2011). The European Forest Sector Outlook Study II. 2010-2030. ECE/TIM/SP/28. United Nations, Geneva.

Vilén T., Gunia K., Verkerk P. J., Seidl R., Schelhaas M. J., Lindner M., Bellassen V. (2012). Reconstructed forest age structure in Europe 1950-2010. *Forest Ecology and Management* 286, 203-218.

<http://dx.doi.org/10.1016/j.foreco.2012.08.048>

Vis M., Dees M. (Eds.) (2011). *Biomass Resource Assessment Handbook: Harmonisation of Biomass Resource Assessments, Best Practices and Methods Handbook*. VDM Verlag Dr. Müller, Saarbrücken.

Wallenius T., Niskanen L., Virtanen T., Hottola J., Brumelis G., Angervuori A., Julkunen J., Pihlström M. (2010). Loss of habitats, naturalness and species diversity in Eurasian forest landscapes. *Ecological Indicators* 10, 1093-1101.

<http://dx.doi.org/10.1016/j.ecolind.2010.03.006>

Walmsley J. D., Godbold D. L. (2010). Stump harvesting for bioenergy - A review of the environmental impacts. *Forestry* 83, 17-38.

Williams M. (2000). Dark ages and dark areas: global deforestation in the deep past. *Journal of Historical Geography* 26, 28-46.

<http://dx.doi.org/10.1006/jhge.1999.0189>

Wolfslehner B., Seidl R. (2010). Harnessing ecosystem models and multi-criteria decision analysis for the support of forest management. *Environmental Management* 46, 850-861.

<http://dx.doi.org/10.1007/s00267-009-9414-5>

Ylitalo E. (Ed.) (2012). *Finnish statistical yearbook of forestry 2012*. Finnish Forest Research Institute, Sastamala.