Forest decision support systems for the analysis of ecosystem services provisioning at the landscape scale under global climate and market change scenarios

Eva-Maria Nordström[1]*, Maarten Nieuwenhuis[2]*, Emin Zeki Başkent[3], Peter Biber[4], Kevin Black[2], Jose G. Borges[5], Miguel N. Bugalho[6], Giulia Corradini[7], Edwin Corrigan[2], Ljusk Ola Eriksson[1], Adam Felton[8], Nicklas Forsell[9], Geerten Hengeveld[10], Marjanke Hoogstra-Klein[10], Anu Korosuo[9], Matts Lindbladh[8], Isak Lodin[8], Anders Lundholm[2], Marco Marto[5], Mauro Masiero[7], Gintautas Mozgeris[11], Davide Pettenella[7], Werner Poschenrieder[4], Robert Sedmak[12,13], Jan Tucek[12] and Davide Zoccatelli[7,14]

*Corresponding authors.
E-MN. Address: Department of Forest Resource Management, Swedish University of Agricultural Sciences (SLU), 901 83 Umeå, Sweden. Telephone: +46 (0)90 7868258. Email: eva-maria.nordstrom@slu.se
MN. Address: UCD Forestry, School of Agriculture and Food Science, University College Dublin, Belfield, Dublin 4, Ireland. Telephone: +353 (0)1 7167004. Email: maarten.nieuwenhuis@ucd.ie

[1]Department of Forest Resource Management, Swedish University of Agricultural Sciences (SLU), 901 83 Umeå, Sweden. Email: eva-maria.nordstrom@slu.se, ola.eriksson@slu.se
[2]UCD Forestry, School of Agriculture and Food Science, University College Dublin, Belfield, Dublin 4, Ireland. Email: maarten.nieuwenhuis@ucd.ie, kevin.g.black@gmail.com, edwint.corrigan@gmail.com, anders.lundholm@ucdconnect.ie
[3]Faculty of Forestry, Karadeniz Technical University, 61080 Trabzon, Turkey. Email: eminzekibaskent@gmail.com
[4]Chair of Forest Growth and Yield Science, TUM School of Life Sciences Weihenstephan, Technical University of Munich (TUM), Hans-Carl-von-Carlowitz-Platz 2, Freising 85354, Germany. Email: peter.biber@lrz.tum.de, werner.poschenrieder@lrz.tum.de
[5]Forest Research Centre, School of Agriculture, University of Lisbon, Tapada da Ajuda, Lisbon 1349-017, Portugal. Email: joseborges@isa.ulisboa.pt, marcovmarto@isa.ulisboa.pt
[6]Centre for Applied Ecology (CEABN-InBIO), School of Agriculture, University of Lisbon, Tapada da Ajuda, Lisbon 1349-017, Portugal. Email: migbugalho@isa.ulisboa.pt
[7]TeESAF Department, University of Padova, Agripolis, v.le dell'Università 16, Legnaro I-35020, Italy. Email: giulia.corradini@unipd.it, mauro.masiero@unipd.it, davide.pettenella@unipd.it, zoccatelli.davide@gmail.com
[8]Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences (SLU), Box 49, 230 53 Alnarp, Sweden. Email: adam.felton@slu.se, matts.lindbladh@slu.se, isak.lodin@slu.se
[9]Ecosystem Services and Management Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria. Email: forsell@iiasa.ac.at, korosuo@iiasa.ac.at
[10]Forest and Nature Conservation Policy Group, Wageningen University and Research, Droevendaalsesteeg 3, 6708PB Wageningen, the Netherlands. Email: geerten.hengeveld@wur.nl, marjanke.hoogstra@wur.nl
[11]Institute of Forest Management and Wood Science, Aleksandras Stulginskis University, Studentu 11, LT-53361 Akademija, Lithuania. Email: gintautas.mozgeris@asu.lt
[12]Department of Forest Management and Geodesy, Technical University in Zvolen, T.G. Masaryka 24, Zvolen 960 53, Slovakia. Email: sedmak@tuzvo.sk, tucek@tuzvo.sk

[13]Department of Forest Management, Czech University of Life Sciences Prague, Kamýcká 1176, 165 21 Prague 6-Suchdol, Czech Republic
[14]Institute of Earth Sciences, The Edmond J. Safra Campus - Givat Ram, Hebrew University of Jerusalem, Jerusalem 9190401, Israel

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Abstract

Sustainable forest management is driving the development of forest decision support systems (DSSs) to include models and methods concerned with climate change, biodiversity and various ecosystem services (ESs). The future development of forest landscapes is very much dependent on how forest owners act and what goes on in the wider world, thus models are needed that incorporate these aspects. The objective of this study is to assess how nine European state-of-the-art forest DSSs cope with these issues. The assessment focuses on the ability of these DSSs to generate landscape level scenarios to explore the output of current and alternative forest management models (FMMs) in terms of a range of ESs and the robustness of these FMMs in the face of increased risks and uncertainty. Results show that all DSSs assessed in this study can be used to quantify the impacts of both stand and landscape-level FMMs on the provision of a range of ESs over a typical planning horizon. DSSs can be used to assess how timber price trends may impact that provision over time. The inclusion of forest owner behavior as reflected by the adoption of specific FMMs seems to be also in the reach of all DSSs. Nevertheless, some DSSs need more data and development of models to estimate the impacts of climate change on biomass production and other ESs. Spatial analysis functionality need to be further developed for a more accurate assessment of the landscape level output of ESs from both current and alternative FMMs.

Keywords: ALTERFOR, biodiversity, forest management models, forest owner behaviour

Introduction

Ecosystem Services (ESs) are the benefits that humans obtain from ecosystems (Millennium Ecosystem Assessment 2005). Since the ES concept includes economic, ecological as well as social values of nature, it can be a used as tool for decision and policy making concerning sustainable resource management. Ecosystem service delivery is strongly dependent on ecosystem management and frequently implies trade-offs among services (Bugalho et al. 2011, 2016). However, to allow for the analysis of trade-offs and effects of land use and management on the provision of ES, the ES concept needs to be operationalized through quantitative assessments based on mapping and modelling (Seppelt et al. 2011; Borges et al. 2014a; Andrew et al. 2015).

Even before ESs became a widely known concept, forest management was concerned with assessing the benefits produced by forests under different kind of management (Grêt-Regamey et al. 2016; Kindler 2016). Since the start of modern forestry, forest management has mainly focused on wood production and on how to manage forests efficiently for a sustainable yield of wood. However, multiple-use forestry has long been practiced and was formally introduced already in the 1960s in the US (Hoogstra-Klein et al. 2017). Later, the concept of sustainable forest management emphasized the need for inclusion of ecological and social aspects and consideration of future generations (United Nations 1992). In the past 30 years, advanced forest decision support systems (DSS) have been developed to enable analysis of complex problems related to forest management (Reynolds et al. 2008; Borges et al. 2014b). A forest DSS is a software system that can be used for modelling of forest development based on both biological processes and management effects over long time horizons. Though many forest DSSs were initially developed with a strong focus on wood production, the wider perspective required in the analysis of sustainable forest management is driving the development of DSSs to include models and methods concerned with, e.g., climate change, biodiversity and various ESs (Borges et al. 2014b; Vacik and Lexer 2014).

A number of studies have addressed the question of how forest DSSs can be used to assess the future provisioning of ESs. Some of the earliest examples are from the US where DSSs for ecosystem management were developed to support forest management aimed at production of goods and services as well as maintaining ecosystem structures and functions (Rauscher 1999; Reynolds 2005). The Forest

Planning Model (FORPLAN) was developed in the late 1970s to support planning for multiple use and sustained yield of goods and services (Kent et al. 1991). NED (Twery et al. 2005) and the Ecosystem Management Decision Support (EMDS) system (Rauscher 1999; Reynolds 2005) was then developed by the USDA Forest Service, starting some 20 years ago.

In a more recent study, Biber et al. (2015) analyzed the effects of forest management intensity on ESs delivery by compiling information from case studies in ten European countries where ten different DSSs were used for scenario analysis. The results showed that there was an obvious strong positive correlation between management intensity and wood production. However, for biodiversity the correlation with management intensity depended on the forest region in which the case study area was located. In some forest regions there was a trade-off between biodiversity and management intensity, but in others a positive correlation between biodiversity and more intense management was found. For other ESs, the correlation with management intensity was only weak and negative. For instance, there was no clear trend for the relationship between non-wood products (mushrooms, cork, pine cones and grazing) and management intensity. Further, Biber et al. (2015) concluded that local data and DSSs are a useful complement to large-scale studies since they provide the most accurate and relevant information available on a local level. The reader is referred to Corrigan and Nieuwenhuis (2017), Borges et al. (2017) and Hengeveld et al. (2015) for a detailed description of how three of these DSSs were used to assess a wide range of ESs in case study areas in Ireland and Portugal. Further, in their review of the same ten DSSs included in Biber et al. (2015), Orazio et al. (2017) pointed out that even though the set of DSSs is diverse, all of these DSSs can take ecological and socioeconomic conditions into account, in one way or another. However, modelling of tree development and wood production output are still the strongest parts in the DSSs and there is a need to develop the modelling to include indicators for other ESs and biodiversity. Further, only some of the DSSs were able to include climate effects on forest growth and most do not include other land uses. Most DSSs are thus well suited for current conditions but need further development to be useful under a changing climate as well as under new, alternative forest management regimes. This is in line with conclusions from more general reviews of DSSs in forest management (Reynolds et al. 2008; Muys et al. 2010; Vacik and Lexer 2014).

The studies mentioned above focus mainly on scenarios describing the development of the forest over time, given biological processes such as growth and mortality, and the effects of harvesting and silvicultural activities on the delivery of ESs and biodiversity conservation, i.e., the supply side. The demand for ESs is rarely explicitly considered in these scenarios. However, the future development of a forest landscape is very much dependent on what goes on in the world around this landscape. Drivers like economic development, population growth and climate change will affect the demand for various ESs and should also be considered at the landscape level. There are scenarios that could be used for this type of analysis; for instance, the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has set up a scenario framework which allows for global analysis of climate change impacts and mitigation options under different socioeconomic development and covers a wide range of potential future trajectories for global development of climate change, economic growth, population development and overall use of natural resources (IPCC 2013, 2014a, b).

Furthermore, even projecting the forest development subject to external drivers is not sufficient when scenarios are supposed to reflect management responses on landscape level to various policies, climate change and market developments. The forest owner behavior as a response to policy, climate change, changing prices for forest products and other stakeholders will in many cases be an important factor that needs to be considered in the analysis (Mozgeris et al. 2016; Rinaldi et al. 2015).

The challenges in including ESs and biodiversity in scenario analysis using forest DSSs that have been highlighted above are in line with general issues that have been identified as problematic in ESs assessment for decision support: i) use of simplistic approaches due to lack of data and realistic models, ii) focus on only a limited number of ESs, often due to a lack of information on others despite their relevance to decision making, iii) precision, accuracy and uncertainties in assessments are not dealt with, and iv) that the demand for ESs is rarely considered since this usually requires an interdisciplinary approach (Eigenbrod et al. 2010; Seppelt et al. 2011; Wolff et al. 2015; Grêt-Regamey et al. 2016).

The objective of this study is to assess how a number of European state-of-the-art (i.e., the highest level of general development achieved in each country) forest management planning DSSs cope with modeling of ESs. The assessment will focus on the ability of these DSSs to generate landscape level scenarios to explore the output of current and alternative silvicultural approaches and forest management models (FMMs) in terms of a range of ESs and the robustness of these FMMs in the face of increased risks and uncertainty. With this general objective in view, this study more specifically aims to:

- evaluate the capacity of forest DSSs to project the output of ESs over time at the landscape level, under different global climate change and market scenarios and taking forest owner behaviour into account, and
- highlight needs for the further development of DSSs and propose approaches that could be used to improve modelling.

Material and methods

Assessment of DSSs

This study considers nine DSSs (Table 1) that are currently used as decision support tools for European forest management and investigates how they can be used to analyze the impacts of different FMMs on the provisioning of ESs in a range of forest landscapes in nine European countries (Germany, Ireland, Italy, Lithuania, Netherlands, Portugal, Slovakia, Sweden and Turkey). These DSSs are all part of the European Union project ALTERFOR (www.alterfor-project.eu), in which they will be used to examine currently used and alternative FMMs in case study areas in each country and the potential to optimize the forest management with regard to ES provisioning in different European countries. The case study areas are briefly presented in Table 2, including some information on the main ESs and stakeholders in each case study area. The assessment of the DSSs in this study is based on the properties of the DSSs rather than the results from applying the DSSs in the case studies to create scenarios. However, investigating how a DSS handles different ESs requires a context in which the DSS operates, i.e., a landscape in which certain ESs are important and could be quantified in certain ways. Thus, in this study the function of the case studies was to provide a range of forest landscapes with different focuses on ES provision and different stakeholders as a background for the assessment of the DSSs.

[INSERT TABLE 1 AROUND HERE]

[INSERT TABLE 2 AROUND HERE}

More specifically, by forest DSS we mean a software system used for analysis pertaining to the domain of forest management. Thus, it includes stand simulators, growth and yield models, and associated tools that are integrated into systems that make landscape projections for management planning. However, it does not encompass general purpose software systems like Microsoft Excel or GIS software, unless the DSS is implemented on those platforms. With this definition, a mere transfer of data from the DSS to a GIS for calculating an index does not make the GIS part of the DSS as the term is used here.

In the analysis of future output of ESs under various FMMs, the capability to include information on climate change and socioeconomic development from global scenarios as well as the behavior of forest owners at landscape level are important elements. Specific properties that are critical for DSSs to be able to handle these requirements were formulated based on existing knowledge and experiences from the INTEGRAL project (e.g., Biber et al. 2015; Orazio et al. 2017) and other studies (Muys et al. 2010; Vacik and Lexer 2014). These properties are:

1) capability to deal with changing market prices over time for timber and biomass assortments;
2) capability to include climate change effects in landscape level scenarios;
3) the spatial specificity of the landscape scale analyses (i.e., the extent to which location of and spatial relationships between forest stands is known);
4) inclusion of forest owner behaviour, in terms of the existing FMMs that different owner types use and alternative FMMs that may be used in the future.

More detailed descriptions of these properties are presented in the section "Specific DSS properties considered in the assessment". These were defined by the authors in collaboration with researchers within the ALTERFOR project.

Information on the critical properties of the DSSs was solicited from researchers working with the systems in a number of steps. Initially, a questionnaire was sent out, in which a description of each DSS (Table 1) and their capabilities was requested based on a series of targeted questions. The information requested related both to the current status of the DSS at that time and to the developments that were planned to improve the DSS, referring to the specific properties mentioned above. These questionnaires were followed-up with telephone interviews that allowed for further discussion of missing or incomplete answers. A follow up request for information was sent out six months later and the researchers were asked to report on the progress in DSS development and indicate if and how their respective DSSs included the four properties listed above. This information, together with the earlier questionnaires, provided a structure for the reporting of the results in this paper. Based on the comprehensive information resulting from this process, a more detailed analysis was carried out to identify those properties and ESs for which proper DSS design solutions had been found and, more importantly, properties and ESs which in some DSSs were causing difficulties in terms of proper system integration. The purpose of this analysis was to identify basic commonalities, contrasts and 'best practice' among all DSSs in dealing with the critical properties and the analysis was carried out in collaboration with researchers with expertise on the different ESs.

Ecosystem services considered in the assessment

Many forest DSSs are designed to primarily project the output of timber and other biomass, but with increasing focus on sustainable forest management and the need to take other ESs into account, development of DSSs are going in this direction. Besides timber and biomass, this study includes biodiversity and four important ES categories that forest ecosystems provide and that forest management may affect in different ways:

1) Biodiversity conservation (hereafter "biodiversity" and considered an ES) – based on three habitat proxies for biodiversity at both stand and landscape scales, i.e., tree species composition, forest structures (e.g. large trees, dead wood, etc.), and spatial-temporal disturbance patterns. The specifics will of course vary (to some extent) between case study areas and the wildlife supported will depend on context and the proximity of species pools.

2) Carbon sequestration (including carbon storage in the forest) – based on three main carbon pools, i.e., above and below ground biomass, deadwood, and harvested wood products.

3) Other regulatory services (hereafter “regulatory services” and not including carbon sequestration) – other regulatory services apart from carbon sequestration, including forest attributes (e.g. tree species composition, stand age, etc.) that influence the risk and impact of catastrophic events at both stand and landscape scales, i.e., wildfire, windstorms, pests, snowstorms and droughts.

4) Recreational and aesthetic value – based on visual forest characteristics at both stand and landscape scales, conceptualized through the concepts of stewardship, naturalness/disturbances, complexity, visual scale, historicity/imageability, and ephemera (i.e., landscape changes that are the outcome of seasonal variation (Ode et al. 2008)).

5) Water – includes five water-related ESs, i.e., water yield, flood protection, water flow maintenance, erosion control, and chemical conditions.

Variables that are needed as output from the DSSs for evaluating the effects on ESs under different scenarios and FMMs are listed in Table 3. They were identified as part of this study by experts on these ESs, who developed standards for how each of these ESs should be modeled using a typical forest DSS, based on the available input data and specifying the resulting outputs (Nieuwenhuis and Nordström 2017).

[INSERT TABLE 3 AROUND HERE]

Global climate change and market scenarios applied in the assessment

Global scenarios to be used as a background for landscape level scenarios produced by forest DSSs should provide trends in the demand and prices for various timber assortments at least at the country level based on developments in trade and on global markets. To include effects of climate change on forest growth and development, the global scenarios should also provide information on climate effects, namely temperature and precipitation.

The global scenarios considered in this study provide this information with 10-year intervals until 2100 and reflect three alternative development pathways for this period:

1) Current development – Taking into account the EU policies until 2020 that are in the current legislation, thereafter continuing with some development towards the climate targets, following typical pathways of the past.

2) Rapid development of EU bioenergy sector – Taking into account EU policies that aim at a 80% reduction in emissions by 2050. Outside the EU, it is assumed that only the climate change mitigation policies that were in place before 2015 are in effect.

3) Global development toward the climate targets – Climate policies are assumed to be taken into action globally, but their effects are mostly seen in the latter half of the century.

These three scenarios were prepared using the global land use model GLOBIOM/G4M (Havlík et al. 2011; Kindermann et al. 2013) and were based on the policy targets for the European Union combined with the Representative Concentration Pathways (RCP) - Shared Socioeconomic reference Pathways (SSP) framework developed for the IPCC (IPCC 2013, 2014a, b; van Vuuren et al. 2011, 2014). The framework consisted of two sets of independent scenarios in a matrix that allowed for various combinations of scenarios: the four RCPs corresponding to different levels of radiative forcing, and the SSPs that express the development of socioeconomic drivers. Since these are the most recent scenarios produced by the IPCC based on substantial scientific input, they were the most appropriate scenarios available for this kind of analysis, but any global scenarios providing similar information could be used. The three global scenarios in this study are all based on the SSP2 “Middle of the road” scenario in combination with RCP4.5 (Current development), RCP8.5 (Rapid development of EU bioenergy sector) and RCP2.6 (Global development toward the climate targets). The climate model used to produce these scenarios was HadGEM2-ES.

Specific DSS properties considered in the assessment

Timber assortments and prices

Timber and timber assortments is the basic output for most forest DSSs, but since there may still be differences, the DSSs are categorized into different levels of detail concerning the modeling. Timber assortments are classified in two main categories, 'stemwood' and 'other biomass' (i.e., tops, branches and stumps). For each category, the level of detail provided by each DSS is described using four levels of increasing complexity:

1) harvested wood is given only in total volumes for each category (stemwood and other biomass),
2) harvested wood is given in volumes per stemwood assortments (sawlogs, pulpwood and firewood) and also that the extracted volume of other biomass need to be available,
3) in addition to level 2, harvesting costs have to be included, and
4) in addition to level 3, transport costs should be included as well.

The capability to include and model changing timber prices and the effect on forest management is needed as a link to global climate and market change scenarios that shows how prices for timber change due to, e.g., market developments for bioenergy due to climate policies. For this project, the global scenarios produced with the GLOBIOM/G4M model are downscaled to national level. These price trends were expressed as average decadal mill gate prices for two assortment categories, sawlog and pulpwood. In the DSSs, this price information (and linear interpolation) should be used in the simulation/optimisation of the choice of FMMs over the planning horizon. Price changes should therefore be reflected in the harvest levels. The most important aspect of the prices is their trend, so the global trend should be properly reflected when landscape level scenarios are produced for each case study.

Climate change

The global scenarios described in the section on timber prices also include climate change trends for each country, indicating overall temperature and precipitation changes over the period until 2100 for each country. To fully incorporate climate change effects, the DSSs should be capable of modelling climate change in terms of its impact on tree growth and tree mortality. As these are the fundamental processes behind forest dynamics from tree to landscape level, such DSSs can also provide ESs provision trends under changing climate. In the assessment, climate change trends that can be incorporated in the DSSs are described and variables in the DSSs that are impacted by these trends and the data sources for the models used in the DSSs to represent these impacts are identified.

Owner behaviour

The Forest Landscape Development Scenarios (FoLDS) framework (Hengeveld et al. 2017) has been presented as an approach to model forest owner behaviour, and in this study the FoLDS framework will be used as a baseline for the assessment of how owner behaviour is included in the DSSs.

In the FoLDS framework, different forest owner types (OTs) are defined along with their potential use of different forest management models (FMMs). This can be described using a so-called OT-FMM matrix. In this matrix, the proportions of the forest estate owned by different OTs are identified, and for each OT, the proportions of their forests that are managed using different FMMs are quantified. In order to reflect changing conditions over time, the values in this OT-FMM matrix should be dynamic, reflecting changes in OT proportions and in the FMMs that each OT uses. For instance, forests may be inherited by city dwellers from farmers, resulting in different OT proportions, as well as changed management objectives resulting in the use of different FMMs. At the same time, within (certain) OTs, the changing market conditions (reflected by demand and prices) and the changes in climate will result in changes in the (proportions of) FMMs used. Certain OT and their choice of FMMs may also be influenced by other stakeholders. Existing FMMs are forest management models that are currently being used, while alternative FMMs are management models that will be introduced in the future to deal with changing market and climate conditions, and owner and stakeholder requirements. Existing OTs are categories of forest owners grouped according to their management objectives and use of FMMs. New OTs may develop over time based on changing market, socio-economic, environmental and climate conditions.

Thus, to incorporate the OT-FMM approach in a DSS, data on existing FMM proportions for existing OTs and variables influencing OT behaviour (i.e., the selection and proportions of FMMs used) are needed. In addition, alternative FMMs and new OTs and their behavior need to be defined based on sound assumptions. For each decade (or other period), an OT-FMM matrix in which the proportions of existing and alternative FMMs used by each existing and new OT can then be defined.

Spatial specificity

The level of spatial specificity in the DSS is relevant especially in the modeling of ESs but also affects other aspects (e.g., the possibility to include transportation costs in the costs for harvesting). In this study, spatial specificity in a DSS is considered to depend on the source of the spatial data used in the DSS, the data format, and if forest stands, inventory plots or other basic forest information units are used as a basis or if they are grouped into homogenous strata (based on stand, site and management characteristics) and, if so, at what scale. The reason is that grouping will result in a partial loss of spatial specificity, as the location of each stand is lost in the strata. If no grouping takes place, the level of spatial specificity is still affected by whether the adjacency of stands is known within the DSS and how this information is used.

Results

The results of the assessment of the DSSs are summarized for the ESs and for each property in the following sections. Table 4 shows a classification of the nine DSSs according to their ability to quantify the variables required for the ES provision assessment. A green cell indicates that the variable is part of the DSS and that the ES is assessed within the DSS and a red cell indicates that the variable is not part of the DSS. A yellow cell indicates that some of the analysis required to produce the outputs for the variable in question can only be done outside of the DSS, though based on the DSS simulation/optimisation outputs, i.e., by using models or software that are not part of the DSS. For instance, frequently separate GIS software is needed for spatial analysis since several DSSs lack this functionality. When a DSS does not include certain models, e.g., for dead wood, harvest residues or below ground biomass, this also results in a yellow cell since separate models are then used to calculate the variables based on output from simulation/optimization carried out in the DSS.

Ecosystem Services

Most of the DSSs include the standard forest inventory variables (Table 4); however, non-timber related variables such as those associated with stand structure and dead wood are less often an integral part of the DSSs and need to be quantified outside of the DSS, for instance in a stand-alone GIS, or are not part of the DSS at all. In most DSSs, the definition of decision variables is based on harvest related options. These options need to be considered in order to address concerns with both wood and non-wood goods and services. Nevertheless, the outcome of the simulation or optimization depends in most cases on timber related criteria (i.e., they are the decision variables), while other criteria are more often addressed when analyzing the results of the simulation and optimization processes. This demonstrates that most DSSs have their origin in traditional forest management, with environmental and social elements added at a later stage.

[INSERT TABLE 4 AROUND HERE]

Timber assortments and prices

Concerning the timber assortment 'stemwood', most DSSs can output harvested wood volumes per stemwood assortment (sawlogs, pulpwood and firewood). Furthermore, most DSS may include harvesting costs. In some cases, the analysis is conducted considering stumpage prices and thus harvesting and transportation costs are considered indirectly (e.g., SADfLOR). SILVA is the only DSS that can include transportation costs (based on assumptions on distances). Kupolis, EFISCEN-space, Sibyla, Heureka and ETÇAP can only include transportation costs in the forest up to the roadside.

Most DSSs use look-up tables to account for dynamic timber prices (Supplementary Table S1). In many cases, the modeling would also be based on the assumption that rising timber prices would lead to at least some increased management activity or even changes in FMMs for some OTs. A chain of effects from changing prices to changing FMMs and changes in ESs provisioning levels seems to be expected for most of the DSSs.

Climate change

All but three of the DSSs currently include climate models of some kind (Supplementary Table S2), which allow for the modeling of climate change effects on growth rates, either on tree or stand level. In Kupolis, SADfLOR and ETÇAP, which do not explicitly include climate models, climate change effects could be included in a similar way by adjusting growth rates; the main problem in these cases is the lack of data on climate change effects on growth. In some DSSs the climate change scenarios used to assess the impact on forest growth, and hence forest products supply, do not correspond to the global scenarios used to derive timber price and demand. Therefore, supply and demand are not perfectly balanced and may not be directly comparable in these cases.

Owner behaviour

All of the DSSs can somehow take owner behavior in terms of FMMs into account and make the OT-FMM matrix dynamic over time in scenarios. The OT-FMM matrix describing the current situation is based on multiple sources: information from stakeholders, expert knowledge, scientific studies, forest statistics and inventory data (Supplementary Table S3). These will also be the basic sources for formulation of OT-FMM matrices that describe the future state, but there is obviously a great challenge in making predictions about future OTs and alternative FMMs.

Spatial specificity

The level of spatial specificity varies between the DSSs (Supplementary Table S4). Half of the DSSs use stand-level data and the rest group stands into strata in the analysis, resulting in a loss of stand-level spatial specificity in the assessment of the ESs. Most of the DSSs are spatial to the degree that the locations of stands in the landscape are known, but only two of them (SADfLOR and ETÇAP) can handle the more complex issue of adjacency, i.e., the relative location of stands in relation to each other.

Discussion

This study is motivated by the need to provide policy makers as well as forest owners with decision support on how various FMMs will affect the output of ESs and biodiversity, and how global drivers as well as forest owner behavior on local level can influence future development. The capacity of a number of forest DSSs to perform the kind of analyses needed is assessed based on their capabilities to model the provisioning of ES under various FMMs and properties of the DSSs relevant to that. The discussion focuses on how the DSSs cope with the modelling of timber and biomass, biodiversity, carbon sequestration, regulatory services, recreational and aesthetic value and water. Certain properties of the DSSs and lessons learned concerning methodological approaches are also discussed and needs for future development of the DSSs are identified.

Modelling of ecosystem services

Timber and biomass

For most DSSs in this study, timber is clearly the ES which has been in focus when the DSS was developed and all DSSs are very strong in the modelling of timber, both the standing stock and harvested volumes. This is in line with previous research on forest DSSs (Vacik and Lexer 2014; Nobre et al. 2016). The DSSs can output harvested volumes of stemwood and the basic assortments sawlog, pulpwood and firewood. However, not all these DSSs can model output of residues that can be used for, e.g., bioenergy, probably because this is not a traditional assortment in the area where those DSSs are used. This may be a limiting factor when scenarios with alternative FMMs are created, but using estimates based on results from DSSs applied in similar types of forest could be a solution to this problem.

An issue that required adjustment of the timber and biomass prices used in the modelling was that the global scenarios considered in this study included prices for material delivered to the industry (i.e., mill gate prices) while almost all DSSs only included harvesting and primary in-forest transport costs and not secondary transport costs such as road haulage. This is because the systems are not designed to link harvesting operations in individual stands with the particular industries that will process the timber and biomass, while the prices in the global scenarios consider the industry relevant mill gate prices because the underlying reasoning is based on economic partial equilibrium modelling. This means that the global scenario prices will have to be adjusted in each DSS to reflect the average secondary timber and biomass transport costs within the case study areas.

Biodiversity

As the necessary parameters for modelling population-level responses are generally limited to a small number of forest species (Johansson et al. 2016), the landscape scale implications for biodiversity from forest management alternatives are often projected using biodiversity proxies (Felton et al. 2017b). In this assessment we evaluated three categories of biodiversity proxies: forest structure, tree species composition, and spatial-temporal disturbance patterns, all with demonstrated relevance to the maintenance of biodiversity in production forest stands (Felton et al. 2017a). In this regard most of the DSSs assessed appear to provide at least minimal indicators of direct relevance to each of these three broad categories of habitat-relevant proxies. With respect to tree species composition, for example, all of the DSSs are capable of modeling relevant outcomes. Capturing changes in tree species composition is vital as a particular tree species provides distinctive resources and habitats which may now be rare due to recent and historic shifts in land-use in many regions of Europe (Lindbladh et al. 2014; Reitalu et al. 2013; Wulf and Rujner 2011). These changes are frequently associated with population declines and increased extinction risk for many forest species (Berg et al. 1994; Lindenmayer et al. 2006).

There are however some limitations with respect to DSS capabilities. A subset of the DSSs assessed were unable to project some forest structures, including the provision of dead wood of different sizes, and in one case, the capacity to model large trees. Large trees may be vital to habitat provision in forest ecosystems, due to the resources and environments created by their well-developed crowns, complex bark features, stem hollows, and sap flows (Lindenmayer et al. 2012; Siitonen and Ranius 2015). The presence of old and large trees is also directly relevant to the provision of coarse woody debris within forest landscapes (Jonsson et al. 2006; Lindenmayer and Franklin 2002). Dead wood is also a critical resource for a large number of species in forests, which may represent a quarter of all forest species in some regions (Siitonen 2001; Stokland et al. 2003). The capacity to model dead wood is thus often an important capacity of DSSs when modelling habitat availability in these regions. The inability to do so generally resulted from a lack of available input data for dead wood amounts and categories within different forest types at different stages of forest development, or a lack of model parameters for projecting, for example, dead wood decomposition rates. Qualitative assessments and/or expert input may be means of at least partially compensating for such limitations. Careful consideration of trade-offs is however required. For instance, increased amount of woody debris may lead to significant increase of wildfire hazard in some ecosystems, which may ultimately induce loss of habitat and biodiversity in case of occurrence of severe wildfire.

We also note that there are limitations with regards to the extent to which spatially explicit considerations can be analyzed by these DSSs. In the case of biodiversity conservation indicators, it is crucial that DSSs may extend from stand to landscape scale and include spatial components, as pointed out by previous studies (Filyushkina et al. 2016; Nobre et al. 2016). There are biodiversity components that may only be assessed at the landscape level. This is especially the case with respect to adjacency issues. The spatial configuration of habitat availability and the proximity of source populations are of direct relevance to understanding population dynamics and emergent patterns in forest biodiversity (Fahrig 2003). Additional complexities and concerns may be raised regarding the ability of DSSs to capture the wide variation in resultant habitat availability that arises due to everything from ownership differences in silvicultural interventions to fine scale differences in site conditions. More specifically, the complexities and uncertainties involved in projecting the interactions of climate change, abiotic and biotic disturbance regimes, and forest dynamics, highlight the need for caution when interpreting DSS projections of future habitat availability. Despite these limitations, we believe that in general, current DSSs, in combination with qualitative assessments and expert opinion, should provide output of sufficient resolution to distinguish FMMs in terms of their habitat provisioning capabilities.

Carbon sequestration

The variables listed in table 4 are useful for characterizing carbon stocks and for estimating carbon stock changes or carbon gains and losses. These issues can be addressed, in a harmonized manner, by using well developed conversion factors for standing volume (stocks) or volume increment (carbon gains) in the case of above and below ground biomass (IPCC 2006). In the case of deadwood, carbon fluxes can be estimated using inflows of carbon from harvest residues, the existing deadwood pool and published decomposition factors (see Olajuyigbe et al. 2011; Yatskov et al. 2003). Carbon dynamics of harvested wood products could be derived from timber assortments based on relationships between timber assortments and semi-finished wood products (Donlan et al. 2013) and published half-lives using the harvested wood products decay model (IPCC 2006). However, it must be recognized that the model system boundary would not be limited to regional carbon stock changes given the large influence of timber trade.

Alternative FMMs for carbon sequestration could be used to analyze effects of, e.g., plantation/clearfell versus continuous cover forestry (Lundmark et al. 2016), rotation age and thinning intensity (Chikumbo and Starka 2012), low impact management versus extensive management (Vanderberg et al. 2011), fate of harvested wood products and product substitution (Lundmark et al. 2016; Moore et al. 2012). Different silvicultural practices and forest disturbance events influence forest and product carbon storage over different time periods. The most common approach to account for this is to derive estimates assuming steady-state to steady-state transitions by running model simulations for 3 rotations, typically 200-400 years (e.g., Lundmark et al. 2016).

Carbon assessment only includes aboveground, belowground biomass, deadwood and harvested wood product pools. However, carbon sequestration of European forest ecosystems is also influenced by the balance of numerous other greenhouse gases such as N_2O, CH_4 and CO, particularly in relation to fertilizers, forest fires and drainage of peatland soils (IPCC 2006). In countries where non-CO_2 emissions from forest may be large, such as resulting from the drainage of organic soils (Ireland, Sweden) or forest fires (Portugal, Italy), additional efforts would be required to provide a more comprehensive greenhouse gas footprint. Mineral soil carbon stock changes have not been included in the DSSs because of the large uncertainty and difficulty in deriving these estimates. Current knowledge remains inconclusive on both the magnitude and direction of carbon stock changes in mineral forest soils associated with forest type, management and other disturbances, and cannot support broad generalizations (IPCC 2006). Emissions from drained organic soils, on the other hand are well described and easily estimated if sufficient detail on soil type and extent of drainage is known (IPCC 2006).

In many forest DSSs, land use change (i.e., afforestation or deforestation) can be included, but the impact of such change on the carbon dynamics cannot be modeled, and yet such change will have a profound influence on the regional carbon balance. This is confounded by the inability of most DSSs to provide estimates of soil and dead organic matter stock changes, which may occur for years after a land use transition occurs. Estimation of soil stock changes, in particular, requires a high spatial resolution for input data (i.e., soils types, etc.).

Perhaps the most influential process influencing forest mitigation potential is, and one not considered in this context, the effect of energy and product substitution. Dearing Oliver et al. (2014) suggest that the use of wood products for substitution could reduce global emission by 14% to 31%. Lundmark et al. (2016), suggest that product substitution had the greatest influence on overall mitigation capacity when different FMMs were compared. Life cycle analysis of wood products provides a way of measuring the CO_2 savings that can be made by use of wood products and replacement of high CO_2 emission potential products such as energy, cement, etc. (Sathre and O'Connor 2010). The overall concept is avoidance of emissions by replacement of processes or products using wood as a substitution (Sathre and O'Connor 2010). This is a complex problem and can only be introduced at the stand or regional scale using broad generalizations for the fate of harvested products (see Lundmark et al. 2016). The only feasible solution is to perform sensitivity or scenario analysis on different FMMs and use displacement factors (Sathre and O'Connor 2010) to estimate emission savings due to product substitution above a BAU scenario. The use of the three global scenarios presented for this study may provide a framework.

Regulatory services

Results evince that all DSSs in this study are able to quantify stand-level variables required to assess the likelihood and damage associated to catastrophic events in the respective case study areas. This information is an important basis for supporting regulatory ecosystem services at the landscape level, but not entirely sufficient since spatial aspects are important to the regulatory services defined in this study, i.e., wildfire, windstorms, pests, snowstorms and droughts. Most DSSs lack spatial analysis components to assess how a catastrophic event may spread over a landscape. Moreover, the comparability of results across case studies will depend on the definition of vulnerability classes according to the values of the stand-level variables. The literature underlines the local specificity of models to assess the contribution of each FMM to the mitigation of impacts of catastrophic events. For example, this was demonstrated by research that analyzed the correlation of inventory variables over which forest managers have control and a) the likelihood of occurrence of wildfires (e.g., Botequim et al. 2013; Garcia-Gonzalo et al. 2012), b) the damage caused by wildfires (e.g., Gonzalez et al. 2007; Marques et al. 2011) and c) the damage caused by windstorms (Zeng et al. 2010). For example, in the Mediterranean region an increased frequency of extreme events such as fire and droughts is highly likely as a result of climate change and will result in changes in ES output.

Future climate and forest management are likely to have a large influence on future forest disturbances such as pest outbreaks, forest fires and windthrow effects. These disturbances are recognized as among the most important components of forest greenhouse gas emissions and the effects may last for hundreds of years after a disturbance event (Kurz et al. 2009; Moore et al. 2012; Vilen and Fernandes 2011). It would be important to include also likely emissions from disturbance under different FMMs in scenario analysis. For example, low intervention management may result in limited regeneration and a build-up of fuel sources (dead wood), which could increase the likelihood of fires, windthrow, etc. Ideally, these risks must be included in the FMMs applied in the DSSs. A possible approach is the use of mean disturbance intervals or disturbance probabilities for different forest management scenarios (see Vanderberg et al. 2011). The complexity of modeling risks and effects of climate change and the need for developing this further to provide relevant decision support for the development of adaptation and mitigation strategies has been pointed out in previous reviews of forest DSS (Muys et al. 2010; Vacik and Lexer 2014; Orazio et al. 2017).

Recreational and aesthetic value

Existing studies present experiences made with quantifying the recreational and aesthetic value in forestry as well as in other fields, such as landscape research, and together they add up to an extensive list of possible criteria and indicators that could be used to measure this value. The assessment of the capabilities of the DSSs showed that variables related to other factors than traditional forest attributes and silvicultural activities are difficult to implement. Considering that most forest DSSs have not been specifically developed to include modeling of recreational and aesthetic values, the pragmatic approach to provide output on this value was to focus on variables related to forest attributes (cf. Edwards et al. 2011). Focusing on these attributes provided a list as defined in Table 4.

All DSSs in this study have the capability to provide information on the output of recreational and aesthetic value as they are defined in terms of these variables, but all the DSSs do not include all these variables; what output can be delivered varies between DSSs. In order to still be able to compare outcomes from different DSSs, a potential solution is to accept that the DSSs use different indicators for recreational and aesthetic value and instead determine a total index score based on different indicators for this ES and compare the outcomes for different FMMs for different countries. The forest data commonly used as input for the DSSs might in some cases be complemented with data from other sources. Especially variables related to spatial aspects are out of limits to many DSSs, e.g., spatial relationships between different stands or between a forest stand and another feature in the landscape, and may have to be omitted. However, as is the case for many of the DSSs, GIS analysis may be performed outside the DSS to complement the DSS output.

Water

Most DSSs are not built with a focus on water related ESs. It is often difficult to relate ES indicators to simple parameters at the stand level without additional modeling. For example, most DSSs do not include evapotranspiration, soil water storage, annual erosion or nutrients uptake. To quantify the variation in these indicators additional modelling is required. Some DSSs do have built-in quantification of ESs (such as soil erosion and sedimentation risk for Ireland), but others need to be integrated with additional models. For most DSSs, outputs can be used to feed a simplified model able to evaluate some water related ESs. For instance, though not explicitly included in the DSS, a rough estimation of water yield is relatively simple to obtain from DSS outputs. For erosion control and chemical conditions some of the parameters are available from the DSSs, such as the annual felling area and tree species composition. For a better estimation, soil properties (e.g., water storage capacity and soil infiltration) should be included as well as indicators such as local slopes or proximity to rivers, which is a spatial variable. Flood protection and water flow maintenance are difficult to estimate since important parameters are often missing, but inclusion of soil properties would be of help.

Spatial aspects are important for water related ESs on landscape level and the capabilities of the DSSs in this respect could be improved. An important factor would be the inclusion of other land use than forestry in the analysis, since water related ES provisioning is often similar even under different forest management. However, an explicit spatial distribution of FMMs would also improve the output.

Alternative forest management models

Of the four properties identified as critical for the DSSs to project the output of ESs, the capability to deal with changing timber and biomass prices over time, the capability to include climate change effects, and the spatial specificity of the landscape scale analyses have been discussed above in connection to the ESs. However, the capability to include alternative FMMs that may be used in the future needs some further attention.

The DSSs are mainly developed to address current issues and solve existing tasks. DSSs that are tailored to stands of horizontally homogeneous cohorts have often been designed to describe competition and growth on the stand level rather than on the individual tree level. Such models have successfully been applied to silvicultural systems that focus on large even-aged stands. However, if other ESs beyond wood production, climatic resilience and risk management are to be considered, a multi-species stand structure with a continuous distribution of age classes may become relevant. Such alternative FMMs usually go beyond the scope of operational DSS and there is a risk that alternative FMMs may be limited by the existing functionality of DSSs and the current FMMs, which have also been highlighted by previous reviews of forest DSS (Muys et al. 2010; Filyushkina 2016; Nobre et al. 2016). To use existing empirical growth and yield models to include very different FMMs in scenarios can be problematic, e.g., if a DSS has been built and used mainly for even-aged forestry, models for tree growth and regeneration will probably have to be adjusted or newly developed if the DSS is to be used to create scenarios that include FMMs based on continuous cover forestry. Further development of the DSSs in this respect may thus be essential if indeed the provision of ESs depends on mixed uneven-aged stands. To cover growth and structure development of highly heterogeneous stands, model developers will need to describe the effect of position-dependent thinning interventions on nearest-neighbour competition and growth. While much of the theory implemented within modern DSSs will persist and contribute to future development, many models may require an increase in their spatial discretization down to the individual tree level. Nevertheless, the landscape ecology literature demonstrates that addressing the provision of ESs other than timber may be achieved by targeting landscape structure and composition variables (Borges and Hoganson 2000). It is landscape-scale process and form that provide the framework to ecological functioning (Baker 1992). The relation between the forested landscape spatial structure and its ecological characteristics was highlighted by several authors (e.g., Bradshaw 1992; Franklin and Forman 1987; Naiman et al. 1993). Hunter (1990) further emphasized that biodiversity in a forested landscape would be best preserved in a land mosaic characterized by a diverse array of stands. The DSSs that report spatial analysis functionalities may thus be used to generate alternative landscape-level FMMs and assess their contribution to the provision of a wide range of ESs.

Landscape scale decision support

The DSSs included in this study originated from stand-level forest management planning models that incorporate single tree or stand growth and yield models. As is known from landscape ecology, addressing the provision of ESs other than timber requires the evaluation of landscape-level structures and composition variables. This study has shown that the assessed DSSs have been developed further and are now capable of dealing with the analysis of ESs at the landscape level, but only for the forest component. Only a few forest DSSs are capable of landscape analysis that includes other land cover than forest and other land use than forestry, as shown in a review of the 63 DSSs listed on the wiki produced within FORSYS, the EU-COST Action FP0804 Forest Management Decision Support Systems (Packalen et al. 2013). Ecosystem service and climate impact research, beyond the prediction of productivity and species composition, needs to address the above and below ground interactions within and between forests and with neighbouring landscape units. A widened spectrum of ecosystem services that result from the interaction among different components of the landscape, such as forests, agricultural areas and anthropogenic systems can then be considered. For example, models that use a detailed physiological component (Gutsch et al. 2002) are particularly suitable to represent hydrological processes including lateral fluxes. Coupling of hydrological and ecosystem models may enhance the quality of landscape-related case studies and enables the capturing of feedback processes between the forest and the hydrological system, such as groundwater recharge and nutrient and pollutant discharge (Molina-Herrera et al. 2015).

The study at hand underpins that all the DSSs presented can quantify essential stand properties for assessing forest vulnerability due to catastrophic events, which forms the basis for defining an effective regulatory ecosystem service framework at the landscape level. However, the lateral interaction of landscape elements is particularly relevant in the case of catastrophic events, such as the spread of fire across the landscape (Luo et al. 2014) or the protection of forest areas against storm damage as a result of shelter provided by other forests on the windward side and by other topographical landscape features. Seed dispersal is also an important long-term landscape-level process within the scope of forest resilience after fires and wind throw (Wang et al. 2013). Therefore, quantifying disturbance processes and preventative management approaches is a typical objective of landscape models (e.g. Syphard et al. 2011).

The rapid increase of computational capacity within research and land-use management institutions will promote the integration of all landscape components into the DSSs so that interactions between and within all landscape elements can be incorporated in the ES assessments (e.g. Schumacher et al. 2004). At the same time, the refinement of the forest representation within the DSSs will continue (e.g. through the development of physiological single-tree growth models) and will facilitate a more accurate and detailed assessment of the effects of climate change on the development and productivity of the forest component of the landscape.

Conclusions

To sum up, all DSSs assessed may be used to estimate the impacts of both stand and landscape-level FMMs on the provision of a range of ecosystem services over a typical temporal planning horizon (e.g., one and a half rotation in the case of even-aged structures). Results evince further that DSSs can be used to assess how timber price trends may impact that provision over time. The inclusion of forest owner behavior as reflected by the adoption of specific FMMs seems to be also in the reach of all DSS. Nevertheless, in some cases the DSSs need more data and models that may help to estimate the impacts of climate change on biomass production and other ESs. In scenarios covering long time horizons it is crucial to include modelling of climate change effects, since the outputs of most ESs are likely to change due to a changing climate. In many DSSs, the spatial analysis functionality need to be further developed for a more accurate assessment of the landscape level output of ESs from both current and alternative FMMs. The capability to include alternative and truly innovative FMMs is also an issue for many of the DSSs, e.g., FMMs driven by the production of other ESs than timber and biomass.

Even though the DSSs produce estimates of the same ESs using the same variables, different methods are used in the modelling approaches. The question is if the methodologies used to estimate the ESs have an impact on the outputs and, ultimately, if the outputs, in terms of ES estimates, are really comparable (cf. Biber et al. 2015). However, insisting on uniform methodologies could result in a loss of relevance of ES estimations at the local landscape scale. We hope that this study has taken a few steps in the direction of making outputs of different DSSs comparable by assessing their capabilities to estimate certain ESs in an integrated manner using a range of global scenarios.

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Table 1. Description of the DSSs considered in the assessment

System name	Country	Forestry dynamics model type[a]	Modeling approach[b]	Further information on DSS
SILVA	Germany (GER)	stand dynamics model	simulation	Pretzsch 2009; Pretzsch et al. 2002
Remsoft Woodstock	Ireland (IRL)	tightly coupled integrated stand and forestry dynamics model	optimisation	Corrigan and Nieuwenhuis 2017
InVEST and VALE	Italy (IT)	not forestry dynamics models (GIS and Excel based models)	simulation	InVEST: Kareiva et al. 2011 http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/
Kupolis	Lithuania (LIT)	tightly coupled integrated stand and forestry dynamics model	simulation	Kuliešis et al. 2017
EFISCEN-space	Netherlands (NL)	matrix model of forestry dynamics with a spatial extension	simulation	Schelhaas et al. manuscript in prep.
SADfLOR	Portugal (POR)	tightly coupled integrated stand and forestry dynamics model	simulation, optimisation	http://www.isa.ulisboa.pt/cef/forchange/fctools/en/SimflorPlatform/ StandSimulators http://www.forestdss.org/wiki/index.php ?title=SADfLOR web-based
Sibyla	Slovakia (SVK)	stand dynamics model	simulation	Fabrika and Pretzsch 2013 http://sibyla.tuzvo.sk/index.html
Heureka and HoldSim	Sweden (SWE)	tightly coupled integrated stand and forestry	simulation, optimisation	Stand simulator: Heureka: http://www.slu.se/en/collaborative-centres-and-projects/forest-sustainability-analysis/en-heureka/ Landscape simulator built on AIMMS: https://aimms.com/

		dynamics model		
ETÇAP	Turkey (TUR)	loosely coupled integrated stand and forestry dynamics model	simulation, optimization	Başkent et al. 2013

[a] Corresponds to the categorization of forestry dynamics models in Packalen et al. (2014).

[b] Corresponds to the methods groups categorization of DSSs in Nobre et al. (2016), though the category 'MCDA' was not considered here.

Table 2: Details of the case study areas (CSA)

CSA name (Country)	Area, 1000 ha (% forest)	Forest ownership (%)	Main stakeholders	Main ES	DSS(s) used
Augsburg Western Forests (GER)	150 (33)	50 Private 50 Public	PFO[a], ENGOs[b], forest service forest industry, general public (stable ownership structure for decades)	Timber, Biodiversity, Recreation, Water, Soil protection	SILVA
Lieberose – Schlaubetal (GER)	90 (37)	44 Private 56 Public	PFO (their share steadily increasing), forest service ENGOs, forest industry, general public	Timber, Biodiversity, Recreation, Soil protection	SILVA
Barony of Moycullen (IRL)	81 (16)	22 Private 78 Public	Forest service, advisory services, PFO, ENGO, industries, public, fisheries, investment bodies	Timber, Biodiversity Water, Recreation	Remsoft Woodstock
Veneto (IT)	76 (100)	74 Private 26 Public	PFO, logging enterprises, municipalities, regional forest administration, ENGO	Timber, Biodiversity Water, Erosion control	InVEST VALE
Telšiai (LIT)	254 (34)	63 Private 37 Public	Institute of Forest Management Planning, state forest managers, PFO, ENGO, regional park	Timber, Biodiversity Water, Recreation	Kupolis
The Netherlands (NL)	3,734 (11)	52private 48 public	National and regional government, FOA[c], state forestry, National Trust, non-industrial PFO & general public	Timber, recreation, biodiversity	EFISCEN-space
Sousa Valley (POR)	15 (10)	100 Private 0 Public	FOA, forest owner federation, forest industry, forest service, local municipality, other NGO	Timber, Recreation	SADfLOR
Podpolanie (SVK)	34 (57)	7 Private 93 Public	State forest managers, PFO, ENGO, general public	Timber, Biodiversity Water, Recreation	Sibyla
Kronoberg county (SWE)	847 (77)	83 Private 17 Public	FOA, ENGO, forest industry, Swedish Forest Agency, public	Timber, Biodiversity, Water, Recreation	Heureka HoldSim
Gölcük (TUR)	83 (58)	1 Private 99 Public	General Directorate of Forestry, NGOs, forest industry, public	Timber, Biodiversity, Water, Recreation, Non-wood Forest Products	ETÇAP

[a] private forest owners
[b] Environmental non-governmental organization(s)
[c] Forest owners' association

Table 3. List of variables required as output from the DSSs on stand and/or landscape level for quantification of the ESs (marked in the table as S=stand level and L=landscape level)

Variable	Unit	Comment	Timber and biomass	Recreational and aesthetic value	Regulatory services	Carbon sequestration	Water	Biodiversity
Afforestation	age of forest cover (per period)	Concerns afforestation of non-forest land, not regeneration after final felling		S, L				
Age	year (per period)	Mean age		S, L	S		S, L	
Basal area	m^2/ha (per period)			S, L	S			
Below ground biomass	kt C/ha (per period)					L		
Dead wood, logs	m^3/ha and kt C/ha (per period)	Per species		S, L		L		S, L
Dead wood, stumps and roots	kt C/ha (per period)					L		
Density/openness	stems/ha (per period)			S, L	S			S, L
Fertilization (nitrogen and/or phosphorus)	kg/ha and area fertilized (per period)						S, L	
Final felling area	ha (per period)	For uneven-aged forests: size of contiguous harvested areas. For shelterwood: two figures regarding harvested area / time period are given		S, L			S, L	L
Forest edges	m/ha (per period)	Length of forest edge relative to the landscape area		L				
Forest stand size	ha (per period)	Area of individual stands		L				
Forest stand types	no. of different stand types in the landscape (per period)	Definitions of forest stand types may differ		L				
Harvested wood, total	m^3/ha (per period)		S, L			L	S, L	S
Large dead wood	stems/ha (per period)	Per species, suggestion for size classes (diameter in cm): >30 cm, >40cm, >50cm, >60cm						S, L
Large trees	m^3/ha and stems/ha (per period)	Per species, suggestion for size classes (diameter in cm): >30 cm, >40cm, >50cm, >60cm						S, L
Naturalness	Hemeroby index (per period)	The hemeroby index measures the deviation from the potential natural vegetation caused by human activities (see Winter 2012). Gradients of human influence are assessed on a scale from "natural" or non-disturbed landscapes and habitats to totally disturbed or "artificial" landscapes. In this study the naturalness is assessed based on stand characteristics (varying depending on region and forest type) on the following scale: 0 = natural, non-disturbed forest, 0.33 = close to natural, 0.66 = semi-natural, 1 = relatively far from natural (monoculture, plantations)		S, L				
Protected area	ha (per period)	Area as per IUCN category (Dudley 2008)						L
Residues harvested	m^3/ha or kg/ha, and area where residues are harvested (per period)	In final felling (and thinning if possible/applicable, but these should be separated)	S, L	S, L		L		
Spatial fragmentation	index value per habitat/forest type (per period)	Spatial fragmentation refers to the composition (i.e. the amount of habitat) and configuration (i.e., the size of habitat patches and the extent to which they are aggregated or dispersed of the landscape) and can be described by different landscape measures/indices, e.g., number and mean area of patches, core area and shape index of patches (Baskent and Keles 2005).			L			L
Standing volume	m^3/ha and kt/ha (per period)		S, L			L	S, L	S
Tree height	m (per period)	Dominant height			S			
Tree size diversity	m^3/size class (per period)	Suggestion for size classes (diameter in cm): 1-10, 11-20, 21-30, 31-40, 41-50, 51-60, >61		S	S			S, L
Tree species composition	m^3/ha (per period)	Per species		S, L	S		S, L	S, L
Understory	m^3/ha or no/yes (per period)			S, L	S			
Volume harvested by assortments (sawlogs and pulpwood)	m^3/ha and kt C/ha (per period)		S, L			L		

Table 4. Classification of the nine DSSs according to their ability to quantify the variables required for the ES provision assessment. A green cell indicates that the variable is part of the DSS and that the ES is assessed within the DSS; a yellow cell indicates that the variable is part of the DSS but that the ES is assessed outside of the DSS following the simulation/optimisation; and a red cell indicates that the variable is not part of the DSS. The DSSs included are (left to right, starting at the top row): SILVA (Germany), Remsoft Woodstock (Ireland), InVEST and VALE (Italy), Kupolis (Lithuania), EFISCEN-space (Netherlands), SADfLOR (Portugal), Sibyla (Slovakia), Heureka (Sweden) and ETÇAP (Turkey)

Variable	Unit	Timber and biomass	Recreational and aesthetic value	Regulatory services	Carbon sequestration	Water	Biodiversity
Afforestation	age of forest cover (per period)		R Y Y Y Y G R R G				
Age	year (per period)		G G Y G G G G G G	G G Y G G G G G G		G G Y G G G G G G	
Basal area	m^2/ha (per period)		G G Y Y G G G G G	G G Y Y G G G G G			
Below ground biomass	kt C/ha (per period)				G G G Y G Y G G Y		
Dead wood, logs	m^3/ha and kt C/ha (per period)		G G Y Y Y R G G R		G G G Y Y R G G R		G G Y Y Y R G G R
Dead wood, stumps and roots	kt C/ha (per period)				G G G Y Y R G G R		
Density/openness	stems/ha (per period)		G G Y Y G G G G G	G G Y Y G G G G G			G G Y Y G G G G G
Fertilization (nitrogen and/or phosphorus)	kg/ha and area fertilized (per period)					R G Y R R G R G G	
Final felling area	ha (per period)		G G Y Y G G Y G G			G G Y Y G G Y G G	G G Y Y G G Y G G
Forest edges	m/ha (per period)		R R Y Y Y G Y Y G				
Forest stand size	ha (per period)		R R Y Y Y G Y G G				
Forest stand types	no. of different stand types in the landscape (per period)		G G Y Y G G Y G G				
Harvested wood, total	m^3/ha (per period)	G G G G G G G G G			G G G G G G G G G	G G Y G G G G G G	G G Y G G G G G G
Large dead wood	st/ha (per period)						G G Y R Y R G R R
Large trees	m^3/ha and stems/ha (per period)						G G Y Y G R G G Y
Naturalness	Hemeroby index (per period)		G G Y Y Y G Y G Y				
Protected area	ha (per period)						G G G Y Y Y Y G G
Residues harvested	m^3/ha or kg/ha, and area where residues are harvested (per period)	G G Y Y G G G G R	G G Y Y G G G G R		G G Y Y G G G G R		
Spatial fragmentation	index value per habitat/forest type (per period)						Y R G Y Y G Y Y G
Standing volume	m^3/ha and kt/ha (per period)	G G G G G G G G G			G G G G G G G G G	G G Y G G G G G G	G G Y G G G G G G

Tree height	m (per period)						
Tree size diversity	m^3/size class (per period)						
Tree species composition	m^3/ha (per period)						
Understory	m^3/ha or no/yes (per period)						
Volume harvested by assortments (sawlogs and pulpwood)	m^3/ha and kt C/ha (per period)						

Supplementary Material

for

Forest decision support systems for analysis of ecosystem services provisioning at landscape scale under global climate and market change scenarios

Eva-Maria Nordström, Maarten Nieuwenhuis, Peter Biber, Emin Zeki Başkent, Kevin Black, Jose G. Borges, Miguel N. Bugalho, Giulia Corradini, Edwin Corrigan, Ljusk Ola Eriksson, Adam Felton, Nicklas Forsell, Geerten Hengeveld, Marjanke Hoogstra-Klein, Anu Korosuo, Matts Lindbladh, Isak Lodin, Anders Lundholm, Marco Marto, Mauro Masiero, Gintautas Mozgeris, Davide Pettenella, Werner Poschenrieder, Robert Sedmak, Jan Tucek and Davide Zoccatelli

Supplementary Table S1. DSS information in relation to the use of dynamic timber prices as provided by the global scenarios

DSS (Country)	**Ability to include global price trends in DSS**	**Methodology used**	**Assumptions on how OT reacts to prices**	**DSS outputs influenced by changing prices**
SILVA (GER)	Yes	Look-up table with periodic assortment prices	Depending on OT, higher prices may lead to the use of FMMs that increase harvesting. Reactions are strong (very un-elastic) for economically focused OTs, and quite elastic for OTs focused on other, e.g., biodiversity-related goals.	Harvest volumes, FMM selection by OTs, ES provision levels.
Remsoft Woodstock (IRL)	Yes	Look-up table with periodic assortment prices	Depending on OT, higher prices may lead to the use of FMMs that increase harvesting.	Harvest volumes, NPV, FMM selection by OTs, ES provision levels
InVEST and VALE (IT)	Yes	Look-up table with periodic assortment prices	Higher prices may lead to the use of FMMs that increase harvesting, though timber production is not the main aim of current FMMs.	Harvest volumes, NPV and other financial/economic profitability and risk indicators, ES provision levels
Kupolis (LIT)	Yes	Look-up table with periodic timber prices	Changing prices have no influence on FO behavior as existing FMMs are based on legal and ecological conditions of the forests.	Costs, incomes and profits of forestry activities. More detailed outputs will be generated outside DSS, including NPV by FMM, FOT, etc.
EFISCEN-space (NL)	Yes	Look-up table with periodic assortment prices.	Higher prices may lead to the use of FMMs that increase harvesting.	FMM selection by OTs and all outputs, includingES provision levels
SADfLOR (POR)	Yes	The increase/decrease price rates of the global scenarios are used and applied to initial local prices to compute NPVs	No assumptions made.	FMM selection by OTs and all outputs, including ES provision levels.
Sibyla (SVK)	No	Look-up table with assortment prices, constant over time.	OTs are assumed to expect current prices to persist.	
Heureka and HoldSim (SWE)	Yes	Look-up table with periodic assortment prices.	Depending on OT, higher prices may lead to the use of FMMs that increase harvesting.	FMM selection by OTs and all outputs, including ES provision levels.

ETÇAP (TUR)	To a certain extent	Current prices are guided by interest rate to reflect periodical changes in prices over time.	Depending on OT, higher prices may lead to the use of FMMs that increase harvesting.	All outputs related to prices.

Supplementary Table S2. DSS information in relation to the use of climate change data as provided by the global scenarios. Cited studies are listed in the References section of the article.

DSS (Country)	**Climate change modelling is part of DSS**	**Climate change data source**	**Variables/models affected**	**Scientific basis and references**
SILVA (GER)	Yes	HadGEM2-ES projections	Single tree growth potential	Pretzsch 2009; Pretzsch et al. 2002
Remsoft Woodstock (IRL)	Yes	Met Eireann's C4I projections of A2 and B1 scenarios in IPCC SRES	Stand growth by species, species selection	ClimAdapt. Ray et al. 2009
InVEST and VALE (IT)	Yes	Based on CMCC's regional elaborations via COSMO-CLM (radiation scenarios RCP 4.5 and 8.5)	Stand growth	http://www.cmcc.it/models/3d-cmcc-fem-three-dimension-forest-ecosystem-model Montesarchio et al. 2012
Kupolis (LIT)	No[a]			
EFISCEN-space (NL)	Yes	Any SRES or RCP scenario downscaled to 1 km^2 maps	Stand growth by species	Schelhaas et al. manuscript in prep.
SADfLOR (POR)	In part		Stand growth. A shrub biomass model can estimate the impact on fuel accumulation.	Botequim et al. 2015
Sibyla (SVK)	Yes	Any SRES and/or RCP scenarios providing the projections of temperatures, precipitations, temperature amplitudes, air humidity, content of NOx and SO2 in air and length of growing season.	Tree growth potential and related increments	Fabrika and Ďurský 2005 Fabrika and Pretzsch 2013

Heureka and HoldSim (SWE)	Yes	MPI 4.5: Based on Max Planck Institute MPI-ESM model using radiation scenario RCP 4.5. MPI 8.5: Based on Max Planck Institute MPI-ESM model using radiation scenario RCP 8.5. ECHAMS_A1B: Based on Max Planck Institute climate model ECHAM using emission scenario SRES A1B.	Stand growth	An approximation model of BIOMASS. The BIOMASS model is documented in Bergh et al. 2003; 1998
ETÇAP (TUR)	No			

[a] Kupolis does not currently model changing climatic conditions. However, growth functions and forest regeneration characteristics used for simulation may be adjusted by the user based on, e.g., expert judgement.

Supplementary Table S3. DSS information in relation to the use of Owner Type (OT) and Forest Management Model (FMM). Cited studies are listed in the References section of the article.

DSS (Country)	**a) What variables /parameters determine the distribution of forest area to OTs? b) What is the source of data?**	**a) What variables/parameters determine the allocation of existing FMMs to existing OTs? b) What is the source of data?**	**Source of data for new OTs and for alternative FMMs and associated proportions**
SILVA (GER)	a) The distribution is assumed to be constant based on historical distribution which has been stable. b) Forest inventory data	a) OTs' preferences concerning ESs, wood prices, wood demand. b) stakeholder feedback (especially from EU projects INTEGRAL and ALTERFOR), long-term experience from collaboration with certain OTs	Stakeholder interviews and from forest consulting experience
Remsoft Woodstock (IRL)	a) Land use b) GIS datasets from State forestry board, Irish Department of Agriculture and Ireland's Forest Service	a) Timber prices, species growth rates, ES provision requirements b) Expert knowledge, scientific knowledge, INTEGRAL and ALTERFOR stakeholder meetings	Expert knowledge, in Ireland and in countries where alternative FMMs are already used
InVEST and VALE (IT)	a & b) Expert knowledge, ALTERFOR stakeholder meetings, existing literature on forest owners' attitudes towards FMM (Canton and Pettenella 2010; Mozzato and Gatto 2016) and other relevant scientific and grey literature	a) Owner preferences, stakeholder preferences, wood prices, legal constraints (e.g., Natura 2000 sites) b) Expert knowledge, ALTERFOR stakeholder meetings, existing literature on forest owners' attitudes towards FMM	Expert knowledge, ALTERFOR stakeholder meetings
Kupolis (LIT)	a) Size of estate, total area of forest owned, presence of agricultural land-use in the estate, environmental restrictions on the estate, characteristics of forest stands b) Real estate cadaster, forest cadaster, expert knowledge	a) A set of legal acts regulating the forestry, characteristics of forest stands b) Information available from state forest cadaster, INTEGRAL stakeholder meetings (Mozgeris et al. 2016)	Expert knowledge, stakeholder contacts, involvement of non-academic partner, and other relevant research
EFISCEN-space (NL)	a & b) National forest inventory (Schelhaas et al. 2014) and local inventory (Clerkx et al. 2016)	a & b) National forest inventory (Schelhaas et al. 2014) and local inventory (Clerkx et al. 2016), scientific knowledge (Hoogstra-Klein 2016; Hoogstra-Klein and Burger 2013), INTEGRAL stakeholder meetings (de Bruin et al. 2015; 2017), ALTERFOR stakeholder meetings	Stakeholder contacts, relevant research

SADfLOR (POR)	a) The distribution is based on the history of the region and the corresponding socioeconomic and demographic variables b) INTEGRAL reports, ALTERFOR stakeholder meetings	a) The history of the region and the corresponding socioeconomic and demographic variables. b) INTEGRAL reports, ALTERFOR stakeholder meetings	ALTERFOR stakeholder meetings and workshops
Sibyla (SVK)	a) Ownership rights, forestry and nature conservation legislation b) Forest statistics, expert and scientific knowledge, INTEGRAL and ALTERFOR stakeholder meetings and interviews	a) Ownership rights, forestry and nature conservation legislation b) Forest statistics, expert knowledge, scientific knowledge, stakeholder meetings	Expert and scientific knowledge, stakeholder contacts, ALTERFOR stakeholder meetings, interviews
Heureka and HoldSim (SWE)	a) Size of property b) Government register of properties, map of stands in GIS	a) Preferences related to economic interest, management tradition, biodiversity interest, and degree of involvement in management b) Articles on forest owner strategies (Eggers et al. 2014; 2015), interviews of forest consultants from the forest owners' association; forest statistics on forest operations	Stakeholder contacts, stand-level modelling research
ETÇAP (TUR)	a) The distribution is assumed to be static since almost all forests are state owned by legislation b) Forest inventory data	a) Management guidelines, species type, site factors, timber prices, species growth rates, ES provision requirements b) Knowledge of local foresters, scientific knowledge, ALTERFOR stakeholder meetings, national forest inventory	Major stakeholder contacts, scientific knowledge

Supplementary Table S4. DSS information in relation to the spatial data source, resolution, stratification and adjacency

DSS **(Country)**	**Origin of spatial data (i.e. organisations from which data were obtained)**	**Grouping of stands into strata?**	**If grouping is used, at what scale?**	**Is the location of stands or strata in the landscape known in the DSS**	**If no grouping, is adjacency of stands known in the DSS, and how is this information used?**
SILVA (GER)	Raster inventory plots from Federal country forest services and Federal Republic of Germany (national forest inventory data)	Yes	Case study area, by stratum	Yes, applies to strata; inventory data resolution too low on stand scale	No; spatial metrics applied to set of inventory plots used
Remsoft Woodstock (IRL)	GIS datasets from multiple sources	Yes[a]	Case study area[b]	Yes	No[c]
InVEST and VALE (IT)	GIS datasets from multiple sources	Yes, but single stand optimisation will also be analysed	Case study area/Forest type	Yes	No
Kupolis (LIT)	State forest cadastre data, available from Lithuanian State Forest Service	No (each stand has unique properties)	-	No	No[d]
EFISCEN-space (NL)	GIS datasets from multiple sources (mainly developed by Wageningen University and Research)	Yes (Each inventory plot is individually projected. However, each plot represents a stratum.)	Based on NFI strata	The information is not used in the simulation, inventory data resolution too low on stand scale	No[d]
SADfLOR (POR)	GIS	No, but individual stands may be aggregated into larger analysis areas if needed	-	Yes	Yes. The information may be used in model building to generate spatial conditions' requirements to address ES other than timber. It may be used further to interpret solutions when model solving
Sibyla (SVK)	GIS/National Forest Centre	No (stand level approach)	-	No	No

Heureka and HoldSim (SWE)	SLU Forest Agency Land Survey	No (each stand has unique properties)	-	Yes, in the sense that location of stand vs. property is used.	No[d]
ETÇAP (TUR)	Forest inventory plots and GIS from the General Directorate of Forestry	No (each stand has unique properties)	-	Yes	Yes, the adjacency is created within the DSS and the output is fed back to GIS for graphical/spatial analysis

[a] Initially, but single stand optimisation/heuristics is explored later.
[b] However, only when all stand site and management variables are identical.
[c] Not in the standard Remsoft Woodstock DSS optimiser, but will be explored in the Spatial Optimiser.
[d] The DSS as such is non-spatial. Spatial analyses of landscape patterns are carried out in GIS as post analyses of simulations.

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