TRANSFORMIT

Deliverable 5.4

Catalogue of Decision Support Tools supporting Integrative Forest Management

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DISCLAIMER

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Executive Summary

Decision Support Systems (DSS) are an important instrument facilitating decisions in modern forest management, as they inform decision makers on the best way to implement their activities and evaluate the impacts of these decisions. DSS can support the needs of Integrative Forest Management (IFM), helping stakeholders to integrate biodiversity conservation and climate change adaptation into forest management to ensure the sustainable provision of many ecosystem services. Deliverable 5.4 explores the capacity of DSS to support IFM. The Catalogue of DSS presented here is a flexible instrument to match the necessities of different stakeholder typologies with the potential of DSS. Consulting the Catalogue, forest managers can find the best DSS for IFM under climate change or for integrating closer-to-nature forestry in ordinary management activities. The updates concerning IFM for the DSS in the Catalogue will be available in the ForestDSS Wiki[1] website.

The Catalogue was compiled through a Survey delivered to managers of forest DSS selected across Eurasia and North America. The survey consists in a series of questions for describing the capacity of DSS to support IFM principles, specifically exploring their capacity to visualize, analyse and predict IFM variables. We selected 40 IFM variables related with IFM principles and existing indicators, relying on the results of the TRANSFORMIT project.

The survey was completed by 42 DSS managers and reflects a broad range of institutional ownership and geographical coverage. The DSS were more capable to deal with topics traditionally covered by timber-production oriented forestry, such as the state and development of forest characteristics and management practices and only partially capable to deal with variables related with IFM goals, such as *ecosystem services* for *forest production*, *natural disturbances* for *forest protection*, and *biodiversity aspects* for *forest conservation*.

As concerns *forest production*, while timber yield was commonly supported, most DSS lacked the capacity to represent or simulate non-wood forest products, recreational and aesthetic values, and hydrological services. These functionalities are critical for managing multifunctional forests and public value generation, which are key objectives in IFM. DSS showed moderately high functionality for dealing with carbon cycling, particularly for aboveground and belowground biomass pools. However, DSS were less capable of accounting for carbon in deadwood and soil-important components for carbon accounting to support climate-smart forestry and the bioeconomy sector.

As concerns *forest protection*, the capacity of DSS to increase adaptability and resilience with low impact forestry on landscapes, such as uneven-aged approaches (e.g., continuous cover forestry and selection cutting), was lower than their capacity to deal with regimes widely employed in traditional forestry, such as even-aged management. The DSS capacity to address disturbances was generally low, with a few DSS capable of simulating abiotic disturbances (e.g., storms and wildfires), and even less capable of dealing with biotic disturbances (e.g., insects, fungi). This limits the usefulness of DSS in supporting resilience-based management in the face of climate change.

As concerns *forest conservation*, the DSS capacity to handle ecologically relevant variables related with the formation of habitats for forest dwelling species were lower than their capacity to deal with common forest metrics of stand development, such as tree density, basal area, and biomass. Only a small fraction of DSS could adequately simulate or analyze habitat quality, species of conservation concern, habitats of interest or forest connectivity. On the contrary, current tools often rely on proxies of ecological indicators such as structural attributes (e.g., deadwood) and few species-based indicators. Current DSS need further enhancement to capture ecological complexity in line with IFM's emphasis on sustaining forest conservation.

In synthesis, DSS are key enablers of IFM, expected to provide the operational tools to plan and evaluate multi-functional forest management strategies at different spatial scales. Our survey aligns with these goals and highlights both the progress and shortcomings of current DSS in supporting IFM aspirations, revealing a nuanced picture on the relationships between DSS and IFM.

On the one hand, today's forest DSS are more powerful and comprehensive than ever before as they enable complex analyses and multi-objective planning. They serve IFM increasingly, enabling holistic assessments of forest management, accounting for an array of ecosystem services, climate-related risks and biodiversity values in ways that were not possible a generation ago. *On the other hand*, important gaps remain related with their limited capacity to include ecological aspects, evaluate the impacts of forest management options and improve the user´s experience in terms of visualization and usability. While DSS are relatively robust in supporting traditional forest management and structural metrics, they are less developed in supporting the integrative, multifunctional, and ecologically grounded approaches that IFM requires. There is substantial room for improvement in the representation of ecosystem services, disturbances and biodiversity and for better aligning DSS functionality with stakeholders´ need and policy objectives. *Furthermore*, we found that the DSS analyses are mainly used by researchers, and there may be a gap between research-oriented use and practical use. Addressing these weaknesses through ongoing research, tool improvement, and capacity-building will be essential to harness the full potential of DSS in achieving truly integrative and sustainable forest management. European efforts like the TRANSFORMIT project are at the forefront of adapting and developing DSS for IFM, exemplifying how science-based tools can inform balanced decisions in forestry.

Keywords

ForestDSS Wiki, Decision Support System, Decision Support Tool, IFM Indicators, Integrative Forest Management.

1. Introduction

This Deliverable (henceforth named “**D5.4**”) explores the capacity of Decision Support Systems (DSS) to support Integrative Forest Management (IFM). DSS can support the needs of IFM, helping owners, forest professionals and stakeholders to integrate biodiversity conservation and climate change adaptation into forest management to ensure the sustainable provision of ecosystem services. DSS are an important instrument of decision in modern forest management, as they inform users[1] on the best way to plan their management activities in the forest and some DSS are also able to predict the consequences of different management strategies. DSS can help stakeholders to reconcile multiple interests from forests minimizing the conflicts between biodiversity and the provision of multiple ecosystem services. The Catalogue of DSS described in D5.4 is a flexible instrument to match the necessities of different stakeholder typologies with the potential of DSS. Consulting the Catalogue, forest managers can find the best DSS able to solve their planning problems or to face their necessities, for example finding the best DSS for adaptive forestry under climate change or for integrating closer-to-nature forestry (Larsen et al., 2022) in ordinary management activities. The updates concerning IFM for the DSS described in this Catalogue will be available also in the ForestDSS Wiki[1] website.

Specifically, D5.4 is also an analysis of a Catalogue of Decision Support Systems (DSS) capacities to support Integrative Forest Management (henceforth named “**Catalogue**”). DSS are computer-based systems, which support planning and decision making in semi- and unstructured decision problems. In that context database systems are linked with analytical models and expert knowledge to support various representations of possible outcomes in graphical and tabular means (Sprague and Watson, 1993; Holsapple and Whinston, 1996).

The Catalogue is based on the analysis of the data collected in a survey “Characteristics of Decision Support Tools to implement Integrative Forest Management” (henceforth named “**DSS4IFM Survey**”) conducted during the TRANSFORMIT project. IFM variables included in D5.4 derived from the D5.1 “Pool of potentially relevant indicators for Integrative Forest Management” (Linser et al., 2024) and the D5.2 “Participatory agreed set of key indicators for monitoring and reporting IFM” (Linser et al., 2025). Building on existing indicator sets (CBD, Forest Europe, Montreal Process, UN SDGs, FSC, PEFC, EuropaBON), and relevant research projects (e.g. RESONATE), IFM indicators measure and assess forest biodiversity, ecosystem services, adaptive capacity and resilience of forests, economic performance. IFM indicators comprise national level indicators which can be downscaled to lower-level landscape or FMU indicators.

D5.4 is the end-product of the TRANSFORMIT Task 5.4 “Screening of Decision Support Systems”. The Task 5.4 is divided into three sections:

(I) Developing a Protocol for describing existing Decision Support Tools/Systems (henceforth named “**Protocol**”) based on the requirements of Integrative Forest Management (IFM).
(II) Using the Protocol to describe DSS characteristics under different European conditions and in different biogeographical European regions, North America and China.
(III) Producing a Catalogue suitable for informing forest planners and other forest professionals about which DSS are applicable in IFM practices.

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[1] representatives of different interests in the forest, Living Lab representatives, etc

2. Methods for the development of the DSS4IFM Survey

2.1 Exploratory Survey to select DSS for the DSS4IFM Survey

We selected the forest DSS to include in the DSS4IFM Survey based on their representativeness of different functionalities (visualization, analysis, simulation), on the diversity of geographic coverage, types of institutions, and end-users.

We selected the DSS for the Catalogue primarily from a previous Exploratory Survey named “Survey for Identification of forest Decision Support Systems (DSS)” conducted during the first phase of the TRANSFORMIT project that identified actively used forest DSS. The exploratory survey was sent to 438 DSS managers worldwide and discovered 38 new DSS not previously included in any web DSS database (i.e., forestdss.org wiki[2], Formodels iefc[3], Johnson et al. 2007) (Figure 1). The general description of the newly discovered 38 DSS was added to the ForestDSS Wiki[1] website. The Exploratory Survey was completed in July 2024.

Then we evaluated this first initial selection of DSS against the selection criteria described above and added new DSS to the Catalogue which could increase its representativeness. When contact persons did not reply to the Survey after several times, we replaced the DSS with an equivalent DSS whenever possible.

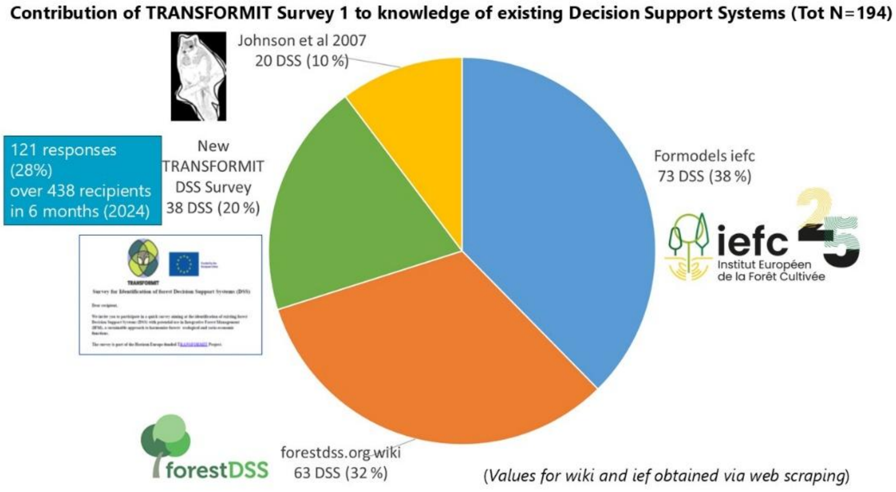

Figure 1. Results of the first DSS exploratory survey.

2.2 General structure of the DSS4IFM Survey

The DSS4IFM Survey describes the capacity of 42 DSS, selected with an Exploratory survey (see 2.1), to visualize, analyse or predict (2.3.1) 40 IFM variables (3.2.2).

The DSS4IFM Survey is divided into a short background section describing basic DSS characteristics and in 6 sections reflecting the following 6 main topics (related with IFM principles for the selection of IFM-practicing enterprises defined in Task 3.1): "habitats and species", "forest structure and processes", "forest health and disturbances", "ecosystem functions and services", "carbon cycling" and "forest management". When it was possible,

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[2] http://forestdss.org/wiki/index.php?title=Main_Page
[3] https://www.plantedforests.org/formodels_database_forest_modeles_liste/

the DSS4IFM Survey was compiled directly by the respective DSS managers/designers, otherwise by the TRANSFORMIT staff.

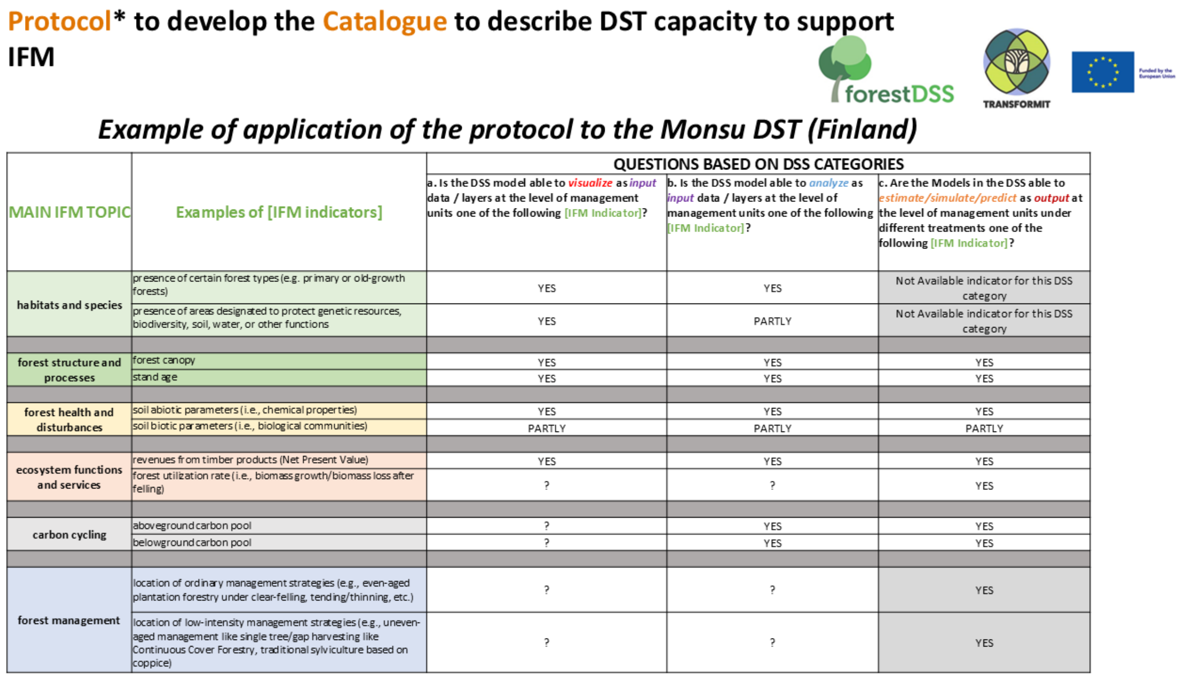
2.3 Protocol for the description of DSS

2.3.1 Protocol Structure

We developed a **Protocol** (see an example for the MONSU DSS in Figure 2) as a series of questions for describing the capacity of DSS to support IFM principles. These questions are all based on which typology the DSS belongs to of the main two typologies defined by Power (https://dssresources.com/dsstypes/): "data driven" and "model driven" DSS (see the frame below for extended definitions). Data-driven DSS are DSS able to *visualize* and/or *analyse* input variables, while model-driven DSS can also *predict* variables as output. The Protocol builds on the community of practice “Forest Management Decision Support Systems”[4].

The DSS4IFM Survey employs the Protocol to explore the capacity of each DSS to deal with IFM variables in these three ways. Respondents (i.e., DSS users) had to indicate whether their DSS was able to *analyse* data and information, *visualize* information by various means and/or to *simulate/ predict* the effects of IFM. The alternatives to each reply were "Yes", "Partly", "No".

The Protocol was completed in December 2024.



Protocol* to develop the Catalogue to describe DST capacity to support IFM

Example of application of the protocol to the Monsu DST (Finland)

MAIN IFM TOPIC	Examples of [IFM indicators]	QUESTIONS BASED ON DSS CATEGORIES		
		a. Is the DSS model able to *visualize* as *input* data / layers at the level of management units one of the following [IFM Indicator]?	b. Is the DSS model able to *analyze* as *input* data / layers at the level of management units one of the following [IFM Indicator]?	c. Are the Models in the DSS able to *estimate/simulate/predict* as ***output*** at the level of management units under different treatments one of the following [IFM Indicator]?
habitats and species	presence of certain forest types (e.g. primary or old-growth forests)	YES	YES	Not Available indicator for this DSS category
	presence of areas designated to protect genetic resources, biodiversity, soil, water, or other functions	YES	PARTLY	Not Available indicator for this DSS category
forest structure and processes	forest canopy	YES	YES	YES
	stand age	YES	YES	YES
forest health and disturbances	soil abiotic parameters (i.e., chemical properties)	YES	YES	YES
	soil biotic parameters (i.e., biological communities)	PARTLY	PARTLY	PARTLY
ecosystem functions and services	revenues from timber products (Net Present Value)	YES	YES	YES
	forest utilization rate (i.e., biomass growth/biomass loss after felling)	?	?	YES
carbon cycling	aboveground carbon pool	?	YES	YES
	belowground carbon pool	?	YES	YES
forest management	location of ordinary management strategies (e.g., even-aged plantation forestry under clear-felling, tending/thinning, etc.)	?	?	YES
	location of low-intensity management strategies (e.g., uneven-aged management like single tree/gap harvesting like Continuous Cover Forestry, traditional sylviculture based on coppice)	?	?	YES

Figure 2. Protocol for describing the capacity of DSS to support IFM principles. Examples of questions for each topic answered for the Monsu DSS (Finland).

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[4] http://www.forestdss.org/CoP/community

Data-driven and model-Driven DSS sensu Power

Data-driven DSS and Model-Driven DSS are the main DSS typologies along a gradient of DSS types (Figure 3 redesigned from Fernando and Baldelovar, 2022).

Figure 3. Types of Decision Support Systems.

Data-driven DSS is a type of DSS that emphasizes access to and manipulation of a time-series of internal data and sometimes external data. Simple file systems accessed by query and retrieval tools provide the most elementary level of functionality. Data warehouse systems that allow the manipulation of data by computerized tools tailored to a specific task and setting or by more general tools and operators provide additional functionality. Data-driven DSS with On-line Analytical Processing provides the highest level of functionality and decision support that is linked to analysis of large collections of historical data. Executive Information Systems (EIS) and Geographic Information Systems (GIS) are special purpose Data-Driven DSS.

Model-Driven DSS emphasize access to and manipulation of a model, for example, statistical, optimization and/or simulation models. Simple statistical and analytical tools provide the most elementary level of functionality. In general, model-driven DSS use complex simulations, optimization or multi-criteria models to provide decision support. Model-driven DSS use data and parameters provided by decision makers to aid decision makers in analysing a situation.

2.3.2 Criteria for the selection of the IFM variables in the Protocol

Indicators of IFM (see D5.2) should be incorporated in DSS, for example, based on the country-level INTEGRATE project reports[5] and/or modelling scopes from the FORSYS project (Cost Action FP 0804, Borges et al., 2014). IFM variables have been selected to represent both typical variables that are usually dealt with by DSS and IFM indicators derived from Task 5.1 and its outcome D5.1: Potentially relevant indicators for Integrative Forest Management (Linser et al., 2024). The selected 40 IFM variables cover all the 6 main topics related with IFM principles: "habitats and species", "forest structure and processes", "forest health and disturbances", "ecosystem functions and services", "carbon cycling" and "forest

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[5] https://efi.int/projects/integrate-integration-nature-protection-forest-management-and-its-relation-other-forest

management". A complete list of IFM variables with definitions and measurement units is reported in the Deliverable Supporting Documents in Appendix A in Table S1.

The process of selection and adaptation of the IFM variables was completed in February 2025.

2.3.3 Testing phase of the DSS4IFM Survey

The Protocol and the IFM variables were combined in an Excel file which represented the testing version of DSS4IFM Survey. The Protocol was tested for 3 DSS managed by TRANSFORMIT colleagues. Specifically, the DSS managers from EFI, BOKU, LUKE, WUR and University of Eastern Finland (UEF) tested both the questions and the variables adding explicative comments and suggesting edits or deletions.

The Testing phase of the DSS4IFM Survey was completed in February 2025.

2.3.4 Methods for the development of the DSS4IFM Survey

The DSS4IFM Survey was finally conducted using Webropol[6], an online survey and analysis tool. The DSS4IFM Survey was originally sent by email to 66 DSS managers representing 55 DSS from 21 countries of which 16 were European countries.

The DSS4IFM Survey was available to respondents from March to May 2025.

2.4 Data storage

The data of the DSS4IFM Survey will be permanently stored into the ForestDSS Wiki website[7]. It will be openly usable for stakeholders beyond project duration, enabling the future use and adding new information to the database alongside DSS developments. There are also plans for linking the survey data with the EFI BioGateway[8] and related Bot. Factsheets describing the generalities of each DSS (state of activity, contact persons, institution, country and link to the ForestDSS Wiki website[9] when available), capacity of each DSS to deal with the six topics and specific IFM variables are reported in the Deliverable Supporting Documents in Appendix B.

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[6] https://webropol.com/
[7] http://forestdss.org/wiki/index.php?title=Main_Page
[8] https://biogateway.efi.int/
[9] http://forestdss.org/wiki/index.php?title=Main_Page

3. Results of the DSS4IFM Survey

3.1 DSS characteristics

3.1.1 Survey completeness

The DSS4IFM Survey was completed by DSS managers for 42 DSS, which means 76% of the DSS originally selected with our exploratory survey. Some managers of DSS considered as relevant for our study (Agflor, BioSum, BMAS, CAPS, CLAMS, EFIMOD, EMDS, HARVEST, MONTE, NED, PLANFLOR and SIMA) were not available therefore these DSS were excluded from the survey.

3.1.2 DSS current usage

Almost all DSS (90%) were still in use, either by an institution or privately, at the time of the survey. The sole dismissed DSS were AFFOREST-sDSS (developed by Group on Earth Observations Global Agricultural Monitoring), ETÇAP (Karadeniz Technical University), Optimal (CZU) and Tosia (EFI).

3.1.3 DSS by institutions and countries

The DSS were managed either by international institutions at EU level (i.e., Institut Européen de la Forêt Cultivée (IEFC) and European Forest Institute (EFI)) or by institutions related with single countries (Table 1). The DSS were mostly owned and/or developed by universities (46.3%), public research institutes (32.2%), European Research Organizations (7.3%), territorial sustainability organizations (7.3%) and private companies (4.8%) (Table 1).

Most of these countries were pan-European, of which 14 Schengen EU-member countries (Austria, Belgium, Czechia, Finland, France, Germany, Hungary, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, Sweden), 2 Schengen non-EU countries (Switzerland, Norway) and five non-Schengen and Non-EU countries (Canada, Russian Federation, Turkey, United Kingdom, United States of America). Most of the countries/groups of countries were represented by a single DSS, with few exceptions for Finland (7 DSS), Spain (4), EU (3), Germany (3), Switzerland (3), Italy (2), Norway (2), Russian Federation (2), United Kingdom (2) and United States of America (2).

3.1.4 Types of DSS

DSS could be classified equally into the three DSS types identified by Power (see the frame in 2.3.1 “Protocol Structure” for extended definitions), with, across all IFM variables, 62.3% of the DSS able to visualize at least some IFM variables in various formats (e.g., maps, graphs, tables) to support interpretation, 67.3% of the DSS able to analyse IFM variables by processing spatial and non-spatial data to generate insights and 66.6% of the DSS with capacity to simulate/predict IFM variables.

Table 1. Classification of the DSS included in the survey DSS4IFM by institutions and countries.

DSS Acronym	Name Institution	Type of Institution	Country
3D-CMCC-FEM	National Research Council of Italy (CNR)	🧪 Public Research Institute	Italy
4C	Potsdam Institute for Climate Impact Research (PIK)	🧪 Public Research Institute	Germany
AFFOREST-sDSS	Group on Earth Observations Global Agricultural Monitoring (GEOGLAM)	🧪 Public Research Institute	Switzerland
AFM Toolbox	University of Natural Resources and Life Sciences, Vienna (BOKU)	🏛 University	Austria
AVVIRK-2000	Norwegian University of Life Sciences (NMBU)	🏛 University	Norway
CAFÉ	Universitat Politècnica de València	🏛 University	Spain
Capsis	French National Research Institute for Agriculture, Food and Environment (INRAE)	🧪 Public Research Institute	France
DLES	Russian Academy of Sciences	🧪 Public Research Institute	Russian Federation
EFIMOD	Russian Academy of Sciences	🧪 Public Research Institute	Russian Federation
EFISCEN-space	Wageningen University & Research (WUR)	🏛 University	Netherlands
eMetsä	Stora Enso	🏢 Private Company	Finland
ESC	North Devon UNESCO Biosphere	🌍 Territorial Sustainability Organization	United Kingdom
ETÇAP	Karadeniz Technical University (KTU)	🏛 University	Turkey
FEMS	University of Alberta (U o A)	🏛 University	Canada
Forest Explorer	Universidad de Valladolid (Uva)	🏛 University	Spain
ForestGALES	Institut Européen de la Forêt Cultivée (IEFC)	🌍 European Research Organization	EU countries
FORMES	Centre de Ciència i Tecnologia Forestal de Catalunya (CTFC)	🧪 Public Research Institute	Spain
FOX	REKK Foundation	🌍 Territorial Sustainability Organization	Hungary
GAYA 2.0	Norwegian University of Life Sciences (NMBU)	🏛 University	Norway
GISCAME	Rheinische Friedrich-Wilhelms-Universität Bonn	🏛 University	Germany
Habplan	National Council for Air and Stream Improvement, Inc. (NCASI)	🧪 Public Research Institute	USA
Heureka	Swedish University of Agricultural Sciences (SLU)	🏛 University	Sweden
Hylobius MSS	Forest Research (FR) in Forestry Commission (FC)	🧪 Public Research Institute	United Kingdom
I +software	European Forest Institute (EFI)	🌍 European Research Organization	EU countries
iLand	Technical University of Munich (TUM)	🏛 University	Germany
Landis-II	University of Missouri	🏛 University	USA
MASSIMO	Swiss Federal Institute for Forest, Snow and Landscape Research (WSL)	🧪 Public Research Institute	Switzerland
MEDFATE	Centro de Investigación Ecológica y Aplicaciones Forestales (CREAF)	🧪 Public Research Institute	Spain
MELA	Natural Resources Institute Finland (Luke)	🧪 Public Research Institute	Finland
Metsään.fi	Finnish Forest Centre (Metsäkeskus)	🌍 Public authority	Finland
Monsu	University of Eastern Finland (UEF)	🏛 University	Finland
MOTTI	Natural Resources Institute Finland (Luke)	🧪 Public Research Institute	Finland
Multisilva	Luxembourg Institute of Science and Technology (LIST)	🧪 Public Research Institute	Luxembourg
Optimal	Czech University of Life Sciences (CZU)	🏛 University	Czechia
PractiSFM	University College Dublin (UCD)	🏛 University	Ireland
Pri.For.Man. DSS	University of Udine (Uniud)	🏛 University	Italy
Sim4Tree	Katholieke Universiteit Leuven (KU Leuven)	🏛 University	Belgium
SIMO	Simosol	🏢 Private Company	Finland
StandsSIM Web	Universidade de Lisboa	🏛 University	Portugal
ToSIA	European Forest Institute (EFI)	🌍 European Research Organization	EU countries
Virtual Forest 2.0	Finnish Geospatial Research Institute (FGI)	🧪 Public Research Institute	Finland
W2C (WIS.2 Cockpit (SmartForest))	Bern University of Applied Sciences (BFH-HAFL)	🏛 University	Switzerland

3.2 DSS and IFM

3.2.1 DSS functionality by topics

DSS showed the highest *total functionality* (Figure 4), i.e. the capacity of analysing *and* visualizing *and* simulating, for IFM variables associated with forest structures and processes (44%), carbon cycling (40%) and forest management aspects (35% of all the IFM variables across all DSS). Instead, the DSS *total functionality* was lower when dealing with IFM variables associated with ecosystem functions and services (25%), forest health and disturbances (22%), and habitats and species (22%). However, *partial functionality* was shared, on average, by only 18% of the DSS. On the other hand, the topics for which DSS showed the highest levels of *no functionality* at all (i.e., no capacity to analyse, visualize or predict IFM variables) were ecosystem functions and services (59%), forest health and disturbances (56%) and habitats and species (55%).

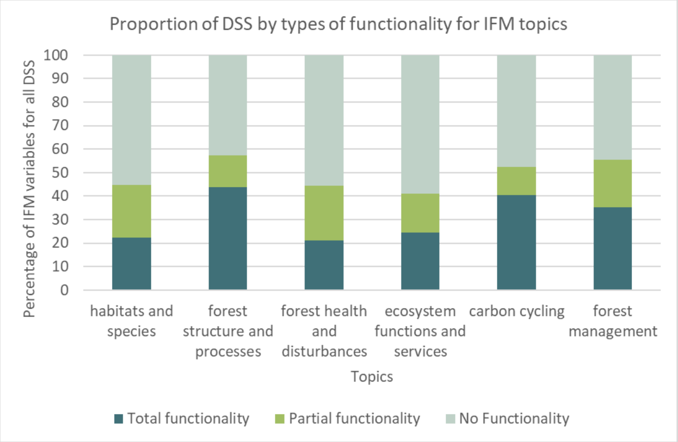


Figure 4. Percentage of IFM variables for all types of functionalities for each topic across IFM variables. Functionality is considered as the capacity of a DSS to Visualize (V), Analyse (A) and Predict (P) IFM variables related with each topic.

3.2.2 DSS and IFM variables

The capacity of DSS to visualize, analyse and simulate single IFM variables is explored for each topic related with IFM principles in the following paragraphs.

3.2.2.1 DSS Capacity to deal with ecosystem functions and services

Overall, the surveyed DSS showed low *total functionality* to deal both with ecosystem functions and services (on average 24% of the DSS) (Figure 5). However, DSS showed high *total functionality* for dealing only with timber production (62% of the DSS) but much lower total functionality to deal with other functions and services (11-19%). *Partial functionality* was shared, on average, by only 17% of the DSS. On the other hand, on average 59% of the DSS showed *no functionality* at all, especially for dealing with non-wood forest products (79%), recreational (71%) and aesthetic (69%) forest values, but also for hydrological functions (60%).

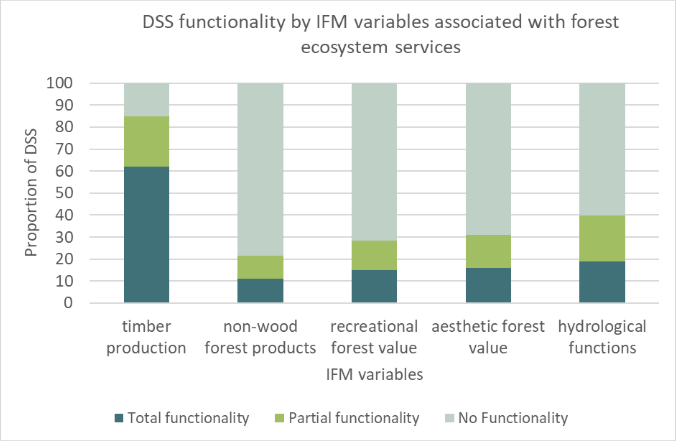
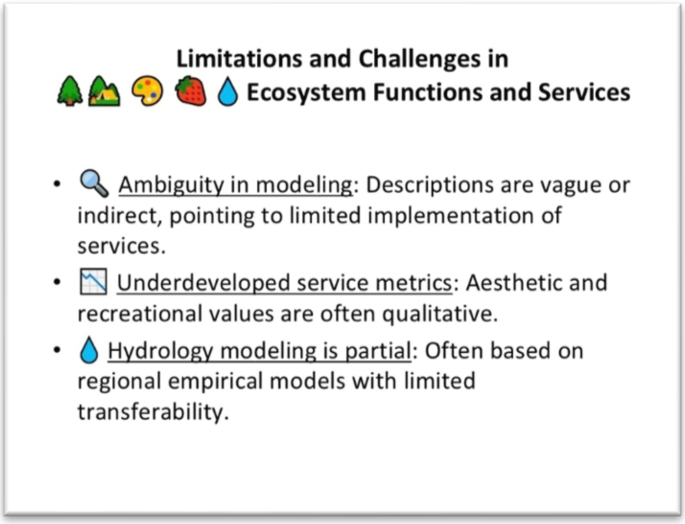


Figure 5. Percentage of DSS by types of functionalities for IFM variables associated with forest ecosystem services and functions. Functionality is considered as the capacity of a DSS to Visualize (V), Analyse (A) and Predict (P) IFM variables.



Limitations and Challenges in
🌲⛰ 🎨 🍓 💧 Ecosystem Functions and Services

- 🔍 Ambiguity in modeling: Descriptions are vague or indirect, pointing to limited implementation of services.
- 📉 Underdeveloped service metrics: Aesthetic and recreational values are often qualitative.
- 💧 Hydrology modeling is partial: Often based on regional empirical models with limited transferability.

Figure 6. Illustration of challenges and limitations identified by DSS managers for ecosystem services and functions within forest DSSs.

Among the 8 DSS which were able to deal with non-wood forest products, we found that the most represented categories were (Figure 7) mushrooms and fungi (88%) (e.g., truffles, chanterelles, morels), edible forest products (38%) (e.g., berries, nuts, wild apples) and bark extracts (14%).

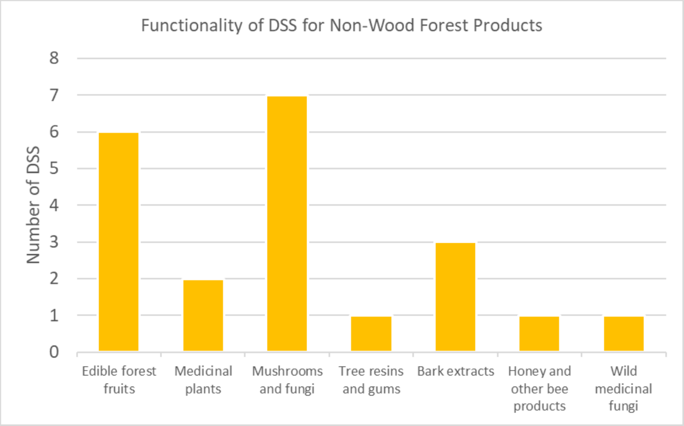


Figure 7. Number of DSS by types of functionalities for IFM variables associated with Non-Wood Forest Products.

3.2.2.2 DSS Capacity to account for forest carbon

On average, 40% of the DSS showed the highest total functionality (Figure 8), especially for dealing with aboveground (51% of the DSS) and below-ground (43%) tree/shrub carbon pools. Instead, the DSS total functionality was lower when dealing with deadwood (33%) and soil (34%) carbon pools. Partial functionality was shared, on average, by 12% of the DSS. On the other hand, on average 48% of the DSS showed no functionality, with the highest levels for soil (56%) and deadwood (55%) carbon pools.

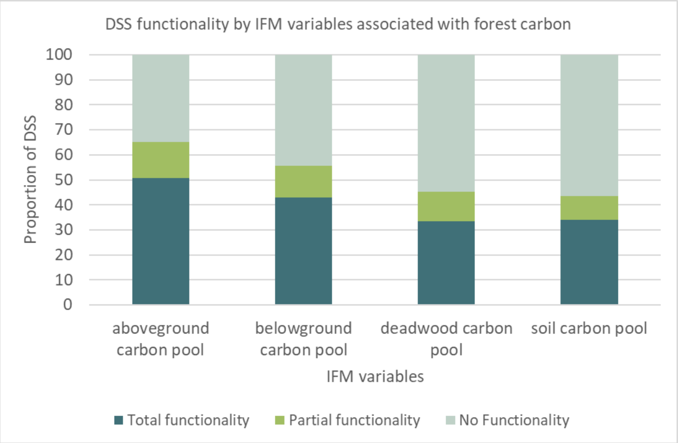
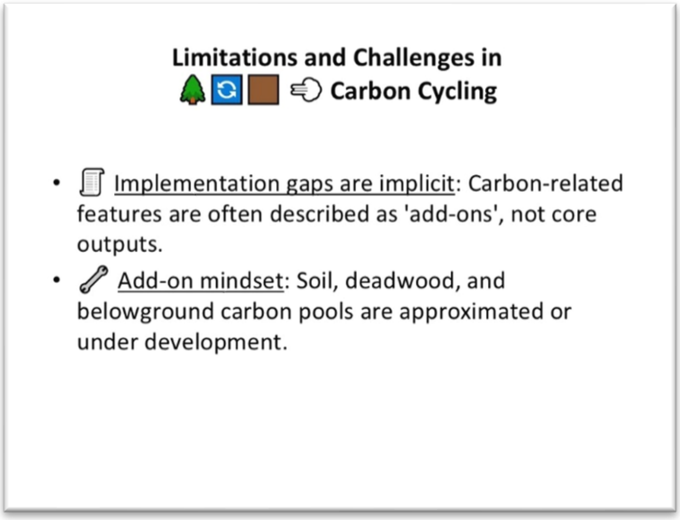


Figure 8. Percentage of DSS by types of functionalities for IFM variables associated with forest carbon. Functionality is considered as the capacity of a DSS to Visualize (V), Analyse (A) and Predict (P) IFM variables.



Limitations and Challenges in
🌲🔄🟫💨 Carbon Cycling

- 📜 Implementation gaps are implicit: Carbon-related features are often described as 'add-ons', not core outputs.
- 🔧 Add-on mindset: Soil, deadwood, and belowground carbon pools are approximated or under development.

Figure 9. Illustration of challenges and limitations identified by DSS managers for forest carbon cycling within forest DSSs.

3.2.2.3 DSS Capacity to consider forest management

DSS showed the highest *total functionality* (Figure 10) for dealing with gradients of management intensity (47% of the DSS), specifically for dealing with widespread management regimes like even-aged forest management (49%) and set-aside (i.e., non-management, 52%). Instead, the DSS *total functionality* was lower when dealing with management strategies and regimes applied less frequently in forestry and that are more often associated with IFM, like spatially explicit management plans (29%), uneven-aged-management (35%), or for specific scenarios of change in climate/land-use/socio-economic outlook/disturbance (28%), transformative strategies (18%) and for strategies of forest restoration (24%). Conversely, the management regimes for which DSS showed the highest levels of *no functionality* were transformative strategies (54%), strategies of forest restoration (62%) and spatially explicit plans (64%).

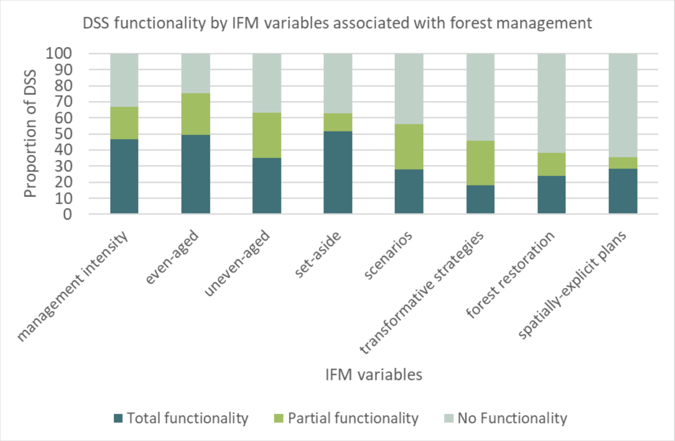
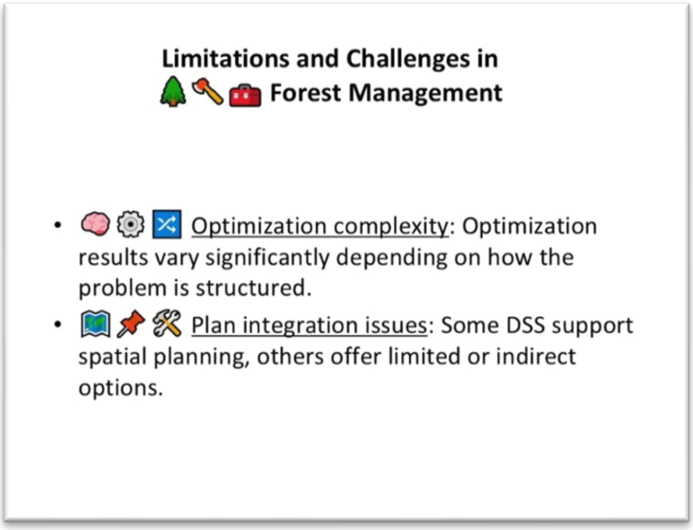


Figure 10. Percentage of DSS by types of functionalities for IFM variables associated with forest management. Functionality is considered as the capacity of a DSS to Visualize (V), Analyse (A) and Predict (P) IFM variables.



Limitations and Challenges in
🌲🔨🧰 Forest Management

- 🧠⚙️🔀 Optimization complexity: Optimization results vary significantly depending on how the problem is structured.
- 🗺️📌🛠️ Plan integration issues: Some DSS support spatial planning, others offer limited or indirect options.

Figure 11. Illustration of challenges and limitations identified by DSS managers for forest management within forest DSSs.

Among the 36 DSS which were able to deal with even-aged management, we found that the most represented categories were (Figure 12) clear-cutting (89%) (i.e., removal of all trees in a stand, followed by replanting or natural regeneration), thinning from below (89%) (i.e., removing suppressed and lower-canopy trees to reduce competition for dominant trees), shelterwood system (72%) (i.e., gradual removal of overstory trees in multiple harvests to allow natural regeneration under partial shade), thinning from above (67%) (i.e., removing dominant trees to release co-dominant trees and encourage their growth) and seed-tree methods (58%) (i.e., leaving a small number of mature trees to provide natural seeding before final harvest).

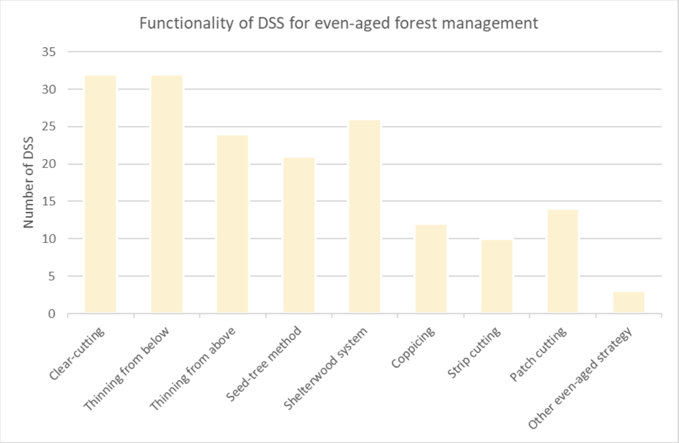


Figure 12. Number of DSS capable to deal with even-aged management.

Among the 28 DSS which were able to deal with uneven-aged management, which is more closely related with IFM than even-aged management, we found that the most represented categories were (Figure 13) continuous cover forestry (82%) (i.e., applying selective harvesting to maintain a permanently forested landscape with natural regeneration), targeting diameter harvesting (64%) (i.e., removing trees once they reach a predetermined size while retaining smaller trees for future growth) and group selection/gap cutting (61%) (i.e., harvesting small clusters of trees to create openings for regeneration while maintaining overall stand structure).

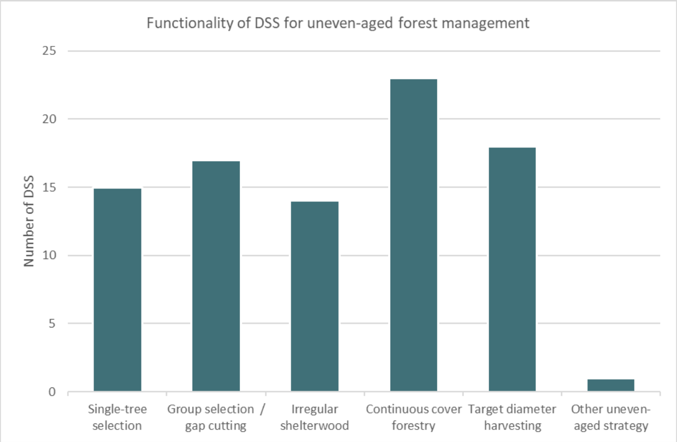


Figure 13. Number of DSS capable to deal with uneven-aged management.

Among the 30 DSS which were able to deal with scenarios, we found that the most represented types were (Figure 14) forest management scenarios (i.e., a combination of management regimes, 90%), scenarios of climate change based on Representative Concentration Pathways (70% of the DSS), and natural disturbance scenarios (57%).

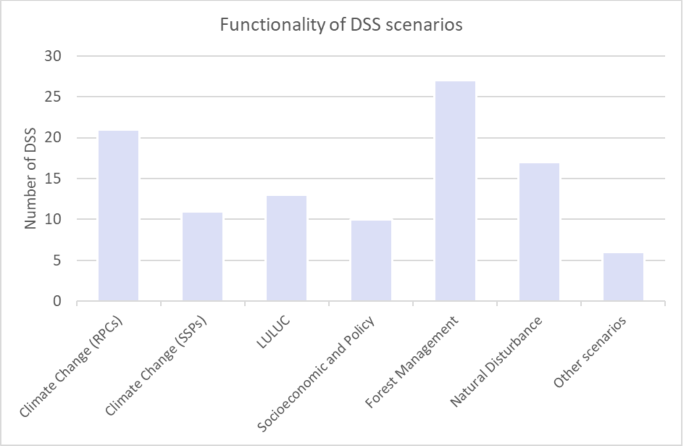


Figure 14. Number of DSS capable to deal with scenarios.

Among the 24 DSS which were able to deal with transformative strategies, we found that the most represented types were (Figure 15) diversification of tree species (75%), prolonging rotation length (75%), continuous cover forestry (71%) and set-aside (71%).

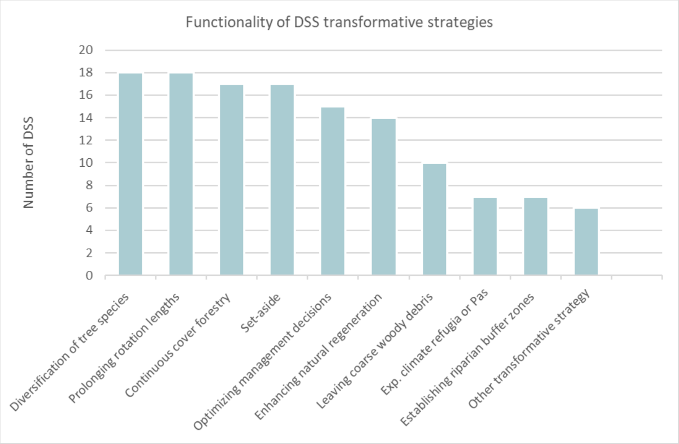


Figure 15. Number of DSS capable to deal with transformative strategies. All “Other transformative measures” are lumped together and represent ≤ 6 DSS each and include: establishing riparian buffer zones, assisted migration, passive and active restoration, minimizing soil disturbance, promoting non-timber forest products, enhancing wood product longevity, precision forestry, participatory forest management, payment for ecosystem services, prioritizing long-lived products, developing bio-based materials, timber tracking.

Among the 19 DSS which were able to deal with restoration measures, we found that the most represented types were (Figure 16) restoring tree species diversity (74%), increasing deadwood (68%), restoring closer-to-nature forest structure (53%), removal of non-native species (53%) and introduction of native species (53%).

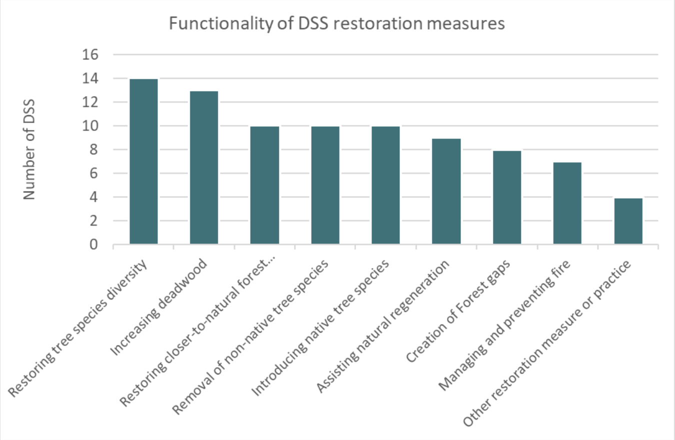


Figure 16. Number of DSS capable to deal with restoration measures. All “Other restoration measures” are lumped together and represent ≤ 4 DSS each and include: restoring forest connectivity, restoring riparian forest habitats, enhancement of microhabitats, reintroduction of keystone species, restoring soil fertility and structure.

3.2.2.4 DSS Capacity to consider hazards and natural disturbances

Overall, the surveyed DSS showed low *total functionality* to deal both with a-biotic (24% of the DSS) and biotic (18%) disturbances (Figure 17). *Partial functionality* was shared, on average, by only 13% of the DSS. On the other hand, on average, more than half (56%) of the DSS showed *no functionality* at all to deal both with a-biotic (48% of the DSS) and biotic (63%) disturbances.

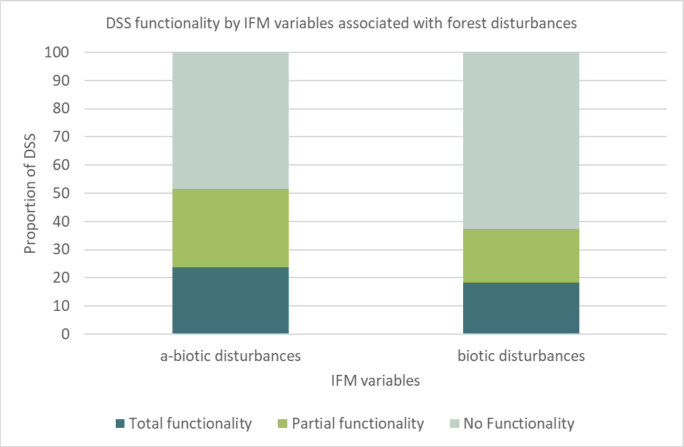
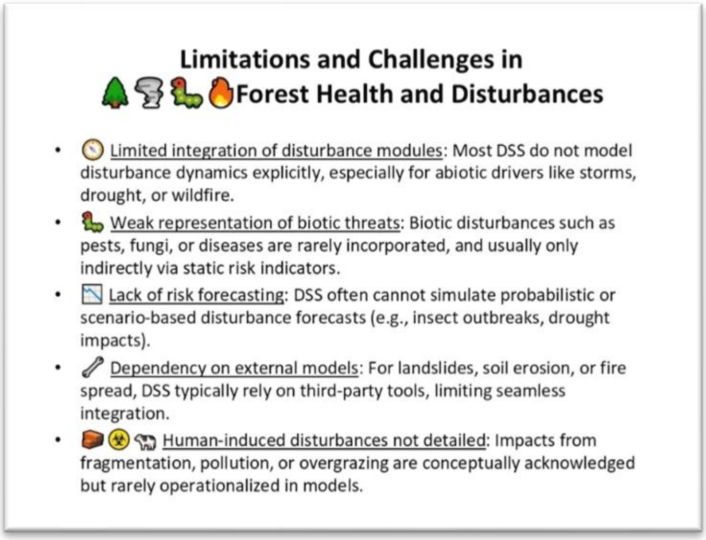


Figure 17. Percentage of DSS by types of functionalities for IFM variables associated with forest disturbances. Functionality is considered as the capacity of a DSS to Visualize (V), Analyse (A) and Predict (P) IFM variables.



Limitations and Challenges in
🌲🌪️🐛🔥Forest Health and Disturbances

- 🧭 Limited integration of disturbance modules: Most DSS do not model disturbance dynamics explicitly, especially for abiotic drivers like storms, drought, or wildfire.
- 🐛 Weak representation of biotic threats: Biotic disturbances such as pests, fungi, or diseases are rarely incorporated, and usually only indirectly via static risk indicators.
- 📉 Lack of risk forecasting: DSS often cannot simulate probabilistic or scenario-based disturbance forecasts (e.g., insect outbreaks, drought impacts).
- 🔧 Dependency on external models: For landslides, soil erosion, or fire spread, DSS typically rely on third-party tools, limiting seamless integration.
- 🧱☣️🐄 Human-induced disturbances not detailed: Impacts from fragmentation, pollution, or overgrazing are conceptually acknowledged but rarely operationalized in models.

Figure 18. Illustration of challenges and limitations identified by DSS managers for forest health and disturbances within forest DSSs.

Among the 23 DSS which were able to deal with a-biotic disturbances, we found that the most represented categories were (Figure 19) storms (70%) (i.e., windthrow, hurricanes and tornadoes), wildfires (52%), drought (30%) and soil erosion (22%).

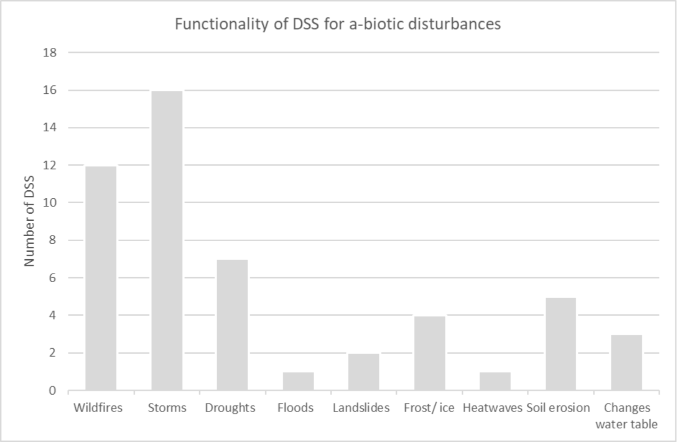


Figure 19. Number of DSS capable to deal with a-biotic disturbances.

Among the 16 DSS which were able to deal with biotic disturbances, we found that the most represented categories were (Figure 20) insect outbreaks (88%) (i.e., bark beetles, defoliators, sap-sucking pests), fungal diseases (50%) (i.e., root rot, rusts, cankers) and human-induced disturbances (38%) (i.e., logging, land conversion, pollution, fragmentation).

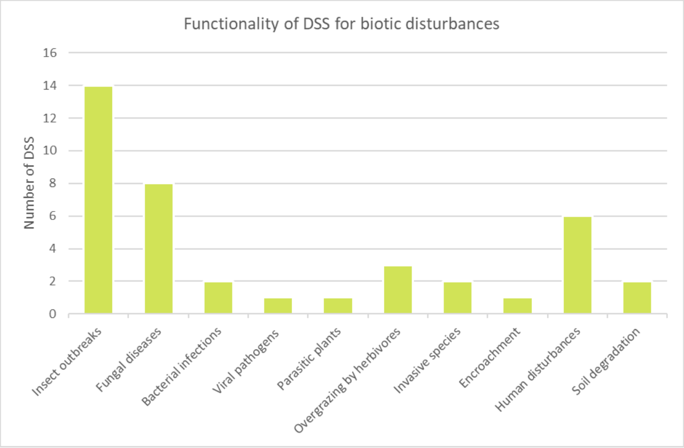


Figure 20. Number of DSS capable to deal with biotic disturbances.

3.2.2.5 DSS Capacity to represent forest structure and processes

Across IFM variables associated with forest structure and processes, DSS showed the highest *total functionality* (Figure 21) for common forest descriptors at local level, such as tree biomass (69%), stand density (67%), basal area (62%), commercial trees (60%), tree diameters (56%) and stand age/age structure (56% of the DSS). Instead, DSS *total functionality* was lower when dealing with IFM variables that can be estimated either via remote sensing, like canopy cover (31%), or by specific models, such as decomposition rate (21%), deadwood amount (35%), decay classes (13%), native/non-native trees (31%), uneven-aged structures (38%). The highest levels of *no functionality* was for canopy cover (59%), decomposition rate (59%), decay classes (72%), tree regeneration (53%) and native/non-native tree species (52%).

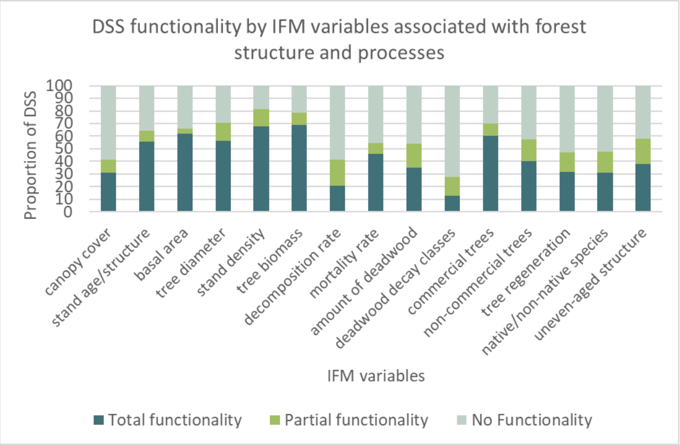
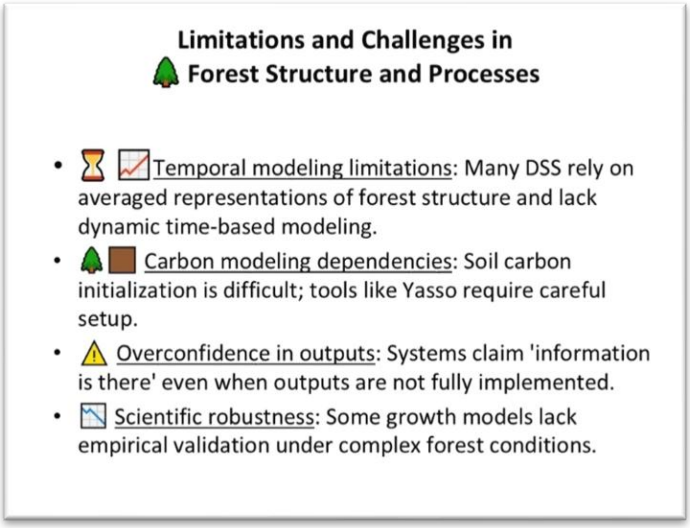


Figure 21. Percentage of DSS by types of functionalities for IFM variables associated with forest structure and processes. Functionality is considered as the capacity of a DSS to Visualize (V), Analyse (A) and Predict (P) IFM variables.

All 16 DSS which were able to deal with deadwood amount were also able to discriminate between quantities of standing deadwood and lying deadwood and all DSS able to deal with commercial (30 DSS) and non-commercial (25 DSS) tree species were also able at least to discriminate between coniferous and broadleaved trees.



Limitations and Challenges in
🌲 Forest Structure and Processes

- ⌛ 📈 Temporal modeling limitations: Many DSS rely on averaged representations of forest structure and lack dynamic time-based modeling.
- 🌲🟫 Carbon modeling dependencies: Soil carbon initialization is difficult; tools like Yasso require careful setup.
- ⚠ Overconfidence in outputs: Systems claim 'information is there' even when outputs are not fully implemented.
- 📉 Scientific robustness: Some growth models lack empirical validation under complex forest conditions.

Figure 22. Illustration of challenges and limitations identified by DSS managers for forest structure and processes within forest DSSs.

3.2.2.6 DSS Capacity to deal with biodiversity objectives

Overall, the surveyed DSS showed low total functionality to deal with different biodiversity objectives (on average 22% of the DSS) (Figure 23). DSS showed relatively more, but still low, total functionality for dealing with forest types (32%), habitat trees (30%), retention trees (28%) and less total functionality for dealing with species of conservation concern (19% of the DSS), habitats of interest (14%) and connectivity aspects (12%). However, partial functionality was shared, on average, by 22% of the DSS. On the other hand, on average more than half (55%) of the DSS showed no functionality at all, and especially when dealing with connectivity (75%), habitats of interest (62%) and species of conservation concern (61%).

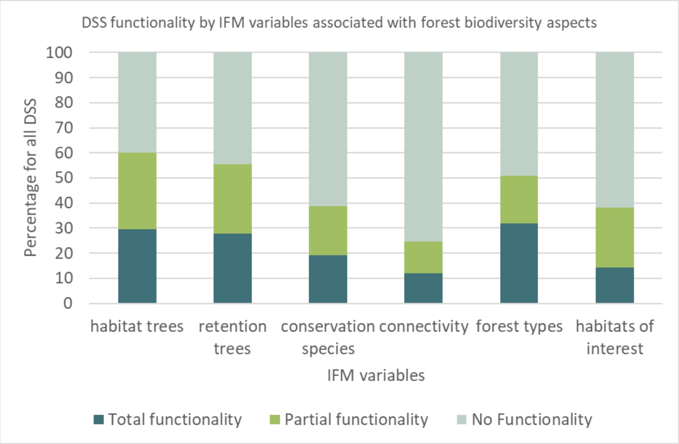
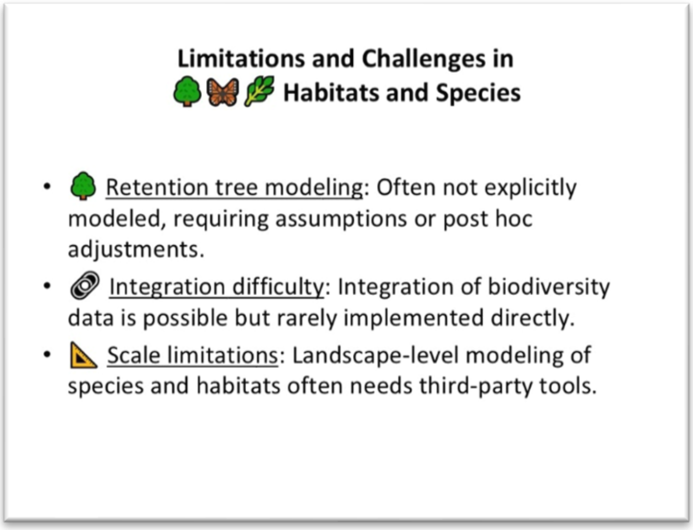


Figure 23. Percentage of DSS by types of functionalities for IFM variables associated with forest biodiversity. Functionality is considered as the capacity of a DSS to Visualize (V), Analyse (A) and Predict (P) IFM variables.



Limitations and Challenges in
🌳🦋🌿 Habitats and Species

- 🌳 Retention tree modeling: Often not explicitly modeled, requiring assumptions or post hoc adjustments.
- 🔗 Integration difficulty: Integration of biodiversity data is possible but rarely implemented directly.
- 📐 Scale limitations: Landscape-level modeling of species and habitats often needs third-party tools.

Figure 24. Illustration of challenges and limitations identified by DSS managers for forest habitats and species within forest DSSs.

Among the 20 DSS which were able to deal with habitats of interest, we found that the most represented categories were (Figure 25) old-growth forests (80%), forest edges (50%), riparian forests (50%), high-elevation forests (50%), and decaying trees and logs (50%).

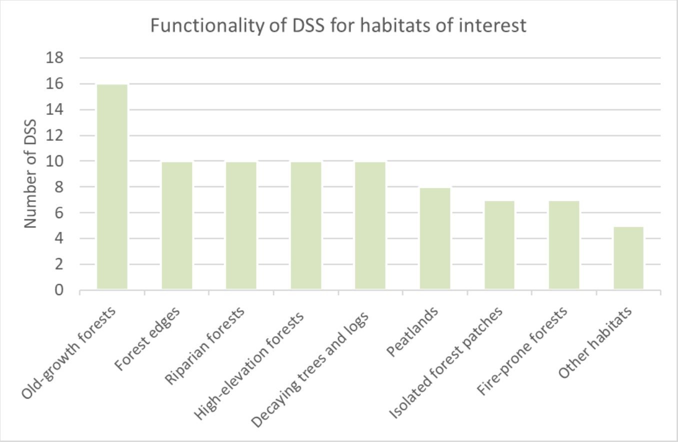


Figure 25. Number of DSS capable to deal with specific habitats of interest. All “Other habitats” are lumped together and represent ≤ 5 DSS each and include: karst forests, limestone forests, wetlands, dense scrubs, rocky outcrops, boulder fields, seasonal ponds, bogs.

4. Discussion

4.1 DSS functionality and capabilities

The DSS4IFM survey provides a comprehensive overview of the current landscape of Decision Support Systems (DSS) relevant to Integrative Forest Management (IFM) across Eurasia and North America. The survey, completed for 42 DSS (76% of the targeted systems), reflects a broad range of institutional ownership and geographical coverage (Figure 26).

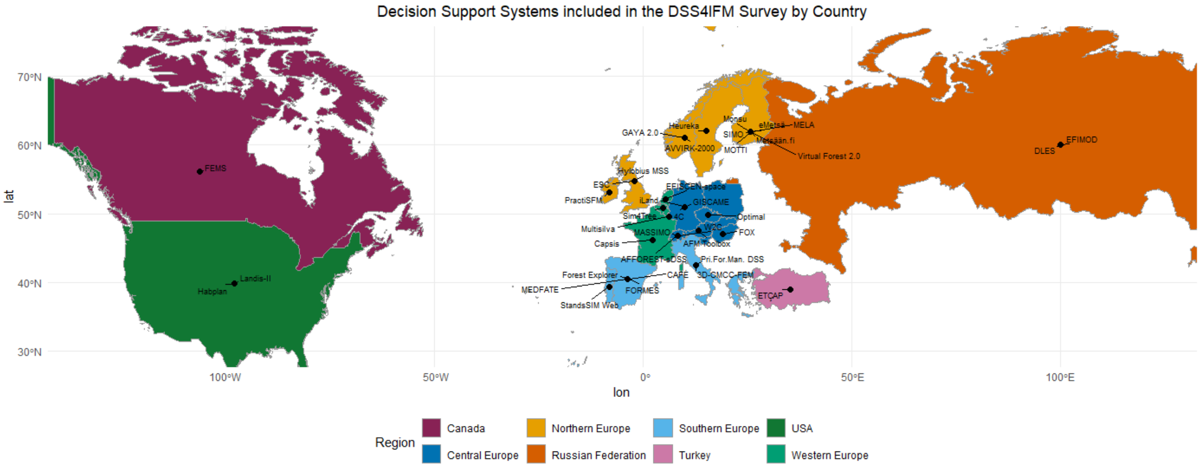


Figure 26. Geographic distribution of the 42 Decision Support Systems included in the DSS4IFM survey, grouped by country and coloured according to European and global regions. Each black point represents the country of location of the DSS, labelled by its name.

Most of the analyzed DSS are currently operational, indicating their continued relevance, though some key systems were excluded due to the unavailability of DSS managers in responding to this survey.

Overall DSS functionality was moderately balanced across the three core capabilities—visualization, analysis, and simulation—with roughly 62-67% of the DSS supporting each. This reflects the fact that DSS are approaching preparedness to become increasingly essential tools for forest managers to cope with complex planning problems (Vacik and Lexer, 2014). However, the results also reveal that the DSS are being developed and maintained largely by research organizations and universities, and they may need some further refinements, methodological updates and technological developments for reaching stabilized use in operational forest management.

4.2 DSS functionality and IFM goals

The DSS in our survey were more capable to deal with topics traditionally covered by timber-production oriented forestry, such as the description and development of forest characteristics and management practices, and less capable to deal with *the three goals of IFM* (Nordström et al., 2019). Specifically, *DSS functionalities were only partially capable to deal with ecosystem services, except for timber production, associated with the IFM goal of <u>forest production</u>, with natural disturbances, associated with the goal of <u>forest protection</u>,* *and with biodiversity aspects, associated with the goal of* *forest conservation* (Figure 27) (Nordström et al., 2019). In the following paragraphs we will examine the DSS capacity to deal with these three IFM goals in detail.

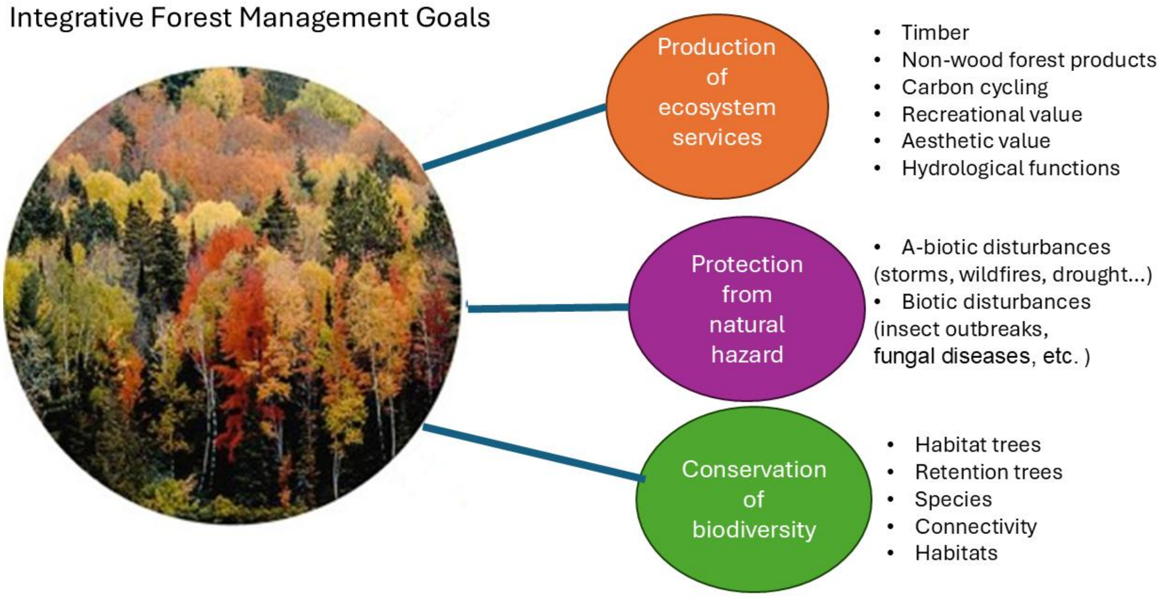


Figure 27. IFM goals and related forest functions.

4.3 DSS capacity of producing forest ecosystem services

One of the core tenets of IFM is managing forests for *production* *of timber, carbon and non-wood ecosystem services – and doing so in a sustainable manner over the long term.* In Europe, the concept of multi-functional forestry has a long tradition, and DSS have been developed or adapted for strategic planning at various scales (Nobre et al., 2016). For example, simulation-based DSS are frequently used to ask "what if" questions about how different management strategies will affect a region's bundle of ecosystem services over decades. The capacity of DSS to answer such questions has been facilitated by the integration of multi-objective optimization techniques (Eyvindson et al., 2018).

In this context, it is also important to indicate that the type of the decision problem and the ecosystem services that are addressed are often closely related to the decision support techniques and models used in the DSS. Segura et al (2014) have also indicated that most of the forest management DSS use simulation modeling methods considering the spatial context and spatial scale of the problem and the number of people involved in taking a decision. Especially Multiple Criteria Decision Making (MCDM) techniques are often linked to problem types that involve the consideration of many goods and services with conflicting dimensions. MCDM techniques were not in the core of the analysis of our analysis, even though some of the analyzed DSS utilize these techniques.

Among all IFM topics, DSS included in our survey were least capable in dealing with ecosystem functions and services beyond timber production. While timber yield was commonly supported, most DSS lacked capacity to represent or simulate non-wood forest products, recreational and aesthetic values, and hydrological services, with some exception (e.g., the MONSU DSS in Figure 28). Although non-wood ecosystem services are critical for forest multifunctionality and public value generation, which are key objectives in IFM, they require *ad-hoc* models that are usually constructed by DSS developers only after timber models. The joint use of expert-based, physiological-based models and empirical approaches could help to improve the capability of the DSS and result in accurate and robust predictions (Calama et al 2020).

Figure 28. An example of the predicted NWFP-potential for 82 ha forest holding located in Central Finland. The yields are predicted as mean annual yield at the beginning of the planning period and then for the future for the three 20-year sub-periods. In most cases, empirical yield models have been used, in connection with some expert reasoning if needed.

DSS showed moderately high functionality for dealing with carbon cycling, particularly for aboveground and belowground biomass pools (e.g., the DSS EFISCEN-Space 1.0 in Figure 29). However, DSS were less capable of accounting for carbon in deadwood and soils—important components for long-term carbon storage and ecosystem integrity. This partial representation of the carbon pools points to a need for broader carbon accounting modules to fully support climate-smart forestry planning (Krumm et al., 2020) and the needs of the bioeconomy sector (Hetemäki et al., 2022).

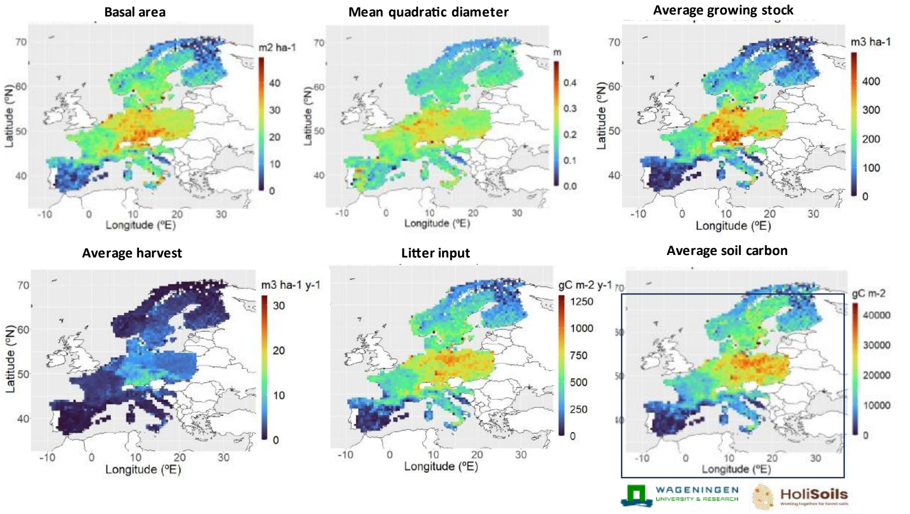


Figure 29. Examples of output of European maps of forest characteristics, timber yield and carbon stock from the DSS EFISCEN-Space 1.0.

The results of the survey emphasize the importance of expanding the scope of DSS to cover a broader range of ecosystem services, rather than focusing narrowly on wood yield. As a matter of fact, over the past decade forest DSS have evolved from single-objective systems (primarily aimed at sustainable timber supply) to more comprehensive, multi-objective tools (e.g., in boreal forest the DSS MOTTI: Triviño et al., 2017; in Mediterranean forest the CAFÉ DSS: Pérez-Romero et al., 2025; in Central European forests AFM Toolbox: Rammer et al 2014). DSS can now explore how altering management affects carbon sequestration, habitat provision, or cultural services, such as recreation and foraging (Thrippleton et al., 2021) alongside timber yields, and even to test how economic factors like timber price trends influence service provision (Nordström et al., 2019). State-of-the-art DSS have been developed to evaluate trade-offs and synergies among diverse ecosystem services (e.g., the DSS Heureka: Mazziotta et al., 2022). Certain services (e.g. biodiversity, soil and water regulation, recreation) may be represented by proxy indicators, and comprehensive valuation of all services is still an area for improvement in DSS.

4.4 DSS capacity of managing forests for protection

IFM places a strong emphasis on forest protection, which is based on adaptability and resilience – the capacity to adjust management to reduce risks from disturbances. In our survey, the capacity of DSS to increase adaptability and resilience with low impact forestry, such as uneven-aged approaches (continuous cover forestry, spatially explicit management plans, and transformative strategies based on diversification and restoration), was lower than their capacity to deal with regimes widely employed in traditional forestry, such as even-aged management (e.g., clear-cutting and shelterwood).

Although many DSS could partially address uneven-aged approaches, their application in planning adaptive or multifunctional forest management scenarios is currently underdeveloped. However, recent DSS reviews have found examples of DSS developed to deal with integrative management regimes, some of them also included in our survey (e.g., EFISCEN-space: Schelhaas et al., 2022, Heureka: Wikström et al., 2011, ETÇAP: Baskent et al., 2009).

For the DSS in our survey the capacity to address both abiotic and biotic disturbances was generally low. While a small subset of DSS could consider disturbances like storms and wildfires, most lacked any capacity to deal with disturbance dynamics, particularly the cascading effects of such disturbances driven by insects, fungi, or human-induced pressures (Patacca et al., 2023). This limits the usefulness of DSS in supporting resilience-based management. The likely reason why hazards are underrepresented in forest DSS is that they have been initially developed to simulate mainly deterministic forest processes, like tree growth and death, while modules for disturbance dynamics contain stochastic processes that have been developed only recently. As a result, disturbance and risk factors have been rarely included in most forest DSS to date (Thrippleton et al., 2021), with some notable exceptions, for example in iLand (Figure 30 from Rammer et al., 2024). Given the increase in the frequency and magnitude of natural disturbances due to climate change, there is a need for continued enhancement of risk modeling, incorporation of real-time monitoring data, and user-friendly tools for updating management plans as conditions change. Strengthening these aspects will be crucial for DSS to foster forest protection via management regimes increasing resilience, based on increasing tree species diversity and stand heterogeneity (Nikinmaa et al., 2024).

Wind disturbance Main reference: Seidl et al. (2014a)

Occurence Wind event, wind direction and speed, gust factor, topographic modification 100m Hourly / Annual

Vertical wind profile Detection of vertical discontinuities in the canopy, tree height 10m Hourly

Turning moment Tree height and diameter, upwind gap size, local sheltering from neighbors Tree Hourly

Critical wind speed Uprooting or breakage, tree diameter, stem weight Tree Hourly

Wildfire disturbance Main reference: Seidl et al. (2014b)

Ignition Base ignition probability, fire weather, fire suppression 20m Annual

Fire spread Fuel, wind, topography, maximum fire size 20m Hourly

Fire severity Fuel, fire weather, tree diameter, bark thickness Tree Hourly

Fuel consumption Pool-specific consumption rates 100m Annual

Biotic disturbances (BITE) Main reference: Honkaniemi et al. (2021)

Potential habitat Climate, land-use, topography 10m-1km 30 years

Introduction Vectors, human activity 10m-1km Annual

Dispersal Dispersal kernel, maximum dispersal distance 10m-1km Annual

Colonization Host availability, climate 10m-1km Annual

Population dynamics Host biomass, climate, carrying capacity 10m-1km Annual

Impact on host population Biomass compartment affected, type of impact Tree Annual

Ips typographus (Spruce bark beetle) Main reference: Seidl and Rammer (2016)

Outbreak initiation Background probability, climate 100m Annual

Beetle development Beetle phenology, climate, daylength 100m Daily

Beetle dispersal Dispersal kernel (passive flight), host search (active flight) 10m Daily

Host colonization Tree defense, tree status (alive vs. fresh dead), number of colonizing beetle cohorts Tree Daily

Overwintering Beetle life stage, climate Tree Daily

Outbreak collapse Decreasing fitness with increasing duration of local outbreak 10m Annual

Tactical management (ABE) Main reference: Rammer and Seidl (2015)

Planting Location, spatial pattern, amount, species, size 2m Annual

Tending and thinning Location, spatial pattern, amount, species, size Tree Annual

Final harvest Location, spatial pattern, amount, species, size Tree Annual

Salvage and sanitation harvesting Disturbance agent, severity and size, location, spatial pattern, amount, species, size Tree, 10m Annual

Strategic management (ABE) Main reference: Rammer and Seidl (2015)

Stand treatment program Target species, silvicultural system, rotation age Stand / Landscape Annual / Decadal

Scheduling Sustainable yield, spatial and temporal dependencies, external constraints Stand / Landscape Decadal

Response to change Change of target species, silvicultural system, rotation age Landscape Decadal

DISCONTINUOUS PROCESSES

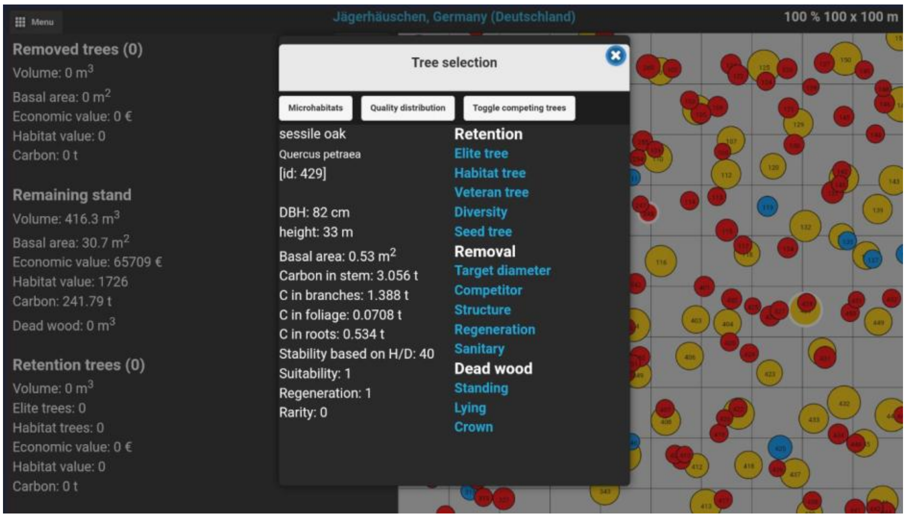
Figure 30. Discontinuous processes simulated in the DSS iLand. Each row represents a discontinuous process caused by natural (top four) or human (bottom two) agents, with sub-

processes and their main drivers in cells. The tags in each cell indicate the main entity or spatial resolution and the primary time-step of the process. (from Rammer et al., 2024)

4.5 DSS capacity of characterizing forest structures for conservation

The description of forest variables associated with structures and processes supporting habitats and species is central in the mission of IFM of supporting forest conservation (Krumm et al., 2020). The capacity of DSS to handle these ecologically relevant variables (e.g., canopy cover, decay classes, decomposition rate, and natural regeneration) related with the formation of forest structures suitable as habitats for forest dwelling species (Lachat et al. 2025) were generally low.

The functionality of DSS with respect to biodiversity variables associated with forest conservation was one of the weakest areas in the survey. Only a small fraction of DSS could adequately simulate or analyze habitat quality, species of conservation concern, or forest connectivity (e.g., the I+ Software in Figure 31).



Removed trees (0)
Volume: 0 m^3
Basal area: 0 m^2
Economic value: 0 €
Habitat value: 0
Carbon: 0 t

Remaining stand
Volume: 416.3 m^3
Basal area: 30.7 m^2
Economic value: 65709 €
Habitat value: 1726
Carbon: 241.79 t
Dead wood: 0 m^3

Retention trees (0)
Volume: 0 m^3
Elite trees: 0
Habitat trees: 0
Economic value: 0 €
Habitat value: 0
Carbon: 0 t

sessile oak
Quercus petraea
[id: 429]

DBH: 82 cm
height: 33 m
Basal area: 0.53 m^2
Carbon in stem: 3.056 t
C in branches: 1.388 t
C in foliage: 0.0708 t
C in roots: 0.534 t
Stability based on H/D: 40
Suitability: 1
Regeneration: 1
Rarity: 0

Figure 31. Examples of output of structural and biodiversity variables from the DSS I+ Software.

While DSS often shared partial functionality to deal with these variables, a large share of DSS completely lacked the ability to address biodiversity variables. This functional gap suggests that current DSS are poorly equipped to support biodiversity conservation as a core IFM goal, because they still have limited capacity to represent biodiversity and the full complexity of forest ecosystems. On the contrary, current tools often rely on proxies of ecological indicators such as structural attributes (e.g., deadwood) and few species-based indicators. The biodiversity metrics are calculated from models which have as input variables the state of the forest (e.g., DBH and amount of deadwood) derived from eco-physiological processes (growth and death) and their future states, rather than by ecological theory. These limitations trace back to the historical timber-centric focus of forest planning, where economic yield was prioritized over ecological values (Hunault-Fontbonne and Eyvindson, 2023). Furthermore, models linking species and habitats with forest structure are scarce, because their assessment is usually beyond the expertise of the staff conducting forest inventory (Alberdi et al., 2019). However, some DSS have begun to include biodiversity criteria (e.g. habitat suitability indices or structure-based proxies) alongside timber objectives, being able in some cases to evaluate biodiversity outcomes under different management scenarios (e.g., MONSU, Pukkala, 2004; and MOTTI, Mönkkönen et al., 2014). This ability to incorporate biodiversity in scenario analyses is a strength, but current DSS need further enhancement to capture ecological complexity in line with IFM’s emphasis on sustaining forest conservation (Krumm et al., 2020).

5. DSS limitations and challenges in implementing IFM

DSS managers have identified a diverse set of challenges when operationalizing IFM topics.

In the context of *forest production*, DSS managers face significant limitations in modelling *ecosystem services* and *carbon dynamics*. Many DSSs treat ecosystem functions—such as recreation, aesthetics, and hydrology—as loosely defined or qualitatively assessed outputs, relying on proxy indicators rather than dedicated models. Regional variability and lack of transferable empirical models further constrain implementation. Similarly, carbon cycling is often handled as an add-on rather than a core system component. Key carbon pools, especially soil and deadwood, are difficult to initialize and frequently approximated. These gaps hinder the ability of DSSs to support integrated forest production planning accounting for multifunctional ecosystem values.

When it comes to *forest protection*, DSS struggle to represent the complexity of *natural* and *human-induced* disturbances. *Biotic and abiotic disturbance* dynamics-such as insect outbreaks, drought, and fire-are rarely modelled explicitly and are instead inferred from static risk indicators or external modules. Forecasting capabilities for these disturbances are generally lacking. Adaptive forest management planning also presents challenges: optimization routines are often context-specific and sensitive to model structure, and spatially explicit planning remains inconsistently supported. Together, these limitations reduce the effectiveness of DSSs in simulating resilience, vulnerability, and protective strategies across forest landscapes.

Finally, *forest conservation* goals are hindered by limited representation of *biodiversity* and *structural complexity* in DSSs. Habitat-related indicators, such as retention trees or species distributions, are not always embedded in model logic and may require manual input or post hoc analysis. Integration of biodiversity data is technically feasible but rarely implemented, especially at landscape scales. Forest structure, while central to habitat quality, is often modelled in simplified terms without dynamic progression over time. Multi-layer stand simulations present additional initialization challenges. These constraints make it difficult for DSS to fully support conservation-oriented decision-making grounded in ecological complexity.

In summary, while DSS hold great potential for advancing IFM, their current limitations reflect a mismatch between system capabilities and the multidimensional IFM goals. Addressing these gaps-particularly in ecosystem service representation, dynamic modelling and biodiversity integration-is essential for enabling more robust, goal-aligned forest planning and decision-making that better supports also IFM.

6. Perspectives on DSS potential to support IFM

Integrative Forest Management has emerged as a critical paradigm for balancing productive forestry with biodiversity conservation, climate adaptation, and diverse ecosystem services. In this context, DSS are key enablers of IFM, expected to provide the operational tools to plan and evaluate multi-functional forest management strategies. Our DSS4IFM survey aligns with these goals and highlights both the progress and shortcomings of current DSS in supporting IFM aspirations.

On one hand, today's forest DSS are more powerful and comprehensive than ever before. They increasingly enable holistic assessments of forest management, accounting for an array of ecosystem services, climate-related risks and biodiversity values in ways that were not possible a generation ago. Such capabilities mark significant progress toward the goals of IFM – for example, identifying synergies between timber harvesting, carbon sequestration and biodiversity. *On the other hand*, important gaps and weaknesses remain. Our survey reveals a functional imbalance within current DSS portfolios in delivering IFM solutions. While DSS are relatively robust in supporting traditional forest management and structural metrics, they are less developed in their ability to support the integrative, multifunctional, and ecologically grounded approaches that IFM requires. There is substantial room for improvement in the representation of ecosystem services, disturbances and biodiversity, likely due to a lack of specific studies leading to indicators. *Furthermore*, we interpreted that the DSSs analyses are mainly used by researchers, and there may be a gap between research-oriented use and practical use.

For DSS to fully support Integrative Forest Management, further development is needed to bridge functionality gaps, particularly in underrepresented areas. Leveraging partial capabilities already present in many DSS could be a pragmatic path forward to enhance IFM integration. Strategic enhancements would better align DSS functionality with policy objectives such as provision of multiple forest benefits, ecosystem resilience and biodiversity conservation. However, there is also a gap between the growing complexity of models and tools which forest science is developing (e.g. process based models) to meet the information demands of users on IFM, the amount of data needed for these models and the requirements for smart and easy to use software applications. These discrepancies will become larger, as long as the demands rise and the DSS researchers attempt to meet these demands (Vacik and Lexer, 2014).

Despite the wide availability of forest DSS existing only across Europe (Nobre et al., 2016), their contribution to broad IFM goals is fragmented. A European review noted very limited sharing of DSS between countries and only modest use of these tools to inform higher-level forest policy decisions (Linkevičius et al., 2019). This suggests that the potential of DSS to promote long-term sustainability at larger scales (national or EU level) is not being fully realized.

Another concern is about the usability and uptake of complex multi-objective DSS. Nobre et al. (2016) found that many advanced DSS require significant expertise, and a lack of training or “decision support culture” among practitioners can impede their adoption in routine management. IFM’s long-term vision implies that managers need tools that are not only technically robust but also accessible for decision-making, for example offering an immersive experience by merging forest inventory measures with laser scanning (e.g., the Virtual Forest 2.0 in Figure 32). Therefore, beyond technical improvements, studies call for better user education and participatory features in DSS, e.g. involving stakeholders in setting objectives or weighing trade-offs to ensure that multi-functional plans are implemented on the ground (e.g., Eyvindson et al., 2024).

While most of the countries/groups of countries were represented by a single DSS in this survey, some few exceptions have indicated a larger variety of DSS that can be used to support decision making. This indicates also the need to tailor DSS for a specific purpose and need. In this context it could be an interesting aspect to evaluate if there is a relationship between the relevance of IFM in a specific country / region and the capacities of the DSS to address those specific purposes. Especially in cases where forest owners and stakeholder in a country are not so much interested in IFM, there might be also no external driver to adapt and tailor DSS in that direction.

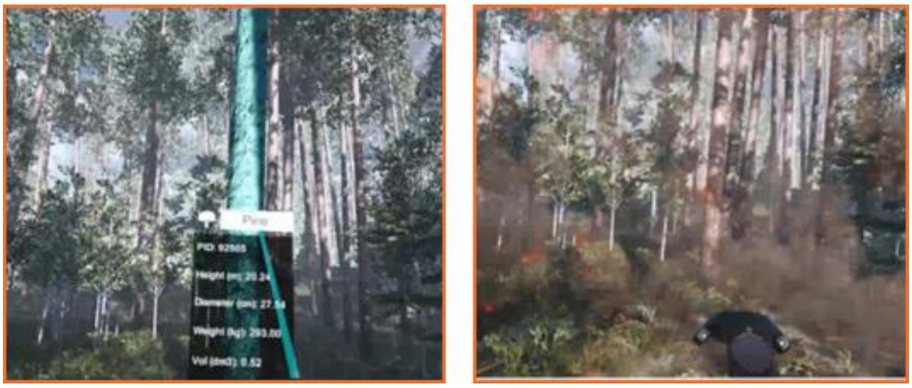


Figure 32. Example of visualization of a scene in the DSS Virtual Forest 2.0. The scene represents a simulation of a clear cut of small trees under 14 m, before cut (left) and after cut (right).

In summary, current DSS do offer frameworks for multi-criteria and long-range planning – a clear strength in support of IFM – but their real-world impact on fostering sustainable, multifunctional forestry is mixed due to issues of specialization, usability, and cross-sector integration. Addressing these weaknesses through ongoing research, tool improvement, and capacity-building will be essential to harness the full potential of DSS in achieving truly integrative and sustainable forest management. European efforts like the TRANSFORMIT project are at the forefront of developing DSS for IFM, exemplifying how science-based tools can inform balanced decisions in forestry.

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