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The European Forestry Dynamics Model

Concept, design and results of first case studies

Tuula Packalen, Ola Sallnäs, Seija Sirkiä, Kari Korhonen, Olli Salminen, Claude Vidal, Nicolas Robert, Antoine Colin, Thierry Belouard, Klemens Schadauer, Ambros Berger, Francisco Rego, Graça Louro, Andrea Camia, Minna Räty, Jesús San-Miguel

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Abstract

The European Forestry Dynamics Model (EFDM) is a joint effort between the European Commission Joint Research Centre and partners in the EU Member States for the development of a forestry dynamics model. The model is expected to project the state of Europe's forests given different climatic, economic and management scenarios. EFDM was designed as a flexible system to facilitate the different types of data input that are available from the diverse National Forest Inventories. The model captures different typologies such as site productivity, ownership and the probability of natural disturbances. Specifically, EFDM is able to process detailed national-level input data such as National Forest Inventories (NFI) outputs, as well as related national-level expertise in social and economic domains. In this way, the system supports effective utilization of the collaborative expertise in the parameterization of scenarios. This document is intended as a general introduction to the EFDM. Experiences gained from the EFDM test applications by five NFI teams (Austria, Finland, France, Portugal and Sweden) are also summarized in this report.

The European Forestry Dynamics Model: concept, design and results of first case studies

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1 Introduction

1.1 Need for forestry dynamics modelling in Europe

According to the new EU Forest Strategy[1] , Member States (MS) are expected to increase harvest rates of as much as 30% by 2020 with respect to the 2010 figures. Wood will become of ever-increasing importance; it is foreseen that forest biomass will supply approximately 42% of the 20% renewable energy target for 2020[1]. This translates to the total harvested amount today, only to cover the energy requirements. Although wood is still the main source of financial revenue from forests, demand for non-wood forest products and other ecosystem services will be increasingly significant. The sustainable management of forests has therefore come to mean more than the sustainable production of wood. The rural development policy is the main instrument for the implementation of the EU Forest Strategy; some of the measures included in the Regulation (EU) No 1305/2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD), are specifically dedicated to improving the multi-functionality of forests and ensuring their sustainable management. Furthermore, several Commission policies have been debated under the Resource Efficiency Flagship Initiative of the Europe 2020 strategy[2] to tackle the multi-faceted approach in resource efficiency, including forests. According to international agreements, sustainable forestry aims to safeguard the viable production of goods and services to the society.

Production depends on forest resources and their management. In the EU the responsibility of forest policies lies with the Member States according to the principle of subsidiarity. Forests are therefore managed by private and public operators at the local level, guided by MS in which the forests are rooted, through national forest programmes and legislation. Management is thus a national and owner-level issue. However, forests are related to several European sectorial policies, as detailed in the Green Paper on Forest Protection and Information in the EU[3] and in the State of Europe's Forest 2011 report (Forest Europe, 2011). Energy is often central to forest-related policies[4,5], but so is biodiversity[6] and bio-economy[7]. Several Directives also are directly linked to the sustainability of forests: The Water Framework Directive[8]; EU Birds and Habitats Directives[9]; the Renewable Energy Directive[10]. From a Global perspective, Europe has reporting obligations to UNFCCC under the Kyoto Protocol on the LULUCF activities[11] and those agreed at the United Nations Conference on Sustainable Development in Rio 2012[12]. The

[1] COM(2013) 659 final. A new EU Forest Strategy: for forests and the forest-based sector
[2] COM(2011) 21 final. A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy
[3] SEC(2010) 163 final
[4] COM(2011) 112 final. A Roadmap for moving to a competitive low carbon economy in 2050
[5] COM(2011) 885 final. Energy Roadmap 2050. Brussels
[6] COM(2011) 244 final. Our life insurance, our natural capital: an EU biodiversity strategy to 2020
[7] COM(2012) 60 final. Innovating for Sustainable Growth: A Bioeconomy for Europe
[8] Directive 2000/60/EC establishing a framework for Community action in the field of water policy
[9] Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora
[10] Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. 23.4.2009
[11] Decision No 529/2013/EU on accounting rules on greenhouse gas emissions and removals resulting from activities relating to land use, land-use change and forestry and on information concerning actions relating to those activities
[12] COM(2013) 92 final. A decent life for all: Ending poverty and giving the world a sustainable future

new EU Forest Strategy emphasizes that EU policies associated to forests have to be taken into account in national forest policies.

It is also true that the effects of European forest-related and forest-focused policies on national forest management, and subsequently on local forest dynamics and state, should be taken into consideration. The long term response in MS may be unexpected given, for example, the EU's biofuel targets. The forest-wood chain may be affected in the short-term, while forest management practices may be affected in the long-term. This naturally has consequences on forests, forestry, the forest sector, as well as on other forest-related sectors.

Tools are required to facilitate the horizontal and vertical orchestration of forest-related policies with forest-focused requirements outlined in the new EU Forest Strategy. Most importantly, there is a need for a tool-set that is able to assess the potential impacts of the interacting relationships between the domains of economy, ecology and energy, made increasingly complex by the new requirements for alternative fuel sources. An important component of this tool-set is a forestry dynamics model, hence the development of the European Forestry Dynamics model (EFDM). EFDM has been designed to be able to model local management choices based on owner profiles, site location and quality, dominant species, forest age and growing stock, thus contributing to a larger framework whose scope is to estimate the interlinked impacts of climate change and European policies affecting forest management within the framework set by global markets.

1.2 Pre-requisites for a European forestry dynamics model

Forest ecosystems are dynamic environments. They change over time because of different natural phenomena such as growth, decay, death and re-growth. A quantitative model of forestry dynamics is therefore required to capture the potential impacts of policies on forest management and their implications on forestry as a whole. A pan-European forestry dynamics model should be able to assess the future status of forests under a wide range of potential scenarios of socio-economic and ecological developments. The model should encapsulate the potential forest management decisions by forest owners under different socio-economic demands and pressures from markets and policies. In addition, there can be abrupt changes in forest ecosystems due to human activities or catastrophes such as fire, storm, drought, flooding and pests.

In order to capture all of these elements, the model should (i) be based on a sound scientific methodology corresponding to best practices for forest projections; (ii) deal with dynamics based on probabilities of different natural processes and forest management; and (iii) rely on the best available data sets and expertise on socio-economic context. These datasets should focus on appropriate modelling units and be sourced from expert knowledge on management practices under different socio-economic (market and political) scenarios. Furthermore, in order to expand the user community of the model, it should be made available as generic, free and open source software. It should also facilitate transparent harmonization and parameterization for different ecological and socio-economic conditions as well as related documentation of input data, scenario assumptions and outputs.

It is within this context that a new tool for forestry dynamics modelling is being developed collaboratively between the European Commission Joint Research Centre (JRC) and partners from EU Member States (MS). EFDM is designed to effectively utilize national expertise and data while improving policy relevance of scenario modelling. It therefore relies on detailed expert-based and national-level input to produce harmonised forestry scenarios across Europe.

This document presents the concept of EFDM, together with on-line services designed for sharing the model and its development efforts. Furthermore, the document summarizes lessons learned from pilot applications in five countries (Austria, Finland, France, Portugal and Sweden), draws some conclusions from these case studies and outlines envisaged future developments of EFDM.

2 State-of-the-art in forestry dynamics modelling

Several forest or forestry (covering both forest and management) dynamics models have been developed over the years. They can be divided into several types:

- Forest (stand) dynamics models that can be used iteratively (over modelling units) such as Motti in Finland (Salminen et al. 2005), PrognAUS in Austria (Ledermann 2006), Silva in Germany (Pretzsch et al. 2002), as well as some models developed in the CAPSIS platform in France (Dufour-Kowalski et al. 2012);
- Loosely coupled integrated stand and forestry dynamics models such as SPECTRUM in the USA (USDA Forest Service 2008);
- Tightly coupled integrated stand and forestry dynamics models such as Heureka in Sweden (Wikström et al. 2011) or MELA (Siitonen et al. 1996) and SIMO (Kangas & Rasinmäki 2008) in Finland;
- Spatial (grid) landscape simulators such as Landis in the USA (Scheller & Mladenoff 2004) or SELES in the USA (Fall & Fall 2001);
- Models of C dynamics which are inventory based and driven by empirical yield data such as CBM in Canada (Kurz et al., 2009);
- Matrix models of forestry dynamics either without a spatial extension such as EFISCEN (Schelhaas et al. 2007) and its predecessors (Sallnäs 1990; Nilsson et al. 1992), or with a spatial extension e.g. VDDT+Telsa in the USA (Merzenich et al. 1999) and SMAC+LandSim in Sweden (Pryimachuk 2010).

Matrix modelling is widely used in population ecology to model the dynamics of wildlife or human populations (Caswell 2001). In forestry dynamics modelling, a transition matrix expresses the probability of a unit (a tree, stand or other forest area) leaving its current position within a matrix to join a different position within the matrix, thus acquiring the characteristics (state and related transition probabilities) of this new category. Typical transitions in forestry dynamics modelling relate to natural processes such as tree recruitment, growth, and mortality due to ageing, competition or disturbances, or being subject to some management activity such as harvesting (Zhou and Buongiorno 2005).

In the simplest case of transition, the state of a unit (tree, stand, forest area etc.) is changed due to natural process of growth in the absence of management activities. When modelling transitions dependent on management activities, the user should estimate the likelihood for any class of trees or forest stand or area to be managed in a particular way. A forest stand or area of a certain age or volume could be more likely to be subject to afforestation, thinning or harvesting. The probability of natural disturbances might also be affected by the age, volume and dominant species.

For example, in EFISCEN transitions occur in a state space defined by age-volume classes: when forest ages, it gains volume, and the growth rate depends on factors such as region, site and dominant species. The model is conceptually easier to grasp if one imagines multiple transition matrices (Figure 1). The transition matrix includes transition probabilities between all states of the state space. In EFISCEN, different factor compositions ("forest types") may have different probabilities for each natural process or activity. Therefore, the number of matrices is defined according to the number of factors, and the size of the matrices is defined by the number of classes for volume and age.

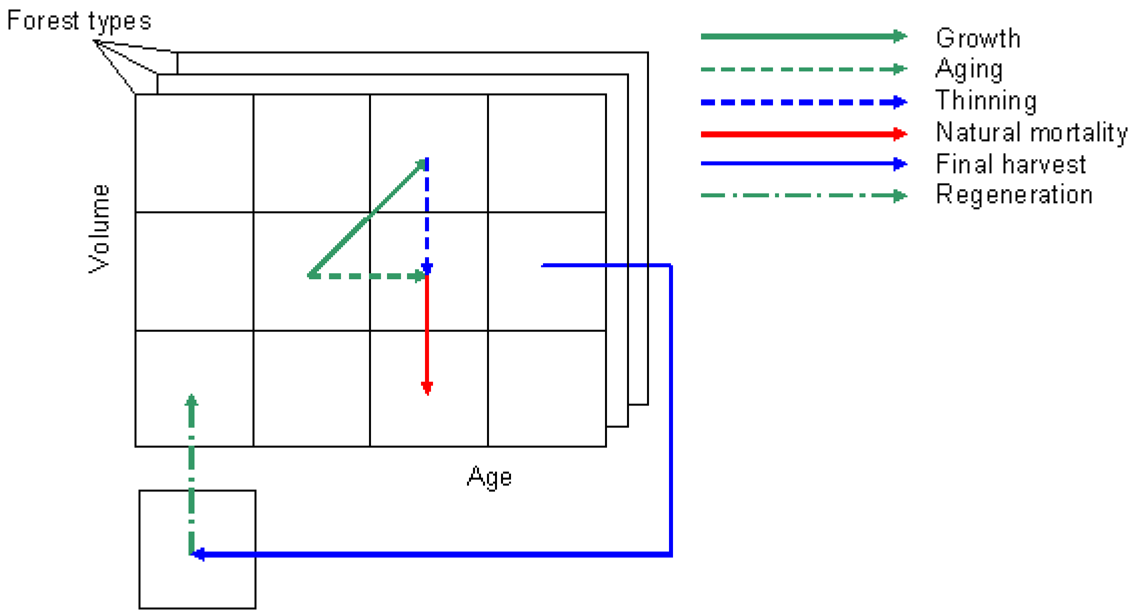

Figure 1. In EFISCEN, a separate matrix is set up for each forest type (a factor combination defined according to species, region, site class and owner). Aging of the forest is simulated by moving area to a higher age class, while growth is simulated by moving the area to a higher volume class. Transition probabilities are derived from increment figures from the input data, or from growth and yield tables.
(Retrieved 5 July 2013, http://www.efi.int/portal/virtual_library/databases/efiscen/modelling_approach/)

The same approach has been applied for even-aged forests both at European (e.g. Nabuurs et al. 2007) and national level (e.g. Eriksson et al. 2007). In addition, the matrix modelling approach has been applicable for uneven aged, mixed species (see e.g. Wernsdörfer et al. 2012). The model can be easily tailored to take into account the growth of the forests, ageing of mature stands and natural mortality, as well as management activities such as thinning and final harvest and regeneration.

3 The European Forestry Dynamics Model (EFDM)

3.1 The EFDM concept

Based on the analysis of system requirements and potential options for the development of a European forestry dynamics model, a matrix-modelling approach was selected for the EFDM because it provides a simple but flexible solution to assess the changes in the state of forest resources under diverse forest growth and management conditions.

EFDM is an area-based matrix model, meaning that forest areas (not trees or stands) are transiting between elements of a set of fixed states. The transitions are controlled by activities that are defined for each state.

Given a set of fixed states S, let's denote by X_t the initial area distribution over the states, and by **P** the transition probabilities between different states (S) guided by the activities **A**, defined over S (Figure 2). Then

$$X_{t+1} = \mathbf{P} \times \mathbf{A} \times X_t$$

When applied to even-aged forests, the set S is usually (but not compulsorily in EFDM) defined by age classes and standing volume which can be visualized as an age-volume matrix. A common age-volume matrix is associated with all the different "forest types" which in turn are defined by combination of factors such as, for example, region, species, site quality and/or ownership.

In practice, there is a set of transition matrices, one per each (fixed) factor combination. In addition, in EFDM the transition probabilities are combined with conditional activities probabilities. As a result we have a transition matrix per factor combination and per activity. Therefore in summary, EFDM is a Markov model defined by the collection of factors, activities and transition probabilities.

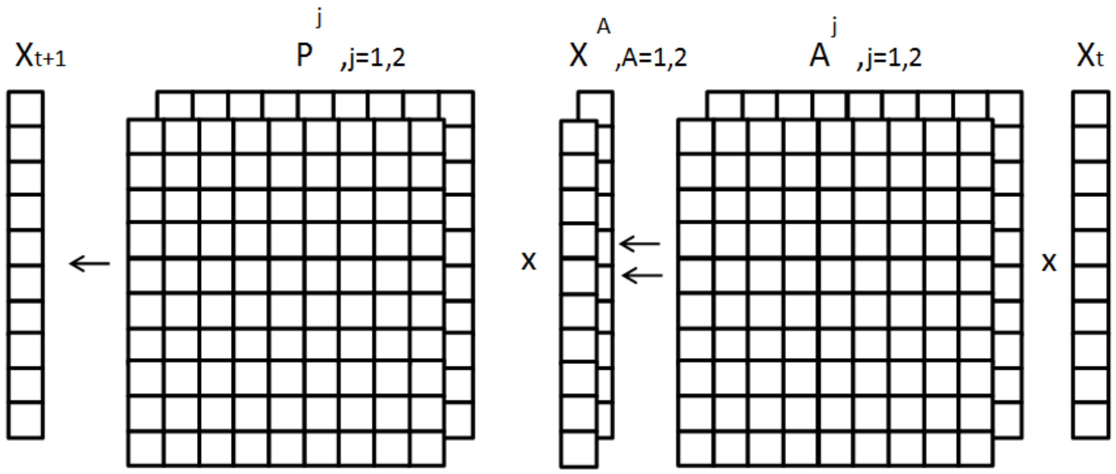

Figure 2. A simple example to illustrate the EFDM concept. X_t is a vector of N states, updated every simulation period with a simple multiplication procedure. $P^{(j)}$ is a matrix for transition probabilities, conditional to activity *j* and usually constant over time. $A^{(j)}$ is a diagonal NxN matrix for probabilities $a^{(j)}_i$ that an area in state *i* receives the *j*th activity. In

this example, only two activities *j* are considered. In the figure, the multiplication procedure is divided into two steps. In the first, the state vector X_t is multiplied with the activity probabilities matrix A^j resulting in an intermediate matrix X^A for the share of X_t for which P^j will be applied in the second step.

3.2 The EFDM system

The core of EFDM was implemented as generic, platform-independent, free and open source (F/OSS) R software that processes tabular data (Figure 3), with an option of data being geographically referenced depending on the definition of modelling units.

EFDM reads in X, **P** and **A** from files provided by the user and multiplies them. The R environment, however, supports building more dynamic input through user-defined add-ons sitting on, for example, the NFI data. In an ideal situation sufficient plot data is available to estimate the transition probabilities. In the absence of sufficient plot data, a recursive Bayesian filter can be applied.

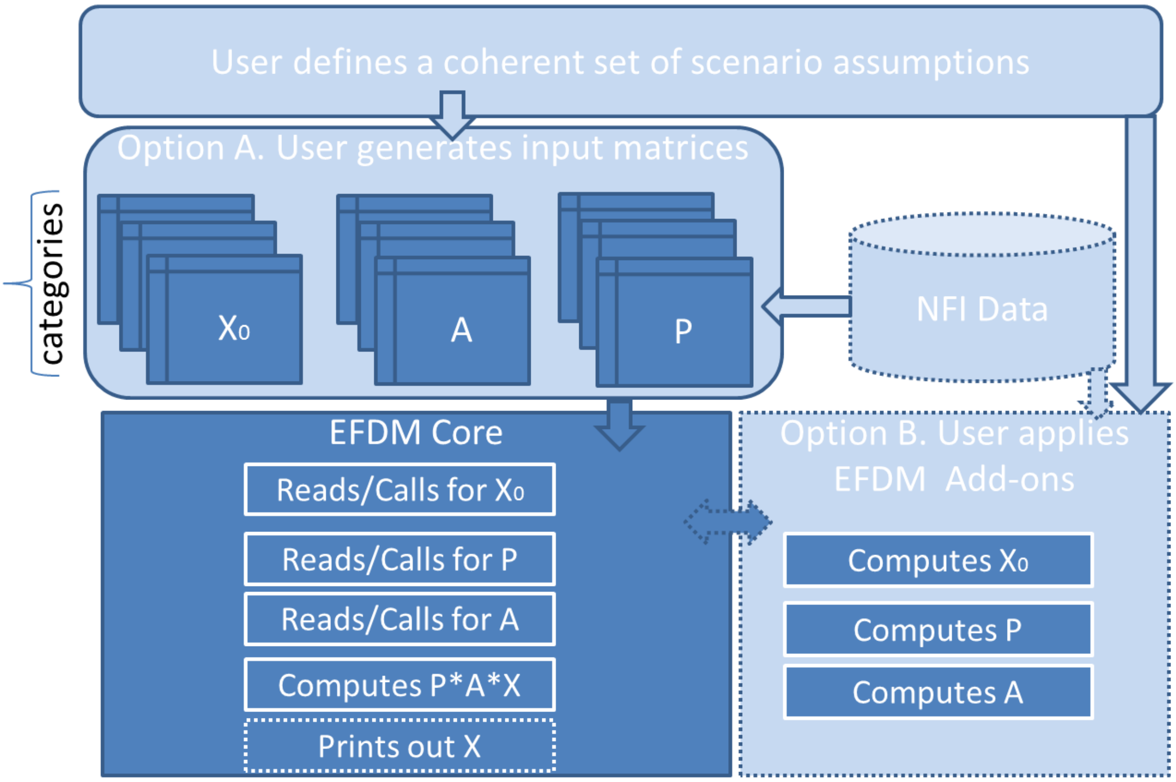

Figure 3. The EFDM system.

3.3 The EFDM online services

The EFDM software version SC10 is released at https://webgate.ec.europa.eu/CITnet/stash/projects/FISE, with instructions and additional information on the EFDM Wiki pages https://forestwiki.jrc.ec.europa.eu/efdm/index.php/Main_Page . To fulfil the EC requirements for software, software complies the EUPL license which requests acknowledgement of authors and allows re-use and re-distribution of software.

4 Application of EFDM in five National Forest Inventories

4.1 Outlines

In the first phase of model development, the concept was tested in five countries, Austria, France, Sweden, Finland and Portugal (Figure 4), thus covering different ecological and socio-economic conditions in Europe (Table 1). Austria, France and Sweden elected to project the future development without incorporating management activities, while Finland simulated the development in response to standard management activities. Portugal tested modelling under both a "no management" scenario, as well as taking into account management under fire risk (Rego et al. 2013). Whereas Austria and Sweden covered their entire national territories, Finland modelled the southern part of the country; France modelled the Aquitaine region; and Portugal concentrated on Eucalyptus plantations. Finland, Portugal and Sweden defined the state space of their even-aged forests by age and volume classes. France defined their state space by stem number and diameter, more applicable also for uneven-aged forests. Both Austria and France tested the model for even-aged and uneven-aged forests. For example Austria defined three different state space models, testing also the use of state space based on number of stems and volume for modelling dynamics of even-aged forests.

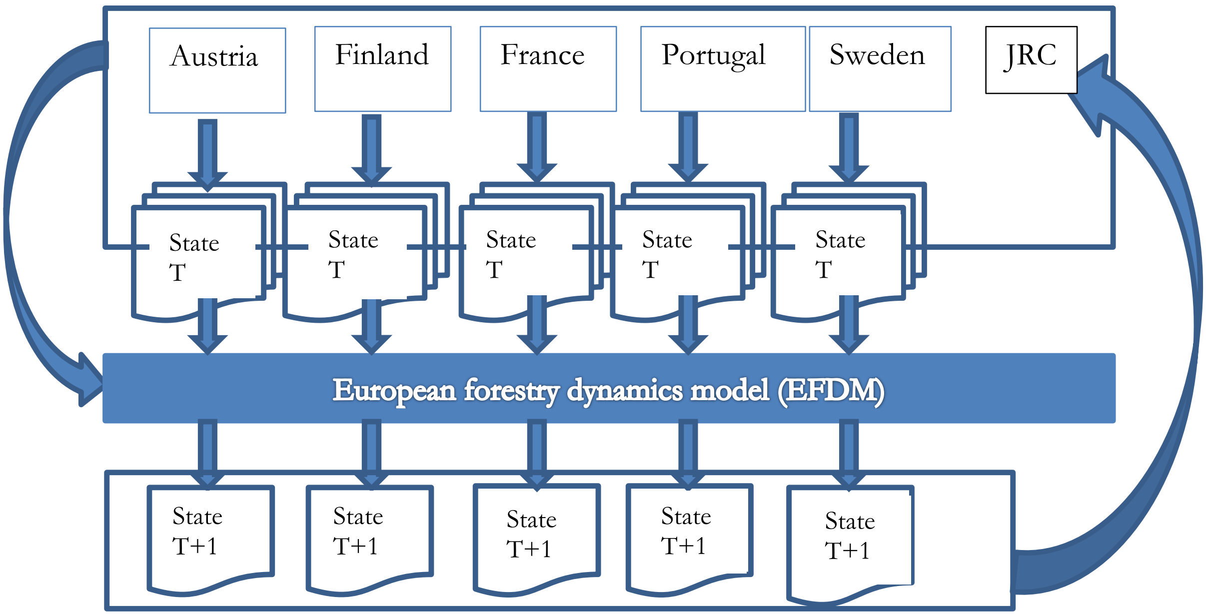

Figure 4. The setup for collaboration between the JRC and partners in the NFIs.

Table 1. The EFDM modelling setup for the national case studies

	Forest-type coverage		Geographic coverage			Activities modelled		
	Even-Aged	Uneven-Aged	National	Regional	Other	Not managed	Standard managed	Fire risk
Austria	X	X	X			X		
Finland	X			Southern Finland			X	
France	X	X		Aquitaine		X		
Portugal	X				Eucalyptus plantations		X	X
Sweden	X		X			X		

In all cases, the National Forest Inventory (NFI) knowledge about forest states, activities such as management activities and their interrelations was utilized in the model definition and estimation. The initial state (X_t) was estimated using pre-existing NFI plot data, while the transition matrix (**P**) was estimated using two consecutive measurements of NFI plots (Austria and Sweden), increment measurement of NFI plots (Finland and France), or growth information from pre-existing functions (Portugal). The estimation of the initial state (X_t) matrix was a simple classification, while the **P** matrix was estimated using a Bayesian procedure. The national analyst provided the activity matrix (**A**).

The NFI application of EFDM consisted of the following generic steps:

1. Definition of level of aggregation for factors used for input and intermediate matrices (Table 2), including the classification of the state space (e.g. age and volume) and factor combinations ("forest types") for which to track transitions separately;

2. Compilation of the forest initial state matrix (X_t) from NFI data;

3. Estimation of basic ("no management") transition probabilities (**P**) based on pairwise observations from NFI data, single growth observation, growth and yield models or expert knowledge;

4. Estimation of activity probabilities (**A**) for each defined factor combination based on NFI data such as recorded management activities (Antón-Fernández, et al. 2011), guidelines for forest management (for the "school-book" scenario) or national statistics (for the "business as usual" scenario);

5. Running the EFDM to generate an output matrix for future states of forests in case of "no management", "school-book" or "business as usual" scenario.

6. Comparison of the EFDM output with national model and evaluation of results

Table 2. Definition of factors and factor levels by NFIs.

	State space (number of classes)	Factors and their levels	Total number of

	Age	Volume ha-1	No. of Stems ha-1	Volume ha-1	No. of stems ha-1	Diameter	Region	Altitude	Site class	Dominant species	Rotations	factor combina-tions
Austria	35	15	10	15				3		3		9
Finland	26[27]	11[12]					1		4	3		12
France					13-16	13-16	2			12-13		24-26
Portugal	25	11[12]							5		3	15
Sweden	33[34]*	10[11]	-	-			5		4	3		60

*The number of classes inside brackets [] include a class for bare land.

4.2 Results and Discussions

Countries compared the EFDM outputs with the results for "no management" (Austria, France, Sweden) or "school-book" scenarios (Finland, Portugal) either to their national models with the same scenario assumptions (Finland, France, Sweden); or to national statistics (Austria, Portugal).

Differences between the EFDM outputs and the measures selected for comparison varied from 0 (France) to ten (Portugal) percent. The magnitude of variation depended, for example, on the interventions considered: in Portugal the volume development was overestimated if the impact of disturbances was not taken into account. In Austria, the EFDM results for even-aged forests are similar to those tracked by statistics, although there are some differences in certain strata and the age-volume models yield slightly higher standing stock changes which may be caused by the fact that even-aged (managed) stands are generally found on the more productive sites. In Finland, differences between the results from the two models increase over time. In France, the compatibility of the two models was secured by including an additional ingrowth module to EFDM. In Sweden the average annual increment figures calculated over a long time period are almost the same from both models, although the patterns over time differ.

In summary, all NFIs considered EFDM a feasible modelling approach at national level, especially for tackling issues traditional models have difficulties with such as uneven-aged forestry or management under risk.

Table 3. A summary of the comparison and evaluation from national case studies.

Country	Source for comparison	Comparison measure	Comparison results
Austria	Statistics on increment	Annual increment ($m^3ha^{-1}a^{-1}$) over 70 year time period	Difference 0.1 $m^3ha^{-1}a^{-1}$
Finland	National model (Siitonen et al. 1996)	Annual increment ($m^3ha^{-1}a^{-1}$) over 30 year time period	Difference 0.1-0.5 $m^3ha^{-1}a^{-1}$
France	National model (Wernsdörfer et al. 2012)	Stem volume (m^3) until 2025	Exactly the same
Portugal	NFI results on volume	Average volume (m^3ha^{-1})	For no management: ~10 m^3ha^{-1} depending on site quality For management under fire risk: 0.2-0.8 m^3ha^{-1}
Sweden	National model (Wikström et al. 2011)	Annual increment ($m^3ha^{-1}a^{-1}$) over 100 year time period	Difference 0.4 $m^3ha^{-1}a^{-1}$

5 Conclusions

5.1 Lessons learned from the EFDM development

EFDM is considered a sound tool supporting the assessment of policy impacts on forests through management and the generation of scenarios for sustainable management of forests in Europe at sub-national, national and international level. First, EFDM is a simple model based on aggregated units (areas) and the simulation carried out through the multiplication of matrices. Second, EFDM is a generic tool that can easily be tailored for different ecological and socio-economic conditions. Third, EFDM is a flexible system and expandable framework that supports effective utilization of the best available expertise in the parameterization of scenarios. Fourth, EFDM is a software with a standard input interface (the same structure can be used for all countries) that will help in harmonizing national results. Fifth, EFDM is based on free and open source software and thus improves the credibility of scenario modelling at national and European level by facilitating transparency in documentation and evaluation of modelling results. It supports capacity building, especially in countries that do not have their own modelling tools, as well as collaborative development of new features.

Currently, there are some limitations in the software. Transition probabilities are assumed to be stationary - probabilities neither increase nor decrease - as a function of time. This feature is not conducive to climate change impact studies. Furthermore, if a fixed harvest level is demanded from EFDM, this is sought through a series of iterations, in contrast to models such as Heureka-PlanWise in Sweden (Wikström et al. 2011) or MELA (Siitonen et al. 1996) and SIMO (Kangas & Rasinmäki 2008) in Finland, in which it can be solved directly by mathematical optimization.

5.2 Lessons learned from the EFDM application

The EFDM approach based on collaboration among MS enhance the policy relevance of scenario modelling in the EU through (i) a novel scientific methodology; (ii) exchange of best practices for scenario modelling; (iii) effective utilization of MS knowledge and local data in the parameterization of scenarios; (iv) improved capacities in MS for the production of harmonized and transparent forestry scenarios. This initial assessment of the performance of EFDM has proven the model to be capable of successfully assessing the dynamics of forestry in the heterogeneous pool of test sites. Hence, EFDM will be gradually expanded to other European countries by involving more MS through collaborative agreements.

As a result of the test phase, some recommendations were made for the improvement of the model and its use., The user-friendliness of the software could be improved, for example, by adding output options, such as the production of graphs, tables and statistics after every step run of the model. In order to consider different ecological and socio-economic conditions, EFDM should facilitate the definition of alternative management activities and different natural disturbances as well as the generation of output variables for different forest products and services (e.g. biomass, quantities of harvested wood in terms of timber assortments). Following this, the model could be connected to other models using this information as an input.

The EFDM model is flexible and facilitates the use of diameter-volume or age-volume matrices as a starting point. However, further research is required to find a harmonized way to deal with different types of uneven-aged forests. Particularly in Mediterranean region, where the majority of forests are not even-aged.

5.3 Way forward for EFDM

Within the collaboration between the JRC and partners from EU MS, EFDM will be further developed to be used by and within EU MS. To facilitate the use of EFDM, there is a need for (i) the enhancement of the user interface to simplify model use for and by other European countries, in order to handle even-aged forests and related management practices, forest products and services, and (ii) the elaboration of the matrix modelling concept to handle forests that are not even-aged; as well as multi-layer forests and related management practices.

In the next phase of development, the functionalities of the EFDM user interface will be enhanced and the EFDM suitability and performances will be tested in a wider range of environmental and socio-economic conditions in European countries, with special emphasis on countries that were not included in the model development phase. Furthermore, the basic EFDM concept will be tested more thoroughly for uneven-aged forests. In the future, the model should also be further developed to handle more complex natural disturbances and the related potential impact of climate change.

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