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Simulation tools for decision support to adaptive forest management in Europe

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Abstract

In forest management there is a tendency towards measuring more cost-effective and simulating more. In this context the development of reliable, user friendly forest simulators has become economically relevant. The objective of this perspective paper is to highlight the recent trends in forest simulation and to identify the remaining challenges to make forest simulation a reliable tool for forest policy and management.

Experiences with forest simulators for various purposes in different geographical contexts illustrate how the important challenges of forest decision support can be addressed through flexible customization for different end-user categories, offering spatially explicit approaches at the landscape scale, and integrating empirical and mechanistic models in hybrid and bayesian simulation approaches.

Recent development trends in forest simulation for decision support are mainly related to the ever increasing calculation speed and capacity of computers, facilitating the development of robust tools with comfortable user interface and realistic functions and options. Another trend is the combination of simulation tools with optimization and choice algorithms fading away the difference between simulators and decision support systems.

The remaining challenges are basically in the high expectations of stakeholders concerning the ability of simulators to predict a range of outcomes in terms of ecosystem services and sustainability indicators, as well as the quality of their outcome in terms of output credibility to stakeholders. Need for accepted and realistic model validation and verification methods preferably using empirical data is crucial in this matter.

Key words: multi-objective forest planning; forest model; simulator; decision support system; climate change.

Resumen

FALTA TÍTULO EN CASTELLANO

En la planificación de la gestión forestal existe la tendencia a medir menos y similar más. En este contexto, el desarrollo de simuladores forestales es económicamente relevante para el gestor. El objetivo de este artículo es el de discutir y enfatizar tendencias en el ámbito de la simulación forestal e identificar retos importantes para que la simulación forestal sea una herramienta fiable en el proceso decisorio de la planificación forestal y en el de desarrollo de políticas. Varios ejemplos de simuladores forestales existentes y que responden a objetivos y escalas geográficas dis-

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tintas, ilustran como la capacidad analítica de los gestores puede mejorar sustancialmente para responder a los grandes retos en el proceso decisorio de la gestión forestal. El artículo presenta simuladores que responden a necesidades de diferentes usuarios y hacen frente a distintas cuestiones, utilizando distintos enfoques y herramientas; desde simuladores espacialmente explícitos basados en modelos empíricos que son integrados con herramientas de optimización, hasta simuladores mecanísticos o basados en enfoques híbridos y bayesianos. El desarrollo más reciente en simulación forestal esta sobretodo relacionado con el incremento de capacidad de cálculo de los computadores, lo que ha facilitado el desarrollo de herramienta robustas y visuales, fáciles de utilizar por los usuarios finales. Otra tendencia, importante es la combinación de herramientas de simulación con técnicas de optimización númerica, lo cual posibilita el desarrollo de los mas modernos sistemas de soporte a la decisión. Uno de los retos más importantes es el de colmar las altas expectativas de los principales agentes y centros decisores forestales en relación a la capacidad de los simuladores y sistemas de apoyo a la decisión para proporcionar información relevante en relación a los servicios ecosistémicos e indicadores de sostenibilidad. En este contexto, es necesaria la validación de los diferentes modelos que configuran los simuladores haciendo uso de información empírica disponible.

Palabras clave: planificacion forestal multi-objetivo; modelos forestales; simuladores; sistemas de soporte a la decisión; cambio climático.

Introduction

In a context of increasing labour cost for inventories and field observations and a decreasing calculation cost thanks to increasing computer power there is a trend towards measuring more cost-effective and simulating more. Policy makers and governmental planners in the forest sector start to rely on simulators to do trend analyses of forest resources and prepare the stakeholder dialogue on multiple objective forest management decisions (Kangas and Kangas 2002). In such a context developing reliable and user friendly forest simulators has evolved from a merely scientific exercise to an economically relevant challenge. Rather than to make a review of available forest simulators in Europe, the objective of this contribution is to focus on the challenge of making forest simulation an applied tool for forest policy and management and to discuss the remaining challenges with a focus on recommendations for future development. We will do so using recent experiences with simulators for a variety of purposes in different geographic contexts.

Models, simulators and decision support systems are defined in Table 1. Where models try to give a mathematical description of a physical process, simulation tools use these models for automated calculation and visualisation of scenario outcomes, while decision support systems (DSS) provide support to solve ill-structured decision problems by integrating database management systems with operational research methods, forest simulation models, graphic display and tabular reporting capabilities, and knowledge of experts and stakeholders. DSS may include simulation tools as an input for optimization and management advice to a user (Fig. 1).

In a context of changing climate and adaptive forest management, simulation tools integrating mechanistic models should be used as predictive components in state-of-the-art decision support systems. In other words, simulation is a key step in good decision support because simulation models provide information on the

Table 1. Definitions of model, simulator and decision support system (adapted from COST Action FP0603 «Forest models for research and decision support in sustainable forest management» definitions at http://www.isa.utl.pt/def/fp0603forestmodels/wiki-forest-models.html)

Model	Mathematical description of the real world. A mechanistic model describes the processes in terms of fundamental biophysical relationships, without specifying how they are to be solved.
Simulator (syn. Simulation tool)	Tool that calculates results for a model using a sample of representative scenarios. Simulators for decision support may preferentially focus on model simplification, automation and visualization.
Decision Support System (DSS)	Tool providing support to solve ill-structured decision problems by integrating user interface, simulation tool, expert rules, stakeholder preferences, database management and optimization algorithms.

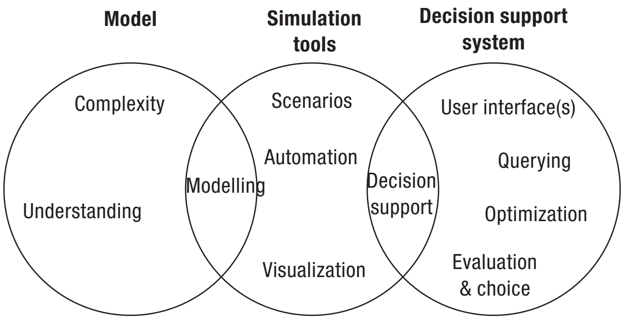

Figure 1. Main features of models, simulation tools and decision support systems.

likely outcomes of alternatives from which a DSS can identify the most preferable one to maximise different user-defined objectives (see *e.g* Gilliams *et al.,* 2005). In absence of a genuine DSS, stand alone simulation tools often include a user interface with attractive output visualization features to provide decision support (Fig. 1). In either case, simulation becomes an essential activity in flexible, interactive and iterative forest management planning (Gustafson *et al.,* 1996; Pukkala, 2002; Phillips *et al.,* 2004) (Fig. 2) and could ultimately contribute to help stakeholders and decision makers arrive at reasoned and reasonable decisions about forest resource management (Reynolds *et al.,* 2008).

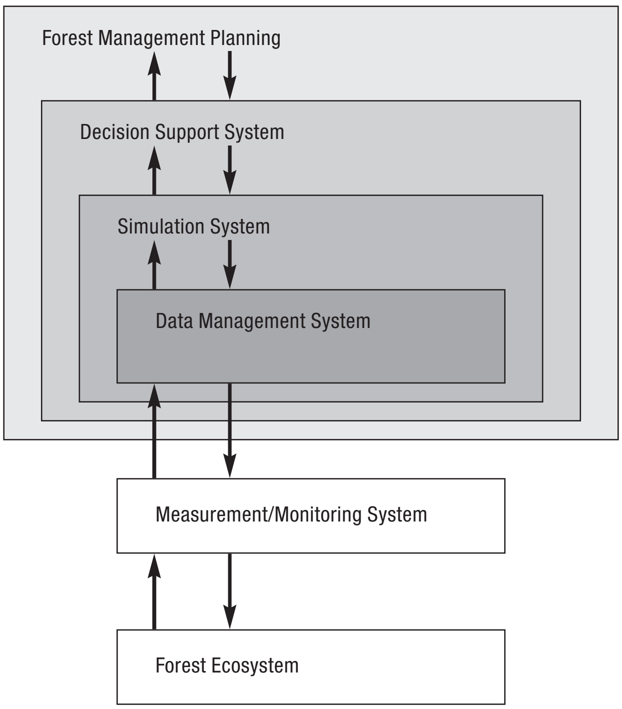

Figure 2. Position of simulation in flexible forest management planning under global change (modified after Pukkala, 2002).

In this contribution we will first visit some recent examples of forest simulators. With these examples we will show how simulators addressed some important challenges of applied forest simulation for decision support. After that we will discuss the recent trends in forest simulation and the remaining challenges for further development.

State-of-the-art examples of forest simulators

With these examples, some of them with free access on the internet, we show how simulators can be tailored to end user requirements, which policy or planning relevant features spatially explicit simulators have and what additional application power hybrid simulation through model linkage can offer.

Customizing simulators for end users

Today, the most common mode of decision support is still that scientists run the model for managers, which is not the best way to obtain transparency, credibility and ownership towards the end-user. The best way to foster model application in practice is to tailor a model as suitable as possible to the requirements of the end-user, by identifying different user-groups and developing specific interfaces for each group. A clear separation between graphical user-interface and the model itself makes the customizing easier. In the SILVA 3.0 simulator, a prognosis model for forest management in Central Europe (Pretzsch, 2002) this was implemented by a client-server solution. The client represents the steering unit, where the user-interface is developed in close contact with the end-user. On the other hand all model algorithms for the prediction of growth, mortality, regeneration, and response to forest management interventions are not user specific and run on a server so that they can be combined with different user-interfaces (so called front-ends). By means of the user-interface the input of initialisation data for a model run, the output of the simulation results, and the steps of a prognosis process are specified, and a specific sequential usage of different modules of the model is activated. During the development process several end-users were identified: a first user group comprising scientists and consultants apply the model in interactive mode for a rather limited number of cases, *e.g.,* for analysis of silvicultural operations, expert's opinion for lawsuits, or economic valuation. They require flexibility of scale to use the model on the stand, enterprise, region, or national level, or even for different countries, which will go beyond the standard application. This user group familiarizes quickly with new tools, adapts software easily for their specific purpose, and requires the lowest customization and training. A second user group are public and private forest managers and planners. They apply models for development of silvicultural guidelines, preparation of management plans, or assessment of sustainable annual cut. They would typically use SILVA mainly in batch mode for some 1,000-10,000 inventory plots, calculate several thinning options per plot or stratum, and repeat each run 5-20 times in order to get mean and standard error as results. This group requires the development of a user-friendly interface. Often enterprise-specific algorithms are integrated as selectable modules, *e.g.* for stratification of inventory data, thinning options, assortment rules, or harvesting techniques. Especially in this user group models face a general skepticism or ignorance towards software application in forestry. For some users, models seem to be a threat to their silvicultural expertise or may recall the former knowledge monopoly of state forest headquarters. Remedies for these hurdles are training courses, model application in team sessions, technical support for scenario analysis and treatment of the results as internal affair of the enterprise. Students education in model application will help to overcome the skepticism towards models and modern decision support tools in the longer term. A third and last group of users are trainers, teachers, and consultants, who apply the model for educational or advisory services. Like private asset consultants, these users apply software to base their advice on calculations and quantitative analyses of different options. For this purpose they use the interactive version of SILVA and simulate just a few stands and silvicultural options to show the effect of alternative decisions in a clear and simple way. The model designers supply in concertation with such users a set of pre-calculated scenarios for archetypal forest stands and management options. Those calculations are selected and worked out together with the users in advance. In such way models can bridge the gap between increasing but more and more detailed and scattered system knowledge and increasing information demands about dynamics on stand level. Models should not dictate but support decisions and training by prognosis and scenario analysis (Pretzsch *et al.,* 2008).

Issues of sustainable forest management can be addressed at different spatial and temporal scales, dependent on the stakeholders involved. Policy makers will generally be interested in region- or nationwide effects of policy choices on *e.g.* wood supply or blue water availability, whereas forest managers are more focussed on management planning for specific local objectives such as quality wood production or biodiversity (Holvoet and Muys, 2005; Heil *et al.,* 2007a). SimForTree is a simulator under development (www.simfortree.be), based on the mechanistic ANAFORE model (Deckmyn *et al.,* 2008), operating at two scale levels identified as a result of intensive interaction with potential end-user groups. The underlying idea is to develop multiple tools for targeted use, rather than one integrated all-round tool which would have difficulty to match the needs of all users. The two SimForTree versions are designed at a different spatial scale (1 *vs* 0.01ha grid size), spatial extent (whole country vs forest management unit) and time resolution (5 *vs* 1 year), and integrate the ANAFORE output to address either policy questions (standing stock per species, landscape diversity, total C-pools) or management planning (timber quality grading, thinning prescription, stand diversity, site characteristics).

Another way of adapting models to end-user requirements is to simplify them into so-called metamodels. Metamodels are often derived from complex mechanistic models *e.g.* by decreasing the mechanistic level of detail, by decreasing the time resolution (*e.g.* from hourly to fortnightly time steps) or by performing regression between output and input of multiple runs with a complex model. Further simplifications for the end-user may be introduced by allowing only discrete input classes of commonly available variables. As an example we refer to the METAFORE-metamodel (downloadable at www.sl.kvl.dk/afforest as part of the AFFOREST sDSS), which was derived from complex models CenW (Kirschbaum, 1999) and Nucsam (Kros, 2002), and which simulates for any combination of discrete climate, soil and previous land use classes the environmental performance of new forests on agricultural land in terms of carbon sequeststration, groundwater recharge and nitrate leaching (Heil *et al.,* 2007b; Van Deursen *et al.,* 2007).

Spatially explicit simulation

For various stakeholder categories, the consequences of different forest planning options should also be predictable at landscape level, which requires specific output variables for this higher scale level and quantitative linkages between forests of different types and management, grassland, and arable land.

The MONTE system (Pukkala, 2003; Palahí *et al.,* 2004; www.forecotech.com) offers decision support in South European forests on fire risk, habitat protection, multiple forest products and functions. MONTE includes individual-tree level models to predict forest stand development, models for non-timber products like mushrooms, a risk model for forest fires and different habitat models for key animal species. Such models are used to predict the consequences of different management alternatives that represent the decision space of the planning problem. MONTE is complemented with heuristic optimization techniques and a forest planning model writer that allows the formulation and solving of multi-objective planning problems for a certain forest landscape. Management objectives can be spatially explicit by using specially designed landscape metrics which enhance the importance of a special landscape configuration and composition to minimize the risk of fires or improve the suitability of the landscape for an important animal species. MONTE is in addition augmented with virtual reality tools that allow the decision maker to see the effects of a given plan or alternative in a selected forest stand or in the whole landscape.

In many parts of Europe such as mountain areas, forests are intimately connected to other landscape elements such as pastures to form agro-silvo-pastoral systems (Etienne, 1996; Rigueiro-Rodríguez *et al.,* 2009). Changes in both natural (global warming, episodic events) and anthropogenic (grazing pressure, forest management) driving forces may lead to dramatic shifts in vegetation dynamics with strong impacts on landscape structure, ecosystem functioning and related services. The extension of forest simulation to such heterogeneous landscapes requires spatially explicit, dynamic models that link tree establishment, growth and mortality with grassland dynamics and livestock habitat use. An example is given by WoodPaM (Gillet, 2008), a model of pasture-woodland dynamics based on a hierarchy of spatio-temporal organization levels. At first designed for strategic and theoretical purposes, this model is being adapted and tested to allow realistic simulations of adaptive management scenarios of silvopastoral landscapes in the Swiss Jura Mountains, including integration *versus* segregation of land use.

Hybrid simulation

Hybrid approaches combining empirical and process-based models have been suggested as an approach that could manifest both wide applicability in terms of realistic predictions, and flexibility under changing environmental conditions and management options (*e.g.* Valentine and Mäkelä, 2005; Pinjuv *et al.*, 2006; García-Quijano *et al.,* 2005). An operative hybrid model study was conducted by Matala *et al.* (2005, 2006), who incorporated climate-change impacts from the process-based FinnFor model (Kellomäki *et al.,* 1993) to the empirical MOTTI and MELA simulators (Hynynen *et al.,* 2002). The one-way link between

a) b)

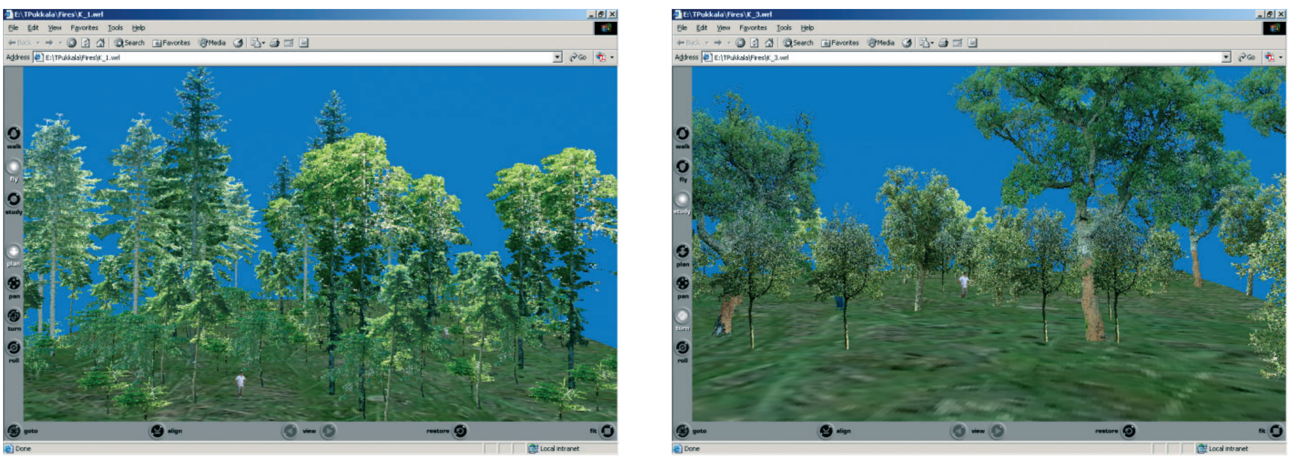

Figure 3. Virtual reality photos for two simulated forest stands; a) a mixed coniferous forest stand and b) a cork oak stand using MONTE (Pukkala, 2003). MONTE simulates forest stand development and interactive virtual reality visualizations can be produced at any point in time.

models was made by means of species-specific transfer functions describing the increase in stem volume growth of trees as a function of elevated temperature and CO_2, stand density and tree competition status in a stand. This method allows the inner dynamics of the statistical model to be followed when the impacts of temperature and CO_2 elevation on tree growth are introduced into the calculation of volume growth. However, the results remain largely specific to the particular case studies, and the reliability of the environmental response relies upon that of the process model. Furthermore, if both the empirical and process-based models are rather complex, the evaluation of the causal chains of the climate impact in the combined model may not be straightforward.

Another increasingly implemented strategy to combine the strengths of mechanistic and empirical approaches is to calibrate mechanistic models with empirically obtained datasets using Bayesian model optimization (Van Oijen *et al.,* 2005). The results are empirically enabled mechanistic models with more predictive power, turning them from an interesting research instrument into a management application tool (Deckmyn *et al.,* 2009).

Trends in simulation for decision support

The more diverse the goods and services demanded from our forests are, the more complicated and challenging becomes their planning and decision making. However, this should not cause the retreat to ad hoc planning and short-term thinking; it rather underlines the urgent need for appropriate concepts and tools for decision support. Currently we consider a trend towards a «toolization» of planning; developers show tools upon users who can hardly cope with these manifold models. Tools are only helpful if they fit exactly into the concept and data flow of the planning procedure. Guiding principles and concepts for future planning are scenario analysis including visualisation and optimisation. In this section, we make a distinction between trends in the simulation and its software implementation, and in the decision support peripherals.

Trends in simulation

In addition to the appearance of new models, which enable the simulation of emerging management challenges, *e.g.* related to NWFP, risks, timber quality, etc. (see Calama *et al.,* 2010; Mäkäla *et al.,* 2010, in this issue), most trends are related to the ever increasing calculation speed and capacity of computers.

Computer programs are improving together with improvement of simulation algorithms. As a consequence, simulators become accessible to everybody, not only for a small group of scientists. They become robust tools with comfortable user interface and many of offered functions. The following trends are worth mentioning:

a) Systems of structured dialog windows with intuitive and attractive user interface.

b) An important aspect of quick innovation is the visualization capacity of simulation tools, evolved from data visualization using graphs, maps, etc., to advanced visualization in a 3D virtual reality thanks to advances in computer graphics (rendering) (Fabrika, 2003; Pretzsch and Seifert, 1999; Seifert 2006, 2008). For this purpose Virtual Reality Modelling Language (VRML), Direct3D and OpenGL libraries are used. At the same time these libraries support abilities and performance of the newest graphic cards and accelerators of physical processes. Visualization is an essential analytical tool to evaluate forest responses to management, but can also be very helpful to evaluate public perception of management. An interesting issue here is how close to «computer game quality» science-based decision support should get, where high-grading visualization quality might go at the expense of scientific quality, or might lead to loss of credibility due to «gaming association».

c) Connection to SQL-based relational databases, composed from structured tables, attributes, indexes and relations.

d) Possibilities for batch execution of simulations of many stands without any assistance of user and production of consistent outputs in form of database mentioned above,

e) Modularity in form of independent software units (Fabrika and Ďurský 2006) concentrated on specific tasks (generating stands, specification of site conditions, thinning prescription, growth prognosis, output calculation, visualization of results and so on), as is presented in Figure 4.

f) Interface to current information from field expertise and forest inventory by simple import, eventually to the newest technologies of terrain laser scanning (this technology is probably going to have a big influence on data achievement in the future).

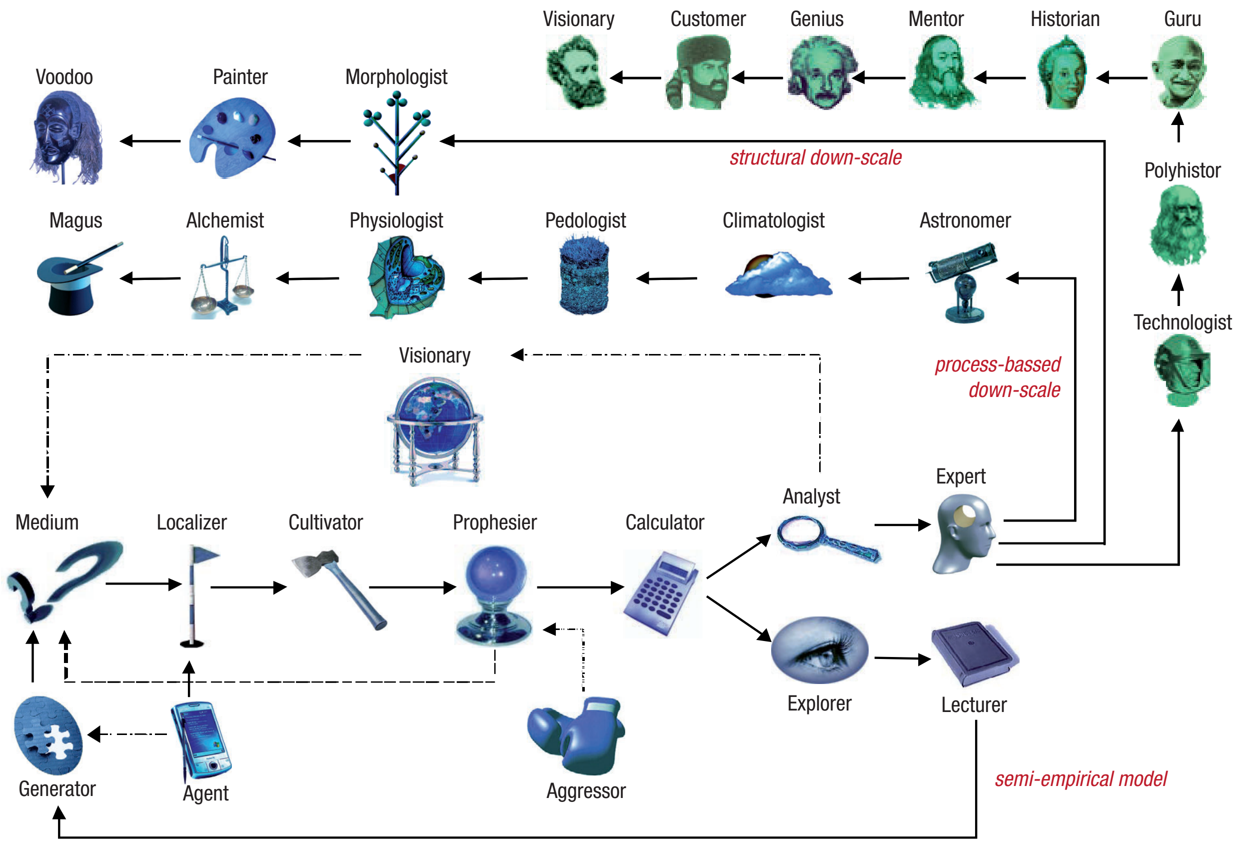

Figure 4. Software modularity exemplified by the software SIBYLA (Fabrika and Ďurský, 2006). The figure presents four independent groups of the software units: semi-empirical components, components of process-based down-scale, components of structural down-scale and components for public relation purposes. The software units are independent and they are able to exists and works separately. But they cooperate through the defined interface and input-output database. Autonomous tasks of the software units is reason that entire software suite is very flexible and powerful. Functionality of the units can be demonstrated by several examples of tasks: import of data from field forestry (Agent), generation of missing or unknown data (Generator), specification of climate, soil and site parameters (Localizer), specification of management concepts (Cultivator), growth prognosis (Prophesier), data visualisation and virtual reality (Explorer), GIS functionality (Cartographer), calculation of sun radiation (Astronomer), weather generator and climate change generator (Climatologist), specification of soil processes (Pedologist), specification of plant physiological processes (Physiologist), control of all process-based parameters (Alchemist), process-based down-scale of semi-empirical prognosis (Magus), specification of growth grammars (Morphologist), options for tree visualisation (Painter), structural down-scale by tree morphology (Voodoo) and so on.

g) Link to geographical information systems (Surový *et al.,* 2007), which provide data background (localization of stands in real terrain situation, real site, and real data from forest inventory); the newest trends are 3D GIS tools including terrain model covered by ortho-photo images which are similar to interactive «flight simulators», with possibilities of virtual walk-through, virtual flythrough and interaction with trees.

h) Production of thematic maps in GIS environment as output of spatially dependent growth simulations and possibility of next spatial analysis joined to knowledge base and multi-criteria evaluation techniques (Sodtke *et al.,* 2004; Fabrika, 2007a).

i) Implementation of high performance computing (HPC) in software solutions on the basis of parallel computing, distributed computing or grid computing; the approach enables acceleration of prognosis for large areas many times.

j) Utilization of web services and web forestry information systems integrated with 3D GIS, growth simulator and virtual reality (Fabrika ,2007b), using for example JAVA or ASP.NET technology.

These software solutions declassify growth simulators to a flexible wide-range usage in forestry and ecology and contributes to their integration into decision-making process. The newest trend is the introduction of tools in the process of education at universities. Special solutions called «training tools» are developed. They are tools that train students to correct management strategies by «turn-based strategy games». Sophisticated hardware extensions like «virtual caves» with stereoscopic projection on 5 cube walls around user seems to be the near future of education and training. Another trend of education is sharing of virtual reality in the Internet environment for example in e-learning processes.

Trends in decision making

Over the recent decade simulation tools have increasingly been combined with optimization and choice algorithms and approaches. Optimization either aims at finding optimal treatment trajectories for individual stands or at the allocation of treatment plans to stands of a larger planning problem as to maximise a given objective function composed by one or more objective variables (*e.g.,* net present value, biodiversity indicator, landscape metric, etc.). Typically, for *operational* planning decisions, *e.g.* the choice between methods of stand tending, many management alternatives need to be explored. In that context, numerical optimization techniques like linear programming or heuristics can be applied (*e.g.,* Von Gadow and Pukkala, 2008; Borges *et al.,* 2002). On the other hand, in *strategic* planning decisions, such as the strategic choice between maximum sustained yield or close-to-nature management, multicriteria decision analysis methods (MCDA) have been used. MCDA methods have drawn considerable attention and promising examples for successful integration in DSS have been presented (*e.g.,* Lexer *et al.,* 2005; Gilliams *et al.,* 2005; Vacik *et al.,* 2007; Twery *et al.,* 2005). For instance, Lexer *et al.* (2005) developed a DSS to support the forestry staff of extension services in southern Austria in preparing informed recommendations for forest management to small private landowners based on owner's goal preferences. The DSS targets stand level decisions concerning treatment programs aiming at a future targeted species mixture type given a particular set of management objectives. It represents a data base driven approach where the user can assess the preferability of a set of prefabricated decision alternatives. The Analytical Hierarchy Process is used to combine explicit goal preferences of the user with simulated outcomes of silvicultural decision alternatives to rank a set of options.

Rather recent is to integrate spatial objectives (connectivity problems, harvest aggregation, landscape structure, etc.) in decision optimization tools (*e.g.* Kurttila, 2001; Gilliams, 2005). There is also a trend to enhance stakeholder involvement through participatory model development or scenario selection.

Starting from recent reviews on DSS there are a number of lessons that can be learned from the successes and failures of decision support system development efforts to date (*e.g.* Reynolds *et al.,* 2007; Rauscher, 1999; Reynolds *et al.,* 2005). Among the most important is that a clear focus on the decision making process that shall be supported as well as on the target user is crucial. If a system/tool attempts to do everything for everyone, it is likely to be too complex to use and is unlikely to be adopted and actually used in practice.

Another lesson to be learned from past development is the need for transparency. A variety of DSSs using «black box» computational techniques may produce good information, but if stakeholders/users cannot follow the reasoning used by the system, they are unlikely to accept its recommendations, no matter what the merits may be. Transparency and understanding of the formal reasoning mode of a decision support tool/ system by users can not be substituted by improved visualization and reporting capabilities. Converging with DSS regarding to key functionalities these findings may apply to simulators as well.

Remaining challenges for forest simulation

The remaining challenges in simulation are basically the unsaturated increase in stakeholder expectations concerning the ability of the system to predict a range of outcomes in terms of ecosystem services, performance indicators, etc., and concerning the quality of this outcome.

Addressing trade-offs between forest ecosystem services with increasing complexity

Addressing more stakeholders questions concerning forest functions or services is often realized by integrating several models in one simulation tool. Although some forest management questions at short-term and regional scales can probably be addressed with existing empirical models alone, any long-term question involving global change and/or adaptive management options need necessarily to be addressed by process-based models with an ecophysiological backbone.

Although many of the discussed process-based models are very complex, they generally rely on mono-specific even-aged forests. A major challenge is to extend these models to mixed and uneven-aged forests within different ecosystems. Including complex population dynamics (such as species interactions and autogenic disturbances) into ecophysiological models could rely on the huge experience with forest gap models, which have become increasingly process-based (*e.g.* Seidl *et al.,* 2005).

Also natural hazard risk models need to be improved and integrated into process-based models if any projection of future forest goods and services is to be credible under changing climatic conditions. Challenges remain with the modelling of (1) effects of extreme climatic events, (2) the probability of damage by storms or fire occurrence under these circumstances, or by biotic risk agents such as bark beetles and diseases, and (3) the amount of damage and its influence on population dynamics. Furthermore, even though genetic diversity might have an important influence on species» adaptive potential and ecosystem resilience to climatic change, most models do not consider this aspect (but see Kramer *et al.,* 2008).

In the past decade a range of initiatives has been taken to develop standards of principles, critera and indicators (P,C&I) of sustainable forest management (SFM) (Holvoet & Muys, 2003), both for the (inter)national policy level (MCPFE, 1998; MCPFE, 2002) and for the forest management unit level (*e.g.* FSC and PEFC). C&I have become a very popular forest management evaluation tool. Several studies have dealt with the identification and use of indicators for SFM at the operational scale (Popp *et al.*, 2001; Wintle and Lindenmayer, 2008). But there is also an increasing demand to predict indicators for the evaluation of the performance of forests under different management scenarios. Available forest simulators provide a large array of outputs, ranging from growing stock and yield related variables to quantification of important ecosystem services, such as carbon sequestration in biomass and soil, water recharge, etc. (García Quijano *et al.,* 2005; Mol Dijkstra *et al.,* 2009; Gilliams *et al.,* 2005) but are not capable of generating the whole indicator set required by SFM standards. Nevertheless every model is able to generate at least a few indicators covering one or more sustainability principles (*e.g.* Pennanen *et al.,* 2007, and Hummel *et al.,* 2006, for the forest area and condition; Chertov *et al.,* 2007, and Merganicova *et al.,* 2005, for carbon and nitrogen cycles and water relations; Pretzsch *et al.,* 2002, for production function; Elemans *et al.,* 2007, and Kint *et al.,* 2009, for ecological function; Van Deurzen *et al.,* 2007, for protection function; García Quijano *et al.,* 2005, for socio-economic function).

It will be necessary to shape simulators better towards the useful output for decision makers, which creates challenges beyond participation. Simulations need to capture crucial system elements and their interactions. This means that current trends of calculating «end of pipe» indicators of SFM may be a too simplistic approach and sometimes even misleading. The demands of SFM call for model integration, considering feedback and feedforward relations between system elements and related indicators (*e.g.* Vacik *et al.,* 2007). Independent parallel consideration of different ecosystem services and functions may miss important interdependencies and generate misleading results, if for instance, disturbances are not explicitly simulated but considered by predisposition indices (Lexer and Seidl, 2009).

Stakeholder issues

Because all management is done by people to meet goals or objectives desired by people, resource management is at its core a social activity. As such, in the development of tools to support decision making the social science component of decision making between land owners, professional forest managers and decision makers, forest dependent communities, and other stakeholders processes should be strengthened. As such, the availability of a simulator or DSS should enable analysis of a variety of options and implications that alternative management approaches have for all components of the ecological-social system.

Challenges with regard to stakeholder participation are to include stakeholders with heterogeneous backgrounds in order to utilize informal knowledge, to increase legitimacy of decisions, and to increase acceptance of decisions. Issues to tackle are: (i) eliciting and expressing stakeholder preferences; (ii) compare options with multiple issues/goals/criteria, (iii) aggregating preferences across stakeholders.

For simulators to become intensively used tools by stakeholders they need to have a low level access (*e.g.* internet application or download), a high level user interface with maximum transparency, and detailed documentation, training opportunities for stakeholders, an active user community, a technical support service and frequent updates, all obvious but often lacking conditions for generalized use.

Scaling issues

Another aspect that needs more attention is the issue of scale. Which processes need to be addressed at which scale, as ecosystem processes and characteristics emerge when changing scale? In Europe, the forest resource is spread over 36 or more countries, each with its own national forest inventory, national research institutes, and culture of forest management. Upscaling higher than the national level is thus especially difficult. Several countries have research groups either working with plant physiological or empirical models. However, upscaling to the strategic level of Europe has been rare. One can distinguish the larger scale process based approaches as from Hughes *et al.* (2006) and Churkina *et al.* (2003) on the one hand, and the empirical data based approaches with the EFISCEN model (Nabuurs *et al.,* 2006; Schelhaas *et al.,* 2007) on the other. The first group runs on physiological processes, and its resolution depends on the resolution of climate data. For every grid cell, the process is run resulting in a climate sensitive forest growth response. Its level of realism is not always great as these simulations seldom take into account forest management. The second group is based on forest inventory data, and its resolution depends on the resolution at which data are obtained. This approach has a higher degree of realism, but has set backs as well since the forest inventories are not harmonised across Europe, uncertainty levels are often not known, data are often more than 10 years old, and the relation to climate changes is minimal. Now with increasing international processes and agreements concerning forest vitality, sustainable forest management, climate change mitigation and adaptation, harmonised upscaling methods are needed, that can still be detailed enough to deal with local management, and *e.g.* local climate and tree species distributions. The first attempts are going on with *e.g.* harmonisation of national forest inventories under the ENFIN COST Action, and with harmonised NFI plot level databases being set up.

Need for accepted and realistic model validation and verification methods

Another challenge for simulators is to create output credible to stakeholders. This can only be achieved by providing ways of verification, preferably with empirical data.

Simulators can only be as good as the models they include. If the simulation results are aimed to serve as decision support, we should be able to provide information about the reliability/uncertainty related to simulation results. If simulation models are to aid on the assessment of sustainability, their capacity to accurately calculate and give output on the state of the forest must be proved in the long term and with data sets that compile punctual forest state and possible climate change influence, giving process based models potentially a higher relevance than conventional models.

As long as simulators are composed of individually fitted empirical models, the validation process (Kozak and Kozak, 2003; Soares *et al.,* 1995) is easily linked to the calibration process by calculating measures of predictive performance on an independent validation dataset, or by cross-validation procedures such as repeated random subsampling or k-fold validation (Stone, 1974; Maggini *et al.*, 2006).

In complex process-based or hybrid simulators the evaluation of the causal chains in the combined submodels is not easy. In these cases, apart from the individual validation of submodels during the calibration process as described, also a coordinated verification of the combined simulator output is needed. However, no clear procedures for such a verification process have been formulated and agreed on yet. We need to develop and apply such standardised validation procedures, to increase the simulator's credibility in a decision process and to be able to compare simulator predictive performances. Such a procedure should at least encompass a phase of uncertainty analysis, a phase of error estimation and a final reporting phase.

The first phase of uncertainty analysis is meant to distinguish and minimise all components of output uncertainty (*i.e.* uncertainty linked to input data, to model formulation and to model calibration). Typically a sensitivity analysis can be performed to study the output response surface to different uncertainty intervals for input variables and model parameters or to different model formulations, in order to focus the uncertainty reduction on those model components with highest potential gain. Different methods are available ranging from one-at-a-time sensitivity analysis to comprehensive Monte Carlo analysis (Saltelli *et al.*, 2000).

Output uncertainty reduction is however no guarantee —and maybe even no requirement— for simulator validity. Where the uncertainty analysis can help to understand the simulator's application range, the trueness of a simulation output is strictly linked to the error estimation in relation to available data. In this phase, more efficient use should be made of the ever increasing availability of multisource long-term forest monitoring databases integrating data from field, eddy towers, laser scanning, satellite imagery, maps, etc. However, many aspects of predictive process-based models can only be validated in a qualitative way, including the long-term projections under changing environmental conditions, since data for these situations are missing per definition. Here only available ecological insight and expert knowledge can be used to verify simulators and ascertain their credibility (Rykiel, 1996).

The final reporting phase should not only focus on each of the previous two phases, but also document the range of the simulator applicability in terms of model concepts and assumptions, ecosystems, regions, time frame and data requirements.

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