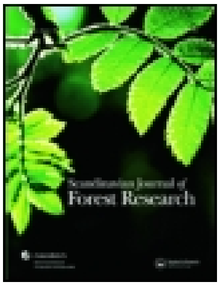

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Past, current and future drivers for the development of decision support systems in forest management

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REVIEW ARTICLE

Past, current and future drivers for the development of decision support systems in forest management

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The potential for development in decision support for forest management is set by decision theory, available technology and methods. Demands for decision support are emerging from contemporary challenges and problems of forest management which act as stimuli for the science community. Objectives and approaches in forest management as well as technologies have been changing throughout history. Accordingly, the demand for tools to support planning and decision-making has evolved. In this contribution, the authors review the historic development of decision support systems (DSS) for forest management and discuss past, current and future drivers. Based on evidence from scientific literature, case studies in the frame of the Forest Management Decision Support Systems (FORSYS) action, as well as experiences of the authors some hypotheses about the future of DSS are drawn. It is shown that in the past, the drivers evolving from forest management as well as decision support technologies have influenced the way of how models and methods have been applied as well as how DSS architectures have been designed. It is concluded that in the future, the challenges for DSS development will increase, as the complexity of decision-making processes and the related models will compete with the user demands which ask for simplicity.

Keywords: forest management; decision support; technology; forest models; multi-criteria evaluation; optimisation; GIS

1. Introduction

1.1. General scope

In the 1960s, researchers began systematically studying the use of computerized quantitative models to support and improve decision-making and planning (Raymond 1966; Turban 1967; Urban 1967). Around 1970, first articles on management decision systems, strategic planning systems and decision support systems (DSS) in general were published in business journals. Within this domain, business administration and managerial decision-making have been initial major areas of DSS development and application (Sprague & Watson 1979; Arnott & Pervan 2008).

Beginning in the early 1980s, DSS also attracted interest within the forestry domain and since then DSS have been increasingly developed in forest sciences. In one of the earliest reviews of DSS development and application in natural resource management, Davis and Clark (1989) cataloged about 100 DSS. Subsequent reviews (Schuster et al. 1993; Mowrer et al. 1997) have also covered attempts to provide computer-based DSS and tools specifically for forest management. It became evident, that decision support for natural resource management has specific requirements which are related to the dynamic and complex characteristics of natural systems and the need to take into account the socioeconomic environment and the related emerging decision-making processes. Stimulated from international policy processes forests and forest management attracted substantial interest of the general public which increased the need for methods and tools to support science-based decision-making and fostered the development of DSS. In parallel, the scientific achievements and experiences gained in decision sciences, ecosystem modeling as well as in information technology have influenced the process of DSS development and their application.

First attempts to provide a science-based decision support framework based on user needs, decision science principles and state-of-the-art technology like interoperability, modularity and transferability of software components can be found in the strategy for the development and application of DSSs for natural resources and the environment (IGDSNRE 1998). The recent calls within research funding frameworks such as the Framework Programs of the European Union (EU) (http://cordis.europa.eu/fp7/) provide evidence that current expectation of policy and administrative decision makers is that science provides ready-to-use DSS for emerging decision problem domains.

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While from the perspective of management and decision sciences, progress in DSS development, including formal conceptual frameworks and cumulative tradition, was analyzed by, among others, Eom (1996), Pervan (1998), Arnott et al. (2005), Martinsons and Davison (2007) and Arnott and Pervan (2008), no such assessment exists for the specific field of forest resource management. Only recently, Johnson et al. (2007) evaluated the capabilities of available DSS to support conservation management of forests in the context of the policy framework of the Montreal process. Reynolds et al. (2008) and Reynolds et al. (2005) provided general overviews on DSS development in forestry and reviewed selected DSS applications in detail. Reynolds (2005) evaluated three forestry DSS originating in the US in detail and used, inter alia, the potential to support phases of an adaptive management process as evaluation criteria.

Extending existing reviews and building on experiences in business domains, this paper sets out to review the development and application of DSS in forest management. In particular, this paper aims to:

(a) review DSS development in forestry from a historical perspective,
(b) identify drivers for DSS development and application in forest management,
(c) and provide an outlook on future needs and trends.

The paper is based on a review of the literature, a quantitative Scopus search, the large repository of DSS cases gathered in the recent EU funded network of experts (COST action FP0403 Forest Management Decision Support Systems (FORSYS), www.forestdss.org) and the extensive personal experience of the authors with DSS development and application in forest management. It is structured as follows: based on an introduction to decision processes in forest management, an overview about the drivers in DSS development in the past is given, justified with evidence from the scientific literature. The review ends with an outlook on future prospects for DSS development in forest sciences.

1.2. Defining DSSs

Decision-making can be supported in many ways. However, the distinction between decision support tools and DSSs is that tools can include anything from a simple look-up table to a simulation model or even a flow chart on paper.

In defining DSS functional as well as technical approaches have been suggested. Drawing on various definitions that have been suggested (e.g. Scott-Morton 1971; Keen & Scott-Morton 1978; Bonczek et al. 1981; Sprague & Carlson 1982) DSS are seen as particularly useful for unstructured, ill- and semi-structured problems. Ill- and semi-structured problems typically deal with situations where, human judgment is vital for problem solving and limitations in human information processing may impede the decision-making process (Rauscher 1999; Martinsons & Davison 2007). Accordingly, Mc Nurlin and Sprague (2004) define DSS as "computer-based systems that help decision makers confront ill-structured problems through direct interaction with data and analysis models." According to Watson and Sprague (1993), a DSS includes three major components: a dialog subsystem, a database subsystem and a model base subsystem. The components of this model-driven definition can be related to the trilogy of interface subsystem, knowledge subsystem and problem processing subsystem as proposed by Holsapple and Whinston (1996). The three-component core architecture (Watson & Sprague 1993; Holsapple & Whinston 1996) is capable of managing data, fitting data to models and providing methods to reach decisions. More pragmatic approaches attempt to categorize the huge number of different DSS developed according to the "degree of action implication of DSS outputs" (Alter 1980); that is, the degree to which the DSS's output could directly determine the decision. Recently, Power (2007) organized DSS into five broad DSS categories including communications-driven, data-driven, document-driven, knowledge-driven and model-driven DSSs.

In accordance with Fischer et al. (1996), Leung (1997) and Rauscher (1999) in the context of this paper, we use a combined functional and technical approach and define DSSs as computer-based tools which provide support to solve ill-structured decision problems by integrating database management systems (DBMS) with analytical and operational research models, graphic display, tabular reporting capabilities and the expert knowledge of scientists, managers and decision makers to assist in specific decision-making activities. This definition implicitly integrates the DSS categories by Power (2007).

1.3. Decision processes

DSSs do not provide ready decisions. Rather they support decision makers in making decisions. There is an entire field of decision science where the primary purpose is to analyze and understand the process of decision-making. Simon (1960) and Mintzberg et al. (1976) developed a general theory of decision analysis that has gradually evolved to represent the foundation of most, if not all, modern decision processes. The trichotomy of intelligence (identifying a problem situation calling for decisions), design (developing possible courses of action) and choice (selecting a course of action from among the available options) was considered by Simon as the "kernel" of any decision-making process re-occurring in manifold forms in different decision-making phases and sub-problems. According to Figure 1, Mintzberg et al. (1976) further decomposed these basic elements into seven core routines of recognition (1) and diagnosis (2), where problems are recognized and cause–effect relationships within a problem domain are determined, searching (3) and designing (4), the decision space to set up ready-made solutions and new possible courses of actions, screening (5), to reduce an overly large set of available options before entering evaluation and choice, where alternative courses of action are ranked through quantitative analysis (6), judgment (7) or bargaining (8). An authorization routine completes the planning sequence. In fact, Janssen (1992), as well as Klein and Methlie (1990), argue that the planning stage of any management process will generally need to be some variant of the Mintzberg et al. (1976) method. Examples from forestry which explicitly refer to the Mintzberg et al. model are Rauscher (1999), Rauscher et al. (2000), Reynolds (2005) and Lexer et al. (2005). Rauscher (1999), Oliver and Twery (1999) and Reynolds et al. (1999) laid theoretical and practical groundwork for thinking about how to apply DSSs to the emerging paradigms of forest ecosystem management with a focus on US forests. Rauscher (1999) coined the term "full-service DSS" for systems which support the entire Mintzberg et al. process.

In fact, people are making decisions with little awareness of the processes they go through to reach conclusions. Here the question arises whether DSS should follow practice or whether normative decision-making processes should be proposed and implemented within DSS. Human decision makers are as much a part of the DSS as any other component. People do not merely "run" a DSS and use its outputs. Rather, they are an integral part of a DSS, providing the system with judgment and values that are critical to and often dominate the decision-making process (Twery et al. 2000). This is well in line with Sprague and Carlson (1982) who see the strength of DSS in a focus on effectiveness rather than on efficiency of decision processes.

2. Drivers of DSS development

DSS development is not a homogeneous field and in its almost 40-year history, several subfields and development lines have emerged partly independent in parallel and partly in mutual dependence. In a technology field as diverse as DSS, chronicling history is neither neat nor linear. Different people perceive the field of DSS from various perspectives and report different accounts of what happened and what was important (cf. Silver 1991; Eom et al. 1998; McCosh & Correa-Perez 2006; Power 2007; Arnott & Pervan 2008; NCSSF 2010).

The potential for DSS development is set by theory, available technology and methods. Demand for decision support is emerging from contemporary tasks and problems of forest management which act as stimuli for the science community. In the following section, we discuss forest management issues and available technology, methods and models as potential drivers for DSS development from a historical perspective.

2.1. Forest management issues

Objectives and approaches in forest management have been changing throughout history. Accordingly, the demand for tools to support planning and decision-making has evolved. The availability of wood was a prerequisite for the expansion and development of all

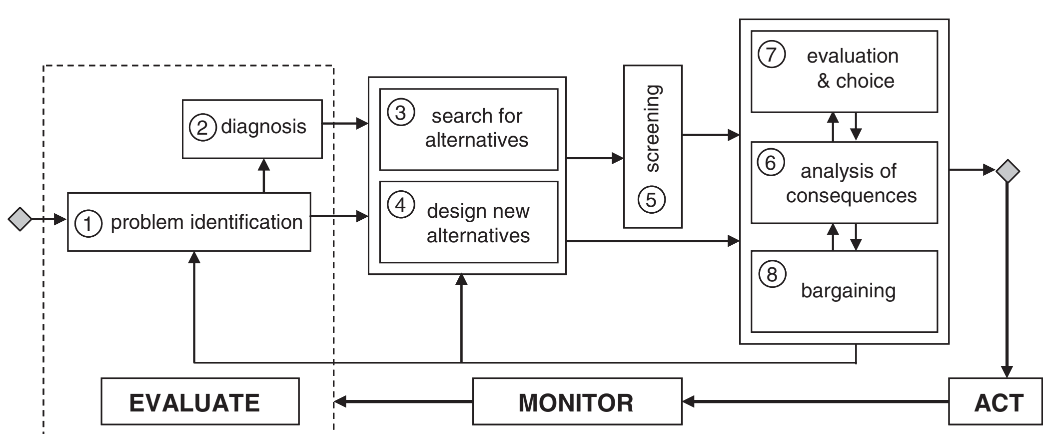

Figure 1. Planning process according to Mintzberg et al. (1976, modified). The adaptive management cycle is closed by the bold arrows feeding back from implementing actions via monitoring to diagnosis and problem identification.

the early civilisations (Perlin 1991). With growing populations, the demands on the forest resource increased and the supply of both wood and non-wood products from the forest became crucial to the development of human populations (Farrell et al. 2000). In the eighteenth and early nineteenth centuries, the forest was no longer seen as a multiple use resource for the needs of the local population but as a means of turning "wood into silver" (Ernst 1998) with a clear dominance of timber production. Due to overexploitation, regulations and guidelines were needed to secure a sustainable supply of timber. In Europe, forestry schools were established in the late eighteenth century and were the origins of classical approaches to growth and yield regulation in even-aged forests (e.g. Carlowitz 1713 in Hausrath 1982, Assmann 1970). The forest was seen as a resource to be utilized in a controlled manner (Farrell et al. 2000).

During the last century, forestry passed through a considerable change of its sociocultural acceptance and public perception. The contribution to the national income and the provision of employment especially in rural areas through timber production, were the major expectations of society in the first half of the century. In the 1960s, the complexity of societal demands increased and foresters were facing more and more challenge to integrate manifold and often conflicting demands into forest management planning (Johann 2007; Fürst et al. 2010). In the US, the term "multiple use" was codified with the Multiple Use-Sustained Yield Act of 1960 (US Department of Agriculture 1993). The practice of multiple-use management had been common in Europe much earlier. With ideas first originating in the nineteenth century (Gayer 1896), a biocentric ecosystem-based approach has developed recently in contrast to the anthropocentric management paradigms (Farrell et al. 2000). It considers the conservation of ecosystems and biodiversity as a value per se and fosters a holistic systems thinking. These general paradigms do not necessarily follow in a neat chronological order, nor did they develop synchronously in different regions of the world. Rather there have been frequent shifts forth and back between these paradigms (Pretzsch et al. 2007). Below various top-down and bottom-up processes, which emerged over the recent two decades fostering one or the other management paradigm, are briefly discussed with regard to their role as driver for DSS development (compare Table 1).

In recent decades, policies in the US have emphasized management of forests as ecosystems that provide many benefits beyond water and timber (Wilderness Act, Endangered Species Act, National Environmental Policy Act) which has led to an ecosystem management approach in more general terms. Additionally, varying ownership patterns lead to increased complexity in the decision-making process for forest management across the landscape.

In the wake of the United Nations Conference on Environment and Development (UNCED) in 1992, the concept of sustainability became an issue of public interest worldwide. In Europe, this trend has led to a series of Ministerial Conferences on the Protection of Forests in Europe (MCPFE) which in 1993 in Helsinki led to the adoption of a Pan-European framework for sustainable forest management

Table 1. Forest management issues as potential driver for DSS development.

Forest management issue	Characteristic problems	Resulting demand for decision support
Sustainable timber production	Timber volume projections, harvest scheduling; scale: stand to landscape	Growth and yield models, optimization techniques for harvesting plans
Maintaining biodiversity	Operational definition of biodiversity, scale: genes to landscape	Indicators for biodiversity, spatial analysis to characterize spatial structures, visualization of results
Ensuring multiple use/ multifunctionality	Quantitative assessment of ecosystem services (ESF); scale: stand to landscape	Quantification of ESF, multi-criteria evaluation of management alternatives
Supporting sustainable forest management (SFM)	Considering ecological, economic and socioeconomic factors at multiple temporal and spatial scales; enabling certification	Implementing sets of criteria and indicators; multi-criteria evaluation of management alternatives
Integrating climate change in forest management planning	Considering uncertainty, ecosystem response to climate change need to be assessed (incl. management and disturbance regimes); scale: stand to landscape	Predictive ecosystem models; techniques to include and communicate uncertainty and risks, analyzing large data sets
Increasing importance of public participation	Increasing importance of transparency, allowing group negotiation processes; scale: stand to landscape	Simple easy-to-understand techniques for (multi-criteria) analysis, visualization,
Implementing adaptive management	Considering uncertainty, documentation of decision processes, management plans must be described in an operational manner	Conceptual and formal integration of methods for inventory, planning, prediction and evaluation

(SFM) at politically binding level (MCPFE 2003). In North America, the Montreal process helped to identify seven criteria to establish a framework for SFM. The evaluation framework uses indicators covering issues such as conservation of biological diversity, sequestering carbon and providing social and economic benefits (US Department of Agriculture 2004).

In parallel to these policy-driven top-down approaches to foster SFM market-based certification schemes were established (e.g. Forest Stewardship Council, program for the Endorsement of Forest Certification) to promote environmentally friendly and socially responsible management of forest resources as an instrument to achieve competitive advantage.

The ecosystem approach is one of the key strategies for implementing the objectives of the Convention on Biological Diversity (CBD 1992). It's 12 principles describe essential cornerstones of a comprehensive strategy for an integrated management of natural resources, aiming at a balance between conservation and sustainable use. The term "integrated management" is used to refer to the management of land, water and living resources across all land-use sectors and policy areas.

According to the paradigms of SFM (MCPFE, Montreal and Tarapoto process), forests serve multiple interests and have to provide a multitude of products, goods and services (Millenium Ecosystem Assessment 2005). Concepts on how to manage forests in a sustainable manner to deliver the various goods, services and benefits include ecosystem management (Christensen et al. 1996; Kohm & Franklin 1997), the ecosystem approach of the CBD (Smith & Maltby 2003), and SFM (Lindenmayer et al. 2000). This has raised the demand to consider ecological, economic and socioeconomic factors at multiple temporal and spatial scales. Following the principles and guidelines of UNCED, a common framework for describing, assessing and evaluating progress in countries' efforts to practice SFM was created (Grayson & Maynard 1997).

In the 1990s, potential global climate change, triggered by the anthropogenic emission of greenhouse gases into the atmosphere, became an issue in the scientific community and in the public as well. Forests in particular, due to their longevity, are expected to be strongly affected by the rapid rate of global change projected for the twenty-first century (IPCC 2007), straining the potential of natural adaptation processes. Challenges for forest resource managers will include the need to balance the societally required portfolio of services and functions (Wang 2004; Lexer & Seidl 2009). Climate change mitigation and adaptation of forest management to a changing climate have become closely interrelated issues that require integration in forest resource planning and decision-making (Spittlehouse 2005; Ogden & Innes 2007; Lindner et al. 2010).

Due to the manifold and often conflicting interests in land-use planning, decision makers recognized the need to understand stakeholders, that is, people or groups who are affected by the decisions they take, and who have the power to influence their outcome (Freeman 1984). With the increasing need to consider stakeholder interests, the traditionally quite narrow view of neutralizing and defeating stakeholders to meet the strategic goals of the company within microeconomics (e.g. Brugha & Varvasovsky 2000) has evolved, to a much broader normative view in sustainability science which in general foresees a stakeholder process for any planning and decision-making procedure (e.g. Donaldson & Preston 1995; Stoney & Winstanley 2001). Through the growing public participation in decisions about the management of natural resources, particularly at local or watershed scales, new demands emerged for assistance in understanding natural resource and environmental issues, developing and evaluating alternatives and projecting the consequences of different courses of action (Mendoza & Prabhu 2003; Vacik, Kurttila, et al. 2013).

Recent EU policy aims to source 20% of the energy needs from renewables by 2020 (Commission of the European Communities 2005). The resulting increased demand for forest biomass sharpened the discussion on the compatibility of an increased timber use from forests, and the sustainable fulfillment of other functions of forests at various spatial scales, such as provision of drinking water, conservation of biological diversity and provision of recreation facilities (Stupak et al. 2007).

Given these increased pressures on forest ecosystems, the maintenance and enhancement of biodiversity, plays an important role within any framework of SFM in its own (Hunter 1999; Millennium Ecosystem Assessment 2005). The integration of biodiversity under the umbrella of SFM has been acknowledged as particularly important, as it is increasingly clear, that setting aside conservation areas will not be sufficient to preserve the diversity level required to maintain the "evolutionary potential" of tree populations and forest ecosystems (e.g. Noss & Cooperrider 1994; Wintle & Lindenmayr 2008).

Given the huge uncertainties regarding future environmental conditions as well as societal demands, adaptive management has recently been viewed as a very promising and intuitively useful conceptual strategic framework for defining ecosystem management (Kohm & Franklin 1997; Rauscher 1999; Rauscher et al. 2007; Khadka & Vacik 2008). The need for climate-change adaptation has recently evoked additional interest in adaptive management approaches. Adaptive management is a continuing cycle of four activities: planning, implementation, monitoring and evaluation (Walters & Holling 1990; Bormann et al. 1993). Planning focuses on deciding what to do. Implementation is concerned with deciding how to do it and then doing it. Monitoring and evaluation are the activities of analyzing whether the state of the managed system was moved closer to the desired goal state or not and whether the chosen management activities have been efficient. New knowledge may have become available and management goals may have changed. At each cycle, the result of the evaluation activity is fed back to the planning activity so that adaptive learning can take place (compare Figure 1). Unfortunately, this general theory of decision analysis is not specific enough to be operational, and itself requires adaptation to specific problem settings.

In forest management decisions need to be taken at various scales, from stand to regional and national. Tactical and strategic decisions as well as different decision-making environments typically require specific decision processes. DSS may be designed for a particular problem, supporting a specific decision process or just a decision-making phase or they may be general and adaptive to fit a range of decision problems and processes. Hence, the different issues emerging in forest management mentioned above stimulated the development of DSSs in general and increased the demand to integrate various techniques, models and methods in a holistic and flexible manner (Table 1).

The need for accurate projections of sustainable harvest levels led to the development of growth and yield models and stimulated the use of optimization techniques. Ensuring multifunctional forest management fostered the need for predictive ecosystem models, the development of criteria and indicator sets as well as multi-criteria analysis techniques for evaluating the tradeoffs between different management options (Table 1). The emerging needs for adapting forest management to climate change has encouraged DSS developers to include techniques for uncertainty and risk analysis, as well as making tools capable of analyzing large data-sets. However, the uptake of these new techniques and the use of models to support decision-making was largely determined by decision sciences and computer technology.

2.2. Technology, models and methods

The history of the implementation of computerized systems for decision support begins in the mid-1960s (compare Figure 2). In the early 1950s, when electronic data processing (EDP) became available, people for the first time were able to operate with a large amount of data in reasonable time. It was in the late 1950s, that many organizations began to utilize transaction processing systems or EDP systems, to automate routine clerical tasks such as payroll, inventory and billing. In the 1960s, the handling of large data-sets was supported by the development of DBMS, which allowed storing information in a database, retrieving and analyzing it. Through the combination of DBMS and Operations Research (OR) techniques, organizations were able to analyze the states of the organization's management system, at any time step through the use of management information systems (MIS). Since then MIS has become an established academic discipline in its own (e.g. Mason & Mitroff 1973; Eom 1996).

The progress in OR and artificial intelligence (AI) methods was highly influential for the creation of a class of information systems which eventually developed into DSS. Within forestry timber harvest scheduling by means of linear programing techniques was among the first OR applications (Reisinger & Davis 1987). AI approaches such as artificial neural networks (ANN; e.g. Zahedi 1993; Turban & Aronson 2004) and rule-based approaches utilizing, inter alia, concepts such as linguistic variables and approximate reasoning from fuzzy set theory (e.g. Zadeh 1973; Dubois & Prade 1996) were instrumental in developing Expert Systems (ES) which, for the first time, made it possible to mimic the decision-making ability of forest experts and professionals, and make expert knowledge accessible to non-experts. Expert knowledge was captured by a set of rules in order to facilitate more rational decisions, independently from the decision maker responsible for it (Thomson & Taylor 1990; Thomson et al. 1993; Rauscher 1995).

ES, MIS and DBMS stimulated the conceptual framework for developing DSS. The idea of using the computer to help decision makers was published as early as 1963 (Bonini 1963). Scott-Morton (1971) can be considered as one of the first, who coined the term 'DSSs' in his PhD thesis. Since then, there has been a growing amount of research in the area of DSS. These computer-based tools provided a common platform to support the process of decision-making by integrating DBMS with analytical and operational research models. In forestry, the first scientific papers appear in the early 1990s (Robak 1984; Reisinger 1985) presenting microcomputer-based DSS for planning forest operations. Interestingly, stimulated by the experience with early DSS Sprague and Carlson (1982, in Eom 1996) suggest enhancing MIS with decision models to increase their power as decision support tools.

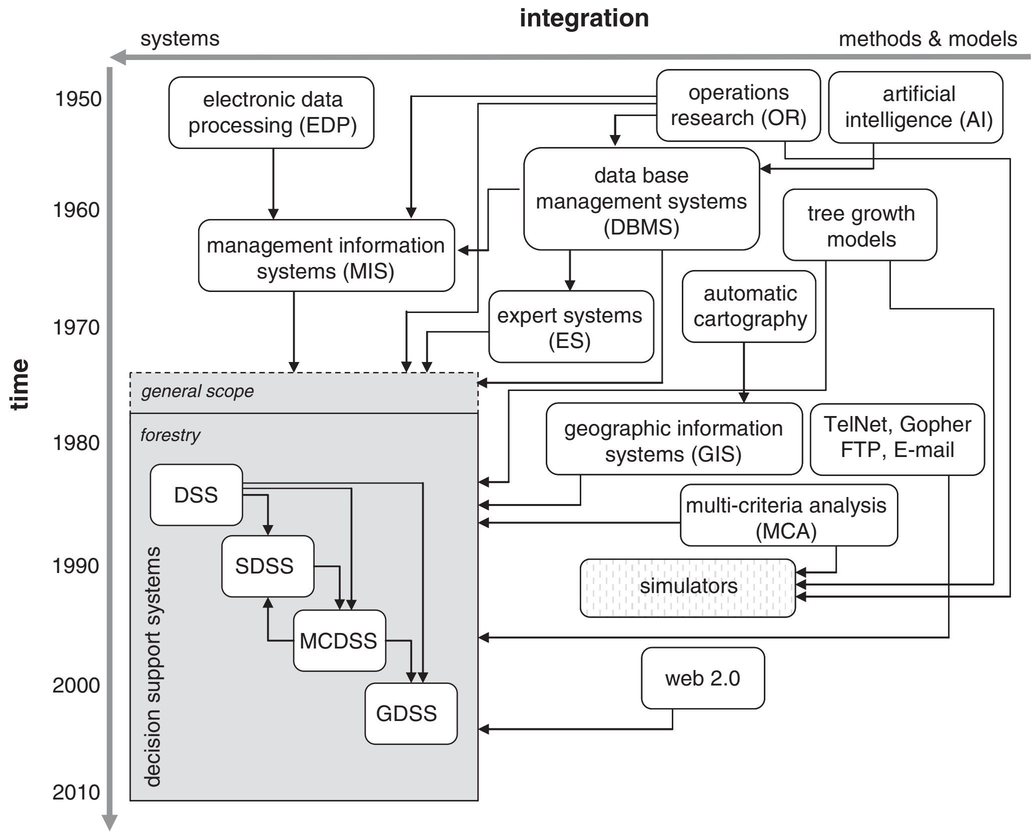

Figure 2. Historical perspective on technical and methodological developments in DSS components combined with integration level of components. Gray box symbolizes DSS in the context of this paper.

DSS consist of two major subsystems – human decision makers and computer systems. The human decision maker not only provides data input to build a database but is also expected to exercise judgment or intuition throughout the entire decision-making process. The basic components of DSS like DBMS, model-base and methods-base management and DSS generator have been described originally by Sprague (1980) and others frameworks have taken that into account (Densham 1991; Malczewski 2006). From a user's viewpoint, the DSS generator is the only component which they have to deal with via the graphical user interface (GUI). An effective user interface must therefore take several important issues into consideration, including choice of input and output devices, screen design, use of colors, data and information presentation format, and use of different interface styles. Through the conceptual and technical achievements, decision makers have been enabled to combine models and methods in a specific manner through the use of the DSS generator. The flexibility to define the operational use of DSS according to a specific decision problem was increased dramatically, by raising the complexity of the software environment as well and supporting interoperability between different tools (e.g. Common Object Request Brokerage Architecture, Blackboard Architecture). Today's DSS generators provide the user with a wide variety of interface modes: menu-based interaction mode, command language style, questions and answers, form interaction, natural language processing based dialog or GUIs. The power of the decision maker to influence and modify the decision-making process was drastically increased.

In the period since DSSs came to prominence, there has been a shift from automatic cartography to geographic information systems (GIS). The potential power of GIS goes beyond producing maps by providing mechanisms for the input, storage, analysis and use of spatial information. GIS on one hand has increased the acceptance of DSSs, as the need to integrate spatial information in decision-making became evident, on the other hand, it provided opportunities to improve analysis and has led to development and application of spatial DSSs (Covington et al. 1988; Fedra & Reitsma 1990; Densham 1991; Riedl et al. 2000). Within forestry, Naesset (1997) was among the first to address new spatial demands in strategic and operational planning for SFM. Recent developments in the field of GIS (web services, interactive dynamic maps) allowed the limitations of present GIS technologies in public participation processes to be overcome (Sturtevant et al. 2007). There was no longer a need to be an expert in Geographic Information Sciences to retrieve information from maps or perform simple queries. Web GIS applications allow an expanded framework of communication and discourse, opening opportunities for public participation across the processes of problem definition and problem resolution including multicriteria analysis as well (Goodchild 2000; Malczewski 2006).

Multi-criteria decision analysis (MCDA) techniques in the field of OR have been integrated with Spatial Decision Support Systems (SDSSs) to help decision makers model trade-offs between multiple and conflicting objectives in multipurpose management implicitly or explicitly. The overall purpose of MCDA methods is to support the evaluation and choice phase of the Mintzberg et al. (1976) decision-making model, by establishing a rank order of available decision alternatives based on facts and subjective preference information. Such methods have drawn considerable attention within forestry and numerous applications have been reported (e.g. Kangas 1992; Vacik & Lexer 2001; Drechsler 2004; Wolfslehner & Vacik 2008). Recently, Mendoza and Martins (2006) have provided a comprehensive review of methods and applications. Since the 1990s, the need to support multistakeholder decision-making settings and participatory decision processes required the adaptation of MCDA methods from single decision maker situations to group decision-making problems.

One decisive process for the development of DSS in the forestry domain was the replacement of traditional timber yield prediction tools such as yield tables by individual tree growth models. Such models originating in the USA and Canada (e.g. Newnham 1964; Botkin et al. 1972; Ek & Monserud 1974) allowed assessing effects of different silvicultural stand management programs on production and vegetation structure ex ante in a flexible manner. The Prognosis Model for Stand Development introduced by Stage (1973) was adopted by the US Forest Service as a common modeling platform to support forest management planning (Crookston & Dixon 2005). Since then it has become one of the most prominent examples of this new class of growth prediction tools. In Europe, tree growth models became slowly established in research in the 1980s (e.g. Sterba 1983; Pretzsch 1992) and it was not before the 1990s, that mature tree growth simulators became available for practical forest management decision support (e.g. Hasenauer 1995; Monserud et al. 1997; Hyninen et al. 2002; Pretzsch et al. 2002). Such models allowed assessing effects of different silvicultural measures on production and vegetation structure in a flexible manner. Over the recent decade, forest growth models have been used in combination with optimization and choice algorithms to support forest planning. While tree growth models have been extended with GUI and visualization (e.g. Pretzsch et al. 2006), they have also been linked with OR and MCDA routines to assist in solving forest planning problems. These components have been integrated technically and functionally in simulator systems (e.g. Pukkala 2003).

From the DSS perspective, there are promising examples for successful integration of growth models such as as the collection of applications of the NorthEast Decision (NED-2) DSS for ecosystem management (Twery et al. 2005), the Forest Vegetation Simulator (Dixon 2002), and the Landscape Management System (Oliver et al. 2008) as well as of MCDA methods (Decision Support Dobrova [DSD], Lexer et al. 2005; Computergestützte Entscheidungshilfe für Nutzungseingriffe im Seilgelände [CONES], Vacik et al. 2004) in "full-service" DSS supporting the complete Mintzberg decision-making process. Spatial multi-criteria decision problems may involve a set of geographically defined alternatives from which a choice of one or more alternatives is made with respect to a given set of evaluation criteria (e.g. Gilliams et al. 2005). Recent developments in information and communication technology have facilitated the integration of new data and new models to build effective multi-criteria SDSSs. For example, the Ecosystem Management Decision Support system (Reynolds 2001) for landscape-level assessments in recent updates integrates ES and MCDA for supporting the problem modeling stage in decision-making.

Within the past 15 years, the Web has grown from a group work tool (using Telnet, Gopher, FTP) for scientists, into a global information space with more than a billion users. Currently, the web is both returning to its roots as a read/write tool and also entering a new, more social and participatory phase. These trends have led to a notion that the Web is entering a "second phase," a new "improved" Web version 2.0 (Anderson 2007). This allows organizations and groups to interact independently from temporal and spatial constraints in decision-making and problem solving. Through the technical achievements and the increased interactivity offered by Web GIS, Blogs and social networks, it has become more and more possible to support active public participation even of large groups. In the context of Geographic Information Science this approach is commonly known as Public Participatory GIS in the literature (e.g. Jankowski & Nyerges 2003). These opportunities prepared the ground for advanced Group Decision Support Systems (GDSS).An initial framework for GDSS in management sciences had been introduced by Huber (1984). Since then within business administration, numerous GDSS examples have been published (cf. Pervan 1998).

3. Evidence from DSS literature

3.1. Scopus analysis

A survey in SCOPUS was conducted to document the publication activity in different journal samples and check whether the drivers mentioned in the previous chapters can be confirmed by the number of scientific publications in the respective field of the drivers. In total, 37 forest science-related journals and 123 journals from the general field of environmental sciences, decision and management sciences were screened. A search for ("decision support systems" OR "DSS" OR "decision support tool" AND "forest management" OR "forest planning") in abstract, title and keywords yielded 577 papers and reviews in all 160 journals between 1988 and 2012. In the 37 forestry-related journals, a total of 258 papers were found. The leading number of papers in these journals was published in Forest Ecology and Management (48), Computers and Electronics in Agriculture (37), the Canadian Journal of Forest Research (25), Journal of Forestry (19) and Forestry Chronicle (18). In narrowing the sample to those papers, which describe a decision support application in a more strict sense, the search was limited to the terms ("decision support systems" OR "DSS" OR "decision support tool" AND "forest management" OR "forest planning") in title and author-keywords. This closer match yielded a total of 223 papers. All further analysis is based on this smaller sample if not indicated explicitly otherwise.

Since 1995, the topic of "decision support" in general became more and more prominent, as the number of papers in all journals increased steadily. While, for instance, four papers appeared in 1996, a total of 22 were published in 2006. The first scientific papers appear in the 1990s lagging about 10 years behind the development in the general field of DSS (Robak 1984; Reisinger 1985; Covington et al. 1988). Interestingly, many of these first prominent forestry-related papers were published in the wider journal sample not related to forest science. Applications about DSSs for operational planning of forest operations (Robak 1984; Reisinger & Davis 1985), for multiresource planning (Covington et al. 1988), for planning small-scale agroforestry systems (García-de Ceca & Gebremedhin 1991) or knowledge-based systems for application of pesticides against gypsy moth (Foster et al. 1991) are some of the early papers. Some of the papers which were published before 1998 later on occurred persistently as important references for later studies in forest-related journals. For instance, the contributions by Davis and Martell (1993), Llewellyn et al. (1996), Naesset (1997) or Tecle et al. (1998) were cited at least 25 times each. The 223 selected documents are cited 1889 times by 1585 documents in Scopus. These citations are coming mostly from the same domain; 29.6% from Environmental Sciences and 27.1% from Agriculture and Biological Sciences. Only a small share of papers is cited from outside the natural science domain, which is an indication that the DSS community in forest management is not well acknowledged by the wider DSS community. Comparing the country of origin for the total of 577 papers, the majority of papers is from Europe (43.4%), followed by United States (22.1%) and Canada (13.7%). Finland (5.9%), United Kingdom (5.1%) and Germany (4.4%) comprise the highest number of papers within Europe.

Comparing the number of papers with DSS content to the overall number of published manuscripts over the last 10 years, forestry-related DSS papers represent only a small percentage. Taking a closer look at the forestry-related journals in the survey who have published most of the DSS-related papers, it seems that, beside some exceptional cases, not more than 2% of all published papers are on the DSS subject (Figure 3). In that context, the journal Computers and Electronics in Agriculture has the highest average share with 2.9% for the period 2000–2012, while in the journal Forest Ecology and Management, only 0.7% of all papers were on DSS over the previous decade. However, the total share of DSS papers with forestry content in journals covering a wider spectrum of disciplines (e.g. Environmental Modeling and Software, Ecological Modeling) is also comparably low. On the other hand, there is even a smaller share of DSS papers with forestry contents published in the classical decision support journals (e.g. DSSs, AI Applications, European Journal of Operational Research). In total over the last 10 years, not more than 40 papers with forestry contents have been published in these journals. This leads to the conclusion that the contribution of the forestry domain to the general DSS science is limited.

Figure 4 displays the number of DSS-related publications on forest management issues in all journals over the period 1997–2012. Looking at the kind of forest management issues that have been addressed in the total sample of all publications, it was found that the topics "sustainability" and "multipurpose" are addressed in more than 50% of all contributions. The most often cited references to forest management are from Sheppard and Meitner (2005) with 82 citations and by Rauscher (1999) with 75 citations. In the context of water management, it is Mysiak et al. (2005) with 84 citations. The topics "water management" "biodiversity," "climate change" and "participation" play only a minor role but have

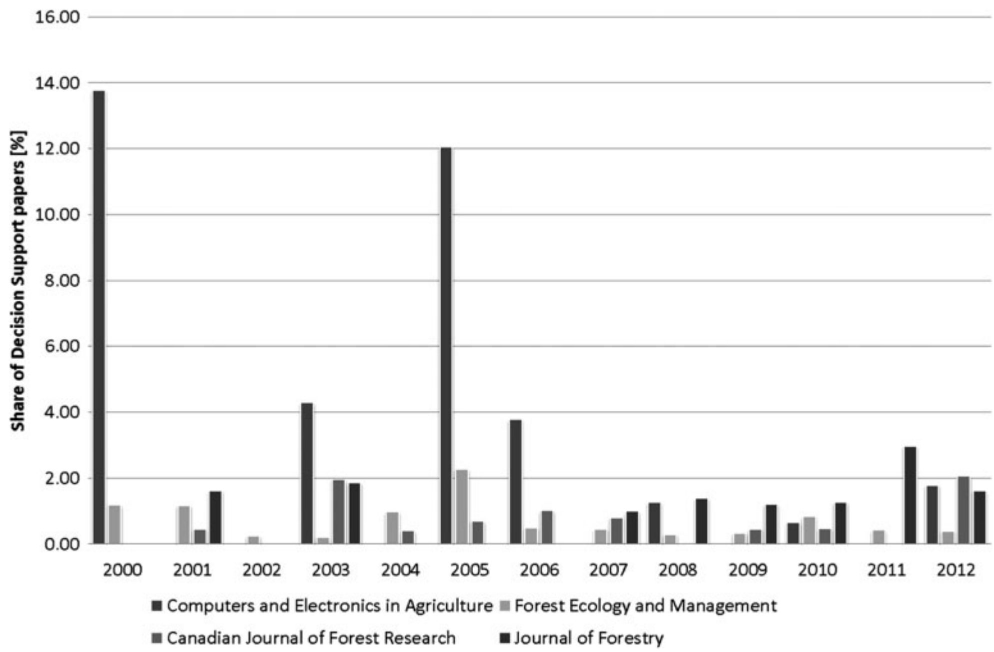

Figure 3. Share of DSS-related publications on forest management and forest planning in selected forest journals.

gained increasing importance since 2000. Interestingly, only in a minority of all papers was one topic addressed exclusively; in most cases, the problem tackled with a decision support tool was multidimensional and considering several management issues.

There are two peaks in the years 2000 and 2005 indicating the political demand of decision support in the context of SFM and maintenance of biodiversity (Figure 4). The increasing trend for the development of DSS tools and techniques may be seen as a consequence of many political documents as well as research agendas (EU research strategy 2010) which explicitly state the demand for DSS. In addition, a number of DSS-related conferences in Vienna 2003 (Rauscher et al. 2005), in Edinburgh 2005 (Reynolds et al. 2007) and Lisbon 2009 (Bettinger et al. 2011)

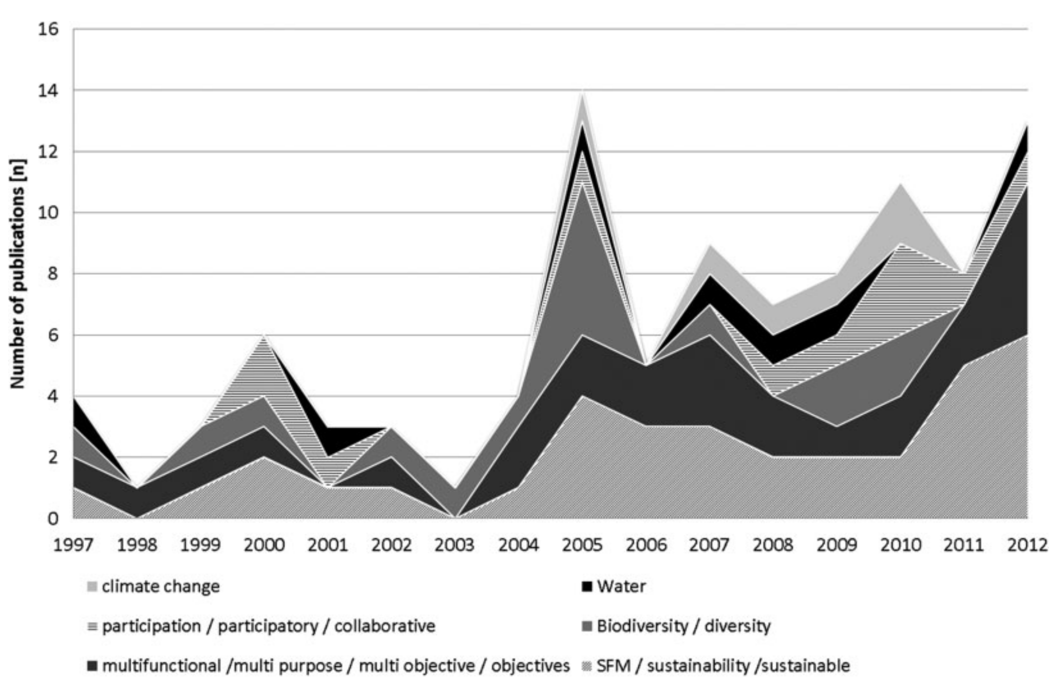

Figure 4. Number of forestry-related DSS publications according to different topics in the period 1997–2012.

have pushed the total number of scientific papers in recent years. The activities and the related final conference of the FORSYS Cost Action in Umea in 2013 will result in a similar boost of articles.

3.2. FORSYS – DSS cases

The COST Action FP0804 (www.forestdss.org) provides an overview of worldwide experiences with developing and applying forest DSSs for forest management as a solid foundation for technological innovation and collaboration between research partners. A review of existing forest DSSs as well as a description of the methods, models and techniques applied was done to provide a repository that could continuously evolve over time and serve as a reference. The repository is based on a Semantic Media Wiki (SMW) that provides the opportunity to share, integrate and re-use information on the web in particular and information systems in general (Marques et al. 2013). In Table 2, a current snapshot of the DSS projects described in the SMW is given, which can serve as an additional source of evidence for the methodological and technological drivers.

According to the different dimensions of a forest management problem, most of the 57 DSS applications that are currently listed support long-term (strategic) planning, consider multiobjectives and concentrate on market wood products in the analysis. In this context, forest models are used to a large extent to predict the consequences of different forest

Table 2. Number of DSS applications listed in the Semantic Media Wiki with respect to different criteria, one DSS may be listed at several criteria (April 2013). $N = 57$ DSS.

Criterion	Total number of DSS descriptions
Supports short-term (operational) planning	14
Supports mid-term (tactical) planning	27
Supports long-term (strategic) planning	40
Supports multi-objective planning	41
Supports single objective planning	19
Includes evaluation of market wood products	47
Includes evaluation of market non-wood products	13
Includes evaluation of market services	14
Includes evaluation of non-market services	25
Includes predictive forest models	47
Includes optimization techniques	27
Includes MCDM methods	48
Allows spatial analysis with a GIS	27
Includes a database	32

management options. MCDM are more often used than optimization techniques to choose among alternatives. Almost half of all DSS cases use a GIS to support spatial analysis.

On average, each DSS is characterized by at least 7 of the 14 criteria, indicating again that most DSS are combining several techniques or approaches.

4. Future trends

The increasing demand for an improved quantification of multiple ecosystem services will foster the elaboration of more comprehensive forest models. For instance, deadwood dynamics need to be represented in forest models to better characterize habitat quality. Additionally, the growing use and production of non-wood forest products will ask for models which are better suited for estimating their quantity and quality (Calama et al. 2011). The increasing impacts of climate change and the need to consider disturbances in general as major drivers in predicting the future conditions of forest ecosystems will require enlarging the functionality of ecosystem models. The inclusion of various disturbance modules will allow estimating the risk for forest management under different climate-change scenarios (Fontes et al. 2010). This will increase complexity of forest models with a large demand for parameterization and empirical validation before implementation in DSSs, and at the same time will increase the required expertise to actually run the models and analyze the resulting output.

Because the evaluation of adaptation and mitigation strategies will call for more sophisticated techniques (e.g. life-cycle assessment, remote sensing, real-time optimization of logistic chains), the need for the analysis of large data-sets will increase as well. DSS dealing with such decision problems might have an increased need for data mining, multiple integer programming or ANN techniques in order to analyze these data volumes.

And beyond these demands, the increasing number of regulatory policies worldwide will ask for an increased consideration of restrictions and constraints in problem structuring, as well as the use of scenario analysis in order to provide feedback for the various "what happens, if" questions. The flexibility and adaptability of DSSs with regard to the definition and quantification of indicators to be used in evaluations will therefore be an important asset.

Within the last 15 years, the Web has grown from a working tool for scientists into a global information space with more than a billion users. Currently, the web is both returning to its roots as a read/write tool and also entering a new, more social and participatory phase. As Reynolds et al. (2005) have pointed out some of the most promising lines of future DSS developments include the use of the Internet to enable easy access to public data and enhance the capability of participatory decision-making processes. The way in which decisions will be made, the time span needed to derive a decision and the number of people involved in these processes will determine these processes. This opens the opportunity for new DSS applications serving different purposes and utilizing different architectures. The following features might be seen as emerging future technological drivers for DSS development:

(1) Social networking can bring people and their knowledge together using several technologies and features: (i) shared voice and visuals (e.g. video conferencing); (ii) shared photos, music and videos; (iii) shared repositories of digital files (e.g. Google Drive, wikis). Additionally, a widespread dissemination of profiles to a trusted circle of friends or the wider public using the new media elements (e.g. blogging, instant messaging, chat) supports knowledge management in general (Vacik, Torresan, et al. 2013).
(2) The gaming industry enabled the dissemination of sociotechnical innovations (e.g. user-controlled avatars, multiuser interaction, 3D animations). Such enablers make it possible to support remote collaborative activities in virtual worlds (e.g. Facebook, MySpace). Members of distributed teams can even teleport their avatars for participating in decision-making processes anywhere.
(3) Recent developments in the field of GIS web services (e.g. Google Earth) allow at least some of the limitations in public participation processes to be overcome. Spatial analysis and studies on land allocation are no longer limited to GIS experts; the broader public is able to engage in such decision-making processes (Bhargava et al. 2007; Thomson et al. 2007).
(4) The "Internet of things" is an additional driver for future DSS developments. It will become possible for almost all devices, humans and processes to be connected to the World Wide Web with a unique identifier. This will allow DSS developers to provide services running on smartphones that communicate with other publicly available and private data. The analog-to-digital transition in technology is expected to lead to the success of forestry programs (e.g. Tang et al. 2009).

In a survey of DSS applications in a broad range of disciplines, Eom et al. (1998) found that over the period from 1988 to 1994 group DSSs, executive support systems, and knowledge-based systems applications were identified to become more prevalent in many organizations. Although management science and operational research models still played a critical role, graphics, AI and visual interactive modeling started to be part of DSS contributions. This trend is likely in forest science as well.

Considering the future methodological demands, it might be worth mentioning that soft systems methodology and qualitative modeling approaches will have an increased potential in supporting collaborative planning (Khadka et al. 2013; Vacik, Kurttila, et al. 2013). Most current DSS approaches have a weak link to problem structuring and do not include qualitative modeling techniques (Hujala et al. 2013). However, compared with the expected future changes in the field of forest management as well as information technology, the advances in the methodological field in general might not contribute to such a large extent as a future driver for DSS development.

5. Conclusions

During the last decades, forestry has passed through a considerable change of its sociocultural acceptance and public perception. Due to the often conflicting interests in land-use planning, decision makers recognized the need to involve stakeholders who are affected by the decisions they take, and who have the power to influence their outcome. Through growing public participation in decisions about the management of natural resources, new demands emerged for tools that support understanding of environmental issues, developing and evaluating alternatives and projecting the consequences of different courses of action. Given the huge uncertainties regarding to future environmental conditions as well as societal demands adaptive management has recently been viewed as a very promising conceptual framework for implementing strategic ecosystem management. The need for climate change adaptation has evoked additional interest in adaptive management approaches in decision support as well.

Hence, the different issues emerging in forest management stimulated the development of DSSs and increased the demand to integrate various techniques, models and methods in a holistic and flexible manner.

Scientific research tries to cover the different demands by improving models, introducing new methods and holistic planning approaches in DSS. The different expectations on decision support led therefore to very complex DSS development projects which cause several dilemmas. On one hand, decision analysts and scientists try to cover the complexity of the real world with sophisticated models and methods, which have the potential to overwhelm decision makers and DSS users. The more complex the demands from policy and the more diverse the expectations of various user groups become, the more complex models will be designed for use in DSS. On the other hand, users expect easy to use and smart tools similar to their day-to-day experience with software in their own working environment or Apps running on their Smartphone. In this context, the design of the GUIs of DSS and the underlying models and methods becomes challenging. The way in which reality is represented in a DSS is depending on the context of the decision support application, the perspective of the actor and the needs of the underlying decision problem. The general purpose of the tool is strongly related to the kind of knowledge transfer processes that should be addressed (Vacik, Torresan, et al. 2013). The higher the demand for meaningful cases and topics is, the more emphasis will have to be put on the way in which information is presented (cf. Harteveld et al. 2010). To lower the barrier for the general use of DSS, more importance has to be given on the consideration of the joy and play factor in the design. Highly motivated and interested decision makers are more likely to conduct a repeated analysis with a decision support tool. Therefore, the development of DSS is causing several dilemmas concerning the meaning, reality and play factor in accordance to the conceptual framework of Harteveld et al. (2010).

Whether a DSS is intended to be used at the scale of an individual private property or at regional to continental scales for policy-makers, the ease of use is a strong factor for its acceptance. Ease of use is a combination of the system's clarity of purpose, interface and support. All three factors are crucial to the adoption and success of a DSS (Reynolds et al. 2005). In the near future, the emerging possibilities of new technologies could allow the development of very smart software applications also in the forest domain (cf. Rosset et al. 2013; Tóth et al. 2013). However, there is a widening gap between such smart software applications and the growing complexity of models and tools which forest science is developing to meet the information demands of users. These discrepancies will become larger, as long as the demands rise and the DSS community attempt to meet these demands. This might lead to a decoupling of the research community working in the field of forest DSSs from the emerging field of advanced analytics and smart technologies.

The expectations of web users for easy-to-use software applications as well as smart technologies on tablets and smartphones are growing day by day. The way in which potential users perceive tools to support decision-making is changing very rapidly as the decision makers of tomorrow are growing up with different technologies. It might therefore be very challenging for the forest science community to cope with the rising technological possibilities and related expectations in DSS development, as the resources used and the number of software engineers to develop such smart applications may not be available.

There are a number of lessons that can be learned from the successes and failures of DSS development efforts to date. 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 decision support tool attempts to do everything for everyone, without a clear focus on the decision problem to be supported, 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. DSSs using "black box" techniques and advanced analytics may produce good information and are able to compute large data-sets in acceptable time, but if 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 cannot be substituted by improved visualization and reporting capabilities.

There is a need to come up with a conceptual framework which allows integrating scientific disciplines and finding common ground for developing DSS according to the end users' needs (Eom & Kim 2006). Rauscher (1999), Oliver and Twery (1999) and Reynolds et al. (1999) laid theoretical and practical groundwork, respectively, for thinking about how to apply DSSs to the emerging paradigms of forest ecosystem management with a focus on US forests. The more general a system is intended to be, the more adaptable it must be on the programming side, because the developers will need to alter, add and remove many features as they encounter new users in new situations. Thus, interoperability and modularity can be an important feature in the design of a system. On the other hand, modularity and adaptability increase complexity, so systems designed for limited uses can be developed much faster and will be much easier to learn (Reynolds et al. 2005).

The need to focus on targeted audiences for developing successful DSS applications will force decision analysts and researchers to tailor DSSs to user needs. The increasing trend to simple applications and modularity of tools will support the design of new DSS architectures, which can be easily adapted to these demands. A general "toolbox" approach, which allows to combine various decision support tools that support different phases of the decision-making process will become more important in the future (cf. Rammer et al. 2013). Considering the constraints of limited funding for DSS development within various research, technology and development projects, a toolbox approach can be easily adapted and allows a continuous development and improvement of the existing tools over several individual project cycles.

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References

Alter SL. 1980. Decision support systems: current practice and continuing challenges. Reading (MA): Addison-Wesley.

Anderson P. 2007. What is web 2.0?: ideas, technologies and implications for education. Volume 1, No. 1. Bristol: JISC.

Arnott D, Pervan G. 2008. Eight key issues for the decision support systems discipline. Dec Supp Sys. 44:657–672.

Arnott D, Pervan G, Dodson A. 2005. A descriptive analysis of decision support systems research from 1990 to 2003. Aust J Inform Syst. 12:178–191.

Assmann E. 1970. The principles of forest yield study. Oxford: Pergamon Press, 506. (Translated from the original German Waldertragskunde 1961).

Bettinger P, Cieszewski CJ, Falcao A. 2011. Perspectives on new developments of decision support systems for sustainable forest management. Math Comput For Nat Res Sci. 3:15–17.

Bhargava HK, Power DJ, Sun D. 2007. Progress in web-based decision support technologies. Dec Supp Syst. 43:1083–1095.

Bonczek RH, Holsapple CW, Whinston AB. 1981. A generalized decision support system using predicate calculus and network data base management. Oper Res. 29:263–281.

Bonini CP. 1963. Simulation of information and decision systems in the firm. Prentice Hall: Englewood Cliffs.

Bormann BT, Brooks MH, Ford ED, Kiester AR, Oliver CD, Weig JF. 1993. A framework for sustainable ecosystem management. USDA Forest Service Gen. Tech. Rep. PNW-331, p. 61.

Botkin DB, Janak JF, Wallis JR. 1972. Some ecological consequences of a computer model of forest growth. J Ecol. 60:849–872.

Brugha R, Varvasovszky Z. 2000. Stakeholder analysis: a review. Health Policy Plann. 15:239–246.

Calama R, Mutke S, Tomé J, Gordo J, Montero G, Tomé M. 2011. Modelling spatial and temporal variability in a zero-inflated variable: the case of stone pine (*Pinus pinea* L.) cone production. Ecol Model. 222:606–618.

CBD. 1992. Convention on biological diversity, United Nations. Nairobi: United Nations Environment Programme.

Christensen NL, Bartuska AM, Brown JH, Carpenter S, D'antonio C, Francis R, Franklin JF, MacMahon JA, Noss RF, Parsons et al. 1996. The report of the ecological society of America committee on the scientific basis for ecosystem management. Ecol. Appl. 6:665–691.

Commission of the European Communities. 2005. Biomass action plan. SEC (2005) 1573; 47.

Covington WW, Wood DB, Young DL, Dykstra DP, Garret LD. 1988. TEAMS: a decision support system for multi-resource management. J For. 86:25–33.

Crookston NL, Dixon GE. 2005. The forest vegetation simulator: a review of its structure, content, and applications. Comp Electron Agri. 49:60–80.

Davis JR, Clark JL. 1989. A selective bibliography of expert systems in natural resource management. AI Appl. 3: 1–18.

Davis RG, Martell DL. 1993. A decision support system that links short-term silvicultural operating plans with long-term forest-level strategic plans. Canad J For Res. 23:1078–1095.

Densham PJ. 1991. Spatial decision support systems. In: Maguire D, Goodchild M, Rhind D, editors. Geographical information systems: principles and applications. Volume 1. New York: John Wiley; p. 403–412.

Dixon GE. 2002. Essential FVS: a user's guide to the forest vegetation simulator. Internal Rep. Fort Collins (CO): US Department of Agriculture, Forest Service, Forest Management Service Center; p. 193.

Donaldson T, Preston LE. 1995. The stakeholder theory of the corporation: concepts, evidence, and implications. Acad Manage Rev. 20:65–91.

Drechsler M. 2004. Model-based conservation decision aiding in the presence of goal conflicts and uncertainty. Biodivers Conserv. 13:141–164.

Dubois D, Prade H. 1996. What are fuzzy rules and how to use them. Fuzzy Sets Sys. 84:169–185.

Ek AR, Monserud RA. 1974. FOREST: a computer model for simulating the growth and reproduction of mixed species stands. University of Wisconsin, College of Agriculture and Life Sciences, Res Rep R. 2635:90.

Eom SB. 1996. Mapping the intellectual structure of research in decision support systems through author cocitation analysis (1971–1993). Dec Supp Syst. 16: 315–338.

Eom SB, Kim E. 2006. A survey of decision support system applications (1995–2001). J Oper Res Soc. 57:1264–1278.

Eom SB, Lee SM, Kim EB, Somarajan C. 1998. A survey of decision support system applications (1988–1994). J Oper Res Soc. 49:109–120.

Ernst C. 1998. An ecological revolution? The Schlagwaldwirtschaft in western Germany in the 18th and 19th centuries. In: Watkins C, editor. European woods and forests. Wallingford CAB International; p. 83–92.

Farrell EP, Führer E, Ryan D, Andersson F, Hüttl R, Piussi P. 2000. European forest ecosystems: building the future on the legacy of the past. For Ecol Manage. 132:5–20.

Fedra K, Reitsma RF. 1990. Decision support and geographical information systems. In: Scholten HJ, Stillwell JCH, editors. Geographical information systems for

urban and regional planning, Dordrecht: Kluwer Academic Publishers; p. 177–190.
Fischer MM, Scholten HJ, Unwin D. 1996. Geographic information systems, spatial data analysis and spatial modelling. In: Fischer MM, Scholten HJ, Unwin D, editors. Spatial analytical perspectives on GIS, GISDATA Series No. 4. London: Taylor & Francis; p. 3–19.
Fontes L, Bontemps JD, Bugmann H, Van Oijen M, Gracia C, Kramer K, Lindner M, Rötzer TJ, Skovsgaard P. 2010. Models for supporting forest management in a changing environment. For Syst. 19:8–29.
Foster MA, Saunders MC, Mierzejewski K, Twardus D. 1991. Development and validation of GypsEX: a knowledge-based system for aerial application of pesticides against gypsy moth. Comput Electron Agri. 5:327–345.
Fürst C, Lorz C, Vacik H, Potočić N, Makeschin F. 2010. How to support forest management in a world of change: results of some regional studies. J Environ Manage. 46:941–952.
Freeman RE. 1984. Strategic management: a stakeholder approach. Volume 1. Boston: Pitman, ISBN 0273019139; 276.
García-de Ceca JL, Gebremedhin KG. 1991. A decision support system for planning agroforestry systems. For Ecol Manage. 45:199–206.
Gayer K. 1896. Der gemischte Wald, seine Begründung und Pflege, insbesondere durch Horst- und Gruppenwirtschaft [The mixed forest, establishment and tending, with a special focus on group and femelsystem]. Berlin. German.
Gilliams S, Raymaekers D, Muys B, Orshoven JV. 2005. Comparing multiple criteria decision methods to extend a geographical information system on afforestation. Comput Electron Agri. 49:142–158.
Goodchild MF. 2000. The current status of GIS and spatial analysis, Part 1 spatial analysis and GIS practitioners. J Geograph Syst. 2:5–10.
Grayson A, Maynard W. 1997. The world's forests – Rio +5: international initiatives towards sustainable management. Oxford: Commonwealth Forestry Association.
Harteveld C, Guimaraes R, Mayer IS, Bidarra R. 2010. Balancing play, meaning and reality: the design philosophy of LEVEE PATROLLER. Simul Gaming. 41:316–340.
Hasenauer H. 1995. MOSES – Ein Einzelbaumwachstumssimulator zur Modellierung von Wachstumsreaktionen [MOSES – a single tree growth simulator for modeling growth response]. AFZ. 50:216–218.
Hausrath H. 1982. Die Geschichte des deutschen Waldbaus. Von seinen Anfängen bis 1850 [The history of German Silviculture. Its early begin until 1850]. Hochschulverlag, Freiburg/Brg; p. 416. German.
Holsapple CW, Whinston AB. 1996. Decision support systems: a knowledge-based approach. St. Paul (MN): West Publishing.
Huber GP. 1984. Issues in the design of group decision support sytems. MIS Quart. 8:195–204.
Hunter ML, editor. 1999. Maintaining biodiversity in forest ecosystems. Cambridge: Cambridge University Press.
Hujala T, Khadka C, Wolfslehner B, Vacik H. 2013. Supporting problem structuring with computer-based tools in participatory forest planning. For Syst. 2:1–13.
Hyninen J, Ojansuu R, Hökkaä H, Salminen H, Siipilehto J, Haapala P. 2002. Models for predicting stand development in MELA system. Finnish Forest Research Institute, Research Papers 835; p. 116.
IGDSNRE. 1998. A strategy for the development and application of decision support systems for natural resources and the environment. Interagency Group on Decision Support for Natural Resources and the Environment. Available from: http://ncseonline.org/NCSSF/DSS/Documents/docs/IGDSNRE_1998_DSS_NRM_Strategy.doc
IPCC. 2007. Climate change 2007: impacts, adapation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, editors. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press; p. 7–22.
Jankowski P, Nyerges T. 2003. Toward a framework for research on geographic information-supported participatory decision making. URISA J. 15:9–15.
Janssen R. 1992. Multi objective decision support for environmental management. Dordrecht, The Netherlands: Kluwer Academic Publishers; p. 232.
Johann E. 2007. Traditional forest knowledge: challenges and opportunities. For Ecol Manage. 249:54–62.
Johnson KN, Gordon S, Duncan S, Lach D, McComb B, Reynolds K. 2007. Conserving creatures of the forest: a guide to decision making and decision models for forest biodiversity. Corvallis (OR): Oregon State University, College of Forestry.
Kangas J. 1992. Multiple-use planning of forest resources by using the analytic hierarchy process. Scand J For Res. 7:259–268.
Keen PG, Scott Morton MS. 1978. Decision support systems: an organizational perspective. Reading (MA): Addison-Wesley. ISBN 0201036673; p. 264.
Khadka C, Hujala T, Wolfslehner B, Vacik H. 2013 Problem structuring in participatory forest planning. For Policy Econ. 26:1–11.
Khadka C, Vacik H. 2008. Applying adaptive collaborative management for social learning: a case study of community forestry in Nepal. In: Maurer et al., editors. Proceedings of I-Know 08 and I-Media 08 – International Conferences on Knowledge Management and New Media Technology, Journal of Universal Computer Science (J.UCS); p. 101–108.
Klein M, Methlie LB. 1990. Expert systems: a decision support approach. Reading (MA): Addison-Wesley; p. 539.
Kohm KA, Franklin JF. 1997. Creating a forestry for the 21st century. Washington (DC): The science of ecosystem management. Island Press; p. 475.
Leung Y. 1997. Intelligent spatial decision support systems. Berlin (Germany): Springer.
Lexer MJ, Seidl R. 2009. Addressing biodiversity in a stakeholder-driven climate change vulnerability assessment of forest management. For Ecol Manage. 258: S158–S167.
Lexer MJ, Vacik H, Palmetzhofer D, Oitzinger G. 2005. A decision support tool to improve forestry extension services for small private landowners in southern Austria. Comp Electron Agri. 49:49, 81–102.
Lindenmayer DB, Margules CR, Botkin DB. 2000. Indicators of biodiversity for ecologically sustainable forest management. Conserv Biol. 14:941–950.
Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, et al. 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For Ecol Manage. 259:698–709.

Llewellyn DW, Shaffer GP, Craig NJ, Creasman L, Pashley D, Swan M, Brown C. 1996. A decision-support system for prioritizing restoration sites on the Mississippi River alluvial plain. Conserv Biol. 10:1446–1455.

Malczewski J. 2006. GIS-based multicriteria decision analysis: a survey of the literature. Inter J Geogr Inform Sci. 20:703–726.

Martinsons MG, Davison RM. 2007. Strategic decision making and support systems: comparing American, Japanese and Chinese management. Dec Supp Syst. 43:284–300.

Marques AF, Rosset C, Rasinmaki J, Vacik H, Gordon S, Nobre S, Falcao A, Weber D, Granitzer M, Eriksson O. Forthcoming 2013. Collaborative development of a semantic wiki on forest management decision support. Scand J For Res.

Mason RO, Mitroff II. 1973. A program for research on management information systems. Manage Sci. 19: 475–487.

McCosh AM, Correa-Perez BA. 2006. The optimization of what? Intelligent decision-making support systems. London: Springer; p. 463–481.

Mc Nurlin BC, Sprague RH. 2004. Information systems management in practice. 6th ed. New York: Prentice-Hall.

MCPFE. 2003. Ministerial Conference on the Protection of Forests in Europe. Improved pan-European indicators for sustainable forest management as adopted by the MCPFE Expert Level Meeting. October 7–8, 2002. Vienna (Austria): Liason Unit Vienna.

Mendoza GA, Martins H. 2006. Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. For Ecol Manage. 230:1–22.

Mendoza GA, Prabhu R. 2003. Qualitative multi-criteria approaches to assessing indicators of sustainable forest resource management. For Ecol Manage. 174:329–343.

Millenium Ecosystem Assessment. 2005. Ecosystems and wellbeing: synthesis. Washington (DC): Island.

Mintzberg H, Raisinghani D, Theoret A. 1976. The structure of unstructured decision processes. Admin Sci Quart. 21:246–275.

Monserud RA, Sterba H, Hasenauer H. 1997. The single tree stand growth simulator PROGNAUS. In: Teck R, Moueur M, Adams J, editors. Proceedings Forest Vegetation Simulator Conference; 1997 Feb 3–7; Fort Collins (CO). Gen. Tech. Rep. INT-GTR-373. USDA Forest Service. Ogden (UT): Interm Res Stn; p. 50–56.

Mowrer HT, Barber K, Campbell J, Crookston N, Dahms C, Day J, Laacke J, Marzenich J, Mighton S, Rauscher M, et al. 1997. Decision support systems for ecosystem management: an evaluation of existing systems. Gen. Tech. Rep. RM-296. Fort Collins (CO): USDA Forest Service, Rocky Mountain Forest and Range Experiment Station; p. 154.

Mysiak J, Giupponi C, Rosato P. 2005. Towards the development of a decision support system for water resource management. Environ Model Soft. 20:203–214.

Næsset E. 1997. A spatial decision support system for long-term forest management plan by means of linear programming and a geographical information system. Scand J For Res. 12:77–88.

NCSSF. 2010. Decision support systems for forest biodiversity: evaluation of current systems and future needs, NCSSF project A10, Newnham 1964. Available from: http://ncseonline.org/ncssf/dss/Documents/?CFID=8462672&CFTOKEN=24917937

Newnham RM. 1964. The development of a stand model for Douglas fir [PhD thesis]. Available from: https://circle.ubc.ca/bitstream/handle/2429/38329/UBC_1964_A1%20N58.pdf?sequence=1

Noss RF, Cooperrider A. 1994. Saving nature's legacy: protecting and restoring biodiversity. Washington (DC): Island Press.

Ogden AE, Innes JL. 2007. Perspectives of forest practitioners on climate change adaptation in the Yukon and Northwest Territories of Canada. For Chron. 83: 557–569.

Oliver CD, McCarter JB, Comnick JM, Ceder K, Nelson CS. 2008. Simulating landscape change using the landscape management system. In: Millspaugh JJ, Frank R, Thompson R, editors. Models for planning wildlife conservation in large landscapes. San Diego (CA): Academic Press; p. 339–364.

Oliver CD, Twery MJ. 1999. Decision support systems/models and analyses. Chapter 28S In: Johnson N, editor. Ecological stewardship: a common reference for ecosystem management. Oxford: Elsevier; p. 661–685.

Perlin J. 1991. A forest journey – the role of wood in the development of civilisation. Cambridge (MA): Harvard University Press; p. 445.

Pervan GP. 1998. A review of research in Group Support Systems: leaders, approaches and directions. Dec Supp Syst. 23:149–159.

Power DJ. 2007. A brief history of decision support systems. DSSResources. COM, World Wide Web. Available from: http://DSSResources.COM/history/dsshistory.html, version 4.0, March 10, 2007.

Pretzsch H. 1992. Konzeption und Konstruktion von Wuchsmodellen für Rein- und Mischbestände. Institut für Ertragskunde der Forstl. Forschungsanstalt München, Bd. 115; p. 332. German.

Pretzsch H, Biber P, Ďurský J, Gadow von K, Hasenauer H, Kändler G, Kenk G, Kublin E, Nagel J, Pukkala T, Skovsgaard JP, Sodtke R, Sterba H. 2002. Recommendations for standardized documentation and further development of forest growth simulators. ForstwCbl. 121:138–151.

Pretzsch H, Grote R, Reineking B, Rotzer Th, Seifert St. 2007. Models for forest ecosystem management: a European perspective. Ann Bot. 101:1065–1087.

Pretzsch H, Utschig H, Sodtke R. 2006. Applications of tree growth modelling in decision support for sustainable forest management. In: Hasenauer H, editor. Sustainable forest management. Berlin, Heidelberg: Springer; p. 131–150.

Pukkala T. 2003. MONTE, Calculation and planning program for even-aged and uneven-aged forests of Catalonia. User's guide. Joensuu.

Rammer W, Schauflinger C, Vacik H, Palma JHN, Garcia-Gonzalo J, Borges JG, Lexer MJ. Forthcoming 2013. A web-based ToolBox approach to support adaptive forest management under climate change. Scand J For Res.

Rauscher HM. 1995. The forest management advisory system. AI Appl. 9:60.

Rauscher HM. 1999. Ecosystem management decision support for federal forests in the United States: a review. For Ecol Manage. 114:173–197.

Rauscher HM, Lloyd FT, Loftis DL, Twery MJ. 2000. A practical decision-analysis process for forest ecosystem management. Comp Electron Agri. 27:195–226.

Rauscher HM, Reynolds KM, Vacik H, editors. 2005. Decision support systems for forest management. Special Issue. Comp Electron Agri. 2:1–3.

Rauscher HM, Schmoldt DL, Vacik H. 2007. Information and knowledge management in support of sustainable forestry: a review. In: Reynolds K, Rennolls K, Köhl M, Thomson A, Shannon M, Ray D, editors. Sustainable forestry: from monitoring and modelling to knowledge management and policy science. Cambridge: CAB International; p. 439–460.

Raymond RC. 1966. Use of the time-sharing computer in business planning and budgeting. Manage Sci. 12:363–381.

Reisinger TW. 1985. A simulation-based approach to evaluating commercial thinning decisions in loblolly pine plantations. South J Appl For. 9:211–216.

Reisinger TW, Davis CJ. 1985. A map-based decision support system for operational planning of timber harvests. Amer Soc Agri Engin.

Reisinger TW, Davis CJ. 1987. Integrating geographic information and decision support systems: a forest industry application. In GIS '87. Volume 2. Second Annual International Conference, Exhibits and Workshops on Geographic Information Systems; 1987 Oct 26–30;
San Francisco (CA); Falls Church (VA): American society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping; p. 578–584.

Reynolds KM. 2001. EMDS: using a logic framework to assess forest ecosystem sustainability. J For. 99:26–30.

Reynolds KM. 2005. Integrated decision support for sustainable forest management in the United States: Fact or fiction? Comp Electron Agri. 49:6–23.

Reynolds KM, Bjork J, Riemann-Hershey R, Schmoldt D, Payne J, King S, Moeur M, DeCola L, Twery M, Cunningham P. 1999. Chapter 28M: decision support for ecosystem management. In: Johnson N, editor. Ecological stewardship: a common reference for ecosystem management. Oxford: Elsevier.

Reynolds KM, Borges J, Vacik H, Lexer MJ. 2005 Information and communication technology in forest management and conservation. In: Hetemaki L, Nilsson S, editors. Information Technology and the Forest Sector. IUFRO World Series Volume 18. Vienna (Austria): International Union of Forest Research Organizations; p. 150–171.

Reynolds K, Rennolls K, Köhl M, Thomson A, Shannon M, Ray D, editors. 2007. Sustainable forestry: from monitoring and modelling to knowledge management and policy science. Cambridge: CAB International; 527 p.

Reynolds KM, Twery M, Lexer MJ, Vacik H, Ray D, Shao G, Borges J. 2008. Decision support systems in forest management. In: Burstein F, Holsapple CW, editors. Handbook on decision support systems 2 – Variations International Handbooks Information System 2. Berlin, Heidelberg: Springer; p. 499–533.

Riedl L, Vacik H, Kalasek R. 2000. MapModels: a new approach for spatial decision support in silvicultural decision making. Comp Electron Agri. 27:407–412.

Robak EW. 1984. Toward a microcomputer-based DSS for planning forest operations. Interfaces. 14:105–111.

Rosset C, Schütz JP, Brand R, Gollut C, Weber D, Fiedle U. 2013. Use of smartphone technologies to facilitate decision making in the forest. In: SLU, editor. Book of abstracts, FORSYS 2013. Umea, Sweden: Decision support systems for Sustainable Forest Management, April 24–26.

Schuster EG, Leefers LA, Thompson JE. 1993. A guide to computer-based analytical tools for implementing National Forest plans. General Technical Report INT-296. Ogden (UT): US Department of Agriculture, Forest Service, Intermountain Research Station.

Scott-Morton MS. 1971. Management decision systems: computer-based support for decision making. Cambridge (MA): Division of Research, Harvard University.

Sheppard SRJ, Meitner M. 2005. Using multi-criteria analysis and visualisation for sustainable forest management planning with stakeholder groups. For Ecol Manage. 207:171–187.

Silver MS. 1991. Decisional guidance for computer-based decision support. MIS Quart. 15:105–122.

Simon HA. 1960. The new science of management decision. New York: Harper and Row.

Smith RD, Maltby E. 2003. Using the ecosystem approach to implement the convention on Biological diversity: key issues and case studies. Gland, Switzerland and Cambridge: IUCN; p. 118.

Spittlehouse DL. 2005. Integrating climate change adaptation into forest management. For Chron. 81:691–695.

Sprague Jr. RH. 1980. A framework for the development of decision support systems. MIS Quart Manage Info Syst. 4:1–26.

Sprague RH, Carlson ED. 1982. Building effective decision support systems. Englewood Cliffs (NJ): Prentice-Hall. ISBN:0130862150.

Sprague RH, Watson HJ. 1979. Bit by bit: toward decision support systems. California Manage Rev. 22:60–68.

Stage AR. 1973. Prognosis model for stand development. Res. Pa INT-137. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT; p. 20.

Sterba H. 1983. Single stem models from inventory data with temporary plots. Mitt. Der Forstlichen Bundesversuchsanstalt Wien, Bd. 147:87–101.

Stoney C, Winstanley D. 2001. Stakeholding: confusion or utopia? Mapping the conceptual terrain. J Manage Stud. 38:603–626.

Stupak I, Asikainen A, Jonsel M, Karltun E, Lunnan A, Mizaraitė D, Pasanen K, Pärn H, Raulund-Rasmussen K, Röse D., et al. 2007. Sustainable utilisation of forest biomass for energy—possibilities and problems: policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. Biomass Bioenergy. 31:666–684.

Sturtevant BR, Fall A, Kneeshaw DD, Simon NPP, Papaik MJ, Berninger K, Doyon F, Morgan DG, Messier C. 2007. A toolkit modeling approach for sustainable forest management planning: achieving balance between science and local needs. Ecol Soc. 12:7.

Tang L, Shao G, Dai L. 2009. Roles of digital technology in China's sustainable forestry development. Inter J Sustain Develop World Ecol. 16:94–101.

Tecle A, Shrestha BP, Duckstein L. 1998. A multiobjective decision support system for multiresource forest management. Group Dec Negot. 7:23–40.

Thomson AJ, Rauscher HM, Schmoldt DL, Vacik H. 2007. Information and knowledge management for sustainable forestry. In: Reynolds K, Rennolls K, Köhl M, Thomson A, Shannon M, Ray D, editors. Sustainable forestry: from monitoring and modelling to knowledge management and policy science. Cambridge: CAB International; p. 374–392.

Thomson AJ, Sutherland JR, Carpenter C. 1993. Computer-assisted diagnosis using expert system-guided hypermedia. AI Appl Nat Resour Manage. 7:17–27.

Thomson AJ, Taylor CMA. 1990. An expert system for diagnosis and treatment of nutrient deficiencies of Sitka spruce in Great Britain. AI Appl Nat Resour Manage. 4:44–52.

Tóth SF, Ettl GJ, Könnyu N, Rabotyagov SS, Rogers LW, Comnick JM. Forthcoming 2013. ECOSEL: multi-objective optimization to sell forest ecosystem services. For Policy Econ.

Turban E. 1967. The use of mathematical models in plant maintenance decision making. Manage Sci. 13:342–359.

Turban E, Aronson J. 2004. Decision support systems and intelligent systems. 7th ed. Upper Saddle River (NJ): Prentice-Hall.

Twery MJ, Knopp PD, Thomasma SA, Rauscher HM, Nute DE, Potter WD, Maier F, Wang J, Dass M, Uchiyama H, et al. 2005. NED-2: a decision support system for integrated forest ecosystem management. Comp Electron Agri. 49:24–43.

Twery MJ, Rauscher HM, Bennett DJ., Thomasma SA, Stout SL, Palmer JF, Hoffman RE, DeCalesta DS, Gustafson E, Cleveland H, et al. 2000. NED-1: integrated analyses for forest stewardship decisions. Comp Electro Agri. 27:167–193.

US Department of Agriculture Forest Service. 1993. The principal laws relating to forest service activities. Washington (DC): US Government Printing Office; p. 1191. ISBN: 0-16-041927-1

US Department of Agriculture Forest Service. 2004. National report on sustainable forests – 2003. FS-766. Washington (DC): USDA Forest Service; p. 152.

Urban GL. 1967. SPRINTER: a tool for new products decision makers. Indus Manage Rev. 8:43–54.

Vacik H, Lexer MJ. 2001. Application of a spatial decision support system in managing the protection forests of Vienna for sustained yield of water resources. For Ecol Manage. 143:65–76.

Vacik H, Kurttila M, Hujala T, Khadka C, Haara A, Pykäläinen J, Honkakoski P, Wolfslehner B, Tikkanen J. 2013. Collaborative planning methods supporting programme-based planning in natural resource management, submitted for publication. J Environ Manage.

Vacik H, Lexer MJ, Palmetzhofer D, Stampfer K, Limbeck-Lilienau B. 2004. Application of the spatial decision support system CONES for regeneration planning in mountain forests. In: FERIC: A Joint Conference of IUFRO 3.06 Forest Operations under Mountainous Conditions and the 12th International Mountain Logging Conference "Improving the Bottom Line". June 13–16, 2004. Vancouver. CD ROM.

Vacik H, Torresan C, Hujala T, Khadka C, Reynolds K. 2013. The role of Knowledge Management Tools in supporting sustainable forest management. For Syst. 2:1–12.

Walters CJ, Holling CS. 1990. Large-scale management experiments and learning by doing. Ecology. 71:2060–2068.

Wang S. 2004. One hundred faces of sustainable forest management. For Policy Econ. 6:205–213.

Watson HJ, Sprague RH. 1993. The components of an architecture for DSS. In: Sprague RH, Watson HJ, editors. Decision support systems: putting theory into practice. 3rd ed. New York (NY): Prentice-Hall; p. 99–110.

Wintle BA, Lindenmayer DB. 2008. Adaptive risk management for certifiably sustainable forestry. For Ecol Manage. 256:1311–1319.

Wolfslehner B, Vacik H. 2008. Evaluating sustainable forest management strategies with the analytic network process in a pressure-state-response framework. J Environ Manage. 88:1–10.

Zadeh LA. 1973. Outline of a new approach to the analysis of complex systems and decision processes. Syst Man Cyber IEEE Trans. 1:28–44.

Zahedi F. 1993. Intelligent systems for business: expert systems with neural networks. Belmont: Wadsworth.