2008

Trends in forestry modelling

Guillermo A. Mendoza
University of Illinois at Urbana-Champaign

Jerome K. Vanclay
Southern Cross University

Publication details

Post-print of Mendoza, GA & Vanclay, JK 2008, 'Trends in forestry modelling', *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, vol. 3, no. 010.
The publisher's version of this article is available at http://dx.doi.org/10.1079/PAVSNNR20083010

Review

Trends in forestry modelling

Guillermo A. Mendoza[1,*] and Jerry Vanclay[2]

Address: [1] Department of Natural Resource and Environmental Sciences, University of Illinois, 1102 South Goodwin Avenue, Urbana, IL 61801, USA. [2] Faculty of Forestry, School of Environmental Science and Management, Southern Cross University, Military Road, Lismore, NSW 2480, Australia.

***Correspondence**: Guillermo A. Mendoza. Email: gamendoz@uiuc.edu

Received: 3 October 2007
Accepted: 21 December 2007

doi: 10.1079/PAVSNNR20083010

The electronic version of this article is the definitive one. It is located here: http://www.cababstractsplus.org/cabreviews

Abstract

Different types of models have been developed and applied to address various problems and issues in forestry. This paper reviews modelling trends in four areas, namely, forest management planning and decision-making, forest dynamics and growth projection, forest landscape and spatial models and participatory forest management models. The first type includes decision models generally structured as optimization models applied to forest planning. These models evolved from single objective to multiple objectives with spatial dimensions, including visualization. The second type includes forest dynamics models designed to examine the growth response of trees using process-based empirical or conceptual models. Demands for 'close to nature' forest management created new challenges for modellers to provide models with expanded capabilities to deal with tree growth, succession, and competition in stands with many species and wide range of tree sizes. The third type takes advantage of increased computational and graphic capabilities to model landscapes and display them as 'virtual' realities. These models combine spatial models such as geographical information systems (GIS), visualization tools and analytical models to form an integrated decision support system. The fourth type includes participatory models designed to accommodate multiple stakeholders in addressing collaborative forest management. These models are particularly adaptable to community-based forest management. Finally, the uses of models as 'learning' tools and as 'problem structuring' tools are also described.

Keywords: Forest modelling, Participatory modelling and analysis, Forest dynamics, Spatial analysis

Review Methodology: The purpose of this review is to describe recent developments and trends in forest modelling. Invariably, the scope of forest modelling is too wide to cover and adequately describe in this review. Hence, the review will confine itself to models that deal with four general areas of forest modelling, namely: forest management planning and decision-making, forest dynamics and growth projection, forest landscape and spatial analysis, and participatory and community-based forest management. Admittedly, these categories of models are not comprehensive and exhaustive, and they do not encompass all areas where models have been developed and used in forestry. Other types of forest-based models such as ecological models, hydrology and watershed management models, wood processing models, forest economic models, wildlife management models, and others are not covered. The review provides a state-of-the-art survey and review of different models and modelling techniques. Hence, the review contains not only recent developments, but also briefly describe the evolution and application of these models.

To keep abreast with up-to-date and new developments in forest modelling, particularly those dealing with the four areas above, we contacted colleagues who are working in these areas and solicited their input. We also took advantage of the different databases and conducted thorough Internet searches, which in most cases led us to relevant literature on the four topics above.

Modelling Trends in Forest Management Planning and Decision-Making

The development and use of models in forestry were methodologically driven by the principles of 'scientific management': the dominant management paradigm up until the turn of the century. This paradigm views forest management as involving the use of forests to meet certain goals and objectives of its owner, whether public or private. Consistent with the scientific management paradigm, most forest management models developed in forestry are 'formal' models. In this context, forest management planning is generally viewed as a problem of decision analysis where formal methods are developed and used to identify the best management strategy that can achieve the goals and objectives in the most efficient manner. Consistent with this management paradigm, many of the models developed adhere to the principles of optimization whereby management alternatives are identified, evaluated and selected based on how well they achieve the goals and objectives. Davies *et al.* [1] and Buongiorno and Gilles [2] describe many of these traditional models and their applications in forest management. The basic single objective optimization model was adopted extensively in many forest management applications, particularly harvest scheduling applications in the timber industry. It was also applied in land management planning such as the case of the national forests in the USA, where a large-scale model called ~~SPECTRUM~~ was used [3]. Mendoza [4] provides a more comprehensive review of recent developments in decision analysis for forest management. From this basic model, a number of refinements and improvements were made to enhance the model's capability to address problems and issues such as those described in the succeeding sections.

Recognizing the limitations of the classic single objective problem described above, a multi-objective model was developed by Mendoza and Prabhu [5, 6]. A number of overview papers on multi-objective models applied to forest management planning have been reported such as Pukkala [7] and Howard [8]. Multi-objective models enabled the incorporation of other non-timber management objectives, which may include aesthetics, ecological, economic, biophysical and environmental concerns, in the identification of best management strategies. Mendoza and Martins [9] provide a comprehensive review of multi-criteria decision analysis in natural resource management.

Prioritizing a set of alternatives, or measuring decision-makers' preferences, are other types of problems addressed by multi-objective models, including multi-criteria analysis (MCA). A number of books and review papers have also been published describing the theory and application of MCA in forestry [10, 11]. There are also extensive literature describing the application of multi-criteria decision-making (MCDM) techniques in forest management planning [5, 6, 9, 12, 13].

Of the many MCDM techniques described in the literature, perhaps the most commonly used is the Analytic Hierarchy Process originally developed by Saaty [14]. Its basic framework is to decompose a decision problem following a hierarchical structure and to pursue the evaluation process using pairwise comparison of AQ1 alternatives. Examples of applications of AHP in forestry have been reported in Schmoldt *et al.* [11]. MCDM has also been used as a framework for pursuing participatory decision-making [10].

Uncertainty is pervasive in forest management given the inherent complexity of the forest ecosystem. To accommodate this uncertainty, two general methodologies have been introduced, namely fuzzy set theory and expert systems. Recent applications of fuzzy set theory in forestry include: forest sustainability assessments [12, 15] timber harvest scheduling [16] and ecological modelling [17, 18].

Many of the models described above have well-defined procedures designed to search an optimal strategy. Typically, the models are 'closed-form'; hence, algorithms can be developed to seek for an optimal solution. A number of heuristic algorithms have been developed and applied in forestry particularly for problems that have peculiar forms. Murray and Church [19] and Weintraub *et al.* [20] offer excellent reviews of these heuristics. Examples of these heuristics are: tabu search [21], simulated annealing [22] and random search [23]. Other heuristic methods applied in forestry are: 2-opt decision choice [24], SNAP II [25] and combinatorial algorithms [20].

Often, forest management problems have spatial constraints that need to be addressed, e.g. fragmentation, off-site effects, edge effects and adjacency constraints. Hof and Bevers [26] describe different spatial optimization models that are sensitive to spatial dynamics particularly for wildlife and timber. Other models sensitive to 'locational' issues include Church *et al.* [27] and Snyder and Revelle [28]. In addition to spatial optimization, other models linked to geographical information systems (GIS) have also been developed and used in forestry. Examples of these applications include: Kyem [29], Jankowski [30] and Jankowski *et al.* [31].

Modelling Trends in Forest Dynamics and Growth Projection

Models of forest dynamics, often termed 'growth models', are usually developed for specific applications, for instance, to provide estimates of future timber harvests and stand structures in the case of forest growth and yield models, or to offer inferences about possible future species composition in the case of succession models. Thus trends follow management objectives, and can usefully be described within three overlapping threads: growth and yield models that predict timber yields in the short to medium term; succession models that predict species composition in the medium to long term; and process models that assess the consequences of climate change. While these three categories are useful for the current review, they are not universally recognized, and it is more common to classify models according to the spatial, temporal and structural detail accommodated in the simulation.

Many reviews of growth and yield models have been offered, most recently by Comas and Mateu [32], Gratzer *et al.* [33], Hasenauer [34], Johnsen *et al.* [35], Parrott and Lange [36], Peng [37], Pinjuv *et al.* [38], Rennolls *et al.* [39], Scheller and Mladenoff [40] and Sun *et al.* [41]. These models build on a long tradition of calibrating models against growth observations in existing stands. Modellers may deal with competition implicitly by including some expression of competition in a growth relationship, or explicitly by modelling potential growth and adjusting it for competition [42]. As with other aspects of models, there is no single optimal approach; the preferred method will depend on the nature of the data available and the purposes to which the model will be used. Calibration approaches offer precision for forecasts within the range of the calibration database, but limit the use of these models to established plantings represented in the available data. New demands on forest management [43] often require predictions outside this envelope of existing calibration data [44] and have led to renewed interest in hybrid models that draw on some elements of process models to offer greater generality. Most hybrid models for pure stands rely on the relationship between site index and the mean annual volume increment [45, 46], but complex stand structures may require nested models that combine the strengths of stand-level empirical models, process-based models, as well as individual-tree representation of stand dynamics [37, 39, 47].

Increasing demands for 'close to nature' forest management [48, 49] create new challenges for modellers to provide growth models with greater capabilities, better able deal with tree growth and competition in stands comprising many species and a wide range of tree sizes [50]. The challenge escalates, because models are needed to inform stand management decisions in new situations (with non-traditional species, sites and management regimes, coupled with the possibility of climate change) for which there are few, if any data, to inform model calibration. It is obvious that the quality of predictions from empirical models relies heavily on calibration data, but process models also rely on calibration [51, 52].

'Close to nature' management implies natural regeneration and requires simulation of natural succession. Recent reviews of succession models were offered by Bugmann [51, 53–55]. Criticism of early succession models was often directed at subjective parameterization and limited spatial scale, but recent examples are more rigorous and have practical application in forest management [55, 56]. However, there remains scope to further 'hybridize' both process and gap models, specifically to offer better insights into spatial structure fostered by single-tree selection harvesting, and to explore implications of climate change for forest vegetation and production [57].

Key issues that warrant further research range from concepts such as interspecific competition [50] and regeneration patterns [44, 57, 58] to evaluation of complex models (such as process models). A user of a 'simple' model can scrutinize the logic evident in the model's source code, and can exhaustively test the model, but such evaluation is generally not possible with process models. It is rare for exhaustive tests and sensitivity analyses of complex models to be completed and published, or for all model parameters to be visible to users of a model – but progress towards better understanding, and greater adoption of such models may depend on such transparency, which may be aided by automated sensitivity testing.

Modelling may also be used in explorative and confirmatory data analysis. Descriptive spatial statistics and tests help researchers to understand patterns, and modelling complements alternative analyses by offering a synthesis based on hypotheses tested from the data. Such models may be disposable, developed to offer a particular insight for a single forest without an intention to provide forecasts or scenarios.

Modelling Trends in Landscape and Spatial Analysis and Visualization

Modelling forest landscapes is one of the more recent and popular uses of forest models. Landscape models have been developed to simulate the changes of forest landscapes resulting from different disturbances, cultural practices, anthropogenic activities or natural processes such as fire. The model developed by Mladenoff [59] called LANDIS (Forest LANdscape DISturbance and Succession) is a good example of how landscapes can be modelled to spatially simulate the long-term dynamics of forest landscapes [60]. As Pennanen *et al.* [61] pointed out, 'spatially explicit simulation models of forest landscape dynamics need to incorporate processes functioning on two levels of spatial hierarchy: landscape level processes (e.g. fire, insect outbreaks, harvesting and seed dispersal) affect several patches or mediate interactions among the patches, and patch-level processes affect individual forest patches, responding to the structures created by the landscape-level processes'.

Integrating forest landscape models with GIS has been one of the more recent trends in landscape modelling. Most landscape models are coupled with GIS only loosely (i.e. GIS is used as a mapping or display tool or for a few data processing functions). Tighter integration of these two models may offer some advantages but to date, the file processing compatibility of the two models makes the tight coupling of the two models a bit cumbersome.

Visualization is another significant and widely accepted use of landscape models. Orland [62] provides an excellent overview of visualization techniques and how they are incorporated in forest planning. Bishop and Karadaglis [63, 64] described how visualization combined with GIS and modelling can be used in natural resource management. 3D visualization of forest landscapes can be used for visualizing stand succession, landscape transformation and regional planning, to benefit the decision-making process and the understanding of forest management [65]. A 3D visualization can display forest changes over time, including changes caused by management activities and disturbances, and it can also demonstrate future development based on existing data and modelling.

The potential for enhancing the capabilities of visualization beyond simple graphical representations was noted by Bishop and Karadaglis [64], where they proposed the linking of visualization approaches with modelling to more fully capture natural resource management, which typically requires prediction of environmental change over time and on large areas. They argued that in combining GIS-based environmental modelling and visualization, complex decisions could be assisted by effective presentation of the outcome of systems modelling [63, 66]. The integration of visualization systems with modelling as part of a multi-disciplinary approach to forest management planning and decision-making is now widely recognized. Tang and Bishop [66] stated that the 'trend for spatial decision-support system (DSS) development is the integration of GIS, modelling and visualization', and presented different integration methodologies including their degrees of interactivity and the levels of integration. They concluded that the 'ideal' forest management system should posses the analytical functions of GIS, prediction capabilities of models and realistic visualization of the forest. Following the idea of integrating visualization and modelling particularly in the context of DSSs, Sheppard and Meitner [67] combined visualization with a known modelling technique called multi-criteria analysis (MCA). This study perhaps exemplified the integration concept at its fullest because it combined modelling-based expert evaluations of alternative forest scenarios that were depicted using realistic 3D landscape visualization under a participatory planning and decision-making environment implemented using MCA. The study focused on combining participatory decision-making particularly in the context of sustainable forest management.

Modelling Trends in Participatory and Community-based Forest Management (CBFM)

CBFM is inherently complex because it involves many stakeholders. Necessarily, it must accommodate multiple objectives and multiple decision-makers. Consequently, Mendoza and Prabhu [68] proposed the use of participatory modelling as a flexible approach to deal with the uncertainty and complexity that typify CBFM. Moreover, Mendoza and Prabhu [68] also argued that traditional modelling approaches may not be suitable for CBFM in part because these methods follow what Checkland [69] refer to as 'hard systems thinking' (HST), which adopt a traditional 'scientific management paradigm' that exhibit highly mechanistic, reductionist, positivist and structured orientation. Generally, traditional models are formulated as the 'search for an efficient means of reaching a defined objective or goal' [69]. Another criticism relates to the failure of HST to pay proper attention to the human component of the planning problem [70]. Checkland [71] also stated that, 'instead of recognizing that decisions are made by "purposeful" and "intentional" human beings whose actions are motivated by their perceptions, the models deal with the human elements either as "manipulatable" components that could be engineered, or worse, ignored altogether'. These limitations and weaknesses of traditional models are magnified when one considers a planning and decision environment that is entirely participatory, where citizens or local communities demand active involvement at various stages in the planning and management of resources that are of interest or value to them, and from which they can derive significant benefits or services.

The brief discussion outlined above calls for a new modelling paradigm better suited for CBFM: one that is fundamentally inclusive, pluralistic and participatory, while at the same time retaining some of the 'analytical' and formal structures of traditional disciplines. Such paradigm must be flexible, robust, and able to deal with ill-defined problems, with objectives that are neither clearly stated nor accepted by all constituents, or with unknown problem components and unpredictable cause-and-effect relationships. The following paragraphs provide an overview of some soft systems modelling approaches developed for CBFM.

Cognitive mapping (CM) is a general approach originally developed by Axelrod [72] that can be used to model complex decision problems composed of dynamic entities (e.g. decision or problem elements within a CBFM), which are interrelated in complex ways, usually including feedback links. CMs are essentially structured ideas laid out purposely for understanding basic relationships and dynamics of a system. The CM is organized as a set of ideas or concepts framed as a network of nodes, arrows or links to represent the relationships of the concepts or ideas. Mendoza and Prabhu [12] describe an application of CM on a community-managed forest in Zimbabwe.

While CM provides some rigor and structured analysis beyond the enumerative listing of problem components, it is still lacking in terms of the more formal analysis demanded of most planning and decision-making models. Cognizant of the need for such analysis, Wolstenholme [73] and Coyle [74] proposed the use of *qualitative systems dynamics*. Qualitative systems dynamics was initially proposed to complement the capabilities of CM. Three models have been developed that exemplify the concept of system dynamics, namely: Co-View (Collaborative Vision Exploration Workbench), Co-Learn (Collaborative Learning) and FLORES (Forest Land Oriented Resource Envisioning System). Co-View is generally described as 'a tool to help facilitators of natural resource management and stakeholders to articulate and explore a shared vision of the future and to develop strategies to achieve it. It is aimed at strengthening the link between visioning and modelling, by making it easier to use a visioning process as the entry point for modelling, and to use the results of simulation modelling to help to generate strategies for achieving the vision' [75]. Co-Learn is a 'software package that facilitates and enables users to navigate around a range of tools and processes. It is intended to be a meta-tool, implemented as a software interface and navigation aid for a suite of computer-based learning support tools. It seeks to support adaptive and collaborative management (ACM) of natural resources by helping people to enjoy learning processes in groups. Co-Learn is intended to be used by both participants in group learning processes, as a navigation aid, and by facilitators of such processes for planning, technical support and record keeping' [76]. FLORES is intended to be a model to help explore the consequences at the landscape scale of policies and other initiatives intended to influence land use in tropical developing. It seeks to provide an accessible platform to foster interdisciplinary collaboration between researchers and resource managers, and to facilitate empirical tests of hypotheses and other propositions [77–79].

Participatory modelling and CBFM are essentially decision-making environments that involve multiple stakeholders, each demanding a say in the management of the resources. Hence, participatory modelling involves a set of individual agents, each agent making decisions based on what they perceives as a rational choice according to established rules or patterns of behaviour as decided upon by the stakeholders. In this context, understanding a stakeholder's activities and interactions requires a tool that is able to represent the individual's knowledge, beliefs and behaviour. *Multi-agent Systems* (MAS) is one such tool. As its name implies, MAS is a general approach that takes into account the presence of multiple agents (actors or stakeholders), each with their unique views, perspectives and behaviour. Each agent or actor acts or reacts (or makes decisions) as they pursue their objectives rationally, or according to their own rules and behavioural patterns. Bousquet *et al.* [80] provided an excellent review of MAS particularly its application to ecosystem management. Janssen and Ostrom [81] also described an excellent overview of different empirical methods and how they can be combined with agent-based models. This is particularly interesting in so far as linking some social theories with formal models. As Janssen and Ostrom [81] stated, the main challenges for agent-based models are, 'how to develop models that are generalizable and still applicable in specific cases, and how to scale up the processes of interaction of a few agents to interaction among many agents'. These challenges manifest themselves in participatory CBFM, which typically involve many agents representing multiple interests.

Lynam *et al.* [82] reviewed other methods that could be categorized as soft systems models. Their paper surveyed and evaluated selected participatory tools that they considered to be effective in natural resource management based on their experience working with forest communities. These models include: Bayesian Belief Network [83], Discourse-based Valuation [84], Participatory Mapping [85], the Pebble Distribution Method and Who Counts [86], Scenario planning [87] and Spidergrams [85].

Models as a Learning Tool

Most forest models are developed to mimic the behaviour of forest ecosystems. Consequently, these models are formulated to describe the 'functioning' of a system through explicit, and often 'functional' or mathematical, description of the interactions and dynamic processes of a forest ecosystem. Despite the elegance, rigour, presumed rationality, objectivity and comprehensiveness of formal models, their acceptance and eventual real-world application by practitioners is often limited. Critics of these models generally point to the strict assumptions, rigidity, rigour and narrow scope of these models as reasons for their lack of acceptance among practitioners. Moreover, lack of stakeholder participation in the design, formulation and development of these models have also been raised as major shortcomings of traditional models.

Recently, there has been a growing emphasis among modellers in developing tools that help communities or stakeholders (e.g. decision-makers) 'learn' through the use of models. Using models as 'learning' tools is really not a new concept because models have always been viewed as tools for planning and decision-support. Hence, essentially models have always been seen as a vehicle or instrument by which insights and other pertinent information can be generated and used in order to make support informed decisions (e.g. learning from model results).

Models as Problem Structuring Tools

Models have also been proposed as a tool for structuring rather than solving problems. Consequently, alternative approaches have been proposed with a range of methodologies whose basic aim is not to identify an answer or develop an objective model of reality, but to facilitate an enriched process that is transparent and participatory. Some of these methodologies include: soft systems methodology of Checkland [88], JOURNEY [89], Decision Explorer [90], Visual Interactive Sensitivity Analysis [91, 92], and MACBETH [93, 94]. Most of these approaches have been developed as DSSs under a computer-assisted, user-friendly environment. All the methods recommend an open-ended process at the start in order to generate a rich picture of the problem at hand Consistent with this open articulation of perspectives or values, Eden and Ackermann [90] proposed the concept of CM as an effective way to explore the values, issues, concerns, perspectives, goals, objectives or 'worldviews' [69] of stakeholders. Mendoza and Prabhu [68] and

Hjrotso [95] describe some of these methodologies in the context of community-managed forests.

Concluding Remarks

Forests are inherently complex. Models can be useful tools to understand the interactions and dynamic processes occurring in the forest, examine different forest management strategies and their impacts, study the development and evolution of trees and other competing vegetation, graphically visualize the responses of forests to human intervention, or observe ecological and economic interactions of the different components of a forest ecosystem.

This review describes the modelling trends in four general areas, namely, forest management planning and decision-making, forest dynamics and growth projection, forest landscape and spatial models and participatory forest management models. Models developed for these four general areas have been applied and served as decision support tools that ensure better, sound and sustainable management of the forests. Increasingly, models are becoming more integrated taking advantage of the strengths of each model making them more flexible, robust and user-friendly.

References

1. Davies L, Johnson N, Bettinger P, Howard T. Forest Management 4th ed. McGraw-Hill, New York; 2001.
2. Buongiorno J, Gilles K. Decision Methods for Forest Resource Management. Elsevier Science (USA); 2003.
3. USDA Forest Service. SPECTRUM: An Overview. Washington Office, Ecosystem Management Center; 2000: Available from: URL: http://www.fs.fed.us/institute/planning_center/files/Spectrum26_Overview.pdf
4. Mendoza GA. Recent developments in decision analysis for forest management. In: Innes JL, Hickey G, Hoen HF, editors. Forestry and Environmental Change: Socioeconomic and Political Dimensions. IUFRO Research Series. CABI Publishing, Wallingford, UK; 2005.
5. Mendoza GA, Prabhu R. Multiple criteria analysis for assessing criteria and indicators in sustainable forest management: a case study on participatory decision making in a Kalimantan forest. Environmental Management 2000;26(6):659–73.
6. Mendoza GA, Prabhu R. Multiple criteria decision making approaches to assessing Forest sustainability using criteria and indicators: a case study. Forest Ecology and Management 2000;131:107–26.
7. Pukkala T (editor). Multi-objective Forest Planning. Managing Forest Ecosystems, Volume 5, Kluwer Academic Publishers, Dordrecht, The Netherlands; 2002. p. 207.
8. Howard A. A critical look at multiple criteria decision-making techniques with reference to forestry applications. Canadian Journal of Forest Research 1991;21:1649–59.
9. Mendoza GA, Martins H. Multicriteria decision analysis in natural resource management: an overview of methods and paradigms. Forest Ecology and Management 2006;230(1–3):1–22.
10. Schmoldt DL, Peterson D. Analytical group decision making in natural resources: methodology and application. Forest Science 2000;46(1):62–75.
11. Schmoldt D, Kangas J, Mendoza G, Pesonon M. The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making. Kluwer Academic Publishers, Dordrecht, The Netherlands; 2001.
12. Mendoza GA, Prabhu R. Qualitative multi-criteria approaches to assessing indicators of sustainable forest resource management. Forest Ecology and Management 2003;174:329–43.
13. Prato T. Multiple attribute evaluation of landscape management. Journal of Environmental Planning and Management 2000;60:325–37.
14. Saaty T. The Analytic Hierarchy Process. McGraw-Hill, New York; 1980.
15. Varma VK, Ferguson I, Wild I. Decision support system for sustainable forest management. Forest Ecology and Management 2000;128:49–55.
16. Bare BB, Mendoza GA. Timber harvest scheduling in a fuzzy decision environment. Canadian Journal of Forest Research 1992;22:423–8.
17. Özesmi U, Özesmi S. A participatory approach to ecosystem conservation: fuzzy cognitive maps and stakeholder group analysis in Uluabat Lake, Turkey. Environmental Management 2003;31(4):518–31.
18. Özesmi U, Özesmi S. Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. Ecological Modelling 2004;176:43–64.
19. Murray A, Church R. Heuristic solution approaches to operational planning problems. OR Spectrum 1995;17:193–203.
20. Weintraub A, Jones G, Meacham M, Magendazo A, Magendazo A, Malchuk D. Heuristic procedures for solving mixed-integer harvest scheduling-transportation planning models. Canadian Journal of Forest Research 1995;25:1618–26.
21. Bettinger P, Sessions J, Boston K. Using tabu search to schedule timber harvests subject to spatial wildlife goals for big game. Ecological Modelling 1997;94:111–23.
22. Lockwood C, Moore T. Harvest scheduling with spatial constraints: a simulated annealing approach. Canadian Journal of Forest Research 1992;23:468–78.
23. Nelson J, Brodie D. Comparison of random search algorithm and mixed integer programming for solving area-based forest plans. Canadian Journal of Forest Research 1990;20:934–42.
24. Bettinger P, Boston K, Sessions J. Intensifying a heuristic forest harvest scheduling search procedure with 2-opt decision choice. Canadian Journal of Forest Research 1999;29:1784–92.
25. Bettinger P, Johnson N, Sessions J. Forest planning in an Oregon case study: defining the problem and attempting to meet goals with a spatial analysis technique. Environmental Management 1996;20(4):565–77.

26. Hof J, Bevers M. Direct spatial optimization in natural resource management: four linear programming examples. Annals of Operations Research 2000;95:67–81.

27. Church R, Murray A, Weintraub A. Locational issues in forest management. Location Science 1998;6:137–53.

28. Snyder S, Revelle C. Multi-objective grid packing model: an application. Location Science 1997;5(3):165–80.

29. Kyem PAK. Using GIS to support multi-objective decision-making in forest management: an experience from Ghana, West Africa. In: Pukkala T, editor. Multi-objective Forest Planning. Kluwer Academic Publisher, Dordrecht, The Netherlands; 2002.

30. Jankowski P. Integrating geographical information systems and multiple criteria decision making methods. International Journal of Geographical Information Systems 1995;9:251–73.

31. Jankowski P, Nyerges TL, Smith A, Moore TJ, Horvath E. Spatial group choice: a SDSS tool for collaborative spatial decision making. International Journal of Geographical Information Systems 1997;11:576–602.

32. Comas C, Mateu J. Modelling forest dynamics: a perspective from point process methods. Biometrical Journal 2007;49(2):176–96.

33. Gratzer G, Canham C, Dieckmann U, Fischer A, Iwasa Y, Law R, *et al.* Spatio-temporal development of forests – current trends in field methods and models. Oikos 2004;107:3–15.

34. Hasenauer H (editor). Sustainable Forest Management: Growth Models for Europe. Springer, Berlin; 2006.

35. Johnsen K, Samuelson L, Teskey R, McNulty S, Fox T. Process models as tools in forestry research and management. Forest Science 2000;47(1):2–8.

36. Parrott L, Lange H. Use of interactive forest growth simulation to characterise spatial stand structure. Forest Ecology and Management 2004;194:29–47.

37. Peng C. Growth and yield models for uneven-aged stands: past, present and future. Forest Ecology and Management 2000;132:259–79.

38. Pinjuv G, Mason EG, Watt M. Quantitative validation and comparison of a range of forest growth model types. Forest Ecology and Management 2006;236:37–46.

39. Rennolls K, Tomé M, McRoberts RE, Vanclay JK, LeMay V, Guan B, *et al.* Potential contributions of statistics and modelling to sustainable forest management: review and synthesis. In: Reynolds K, Thomson A, Shannon M, Köhl M, Ray D, Rennolls K, editors. Sustainable Forestry in Theory and Practice. CAB International, Wallingford, UK; 2007.

40. Scheller RM, Mladenoff DJ. An ecological classification of forest landscape simulation models: tools and strategies for understanding broad-scale forested ecosystems. Landscape Ecology 2007;22:491–505.

41. Sun H-G, Zhang J-G, Duan A-G, He C-Y. A review of stand basal area growth models. Forestry Studies in China 2007;9(1):85–94.

42. Thüriga E, Kaufmann E, Frisullo R, Bugmann H. Evaluation of the growth function of an empirical forest scenario model. Forest Ecology and Management 2005;204:51–66.

43. Vanclay JK. Realizing opportunities in forest growth modelling. Canadian Journal of Forest Research 2003;33(3):536–41.

44. Beetson T, Nester M, Vanclay JK. Enhancing a permanent sample plot system in natural forests. The Statistician 1992;41:525–38.

45. Almeida A, Landsberg JJ, Sands PJ. Parameterisation of 3-PG model for fast-growing *Eucalyptus grandis* plantations. Forest Ecology and Management 2004;193(1–2):179–95.

46. Skovsgaard JP, Vanclay JK. Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. Forestry 2007, doi:10.1093/forestry/cpm041 AQ2

47. Monserud RA. Evaluating forest models in a sustainable forest management context. FBMIS 2003;1:35–47.

48. Çolak AH, Rotherham ID, Çalikoglu M. Combining 'naturalness concepts' with close-to-nature silviculture. Forstwissenschaftliches Centralblatt 2003;122(6):421–31.

49. Nichols JD, Bristow M, Vanclay JK. Mixed species plantations: prospects and challenges. Forest Ecology and Management 2006;233:383–90.

50. Vanclay JK. Spatially-explicit competition indices and the analysis of mixed-species plantings with the Simile modelling environment. Forest Ecology and Management 2006;233:295–302.

51. Johnsen K, Samuelson L, Teskey R, McNulty S, Fox T. Process models as tools in forestry research and management. Forest Science 2001;47(1):2–8.

52. Miehle P, Livesley SJ, Feikema PM, Li C, Arndt SK. Assessing productivity and carbon sequestration capacity of *Eucalyptus globulus* plantations using the process model Forest-DNDC: calibration and validation. Ecological Modelling 2006;192:83–94.

53. Bugmann H. A review of forest gap models. Climatic Change 2001;51:259–305.

54. Landsberg JJ. Physiology in forest models: history and the future. FBMIS 2003;1:49–63.

55. Risch AC, Heiri C, Bugmann H. Simulating structural forest patterns with a forest gap model: a model evaluation. Ecological Modelling 2005;181:161–72.

56. Xiaodong Y, Shugart HH. FAREAST: a forest gap model to simulate dynamics and patterns of eastern Eurasian forests. Journal of Biogeography 2005;32:1641–58.

57. Reynolds JF, Bugmann H, Pitelka LF. How much physiology is needed in forest gap models for simulating long-term vegetation response to global change? Challenges, limitations, and potentials. Climatic Change 2001;51:541–57.

58. Vanclay JK. Modelling regeneration and recruitment in a tropical rainforest. Canadian Journal of Forest Research 1992;22:1235–48.

59. Mladenoff DJ. LANDIS and forest landscape models. Ecological Modelling 2004;180:7–19.

60. Mladenoff D, Baker W (editors). Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, Cambridge; 1999.

61. Pennanen J, Green D, Fortin MJ, Messier C. Spatially explicit simulation of long-term boreal forest landscape dynamics: incorporating quantitative stand attributes. Ecological Modelling 2004;180:195–209.

62. Orland B. Visualization techniques for incorporation in forest planning geographic information system. Landscape and Urban Planning 1994;30:83–97.

63. Bishop ID, Karadaglis C. Combining GIS-based environmental modeling and visualization: another window on the modeling process: In: Proceedings of 3rd International Conference/ Workshop on Integrating GIS and Environmental Modeling. Santa Fe, New Mexico; 1996.

64. Bishop ID, Karadaglis C. Linking modeling and visualization for natural resource management. Environment and Planning B: Planning and Design 1997;24:345–58.

65. Karjalainen E, Tyrvainen L. Visualization in forest landscape preference research: a finnish perspective. Landscape and Urban Planning 2002;59:13–28.

66. Tang H, Bishop ID. Integration of methodologies for interactive forest modeling and visualization systems. The Cartographic Journal 2002;39(1):27–35.

67. Sheppard SRJ, Meitner M. Using multi-criteria analysis and visualization for sustainable forest management planning with stakeholder groups. Forest Ecology and Management. In Press 2007.

AQ3

68. Mendoza GA, Prabhu R. Participatory modeling and analysis for sustainable forest management: overview of soft system dynamics models and applications. Forest Policy and Economics 2006;9:179–96.

69. Checkland PB. Systems Thinking Systems Practise. Wiley, Chichester; 1981.

70. Rosenhead J, Mingers J. Rational Analysis for a Problematic World Revisited: Problem Structuring Methods for Complexity, Uncertainty and Conflict. 2nd ed. John Wiley and Sons Ltd, England; 2001.

71. Rosenhead J (editor). Rational Analysis for a Problematic World: Structuring Methods for Complexity, Uncertainty and Conflict. John Wiley and Sons Ltd, England; 1989.

72. Axelrod RM. Structure of Decisions: The Cognitive Map of Political Elites. Princeton University Press, Princeton, NJ; 1976.

73. Wolstenholme EF. Qualitative vs. quantitative modeling: the evolving balance. Journal of Operational Research Society 1999;50:422–8.

74. Coyle G. Qualitative and quantitative modeling in system dynamics: some research questions. Systems Dynamics Review 2000;16(3):225–44.

75. Center for International Forestry Research (CIFOR). 2000: Available from: URL: http://www.cifor.cgiar.org/acm/pub/co-view.html

76. Center for International Forestry Research (CIFOR). 2002: Available from: URL: http://www.cifor.cgiar.org/acm/pub/co-learn.html

77. Vanclay JK. FLORES: for exploring land use options in forested landscapes. Agroforestry Forum 1998;9(1):47–52.

78. Vanclay JK, Sinclair F, Prabhu R. Modelling interactions amongst people and forest resources at the landscape scale. Small-Scale Forestry 2003;2(2):117–20.

79. Vanclay JK, Prabhu R, Sinclair FL. Realizing Community Futures: A Practical Guide to Harnessing Natural Resources. Earthscan, London; 2006.

80. Bousquet F, Barreteau O, d'Aquino P, Etienne M, Boissau S, Aubert S, *et al.* Multi-agent systems and role games: collective learning processes for ecosystem management. In: Janssen M, editor. Complexity and Ecosystem Management: The Theory and Practice of Multi-agent Approaches. Edward Elgar Publishers, Chettenham, UK; 2002.

81. Janssen MA, Ostrom E. Empirically based Agent-based models. Guest Editorial. Ecology and Society 2006;11(2):37. Available from: URL: http:www.ecologyandsociety.org/vol11/iss2/art37/

82. Lynam T, de Jong W, Sheil D, Kusumanto T, Evans K. A review of tools for incorporating community knowledge, preferences and values into decision making in natural resource management. Ecology and Society 2007;12(1): 2. Available from: URL: http://www.ecologyandsociety.org/vol12/iss1/art5/

83. Cain J. Planning Improvements in Natural Resources Management: Guidelines for Using Bayesian Networks to Manage Development Projects. Institute of Hydrology, Wallingford, UK; 2001.

84. Wilson MA, Howarth RB. Discourse-based valuation of ecosystem services: establishing fair outcomes through group deliberation. Ecological Economics 2002;41:431–43.

85. Lynam T, Bousquet F, Le Page C, d'Aquino P, Barreteau O, Chinembiri F, *et al.* Adapting science to adaptive managers: spidergrams, belief models, and multi-agent systems modeling. Conservation Ecology 2002;5(2):24. Available from: URL: http://www.consecol.org/vol5/iss2/art24

86. Colfer CJP. Who counts most in sustainable forest management? CIFOR Working Paper 7. Center for International Forestry Research (CIFOR), Bogor, Indonesia; 1995.

87. Wollenberg E, Edmunds D, Buck L. Center for International Forestry Research (CIFOR), Bogor, Indonesia; 2000.

88. Checkland PB. Soft systems methodology: overview. Journal of Applied System Analysis 1998;15:27–30.

89. Banxia Software LTD. 2000: Available from: URL: http://www.banxia.com

90. Eden C, Ackermann F. Making Strategy: The Journey of Strategic Management. Sage Publications, London; 1998.

91. Belton V, Stewart T. Multiple Criteria Decision Analysis: An Integrated Approach. Kluwer Academic Publishers, Norwell, MA, USA; 2001.

92. Belton V, Ackermann F, Shepherd I. Integrated support from problem structuring through to alternative evaluation using COPE and V.I.S.A. Journal of Multi-Criteria Decision Analysis 1997;6:115–30.

93. Bana e Costa CA, Ensslin L, Correa E, Vansnick JC. Decision support systems in action: integrated application in a multi-criteria decision aid process. European Journal of Operational Research 1999;113:315–35.

94. Bana e Costa CA, Vansnick JC. Applications of the MACBETH approach in the framework of an additive aggregation model. Journal of Multi-Criteria Decision Analysis 1997;6:107–14.

95. Hjrotso CN. Enhancing public participation in natural resource management using soft OR: an application of strategic option development and analysis in tactical forest planning. European Journal of Operations Research 2004;152:667–83.

Author Queries:

AQ1: Please provide expansion of AHP.
AQ2: Please update reference [46].
AQ3: Please update [67].