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Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms

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Abstract

Multi-criteria decision analysis (MCDA) is an umbrella approach that has been applied to a wide range of natural resource management situations. This paper has two purposes. First, it aims to provide a critical review of MCDA methods applied to forest and other natural resource management. The review seeks to layout the nature of the models, their inherent strengths and limitations. Models are categorized based on different classification schemes and are reviewed by describing their general characteristics, approaches, and fundamental properties. The review goes beyond traditional MCDA techniques; it describes new modelling approaches to forest management. The second purpose is to describe new MCDA paradigms aimed at addressing the inherent complexity of managing forest ecosystems, particularly with respect to multiple criteria, multi-stakeholders, and lack of information. Comments about, and critical analysis of, the limitations of traditional models are made to point out the need for, and propose a call to, a new way of thinking about MCDA as they are applied to forest and natural resource management planning. These new perspectives do not undermine the value of traditional methods; rather they point to a shift in emphasis—from methods for problem solving to methods for problem structuring.

Keywords: Multi-objective planning; Soft systems approach; Participatory modelling; Multi-stakeholder decision-making

1. Introduction

Belton and Stewart (2002) define multi-criteria decision analysis (MCDA) as, "an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter". The general definition stated above outlines three dimensions of MCDA, namely: (1) the formal approach, (2) the presence of multiple criteria, and (3) that decisions are made either by individuals or groups of individuals. Invariably these dimensions are the main reasons why MCDA has been one of the most widely applied models in forest management, because they manifest some of the major forest management issues, namely: (1) the need for a structured and rational management approach that can integrate many of the key forest management elements, (2) the multi-functional or multiple uses of the forests, and (3) the presence of multiple stakeholders and interest groups each with their own views, goals, and demands on how the forest should be managed.

Fundamentally, MCDA has inherent properties that make it appealing and practically useful. Belton and Stewart (2002) portrayed some of these properties as: (1) "it seeks to take explicit account of multiple, conflicting criteria", (2) it helps to structure the management problem, (3) it provides a model that can serve as a focus for discussion, and (4) it offers a process that leads to rational, justifiable, and explainable decisions. Moreover, MCDA also has some desirable features that make it an appropriate tool for analysing complex problems such as those typically found in natural resource management. First, it can deal with mixed sets of data, quantitative and qualitative, including expert opinions. Data pertaining to, and knowledge about, forest ecosystems are seldom complete, known with certainty or fully understood. Hence, the capability to accommodate these gaps in information and knowledge through qualitative data, expert opinions, or experiential knowledge is a distinct advantage. Second, it is conveniently structured to enable a collaborative planning and decision-making environment. This participatory

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environment accommodates the involvement and participation of multiple experts and stakeholders (Mendoza and Prabhu, 2003).

The first objective of the paper is to provide a critical review of MCDA methods applied to forest and other natural resource management. The review, while not intended to be comprehensive, seeks to layout the nature of the models, their inherent strengths, capabilities, and limitations. Models are reviewed at the general classification level describing their general characteristics, approaches, and fundamental properties.

Only MCDA methods that consider the existence of a hierarchy of criteria (multiple objectives) and alternatives are considered. Therefore, other methods that deal with multi-objective planning, particularly those that use single objective optimisation with constraints as other goals, or use penalty functions, are not included. Comprehensive reviews of these methods can be found in Pukkala (2002) and Steiguer et al. (2003).

Many of the methods reviewed fall under what may generally be described as 'hard', or those consistent with the traditional and rational scientific management approach. The review, however, goes beyond traditional MCDA techniques; it describes new advances to forest management beyond the 'hard' management science view. This paper attempts to describe new MCDA paradigms in terms of addressing the inherent complexity of managing forest ecosystems, particularly with respect to their multiple dimensions (or components), the presence of multi-stakeholders, and the inevitable lack of information.

2. Classification of MCDM methods

MCDA approaches have been classified in a number of ways. One of the first categorizations makes a distinction between multi-objective decision making (MODM) and multi-attribute decision making (MADM). The main distinction between the two groups of methods is based on the number of alternatives under evaluation. MADM methods are designed for selecting discrete alternatives while MODM are more adequate to deal with multi-objective planning problems, when a theoretically infinite number of continuous alternatives are defined by a set of constraints on a vector of decision variables (Korhonen et al., 1992; Hayashi, 2000; Belton and Stewart, 2002). A more thorough distinction between these two groups of methods was made by Malczewski (1999) based on the differences pointed by Hwang and Yoon (1981) and Zeleny (1982). These differences are systematically summarized in Table 1.

The general classification of MCDA methods adopted in this paper is the one suggested by Belton and Stewart (2002) because it reflects more directly the range of their application. They classify MCDA methods into three broad categories:

Table 1
Comparison of MODM and MADM approaches (Malczewski, 1999)

Criteria for comparison	MODM	MADM
Criteria defined by	Objectives	Attributes
Objectives defined	Explicitly	Implicitly
Attributes defined	Implicitly	Explicitly
Constraints defined	Explicitly	Implicitly
Alternatives defined	Implicitly	Explicitly
Number of alternatives	Infinite (large)	Finite (small)
Decision maker's control	Significant	Limited
Decision modelling paradigm	Process-oriented	Outcome-oriented
Relevant to	Design/search	Evaluation/choice

(1) *Value measurement models*: ''numerical scores are constructed in order to represent the degree to which one decision option may be preferred to another. Such scores are developed initially for each individual criterion, and are then synthesized in order to effect aggregation into higher level preference models'';
(2) *Goal, aspiration or reference level models*: ''desirable or satisfactory levels of achievement are established for each criterion. The process then seeks to discover options which are closest to achieving these desirable goals or aspirations'';
(3) *Outranking models*: ''alternative courses of action are compared pairwise, initially in terms of each criterion in order to identify the extent to which a preference for one over the other can be asserted. In aggregating such preference information across all relevant criteria, the model seeks to establish the strength of evidence favouring selection of one alternative over another''.

A more detailed description of the three groups can be found in Belton and Stewart (2002), who noted the following comments. In the first group, the values of alternatives reflect a preference order. These preferences are required to be consistent with a relatively strong set of axioms. Though in practice value measurement is not applied in such a rigid framework, these axioms: (a) ''impose some form of discipline in the building up of preference models''; (b) ''help the decision-makers to obtain greater understanding of their own values, and to justify their final decisions when required''; (c) ''encourage explicit statements of acceptable tradeoffs between criteria''.

The second group presents methods for ''situations in which decision makers may find it very difficult to express tradeoffs or importance weights, but may nevertheless be able to describe outcome scenarios, expressed in terms of satisfying aspirations or goals for each criterion''. Available courses of action (alternatives) are systematically eliminated until, in the view of the decision maker, a satisfactory level of performance for this criterion has been ensured. The process should be seen in a dynamic perspective. The decision maker should be able to backtrack the elimination process and cycle through it.

The outranking models focus ''on pairwise evaluation of alternatives, identifying incomparabilities as well as assessing preferences and indifferences''. Preferences evolve ''as part of the MCDA process within the context of the choices to be made''.

In light of the different MCDA methods and possible applications to support decision-making in natural resources management, a question arises in terms of which method is preferred and should be selected. To answer this question, authors undertook comparisons between methods under similar planning situations. Duckstein et al. (1982) made the comparison in terms of: (1) consistency of results between methodologies, (2) robustness of results with respect to changes in parameter values, and (3) ease of computation. Hobbs et al. (1992) also made a comparison based on: (1) the degree of comfort the users feel in using the methods, (2) the confidence the users express in them, (3) the ability of the method to help users to understand the problem, (4) the ability of the methods to be valid, i.e. the resulting choices will be consistent with the actual preferences of the users and (5) the appropriateness and ease of use.

Kangas and Kangas (2002) argued, however, that methods and results are not necessarily directly comparable. Inconsistencies might arise because: (1) ''the choice problem formulations do not reflect the same preference structures'', (2) ''the ways in which preference information is processed vary between different methods'', and (3) ''the methods interpret the criterion weights differently''. The authors also stress that it may be more important to compare the qualities of the methods themselves, than to compare the results obtained by different methods. Hobbs et al. (1992) also conclude that ''careful tutoring and close collaboration between analyst and decision makers are more important than which method is adopted''.

3. Overview of the applications of MCDA in forestry and natural resources management

Over the last two decades, there have been a number of reviews published in the literature dealing with the application of MCDA to natural resources management problems. Examples of these reviews include Mendoza et al. (1986, 1987a), Romero and Rehman (1987), Tarp and Helles (1995), Hayashi (2000), Kangas et al. (2001a) and Steiguer et al. (2003). Books have also been published on applications such as Janssen (1991), Beinat and Nijkamp (1998), El-Swaify and Yakowitz (1998), Schmoldt et al. (2001) and Pukkala (2002). Similarly, a significant number of books have also surveyed MCDA methodologies with reference to some applications to natural resources management (e.g. Cohon, 1978; Hwang et al., 1979; Zeleny, 1984; Yoon and Hwang, 1995; Malczewski, 1999; Belton and Stewart, 2002).

In this paper, a problem-oriented overview is developed along three sub-sections: (1) nature and context of the problem; (2) type and complexity of the method; (3) number and type of decision makers. Authors and date of publication are common elements that can guide the readers across the different tables.

3.1. Nature and context of the problem

The references presented in Table 2 cover the range of MCDA methods from the 1970s until recently. They refer mainly to analyses carried out with real data, rather than simulated, and from different parts of the world, including applications in developing countries. Five of the publications refer to the use of MCDA in the production of management plans for local entities and government (Malczewski et al., 1997; Andreoli and Tellarini, 2000; Siitonen et al., 2003; Kangas and Kangas, 2003; Phua and Minowa, 2005). This suggests that efforts have been made to promote MCDA as a tool to support decisions affecting policies and action plans for natural resources management under different ownership and management scenarios.

The diversity of models and methodological approaches that has been developed also has expanded the application of MCDA to a broad range of natural resources management problems. Strategic and operational forest management have been some of the most frequently analysed problems at diversified scales ranging from management units to watersheds and regions. Land-use planning has also been analysed including the integration of MCDA methods with Geographic Information Systems (Malczewski, 1999). MCDA has also been used to assess forest sustainability by using multi-criteria methods in the selection or assessment of management plans and management alternatives according to a set of sustainability indicators (e.g. Diaz-Balteiro and Romero, 2004).

Other applications of MCDA to decision problems in natural resources management include: (1) the selection of sites for networks of nature reserves (e.g. Snyder et al., 2004); (2) the integration of biodiversity conservation in management plans (e.g. Kangas and Kuusipalo, 1993); (3) wildlife management (e.g. Berbel and Zamora, 1995); (4) environmental conflict mitigation (e.g. Martin et al., 1996; Malczewski et al., 1997; Shields et al., 1999).

3.2. Type and complexity of the problem

Table 3 describes some of the most often used methods for MCDA. Under the first type of models (i.e. value measurement), the Analytic Hierarchy Process (Zahedi, 1986; Saaty, 2001) has been used to structure decision problems and to assess scores that translate DM's preferences into a prioritisation of either objectives or alternatives. Among the goal, aspiration, or reference level methods, goal programming is the most frequently applied and studied MCDA method. Thorough discussion of this method can be found in Mendoza (1987b) and Romero (1990). Some authors proposed an integration of the reference level methods with AHP, using the later for assessing the weight of criteria in the former. This was the case with the integration of Modelling to Generate Alternatives and AHP by Mendoza and Sprouse (1989), of Goal Programming with AHP by Kangas and Pukkala (1992) and of Compromise programming with AHP by Phua and Minowa (2005). In terms of outranking methods, the most frequently applied are those of ELECTRE (Bella et al., 1996; Kangas et al., 2001b; Schmoldt et al., 2001) and PROMETHEE (Kangas et al., 2001b; Laukkanen et al., 2002).

There are many aspects of decision-making concerning natural resources management, and in particular forest management, that cannot be described adequately, or predicted deterministically, such as: future conditions of natural systems, states of interest that are inherently qualitative, risk, and human

Table 2
MCDA applications systematized according to country of application, type of data used, spatial scale, and nature and context of the problem

Reference	Country of application	Illustration example with simulated data	Illustration example with real data	Nature and context of the problem	Spatial scale
Steuer and Schuler (1978)	USA		X	Forest management planning	A 4047 ha sub unit of a national forest
Hallefjord and Jörnsten (1986)	Sweden		X	Multi-objective forest management planning	About 8000 ha stands aggregated by timber class
Mendoza (1987a)	Nigeria		X	Land use allocation in agro-forestry systems	A land unit
Mendoza et al. (1987a)	USA	X		Forest land planning	A 3200 ha forest
Mendoza et al. (1987b)	USA		X	Forest management and land allocation planning	Three management units with 18,211 ha
Bare and Mendoza (1988)	USA		X	Forest land management planning	A 102,629 ha forest area
Mendoza (1988)	USA		X	Forest management planning	A 102,387 ha forest
Mendoza and Sprouse (1989)	USA		X	Forest management planning	A 11,736 ha forest tract
Gong (1992)	Sweden	X		Multiple use forest management	A 10 ha forest
Kangas and Pukkala (1992)	Finland		X	Forest management planning	A 31.4 ha forest
Kangas (1992)	Finland		X	Strategic forest management planning	–
Kangas and Kuusipalo (1993)	Finland		X	Integrate biodiversity in strategic forest planning	A 320 ha forest
Mendoza et al. (1993)	USA		X	Forest management planning	A national forest
Kangas (1994)	Finland	X		Strategic forest management planning	A recreation area
Eskandari et al. (1995)	USA		X	Watershed management	Four watersheds from 546 to 121 ha
Chang et al. (1995)	Taiwan		X	Watershed land resource allocation	A watershed
Berbel and Zamora (1995)	Spain		X	Wildlife management	A 3600 ha forest
Alho et al. (1996)	Finland		X	Analysis of forest plans in terms of habitat suitability for black grouse	A 117 ha forest
Bella et al. (1996)	USA		X	Water allocation conflict	A river basin
Martin et al. (1996)	USA		X	Dealing with conflict over oil and gas interests in a national forest	A national forest
Antoine et al. (1997)	Kenya		X	Land resources appraisal	A district
Pukkala and Miina (1997)	Finland		X	Multi-objective optimisation of stand management	A stand
Malczewski et al. (1997)	Mexico		X	Environmental conflict analysis	A region
Bantayan and Bishop (1998)	Philippines		X	Land-use allocation	A forest reserve
d'Angelo et al. (1998)	USA		X	Selection of the best forestry treatment method	Four watersheds
McDaniels and Thomas (1999)	Canada		X	Selection of the best land use	An undeveloped area of publicly owned suburban land
Pukkala (1998)	Finland	X		Forest management planning	A 50 ha forest holding
Shields et al. (1999)	USA		X	Conflict resolution on oil and gas leasing on a national forest	A national forest
Prato (2000)	USA	X		Watershed management planning towards sustainability	National forest, national park, wildlife refuge, etc.
Prato (2000)	USA	X		Watershed management planning towards sustainability	Farm, ranch, forest
Andreoli and Tellarini (2000)	Italy		X	Assessment of farm sustainability	A region
Hajkowicz et al. (2000)	Australia		X	Evaluation of environmental projects	–
Kangas et al. (2000)	Finland		X	Selection of a tactical forest plan	A 2024 ha forest estate
Martin et al. (2000)	USA			Ranking forest management alternatives	A 755,873 ha forest
Reynolds and Peets (2001)	USA		X	Prioritise watersheds and reaches for protection and restoration	A watershed system
Kangas et al. (2001b)	Finland		X	Strategic natural resources planning	A region
Nhantumbo et al. (2001)	Mozambique		X	Management of the miombo land	A district
Pesonen et al. (2001)	Finland			Strategic forest planning	A region
Vacik and Lexer (2001)	Austria		X	Management of protection forest for sustained yield of water resources	A 2294 ha forest

Table 2 (*Continued*)

Reference	Country of application	Illustration example with simulated data	Illustration example with real data	Nature and context of the problem	Spatial scale
Laukkanen et al. (2002)	Finland		X	Forest management planning	A 30 ha forest holding
Memtsas (2003)	Greece		X	Reserve selection	A region
Oliveira et al. (2003)	Brazil		X	Land allocation	A 2000 ha farm
Siitonen et al. (2003)	Finland		X	Selection of forest reserves	A 10000 ha landscape
Ananda and Herath (2003a)	Australia		X	Regional forest planning	A region
Ananda and Herath (2003b)	Australia	X		Regional forest planning	A region
Kangas and Kangas (2003)	Finland		X	Forest management planning	A 30 ha forest holding
Herath (2004)	Australia		X	Wetland management	A 180 ha wetland
Kangas et al. (2003a)	Finland		X	Forest management planning	A 30 ha forest holding
Kangas et al. (2003b)	Finland		X	Selection of a tactical forest plan	A 2024 h forest estate
Agrell et al. (2004)	Kenya		X	Land use planning	A region
Snyder et al. (2004)	Australia		X	Reserve selection	Land holdings and land systems
Stewart et al. (2004)	The Netherlands		X	Land use planning	A region
Diaz-Balteiro and Romero (2004)	Spain		X	Selecting forest management plans according to sustainability indicators	A 1156 ha public forest
Laukkanen et al. (2004)	Finland		X	Forest management planning	A 128 ha forest
Laukkanen et al. (2005)	Finland		X	Selection of a tactical forest management plan	A 30 ha forest holding
Pasanen et al. (2005)	Finland	X		Selection of a forest management plan	A forest property
Phua and Minowa (2005)	Malaysia		X	Forest conservation planning	A landscape

subjectivity in judgements (Mendoza et al., 1993; d'Angelo et al., 1998; Pukkala, 1998; Malczewski, 1999; Ananda and Herath, 2003b; Kangas and Kangas, 2004). All these situations contribute to uncertainty in decision-making, which are often not considered because of data unavailability and costs (Malczewski, 1999). However, accommodating uncertainty is important in decision-making because it has the potential to lead to inadequately defined alternatives or plans (Kangas et al., 2000). Kangas and Kangas (2004) provide an overview of the different sources of uncertainty and describe different methodologies that can be used to deal with uncertainty in decision-making within the framework of forest-related problems.

In this paper, applications that take explicitly account uncertainty are described in Table 3, along with the methodological approaches used. The review covers the most common approaches to uncertainty that have been applied in natural resources management (see Kangas and Kangas, 2004). In situations where uncertainty is mainly due to randomness, the methods used are probability-based. This is the case, for example, of Gong (1992) who used a Markov process to generate criteria values under certain alternatives. Eskandari et al. (1995) made use of a probability mass function to model payoff values in order to support decisions in the selection of management plans. In what concerns uncertainty in preferences, Prato (2000) demonstrates the use of Bayesian theory integrated into a stochastic programming model to identify the most efficient management plans for a site/landscape, based on the data available and the prior beliefs. A stochastic approach was also used by Alho et al. (1996) to assess the uncertainty in AHP results concerning the ecological effects of forest plans. Regression was then used to analyse the variation in the views of the various experts, and also the internal inconsistencies of individual views. Presented as an alternative to the calculation of a consistency index that is usually incorporated into AHP analysis, this approach derives quantitative estimates of the uncertainties based on the modelling of variance components.

Several authors have proposed probability-based approaches to deal with uncertainty. For example, probability-based utility theory approaches, including uncertainty in decision makers' preference structure have been proposed Martin et al. (1996), Pukkala and Miina (1997), Pukkala (1998), Andreoli and Tellarini (2000) and Vacik and Lexer (2001). Similarly, Kangas and Kangas (2003) and Kangas et al. (2003a,b) used a method called stochastic multicriteria acceptance analysis (SMAA) that attempts to incorporate both the uncertainty derived from the stochastic nature of different criteria and the inconsistency in the preference structure.

There are cases where the uncertainty may be due to imprecision. Probability theory is no longer useful to deal with this source of uncertainty since the outcome of the decision is no longer "true or false" but rather ambiguous (Malczewski, 1999). In this case, some authors have proposed fuzzy set theory and fuzzy logic (Mendoza and Sprouse, 1989; Mendoza et al., 1993; Reynolds and Peets, 2001).

With respect to uncertainty related to the structure of preferences, a deterministic approach commonly used to reduce uncertainty in the judgements concerning the weights of the criteria, is sensitivity analysis. Examples of the application of this method can be found in Kangas et al. (2000) and Ananda and Herath (2003b). Other deterministic methods that have been widely used to deal with uncertain judgements upon different alternatives are the outranking methods, ELECTRE and PROMETHEE. Kangas and Kangas (2002) describe these methods as indicating the degree of dominance of one alternative over another. They enable the utilization of incomplete value information and judgements on ordinal measurement scale. Supposedly, the uncertainty concerning the

Table 3
MCDA applications systematized by model type based on classification suggested by Belton and Stewart (2002)

Reference	Type of model			Number of criteria/number of alternatives	Nature of the criteria	Deals explicitly with uncertainty?	
	Value measurement models	Goal, aspiration or reference level models	Outranking models			Source	Method used
Steuer and Schuler (1978)		Combination of linear programming with vector maximum techniques		5/8	1, timber production; 2, dispersed recreation; 3, hunting forest species; 4, hunting open land species; 5, grazing	No	No
Hallefjord and Jörnsten (1986)		Belenson–Kapur procedure (combination of weighting methods with two person zero sum game) and entropy reference point method		3 and 7/large	(A) 1, variation in sawlog drain; 2, variation in total drain; 3, sawlog drain in period 1. (B) 1, variation in sawlog drain to be minimized; 2, variation in total drain to be minimized; 3, sawlog drain in period 1 to be kept at a ‘‘reasonable’’ level; 4, thinning period 1 to be minimized; 5, thinning period 2 to be minimized; 6, thinning period 3 to be minimized; 7, sawlog drain periods 1–7 to be maximized	No	No
Mendoza (1987a)		Modelling to generate alternatives (MGA)		6/large	1, economic return; 2, operational costs; 3, total area allocated; 4, hired labor; 5, farmer's labor in the first season; 6, farmers labor in the second season	No	No
Mendoza et al. (1987a)		Weighting method, goal programming, STEM method. MGA		2/large	1, present net worth of each management regime; 2, black walnut timber volume	No	No
Mendoza et al. (1987b)		Modelling to generate alternatives		5/large (constrained by HSJ algorithm)	1, timber yield; 2, forage production; 3, developed recreation; 4, dispersed recreation; 5, water production	No	No
Bare and Mendoza (1988)		STEM method		3/large	1, timber harvest plus ending inventory volume; 2, number of animals for five ‘‘indicator’’ species; 3, number of animals for ‘‘indicator’’ species 4	No	No
Mendoza (1988)		Modelling to generate alternatives		7/large (constrained by HSJ algorithm)	1, total return from timber management; 2–7, total utility index for wildlife species k ($k = 1, \ldots, 6$)	No	No
Mendoza and Sprouse (1989)		Modelling to generate alternatives, with use of AHP to prioritise alternatives		3/1	1, discounted net revenue; 2, area suitable for wildlife habitat; 3, area suitable for non-motorized semi-primitive recreation	Aspired objective values	Fuzzy logic
Gong (1992)		Multi-objective dynamic programming		2/large	1, revenue from timber harvest; 2, satisfaction from the standing trees	Stochastic criteria values	Markov decision process
Kangas and Pukkala (1992)		Goal programming, with use of AHP to assess goals relative importance		4/large	1, total volume after 20 years; 2, annual volume increment after 20 years; 3, net income during the first 10-year period; 4, net income during the second 10-year period	No	No
Kangas (1992)	A priority function created with AHP to prioritise alternatives generated with LP concerning wood production			3/6	1, wood production; 2, forest landscape; 3, game management	No	No

Kangas and Kuusipalo (1993)	A priority function created with AHP			5/6	1, net income from timber sales; 2, value of the growing stock at the end of the planning period; 3, area to be regenerated during the planning period; 4, total volume of broad-leaved trees at the end of the planning period; 5, mean amenity value of the forest stands at the end of the planning period	No	No
Mendoza et al. (1993)		Fuzzy multiple objective linear programming		4/large	1, net present value; 2, sediment yield; 3, timber production; 4, forest production	Aspired objective values	Fuzzy logic
Kangas (1994)	A priority function created with AHP			4/6	1, priority for research activities; 2, priority for recreation activities; 3, priority for conservational considerations; 4, priority for wood production	No	No
Eskandari et al. (1995)		Distance-based discrete multi-objective programming		14/4	1, stream flow; 2, sediment yield; 3, deer habitat use; 4, elk habitat use; 5, pigmy nuthatch habitat use; 6, violet-green swallow habitat use; 7, cavity nesters habitat use; 8, aesthetics; 9, total herbage production; 10, perennial grass production; 11, livestock carrying capacity; 12, management costs; 13, growth of merchantable wood; 14, growing stock	Preference structure	Modelling of payoff values with probability mass function
Chang et al. (1995)		Compromise programming and multi-objective simplex method		6/large	1, total discharge of phosphorus, 2, total discharge of nitrogen; 3, total discharge of biological oxygen demanding load; 4, total discharge of sediment yield; 5, employment level by land development; 6, income by land development	No	No
Berbel and Zamora (1995)		Lexicographic goal programming		2/large	1, economic income; 2, number of roe deer at the end of the planning period	No	No
Alho et al. (1996)	A priority function created with AHP			5/10	1, total volume in thousands of cubic metres; 2, share of deciduous species as a percentage of volume; 3, index of scenic beauty; 4, length of boundaries of distinct forest stands in kilometres; 5, proportion of old tree stands as a percentage	Preference structure	Modelling of the variance of experts' views and inconsistency in individual views when finding the mean estimate of preferences
Bella et al. (1996)		Compromise programming	Electre III	18/30	1, operation, maintenance and allocation costs; 2, damage losses; 3, benefit for flood control, recreation, water supply and water quality; 4, scenic reaches; 5, social impact; 6, number of species by reach; 7, catches per hour; 8, temperature; 9, water quality; 10, recreation in visitor-days; 11, percent protection; 12, development possibility; 13, tonnes of sediment produced; 14, capacity exceedance; 15, equity of allocation; 16, conjunctive use possibility; 17, allocation subsidy; 18, flora and fauna	Preference structure	Pseudo-criteria
Martin et al. (1996)	Voting methods and utility theory			It does not apply/7		Preference structure	Utility theory

Table 3 (*Continued*)

Reference	Type of model			Number of criteria/number of alternatives	Nature of the criteria	Deals explicitly with uncertainty?	
	Value measurement models	Goal, aspiration or reference level models	Outranking models			Source	Method used
Antoine et al. (1997)		Aspiration-reservation-based decision support		10/large	1, food output; 2, net revenue; 3, production costs; 4, gross value of output; 5, arable land use; 6, area harvested; 7, food output in bad years; 8, total erosion; 9, self-sufficient ration; 10, erosion at the level of agro-ecological cells	No	No
Pukkala and Miina (1997)	Additive utility function optimized by use of a non-linear programming algorithm, integrated with scenario technique			3/large	1, present value on net incomes; 2, discounted felling value of growing stock; 3, discounted value of a scenic beauty score of the stand	Risk, preference structure	Scenario technique, utility theory
Malczewski et al. (1997)		Integer programming, with the use of AHP to assess criteria weights		21/3	1, water supply for agriculture; 2, accessibility to US markets; 3, cattle population; 4, accessibility to transportation; 5, vegetation types proper for cattle; 6, water supply for tourism; 7, accessibility to water; 8, biodiversity conservation; 9, forest SPP coverage; 10, game population; 11, tourist activity; 12, industrial park areas; 13, accessibility to transportation; 14, accessibility to infrastructures; 15, water supply for industrial and urban development; 16, accessibility to hunting areas; 17, tourist services; 18, sport fishing services; 19, water supply for tourism; 20, tourist water pollution; 21, catchment areas	No	No
Bantayan and Bishop (1998)	A priority function created with AHP			7/4	1, soil stability; 2, recreation; 3, employment; 4, sustainable/potable water, 5, food production; 6, education and research; 7, pollution abatement	No	No
d'Angelo et al. (1998)	Social choice theory			14 (when it applies and it depends on the stakeholders group)/4	1, stream flow; 2, sediment; 3, deer; 4, elk; 5, pygmy nuthatch; 6, violet-green swallow; 7, cavity nesters; 8, herbage production; 9, grass production; 10, carrying capacity; 11, merchantable volume; 12, growth; 13, aesthetics; 14, management costs	Preference structure	Social choice theory
Pukkala (1998)	Multi-attribute utility theory with a heuristic optimisation algorithm			5/7	1, net income during first planning period; 2, net income during second planning period; 3, volume after 2 years; 4, recreation score after 20 years	Risk, reference structure	Scenario technique, utility theory
McDaniels and Thomas (1999)	A structured value referendum with approval voting			21/4	Several organized into the following aspects: 1, environment; 2, social; 3, economic; 4, municipal land use planning	Preferences structure	Approval voting

Shields et al. (1999)	Utility theory combined with voting methods			10 grouped in 3 groups (social, economic and environmental)/7	1, health and safety; 2, community stability; 3, recreation and tourism; 4, commodity access; 5, local economic impact; 6, national economic impacts; 7, species impacts; 8, ecosystem impacts; 9, water quality; 10, air quality	No	No
Kangas et al. (2000)	A priority function created with AHP applied to optimal alternatives generated by MONSU			3/10	1, ecological network; 2, net revenues; 3, volume of the growing stock	Preference structure	Sensitivity analysis of weights, Bayesian approach to pairwise comparisons
Prato (2000)	Utility theory	e-Constraint method		7/2	1, timber cut; 2, income; 3, employment; 4, tax revenues; 5, recreational values; 6, water quality; 7, biodiversity	Stochastic attributes, preference structure	Normal distribution assumed, Bayes theorem, utility theory
Prato (2000)	Utility theory	e-Constraint method		3/2	1, harvest rate; 2, income; 3, costs	Stochastic attributes, preference structure	Normal distribution assumed, Bayes theorem
Andreoli and Tellarini (2000)	Utility theory			Many organized in six groups/all the farms of a region	1, environment; 2, ecology; 3, economy; 4, sociology; 5, psychology; 6, physiognomy/cultural geography	Preference structure	Utility theory
Hajkowicz et al. (2000)	Utility theory with the following weighting methods: fixed point scoring, rating, ordinal ranking, a graphical method			6/5 projects	1, agricultural profitability; 2, enhance natural ecosystems; 3, improve land capability; 4, community benefit; 5, improve attitudes and education; 6, minimize risk	No	No
Martin et al. (2000)	Attribute value function with the swing weighting method			3/6	1, watershed improvement; 2, dispersed recreation; 3, species protection; 4, acres available for leasable development	No	No
Reynolds and Peets (2001)	A priority function created with AHP			3 for watersheds and 4 for reaches/8 watersheds and 85 stream reaches	(A) 1, watershed condition; 2, feasibility of restoration; 3, efficacy of restoration. (B) 1, reach condition; 2, watershed restoration priority; 3, reach-level feasibility; 4, reach-level efficacy	Preference structure	Fuzzy logic
Kangas et al. (2001b)			Electre III and Promethee II	17/4	1, area of commercial forests; 2, FPS's financial surplus; 3, change in timber volume in commercial forests; 4, direct effect on employment; 5, indirect effect on employment; 6, FPS's turnover; 7, area of recreational forest; 8, area of commercial forest with recreational values; 9, recreation value index; 10, area of clearcut forest stands; 11, area of fertilised forests; 12, area of ditch network maintenance; 13, conserved area; 14, area of commercial forests with conservation values; 15, change in dead wood volume; 16, change in the area of old forests; 17, change in the volume of hardwood	Preference structure	Pseudo-criteria

Table 3 (*Continued*)

Reference	Type of model			Number of criteria/number of alternatives	Nature of the criteria	Deals explicitly with uncertainty?	
	Value measurement models	Goal, aspiration or reference level models	Outranking models			Source	Method used
Nhantumbo et al. (2001)		Goal programming		7/large	1, area to be protected as national park and as reserves; 2, area that can be harvested for fuelwood and construction timber; 3, annual allowable cut for industrial roundwood; 4, area for tourism; 5, consumption of firewood per year; 6, is the consumption of poles for housing; 7, demand of wild fruits and animals	No	No
Pesonen et al. (2001)	A'WOT			It does not apply/4	It does not apply	No	No
Vacik and Lexer (2001)	Utility theory			5/49	1, water production; 2, timber production; 3, conservation of biodiversity; 4, recreation; 5, protection against rockfall and avalanches	Criteria values, preference structure	Expert knowledge, utility theory
Laukkanen et al. (2002)	Multi-criteria approval with AHP			5/20	1, net incomes; 2, biodiversity; 3, monetary value of the timber production; 4, scenic beauty of the forest landscape; 5, wild berry yield	Preference structure	Multi-criteria approval
Memtsas (2003)	Simple multi-attribute rating technique (SMART)	Geometric methods-based on distance		4/large	1, number of species represented; 2, sum of the species rarity scores of the species represented; 3, sum of the cell richness scores; 4, sum of the cell rarity scores	No	No
Oliveira et al. (2003)		Goal programming		8/large	1, wood harvest (pine); 2, wood harvest (araucaria); 3, leaves of erva-mate harvest; 4, tourism; 5, pasture; 6, maintenance of employment; 7, increase in the diversity of the flora; 8, increase in the diversity of the fauna	No	No
Siitonen et al. (2003)		Greedy heuristic algorithm		17/large	1, economic expenditure; 2, continuous area and connectivity objectives; ... and several spatial and non-spatial objectives	No	No
Ananda and Herath (2003a)	Multi-attribute value theory			3/3	1, old-growth forest conservation; 2, hardwood timber production; 3, recreation intensity	No	No
Ananda and Herath (2003b)	A priority function created with AHP			3/5	1, timber production; 2, biodiversity conservation; 3, recreation	Preference structure, risk	Sensitivity analysis, risk preference functions
Kangas and Kangas (2003)	Multi-criteria approval and stochastic multi-criteria acceptability analysis with ordinal criteria (SMAA-O)			5/20	1, present value of net incomes within the planning horizon; 2, estimated value of future timber production in the end of the planning horizon; 3, blueberry yield; 4, scenic beauty; 5, biodiversity	Criteria values, preference structure	Joint probability distribution, weights randomly chosen from appropriate distributions, multi-criteria approval

Herath (2004)	A priority function created with AHP		5/3	1, conservation value; 2, business investment; 3, recreation visitor-days; 4, extent of river red gum; 5, number of bird species	No	No
Kangas et al. (2003a)	Hybrid method of the stochastic multi-criteria acceptability analysis with ordinal criteria (SMAA-O) and SWOT (S-O-S)		16/6	Organized as SWOT factors: 1, good hunting possibilities; 2, excellent hiking possibilities; 3, possessing share yields income and recreational possibilities; 4, future timber cutting possibilities in own forests; 5, great distance from current residences; 6, cottage needs repair; 7, cottage is poorly provided as regards facilities; 8, costs of maintenance; 9, repairing will increase usage; 10, additional incomes from renting the cottage to holidaymakers; 11, new facilities will improve the quality of holidays; 12, selling or not repairing the cottage would mean income or saved money; 13, cuttings could spoil the scenery and decrease recreational values; 14, social interaction between partners will fad if the cottage is sold; 15, repairing can cost more than expected; 16, benefits from the forest will be lost	Criteria values, preference structure	Joint probability distribution, weights randomly chosen from appropriate distributions, multi-criteria approval
Kangas et al. (2003b)	Stochastic multi-criteria acceptability analysis with ordinal criteria (SMAA-O)		5/10	1, net income from timber cuttings during the planning period; 2, total volume of the unreserved forest stands after the planning period; 3, recreational value; 4, viability of rare species; 5, risks of environmental hazards to the riparian areas	Criteria values, preference structure	Joint probability distribution converted into stochastic cardinal data, weights randomly chosen from appropriate distributions
Agrell et al. (2004)		Linear programming, interactive weighted Tchebycheff Procedure	10/large	Related to sustainability, economic, environmental and social feasibility over different time horizons	Risk, preference structure	Risk constraints, iteractive adjustment of weights
Snyder et al. (2004)		Weighting method	2/large	1, total area of selected sites; 2, total number of covered land systems	Preference structure	Iteractive adjustment of weights
Stewart et al. (2004)		Genetic algorithm applied to goal programming/reference point approach	3/large	1, number of clusters for each land use; 2, relative magnitude of the largest cluster for each land use; 3, compactness of land uses	Uncertainty in preference structure	Multi-objective weighting (sensitivity analysis)
Diaz-Balteiro and Romero (2004)		Goal programming	11/14	Indicators of sustainability: 1, net present value; 2, veneer volume; 3, final inventory; 4, even flow volume; 5, regulation; 6, uncut area; 7, mixed stands cutting area; 8, ratio harvest volume/stand growth; 9, average rotation age; 10, net carbon; 11, mean cutting area	No	No
Laukkanen et al. (2004)	Voting theory		7/9	1, clearcut area; 2, harvesting volume; 3, capercaille habitat needs; 4, harvesting income; 5, nature conservation; 6, recreation and landscape; 7, local employment	Preference structure	Social choice

Table 3 (*Continued*)

Reference	Type of model			Number of criteria/number of alternatives	Nature of the criteria	Deals explicitly with uncertainty?	
	Value measurement models	Goal, aspiration or reference level models	Outranking models			Source	Method used
Laukkanen et al. (2005)	Multi-criteria approval			5/30	1, net harvesting income; 2, effects on nature conservation values; 3, effects on recreational values; 4, expectation of logging damage; 5, favouring local contractors	Preference structure	Social choice
Pasanen et al. (2005)	Multi-criteria acceptability voting			5/5	1, volume; 2, net income in period 1; 3, net income in period 2; 4, increment; 5, cutting removal	Preference structure	Social choice
Phua and Minowa (2005)		Compromise programming, with use of AHP to assess weights		2/it does not apply	1, biodiversity conservation; 2, soil and water resources	No	No

preferences and also the criterion values is dealt with using pseudo-criteria. This means that two thresholds, namely indifference and preference thresholds, are defined. The indifference threshold for a criterion is a difference between the performances of two alternatives concerning the criterion, beneath which the decision maker is indifferent between the two management alternatives. The preference threshold is the difference above which the decision maker strongly prefers one management alternative above the other. Between these two thresholds there is the zone of weak preference, where the decision maker hesitates. Examples of application of these methods can be found in Bella et al. (1996) and Kangas et al. (2001b). In spite of efficiently dealing with uncertainty concerning the decision rules, Rogers and Bruen (1998) pointed out that these methods might be considered too subjective and unreliable for applications such as environmental assessments. The authors suggest, specifically for ELECTRE III, a new method that involves a ‘‘more comprehensive approach for specifying realistic limits for the thresholds where both criterion error/uncertainty and human sensitivity to differing levels of the criterion are taken into account’’.

3.3. Number and type of decision makers

Table 4 shows an overview of the way decision makers and preferences have been taken into account in MCDA applications to natural resources management. The classification based on the way preferences were included was inspired by the three general approaches to solving MCDA problems suggested by Korhonen et al. (1992), particularly in terms of the moment of the decision maker (DM) intervention. The a priori inclusion is when modelling of the preferences is the starting point of the modelling process. The interactive articulation of preferences assumes that the answer of the DM to specific questions leads the solution process towards the ‘‘most’’ preferred one. Finally, the *posterior* articulation of preferences involves the generation of ‘non-dominated’ solutions, which are presented to the DM for evaluation. The overview in Table 4 presents a wide range of examples of application of the three approaches.

Group multi-criteria decision-making gained some prominence in the 1990s. Earlier, most of the applications assumed the existence of a single decision maker, usually the owner of the land unit or even the analyst. More recently, applications attempt to have all interests represented and, therefore, consider the different groups of stakeholders who hold interest on the management of natural resources, such as conservationists, hunters, local residents, industry and recreationists.

4. MCDA methods for collaborative planning and decision-making

Public participation through involvement of local communities in forest management decision-making gained relevance and wide acceptance following international discussions on sustainable development that ensued after the UN Conference on Environment and Development in Rio (UNCED, 1992).

Table 4
MCDA applications systematized according preferences, number, and type of decision makers involved

Reference	Preferences included	Single DM	Group decision	Type of DM
Steuer and Schuler (1978)	Interactively		X	Planning team
Hallefjord and Jörnsten (1986)	A priori	X		State
Mendoza (1987a)	Posterior	X		State
Mendoza et al. (1987a)	A priori and interactively	X		Analyst
Mendoza et al. (1987b)	Posterior	X		Analyst
Bare and Mendoza (1988)	Interactively	X		State
Mendoza (1988)	Posterior	X		Analyst
Mendoza and Sprouse (1989)	Posterior	X		Analyst
Gong (1992)	Posterior	X		Forest owner
Kangas and Pukkala (1992)	A priori	X		Expert
Kangas (1992)	Posterior	X		Manager
Kangas and Kuusipalo (1993)	Posterior		X	Experts
Mendoza et al. (1993)	Posterior		X	Expert
Kangas (1994)	Posterior		X	Hikers, local inhabitants, nature conservationists, tourism entrepreneurs
Eskandari et al. (1995)	A priori		X	Experts representing water users, livestock producers, foresters, environmentalists, land use planners
Chang et al. (1995)	A priori	X		Analyst
Berbel and Zamora (1995)	Interactively	X		Analyst
Alho et al. (1996)	A posterior		X	Experts representing wildlife researchers, hunters, biologists, and foresters
Bella et al. (1996)	A priori		X	Experts
Martin et al. (1996)	Posterior		X	1, oil company; 2, environmental organizations; 3, local tourist industry; 4, local timber industry; 5, local retail/wholesale merchants; 6, local government units; 7, federal government
Antoine et al. (1997)	Interactively	X		Analyst
Pukkala and Miina (1997)	A priori (objectives, time and risk)	X		Expert
Malczewski et al. (1997)	Posterior		X	The ones that support: 1, agriculture; 2, cattle ranching; 3, bioconservation and forestry; 4, hunting; 5, industry and urban development; 6, tourism and sport fishing; 7, water catchment
Bantayan and Bishop (1998)	Posterior		X	–
d'Angelo et al. (1998)	Posterior		X	1, water users; 2, wildlife advocates; 3, livestock producers; 4, wood producers; 5, environmentalists; 6, managers
McDaniels and Thomas (1999)	Posterior		X	200 randomly selected adults
Pukkala (1998)	A priori	X		Analyst
Shields et al. (1999)	A priori		X	Oil company, environmental organization, local tourism industry, local timber industry, local retail/wholesale merchants, local government units, federal government
Kangas et al. (2000)	Interactively	X		An expert in ecology
Prato (2000)	Interactively	X		Public agency
Prato (2000)	Interactively		X	Local stakeholders
Andreoli and Tellarini (2000)	A priori		X	Stakeholders
Hajkowicz et al. (2000)	A priori		X	1, primary producer; 2, extension officer; 3, environmental conservation representative; 4, governmental natural resources manager; 5, technical expert or scientist; 6, elected representative of local government
Martin et al. (2000)	A priori		X	1, conservationists; 2, stakeholder; 3, a mountain bike interest group
Reynolds and Peets (2001)	Posterior	X		Expert
Kangas et al. (2001b)	A priori		X	Interest groups and the public
Nhantumbo et al. (2001)	A priori		X	1, private sector; 2, state; 3, local communities
Pesonen et al. (2001)	Posterior		X	Managers
Vacik and Lexer (2001)	Posterior		X	Experts
Laukkanen et al. (2002)	A priori		X	–
Memtsas (2003)	A priori	X		Analyst
Oliveira et al. (2003)	A priori		X	Stakeholders

Table 4 (*Continued*)

Reference	Preferences included	Single DM	Group decision	Type of DM
Siitonen et al. (2003)	A priori	X		Analyst
Ananda and Herath (2003a)	A priori		X	1, timber industry; 2, environmentalists; 3, farmers; 4, recreationists; 5, tour operators
Ananda and Herath (2003b)	Posterior		X	1, timber industry; 2, environmentalists; 3, farmers; 4, recreationists; 5, tour operators
Kangas and Kangas (2003)	A priori		X	Forest owners
Herath (2004)	Posterior		X	1, business group; 2, conservation group; 3, recreation users
Kangas et al. (2003a)	A priori		X	Forest owners
Kangas et al. (2003b)	Interactively		X	Not specified
Agrell et al. (2004)	Interactively	X		Expert
Snyder et al. (2004)	Posterior	X		Analyst
Stewart et al. (2004)	A priori	X		Analyst
Diaz-Balteiro and Romero (2004)	A priori	X		Analyst
Laukkanen et al. (2004)	Posterior		X	1, administration; 2, local residents; 3, hunters; 4, timber buyers; 5, conservationists; three groups of experts representing local forest organizations
Laukkanen et al. (2005)	Posterior		X	Three forest owners
Pasanen et al. (2005)	Interactively		X	A group of 20 non-industrial private forest owners
Phua and Minowa (2005)	A priori		X	Conservationists and neutral DM

Increasingly, decisions about how forests and other natural resources should be managed have become more collaborative instead of being within the exclusive domain of experts, resource managers, and other professionals.

In recognition of its importance, the International Labour Office (2000) has stated the following as potential purposes of public participation in forestry: (1) increase awareness of forestry issues and mutual recognition of interests, (2) gather information and enhance knowledge on forests and their users, (3) improve provision of multiple forest goods and services, (4) stimulate involvement in decision-making and/or implementation processes, (5) enhance acceptance of forest policies, plans and operations, (6) increase transparency and accountability of decision-making, and (7) identify and manage conflicts and problems together, in a fair and equitable way. Consequently, because of these developments, citizen involvement is now widely accepted, and in most cases highly recommended (Wondolleck et al., 1996). Moreover, public participation is engendered by two aspects of social sustainability that must be taken into account in forest planning; namely, the need to maintain the social functions of the forest, and the increasing awareness and demand from the citizenry for fair and transparent processes in both the development of forest plans and the evaluation of management alternatives (Pukkala, 2002). This is particularly relevant in forestry because there are usually many objectives at stake and many interests involved that are also likely in conflict.

In view of its participatory nature, forest management methods must necessarily provide for mechanisms to carry out group, or participatory, decision-making. The individuals, along with other members of a community, usually have different expectations and possibly conflicting goals, which will certainly increase the complexity of decision-making in natural resources management.

Before expounding on the methodological aspects of group decision-making, the concept itself requires some clarification. As mentioned before, group decision is called for when many interests and potentially conflicting goals are involved. Group decision is, therefore, more a problem about consistency of the group's goals, preferences and beliefs than with the number of people involved, as pointed by Malczewski (1999). If a single structure of beliefs and interests can be assumed, then group decision-making can be treated in the same manner as individual decision-making, regardless of the number of people actually involved. Between these two extremes there is a gradient of decision situations as illustrated in Fig. 1.

Methodological adaptations of MCDA to group decision-making have evolved in three main aspects of a collaborative decision process: (1) identification of participants; (2) facilitation of participant's contributions with information; (3) aggregation of individual choices and decisions. Unless it is made explicit in the decision problem, the first aspect involves the identification of participants, which should be a clear and transparent process (Buchy and Hoverman, 2000). As Ravnborg and Westermann (2002) pointed, it should also be an ''actor-oriented and social constructivist'' approach that drives itself away from a mistaken perception of a homogeneous community that many participatory methods assume.

Readers are referred to Lahdelma et al. (2000) for a comprehensive characterization of participants' typologies. In most studies, the selection of the stakeholders is done by the analyst based on surveys and available information. Based on previous published work, Herath (2004) systematizes the selection methods in two groups: (a) identification through reputation, focus group or demographic groups or demographic analysis (Grimble and Chan, 1995); or (b) interactive identification, where previously unknown stakeholders reveal others (Harrison and Quershi, 2000). More formal frameworks

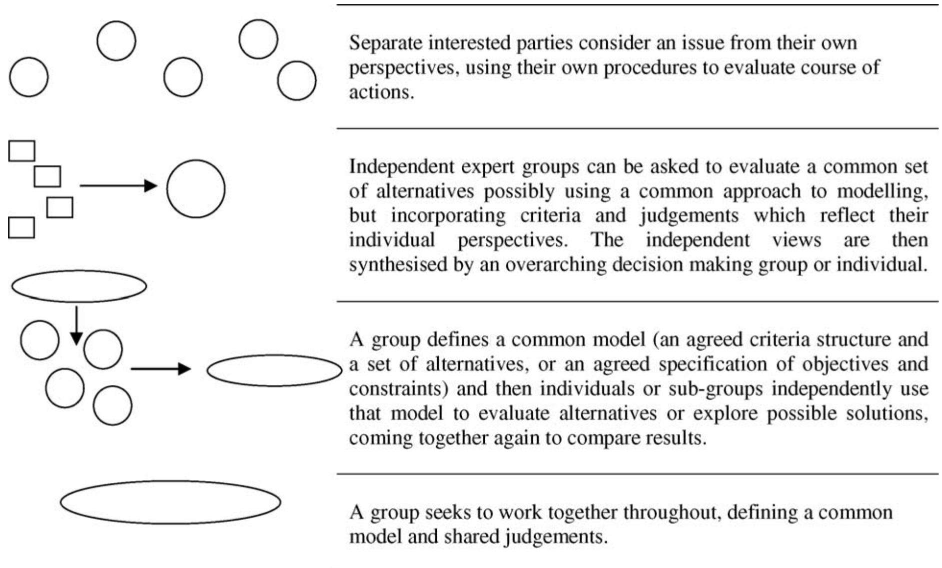

Fig. 1. Gradient of approaches to individual and group decision-making (Belton and Stewart, 2002).

for stakeholders' selection have been suggested by Grimble and Wellard (1997) and Colfer et al. (1999).

After identifying the decision makers, the next step is to facilitate their contribution with information that ultimately leads to the definition of the decision problem (management options, objectives and goals). The contributions under this aspect of MCDA are generally alternative-driven in the sense that decision makers are faced with a set of previously defined alternatives, hence, decision makers contribute only with their preferences by providing judgements on scores, criteria weights and attributes estimates (Keeney, 1992; Mendoza, 1995). This is done through elicitation methods that can be conducted either individually in a passive way, or collectively in a constructive way. Examples of both methods can be found in Hwang and Lin (1987) and Coughlan and Armour (1992). The Delphi method is an example of a passive method (e.g. Mendoza and Prabhu, 2000). This group of methods lack the advantage of decision makers being able to share and hear different opinions through open dialogue. Supporters of the constructive elicitation methods, such as the Focus group (e.g. McDaniels and Roessler, 1998), argue that these methods offer several advantages of an open discussion such as the consistency in the information obtained, and a progressively better definition of the preferences (McDaniels and Roessler, 1998; Laukkanen et al., 2002).

Elicitation methods have benefited greatly from the development of applied software designed as tools to motivate and support public participation. One of the most promising tools is the internet technology and accompanying development tools that allow dispersed and asynchronous working (Belton and Stewart, 2002). Thomson (2000), for example, demonstrates its use in the elicitation and representation of traditional knowledge for use in forest management. The design of computer assisted visualization tools has also been shown to have great potential in assisting elicitation methods (Bell, 2001).

Beyond the generally unstructured sets of information on preferences obtained from the decision makers, there is a need to make choices and decisions that would be considered satisfactory by the group. Thus, individual viewpoints and information gathered ought to be synthesised—the third methodological aspect of group decision that has to be considered. The synthesis of individual preferences can be done assuming either equal or unequal weights for stakeholders (Herath, 2004).

Belton and Pictet (1997) proposed a framework for this purpose where each judgement may be determined, namely by: (1) sharing: to obtain consensus through discussion; (2) aggregating: a process where differences are reduced analytically without discussion, for example by calculating geometric mean; (3) comparing: to reach consensus based on negotiation of individual results. Differences are acknowledged, but not reduced unless they mitigate against overall consensus.

Aggregation of individual judgements presents some problems. Arrow's theorem as described in Laukkanen et al. (2002) states that "there is no method of aggregating individual preferences over three or more alternatives that would satisfy several conditions for fairness and always produce a logical result". Moreover, aggregation may lead to compromise that is uncomfortable and unstable. Aggregation also has the drawback of giving to the analyst the responsibility of aggregating individual preferences in order to integrate them in the analytical procedure.

Aggregation is, however the most convenient method in many situations and it might be useful for individuals or homogeneous groups to explore potential compromise between their own internal conflicts (Laukkanen et al., 2002; Belton and Stewart, 2002). Laukkanen et al. (2002), however, also argued that negotiations might be susceptible to manipulation.

Table 5 lists a sample of the aggregating methods that have been applied in group decision-making, and a brief description

Table 5
Representative methods for aggregation of individual judgements on MCDM approaches

Method	References	Description
Voting models	Laukkanen et al. (2002) and Martin et al. (1996)	Each DM form his/her own judgements for each alternative. The final judgement will be formed based on combinations of these judgements, made by use of voting systems or multi-criteria approval
Aggregation of partial utility/value functions	Belton and Stewart (2002)	After preferences have been expressed in terms of these lowest level criteria, the aggregation step can be applied either across all the criteria in a single operation or may be applied hierarchically by aggregating at each level of the value tree across those criteria which share the same parent criterion at the next highest level in the tree
Paretian analysis	Cohon (1978)	The problem is formulated as a weighted sum of the participants' utilities. The weights are varied over a range of values politically feasible. Values can be selected by examining the results and using knowledge on the political situation. The method is computationally sensitive to the number of DM
Game theory	Cohon (1978)	Interaction among DM is explicitly considered. The utility gained by a DM depends on the actions of all participants in the decision-making process. Each player is faced with an ''efficiency problem'' (the identification of all Pareto-optimal non-inferior alternatives) and a ''bargaining problem'' (the selection of one of the Pareto-optimal alternatives). These are two levels of optimisation. But game theory assumes the first away by assuming a finite set of pregenerated alternatives
Vote-trading models	Cohon (1978) and Easley et al. (2000)	They are used in the analysis of the bargaining model. Computation of vote-trading probabilities for the participants in a group decision problem in which majority rules prevails. There is the key concept of logrolling—trading votes in one issue to secure favourable votes on another. It estimates the ''choice probability'', then used to compute a probability for each alternative of it being chosen by the decision unit
Interactive approaches	Kim and Ahm (1999)	Individual optimisation results can be used to form a group consensus and consider strict or weak dominance values as input for aggregation procedure. This method suggests a procedure that takes account of individual DM's preference strength. The aggregated net strength of an alternative can be defined as the difference between aggregated strength of an alternative over the others and the others over the alternative considered. The alternatives can be ranked by comparing the net strength between alternatives
AHP	Malczewski et al. (1997) and Herath (2004)	Three methods employed for aggregating group member's opinions: (1) geometric mean of individual evaluations is used as element in pairwise comparison matrices and then priorities are computed; (2) in weighted average mean method, priorities are computed and then combined using a weighted arithmetic mean
AHP and fuzzy set theory	Bantayan and Bishop (1998)	Three methods employed: (1) the optimistic: takes the maximum membership from all the evaluation matrices relative to the alternative in question and the calculation is a union operation; (2) the pessimistic: attempts to minimize risk by taking the smallest membership value and the calculation is done by intersection operation; (3) mixed: a reference value, usually the midpoint value in the preference scale is determined. If the all DM agree on the acceptability of an alternative based on an objective, a pessimistic aggregate is used; otherwise an optimistic aggregate is used. In case of disagreement a compromise value is used
Folded normal AHP	Easley et al. (2000)	Assumes that the ratio judgements are probabilistic rather than deterministic, thus relaxing the requirement of consistency in group judgements. The DM, when making their judgements, draws from a distribution (generally assumed to be normal) of random variables for each stimulus, such as an attribute judged on a particular criterion. This use of a distribution function allows to explicitly take into account the variance that is likely to exist in individual and group judgements
Public value forums	McDaniels and Roessler (1998)	The group does not negotiate, but rather provides a forum for individuals to make more informed value judgements about tradeoffs. The method uses the steps of decision analysis to create a well-structured decision problem, in which individuals are asked to provide judgements about appropriate tradeoffs among competing objectives. Answers can be analysed through descriptive statistics. They are compared and reconciled

of the assumptions underlying the methodological approach taken. A review of the more general methodological approaches to synthesize individual judgements can be found in Hwang and Lin (1987) and Belton and Pictet (1997).

5. New paradigms of participatory modelling in natural resource management

Complex problems in natural resources management, involving multiple objectives, multiple decision makers and uncertainty, have been challenging practitioners, planners and MCDA researchers to find more creative and innovative methodological approaches. Moreover, lately, there have been critical discussions about MCDA methods in particular, and traditional modelling approaches in general. These critical discussions point to the limitations of MCDA and the need for new and more flexible modelling paradigms. In this section, soft systems and knowledge-based system approaches are introduced as having potential to overcome some of the limitations of traditional MCDA methods. The critique are not meant to de-value MCDA; rather, they point to new ways of thinking about MCDA, particularly about participatory modelling as it is applied to forest and natural resource management planning.

5.1. The limitations of traditional MCDA approaches

Some of the less obvious limitations of the traditional MCDM methods when dealing with the complexity of natural resources management were summarized by Rosenhead (1989) as follows: (1) 'comprehensive rationality', which unrealistically presumes or aspires to substitute analytical results and computations for judgement; (2) the creative generation of alternatives is de-emphasised in favour of presumably objective feasible and optimal alternatives; (3) misunderstanding and misrepresenting the reasons and motivations for public involvement; (4) a lack of value framework beyond the typical 'utilitarian precepts'.

The limitations and weaknesses of traditional models are magnified when one considers a planning and decision environment that is entirely participatory. In fact, it is doubtful whether these rigid and highly algorithmic MCDA models can be adopted in an environment 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.

In view of the above limitations, a more flexible, robust, and broad approach to MCDA application to natural resources management is needed, one that is able to deal with ill-defined problems, with objectives that might be neither clearly stated or accepted by all constituents, with unknown problem components, and with unpredictable cause-and-effect relationships. A transparent and participatory definition of the planning and decision problems would also be desirable.

5.2. Soft systems approaches and alternative paradigms

In recognition of the limitations of the traditional MCDM methods, a number of authors (e.g. Rosenhead, 1989; Checkland, 1981) proposed an alternative paradigm, perhaps best described as 'soft systems' methods to address what these authors described as wicked, messy, ill-structured or difficult to define problems. According to Rosenhead (1989), these alternative paradigms are characterised by attributes such as: (1) search for alternative solutions, not necessarily optimal, but which are acceptable on separate dimensions without requiring explicit trade-offs; (2) reduced data demands through greater integration of hard and soft data including social judgements; (3) simplicity and transparency; (4) treatment of people as active subjects; (5) facilitation of bottom-up planning; (6) acceptance of uncertainty guided by attempts to keep options open as various subtleties of the problem are gradually revealed. An excellent review of these 'soft methods', or sometimes referred to as soft-operations research (OR) methods, can be found in Belton and Stewart (2002).

In general, soft systems approaches give less emphasis on generating solutions; instead, they give primacy to defining the most relevant factors, perspectives and issues that have to be taken into account, and in designing strategies upon which the problem can be better understood and the decision process better guided. They are also more adequate for addressing complex problems dominated by issues relevant to, and influenced by, human concerns and their purposeful schemes (Mendoza and Prabhu, 2002). By doing so, they recognize the intrinsically complex nature of social systems and consequently attempt to avoid prematurely imposing notions of objectivity, rationality, mechanistic and predictable causality among relevant components of the problem.

Two characteristic features that are central to the soft systems approach are facilitation and structuring. Facilitation aims to provide an environment where participants or stakeholders are properly guided and discussions or debate are appropriately channelled. Structuring, on the other hand pertains to the process with which the management problem is organized in a manner that stakeholders or participants can understand, and hence, ultimately participate in the planning and decision-making processes.

Current participatory approaches seem to exhibit only the facilitation feature. Participatory action research (Selener, 1997) or rural participatory appraisal (Chambers and Guijt, 1995) are examples of these approaches now widely applied, especially in the developing world. Despite the wide popularity of these traditional participatory approaches, it has received some criticism mainly because of their apparent lack of rigor, and their limited analytical and evaluative capabilities (Cooke and Kothari, 2001). Soft-(OR) spans both of these processes. While facilitating a decision process that is transparent and participatory, Soft-OR methods carry the analysis further by adding more formalized representation of the problem particularly the development of structured models that provide a focus and language for discussion (Belton and Stewart, 2002). Rosenhead (1989) calls this alternative paradigm "problem structuring" approach. Exploring values and options in an open environment and the bottom-up approach to problem solving are some of the strengths of the problem structuring methods (Mendoza and Prabhu, 2002).

Hjortso (2004) provides a demonstration of a Soft-OR method for problem structuring called strategic option development and analysis (SODA) in enhancing public participation of a tactical forest management planning process. By providing a way of identifying and structuring subjective concerns and multiple conflicting objectives, SODA facilitates the understanding and agreement within the group. The author adapted the eight activities suggested by Eden (1989) and performed a series of interviews, workshops and analysis. The results obtained pointed to the excellent potential of SODA in enhancing stakeholders' commitment to the final strategic forest plan.

One of the methods used in SODA is cognitive mapping, another Soft-OR method proposed by Eden (1988) as a network of nodes, arrows and links that represent concepts, ideas and their relationships. The result is a qualitative and comprehensive definition of the problem in its multiple facets. Mendoza and Prabhu (2003) have applied cognitive mapping in a qualitative approach to assessing indicators of sustainable forest resources management. The method was used to assess the impact of the indicators by examining their interrelationships and linkages in order to look at their overall cumulative dynamic effects.

In the context of a group decision, cognitive mapping can also be seen as a structured way of group members transmitting concepts and their understanding of the structure of the problem as it was demonstrated in Tikkanen et al. (in press) in a planning exercise involving 23 forest owners. An extensive review of cognitive mapping applied to ecological modelling and environmental management is provided by Özesmi and Özesmi (2004). The same authors also demonstrate a fuzzy adaptation of cognitive mapping to model the views of different stakeholders on the conflict over the creation of a national park.

An alternative approach to cognitive mapping is qualitative systems dynamics (Wolstenholme, 1999), another Soft-OR approach that provides more explicit relationships between the arrows and the nodes in terms of causality, changes and impacts. Purnomo et al. (2004) have demonstrated its application in collaborative planning of community-managed resources. The study started with traditional participatory methods to fully discuss and explore different views and perspectives from the participants. This was followed by collaborative modelling, which used a combination of causality trees and causal loop diagrams to organize, in a systematic and qualitative way, the information collected previously, and to represent the interactions and causal relationships between management components. The direct participation and involvement of the stakeholders in the modelling process enabled them to contribute with their collective knowledge, expertise, and experience.

One of the strengths of Soft-OR methods applied to natural resources management is the capability they offer in structuring, and providing a better understanding of, complex problems under poor data situations. In this case, capturing and representing local knowledge is sometimes the best possible way to obtain information, and to structure a decision problem (e.g. Thomson, 2000; Mendoza and Prabhu, 2002; Sicat et al., 2005; Purnomo et al., 2004). As Thomson (2000) claims, forest management is mainly based on analysis of 'hard' information; hence, research is still needed to find good methods of representing traditional, local or ecological knowledge in order to make them available for modelling and planning. This need led to the development of approaches that formally analyse qualitative decision problems such as: artificial neural networks (e.g. Blackard and Dean, 1999; Moisen and Frescino, 2002; Liu et al., 2003), knowledge bases (e.g. Reynolds et al., 1996, 2000), and expert systems (e.g. Store and Kangas, 2001; Iliadis et al., 2002). Two applications in particular of these new approaches, developed as decision support systems, are the Ecosystem Management Decision Support System (EMDS) developed by Reynolds (1999) and CORMAS (Common-pool Resources and Multi-Agent Systems) developed by Bousquet et al. (1998).

As Reynolds (1999) indicated, EMDS "integrates the logic formalism of knowledge-based reasoning as implemented in the NetWeaver (Rules of Thumb, North East, PA) knowledge-base system, into a geographic information systems". Behind the development of EMDS there is also the acknowledgement that qualitative information became more relevant and needed with the increasingly broader complexity of ecological and natural resources problems. Consequently, EMDS makes use of fuzzy logic to represent and integrate imprecise information (Reynolds et al., 2000). Some examples of the application of EMDS to natural resources management are provided by Reynolds et al. (2000) in the assessment of a watershed condition, by Reynolds et al. (2003) in the evaluation of forest ecosystem sustainability, and by Bourgeron et al. (2000) in conducting large-scale conservation evaluation and conservation area selection.

CORMAS adopts a multi-agent systems application specifically designed for renewable resource management. Multi-agent systems evolved from knowledge-based systems, which makes it possible to represent "knowledge and reasoning of several heterogeneous agents that need to be accommodated in addressing planning problems in a collective way" (Bousquet and Le Page, 2004). A review of its applications to ecosystem management is reported by Bousquet and Le Page (2004). An integrated use of CORMAS, Geographic Information Systems (GIS), and participatory modelling was developed for the Senegal River Valley and was reported by Aquino et al. (2002) as a successful decision aid and local empowerment tool for dealing with resource management issues such as sustainable land-use management. CORMAS has also been the platform used by Purnomo et al. (2005) to develop and analyse a multi-agent simulation model of a community-managed forest.

5.3. Integrated approach to participatory modelling

The overview presented in the previous sections build the case for, and serves as a strong justification for proposing a call to a new way of thinking about MCDM applied to strategic natural resources management planning. The key word for this new approach is integration, in a parallel way, and consistent with the integrated approach proposed by Belton and Stewart (2002). The linking of a qualitative approach to problem structuring that emphasises the social aspects of the forest, with a structured approach that retains some of the analytical capabilities of the "hard systems approach", is one of the key aspects of such an integrated approach. One advantage of an integrated approach is its ability to embrace the strengths of each method. The qualitative soft systems method allows a more participatory decision-making process with active involvement and commitment from the stakeholders. On the other hand, the quantitative and structured approach to the decision-making process is more systematic and the analyses more objective.

The difference between this integrated approach and, one in relation to traditional group MCDM methods, is that decision makers not only provide input to the model, but they also contribute to the modelling process by being involved in identifying model components, dynamics or processes between and among model components, and their relationships

(Purnomo et al., 2004; Mendoza and Prabhu, 2005). Hence, the modelling process is transparent, participatory, and accessible to decision-makers.

A dynamic integration can also be achieved using a tighter coupling of MCDA with participatory modelling. Mendoza and Prabhu (2002) exemplified the integration of MCDM methods (used to aggregate cumulative impacts of ''contributing factors'' in a community-forest system) with a qualitative soft system dynamic model. For example, a computer assisted model called Co-View (Collaborative Vision Exploration Workbench) developed by the Center for International Forestry Research was used to develop a qualitative systems dynamic approach to modelling.

6. Concluding remarks: future directions for MCDA in natural resource management

From the overview and critical reviews of MCDA described in the previous sections, along with the descriptions and discussions about other alternative paradigms, it is clear that MCDA offers a suitable planning and decision-making framework for natural resources management. Because it is inherently robust, it can also provide a convenient platform that lends itself well in bridging the gap between the soft qualitative planning paradigm and the more structured and analytical quantitative paradigm. Approaches that integrate these two paradigms offer some promise in terms of more adequately accommodating the inherent complexity of natural resources management, embracing ecological, biophysical, and social components, and capturing the multitude of concerns, issues, and objectives of stakeholders. Initial efforts attempting such integration indicated a very promising potential for this approach.

Belton and Stewart (2002) also suggested that the way forward for MCDA is to achieve a stronger integration of both theory and practise. They proposed a 'hybridizing' of methodologies that will create opportunities for 'synergistic' accumulation of insights from the different methods. They noted that an integrating framework must identify common elements among the methodologies and highlight the strengths of each method. They suggested further that principles identified by one MCDA school of thought should inform the implementation of methodologies employed by other schools, without these schools having to abandon their own principles. Such integration may lead to what they call, Meta-MCDA. This integration of methods is also a potential direction for future research as argued by Kangas et al. (2001a).

Mingers (2000) also offered a compelling argument for, and a strong justification to, combine soft and hard systems methods. In advancing the idea of mixing methodologies, he proposed a multi-methodology framework (Mingers and Brocklesby, 1997) that allows for mixing, linking, combining, or integrating different methodologies and paradigms. Rosenhead and Mingers (2001) stated that the ''essence of multi-methodology is to utilize more than one methodology or part of thereof, possibly from different paradigms, within a single intervention''. Consequently, Rosenhead and Mingers (2001) identified three broad types of multi-methodology frameworks as follows: *methodology combination*: uses two or more methodologies within an intervention; *methodology enhancement*: uses one main methodology but enhancing it by importing methods elsewhere; *single paradigm methodology*: combining parts of several methodologies all from the same paradigm; *multi-paradigm multi-methodology*: uses methods from different paradigms.

In terms of practise, MCDA must adopt a more participatory posture at all levels of the modelling process. Stakeholders or decision makers must be able to participate and contribute actively to modelling—from identification of model elements, formulation of relationships, and all other model components, including the actual decision-making process. This calls for a more transparent, simple, and easily accessible participatory modelling paradigm and process.

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