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ORIGINAL ARTICLE

Forest management with multiple criteria and multiple stakeholders: An application to two public forests in Spain

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Abstract

Nowadays most forest management problems require the integration of multiple criteria, at the same time as considering the points of view of several stakeholders with different perceptions of predefined criteria. As part of this theoretical orientation, a recent method for aggregating individual preferences expressed through pairwise comparison matrices has been adapted and applied in this paper to elicit social weights in the context of a forest management problem. The method was applied to two public forests in Spain. Four objectives were considered to be relevant in this exercise: biodiversity, net carbon captured, veneer volume and net present value. Twenty-three interviews with graduate students of the forestry school of the Technical University of Madrid were made in a pairwise comparison format. The respective 23 pairwise comparison matrices were aggregated into a final consensus matrix, which aims to represent the social importance attached to the four objectives considered. The applied method allows the establishment of a balance between the majority and minority principles.

Keywords: *Forest management, goal programming, group decision making, multiple criteria decision making, pairwise comparisons, participatory decision making.*

Introduction

The focus of forest management has changed dramatically over the past few years for two reasons. First, modern society is demanding not only private goods with well-defined markets (e.g. timber, forage, hunting activities), but also public goods and services of an environmental nature without established markets (e.g. biodiversity conservation, soil erosion, carbon sequestering) from forest ecosystems. Therefore, there has been a sizeable boom in the literature addressing forest management problems with the help of multiple-criteria decision-making (MCDM) approaches over the past few years (see Diaz-Balteiro & Romero, 2008, for a recent review).

Secondly, the focus of forest management has also changed owing to the manner in which different social groups or stakeholders perceive the relative importance of the different criteria involved in the decision-making process. This multiplicity of stakeholders in the underlying decision-making process means that it is of paramount importance for the forest management field to adopt tools from the group decision-making discipline (Kangas et al., 2005; Mendoza & Martins, 2006; Martins & Borges, 2007).

In short, the forest management discipline needs to integrate multiple criteria as well as multiple stakeholders into models to make them more realistic. Therefore, some sort of merger between MCDM and the group decision-making discipline appears to be necessary. The following are the main attempts made in this direction. Tecle et al. (1998) use two methods to formulate a problem with five objectives in a group decision-making framework: co-operative games and compromise programming. This last method was applied by Phua and Minowa (2005) to integrate the forest conservation priorities of several decision makers.

Several variants of the analytic hierarchy process (AHP) (Saaty, 1980) have been used to achieve a consensus between different judgements from several stakeholders in a forestry context (e.g. Schmoldt & Petersen, 2000, 2001; Leskinen et al., 2006; Ananda, 2007).

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The integration of tactical plans for private forests on a more aggregated scale (landscape level) was addressed by Pykäläinen et al. (2001) by applying an optimization model with an interface to be used in group decision-making problems. This hierarchical model incorporates a multiattribute utility (MAUT) method called HERO (Pukkala & Kangas, 1993). Before applying the MAUT method, the landscape optimum structure was established using a goal programming formulation.

Kangas and Kangas (2003) and Laukkanen et al. (2002, 2004) apply the multicriteria approval (MA) method, suggested by Fraser and Hauge (1998), to group decision-making problems in forestry. The MA approach is an ordinal method that does not require too much preference information from the social groups/decision makers involved. Kangas et al. (2006) combined this method with the fuzzy set theory, while Pykäläinen et al. (2007) applied several ordinal methodologies, including the MA method, to a participatory forest planning case in Finland. The results are compared with a cardinal approach based on utility analysis implemented in an interactive fashion. Recently, in Kangas et al. (2008), some of these techniques have been described and assessed.

This paper aims to take a step towards addressing forest management problems with multiple criteria and multiple stakeholders. In this way, a recently proposed method by two authors of this paper, which is able to aggregate individual preferences expressed as pairwise comparison (pc) matrices, is tested within a forestry scenario. Thus, the method was adapted and applied to a Spanish forest management case study in a context where no spatial goals were considered. Two key references addressing group decision-making problems with explicit spatial forest goals are Jumppanen et al. (2003) and Kurttila and Pukkala (2003). The rest of the paper is organized as follows. The method is described and assessed in the next section. After that, the case study illustrates how this method works. The main conclusions derived from the research, as well as possible further extensions, are presented in the last section.

Materials and methods

Analytical framework

The two most widely used methods for the aggregation of pc matrices are the geometric mean method and the weighted arithmetic mean method (e.g. Dyer & Forman, 1992; Barzilai & Golany, 1994). The popularity of these two methods is due mainly to the facts that they satisfy reciprocal properties for every pc matrix and that they are computer friendly.

In the case study analysed in the next subsection, the individual pc matrices were obtained empirically and do not have satisfactory properties such as consistency or reciprocity. Hence, non-conventional pc matrix aggregation procedures had to be used. A recently proposed method for aggregating pc matrices without satisfactory properties such as reciprocity (González-Pachón & Romero, 2007) was chosen. This method was adapted to the problem situation using the following notation: $i =$ number of criteria involved $(1, 2, \ldots, n)$, $k =$ number of stakeholders involved $(1, 2, \ldots, m)$, $m_{ij}^{(k)}$ = ratio value that quantifies the judgement made by the kth stakeholder when comparing the ith criterion with the jth criterion (i.e. this type of ratio information represents the problem data and has a cardinal character), $m_{ij}^{(c)}$ = consensus ratio value that quantifies the aggregated judgement when ith criterion is compared with jth criterion (i.e. this type of ratio represents the problem unknowns), and W_i = consensus preferential weight attached to the ith criterion compatible with the previously obtained consensus ratio values $m_{ij}^{(c)}$. These weights represent the final output provided by the model.

Accordingly, there are m pc matrices: $\mathbf{M^1}, \mathbf{M^2}, \ldots, \mathbf{M^m}$, that is, one matrix for each stakeholder or social group. These matrices do not necessarily have satisfactory properties such as reciprocity and consistency. González-Pachón and Romero (2007) propose searching for a pc consensus matrix $\mathbf{M^c}$ that differs "as little as possible" from $\mathbf{M^1}, \mathbf{M^2}, \ldots, \mathbf{M^m}$. To do this, they proposed minimizing the distance between $\mathbf{M^c}$ and $\mathbf{M^1}, \mathbf{M^2}, \ldots, \mathbf{M^m}$ through the following distance function optimization problem for a generic metric p:

$$\text{Min}\left[\sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{\substack{j=i\\ j\neq i}}^{n}|m_{ij}^{(k)} - m_{ij}^{(c)}|^{p}\right]^{1/p}$$

s.t.

$$0.111 \le m_{ij}^{(c)} \le 9 \quad i,j \in \{1,\ldots,n\} \tag{1}$$

Some scale conditions appear in the constraint set and, in this respect, the widely used Saaty scale was chosen. Appendix 1 shows the scale used and the meaning of the extreme values 9 and 0.111, as well as the meaning of the intermediate values of the scale. The optimization problem (1) is not computable. However, it can be easily reduced to the following Extended Goal Programming (EGP) formulation, which is very easy to compute (for technical details relative to the following model see Romero, 2001; González-Pachón & Romero, 2007):

Achievement function:

$$\text{Min } (1-\lambda)D+\lambda\left[\sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{\substack{j=i\\ j\neq i}}^{n}(n_{ij}^{k}+p_{ij}^{k})\right]$$

s.t.

Goals and constraints:

$$m_{ij}^{(c)}-m_{ij}^{(k)}+n_{ij}^{k}-p_{ij}^{k}=0$$

$$i,j\in\{1,\ldots,n\}\quad k\in\{1,\ldots,m\}$$

$$\sum_{i=1}^{n}\sum_{\substack{j=i\\ j\neq i}}^{n}(n_{ij}^{k}+p_{ij}^{k})-D\leq 0\quad k\in\{1,\ldots,m\}$$

$$0.111\leq m_{ij}^{(c)}\leq 9\quad i,j\in\{1,\ldots,n\}$$

$$\underline{\mathbf{n}}\geq 0,\underline{\mathbf{p}}\geq 0$$

$$\lambda\in[0,1]\text{ (control parameter)}\tag{2}$$

The variables n_{ij}^{k} and p_{ij}^{k} of model (2) are the negative and positive deviation variables of the GP model, now playing the role of auxiliary variables measuring the underachievement and the overachievement, respectively, between the consensus ratio value $m_{ij}^{(c)}$ and the ratio value $m_{ij}^{(k)}$ for the *k*th stakeholder. Variable *D* represents the maximum deviation, i.e. the discrepancy of the stakeholder that is most displaced from the consensus obtained. For $\lambda=1$, model (2) provides the consensus solution that optimizes the utility group, i.e. the solution for which the aggregated consensus is optimized. For $\lambda=0$, model (2) provides the consensus solution that optimizes the utility of the person most displaced from the solution, i.e. the solution for which the consensus is most balanced. Intermediate solutions, if they exist, can be obtained for values of the control parameter λ within the open interval (0, 1). In short, control parameter λ can be interpreted as being the trade-off or marginal rate of transformation between majority consensus ($\lambda=1$) and minority consensus ($\lambda=0$).

Once the consensus matrix $m_{ij}^{(c)}$ has been elicited, it is a relatively simple exercise to derive the preferential weights compatible with the information contained in the matrix. Since the consensus matrix obtained is not necessarily reciprocal, the well-known technique proposed by Saaty, based on the calculation of the maximum eigenvalue, cannot be applied. However, these weights can be easily derived by resorting to a straightforward GP formulation (e.g. González-Pachón et al., 2003).

Case study

Let us start with a brief description of the key features of the forests in the case study. Matarrucha and El Monte are public forests, situated in the district Vilviestre del Pinar in north-eastern Spain (Sierra de la Demanda) at an average altitude of 1100 m. The forests are populated mainly by coni fers and cover a total area of 2642 ha. The most dominant species are *Pinus sylvestris* L. and *Pinus pinaster* Ait. There is also a pasture exploitation. The wildlife and game resources are quite considerable, but the main forest management objective is timber production. The main game species are roe deer and wild boar. The forest has been managed up until now by using traditional methods, which are not based on optimization approaches. To reorganize the management of the Matarrucha and El Monte forests, the following criteria were considered relevant for building a sensible management optimization model.

- Biodiversity (BIO): this criterion aims to reflect the maintenance of the current diversity of the forest in terms of wildlife and game resources.
- Net carbon captured (NCC): this criterion measures the net carbon captured by the timber stands across the planning horizon.
- Veneer volume (VV): this criterion aims to measure the part of the timber volume with more commercial value.
- Net present value (NPV): this criterion measures the economic profitability attached to each potential investment plan.

The four criteria are defined in the sense of more is better. The first two criteria are ecological, while the other two are economic. To formulate an optimization model to organize the management of the forest, it is necessary to estimate the preferential weights to be attached to each of the four criteria defined above. These criteria embrace aspects that habitually characterize a sustainable forest management (Vierikko et al., 2008).

To do this, 23 postgraduate students from the Technical University of Madrid's Forestry School were interviewed. This sample of students played the role of stakeholders potentially involved in this type of decision-making process. The interviews were formulated as a pairwise comparison. Each postgraduate student was asked questions of the type: Of the *i*th criterion and the *j*th criterion, which one is more important and by how much? The questions were formulated with the help of the Saaty verbal scale (Saaty, 1977, 1980), which has been widely used and tested in practice. Note that the scale is verbal, i.e. stakeholders are not required to give numerical responses (e.g. biodiversity is moderately more important than veneer volume). Saaty's scale transforms the verbal statements into numerical values (see Appendix 1). This yields the ratio values $m_{ij}^{(k)}$. These values quantify the judgement made by the *k*th stakeholder when comparing the *i*th criterion with the *j*th criterion.

Notice that the main forestry features of the case study were introduced with a written and oral presentation, first in a group showing the current forest management plan, and later individually. Thus, the respondents did not make abstract pairwise comparisons but had a clear picture of the particularities of the analysed forest. This method avoided some common mistakes in this type of exercise. For example, no meaningless questions were asked, e.g. How important is biodiversity conservation, generally, compared to economic profitability? (see Keeney, 2002, for a precise analysis of this type of common mistake).

No assumptions about the consistency of the judgements provided by the postgraduate students were made in this exercise. Therefore, 4(4–1) judgements were needed from each person interviewed. First, three questions were asked corresponding to the upper part of the matrix for the 23 respondents, and around 4 weeks later the questions corresponding to the lower part of the 23 matrices were asked. In this way, the reciprocal consistency of the interviewers was tested. The results obtained in this direction were very conclusive, since in none of the 23 matrices did the reciprocity condition hold (i.e. $m_{ij}^{(k)} \neq 1/m_{ij}^{(k)} \forall i,j$).

Results

The 23 non-reciprocal Saaty matrices obtained appear in Appendix 2. The next step was to aggregate the 23 matrices to obtain an aggregated matrix representing a consensus solution for the different preferential views given by the respondents. The results shown in Table I were obtained by applying model (2). It should be noted that in this table variable *D* measures the deviation between the consensus obtained and the view of the minority (see model 2), while variable *A* measures the deviation between the consensus obtained and the view of the majority, i.e. the value achieved in the optimum solution by the second term of the achievement function of model (2).

The trade-off curve between the amount of consensus from the point of view of the majority and the amount of consensus from the point of view of the minority is calculated from the last two columns of Table I (see Figure 1). Note that the slopes linking the corner points measure the marginal rate of transformation between these two opposite measures of consensus (majority versus minority).

From the analysis of the information contained in Table I, the following conclusions may be drawn. (1) The optimum aggregated consensus is obtained for values of the control parameter λ greater than 0.5. (2) The most balanced consensus is obtained for values of control parameter λ of less than 0.05. (3) In between the two opposite poles (optimum aggregated consensus and most balanced consensus), there are six intermediate solutions or consensus

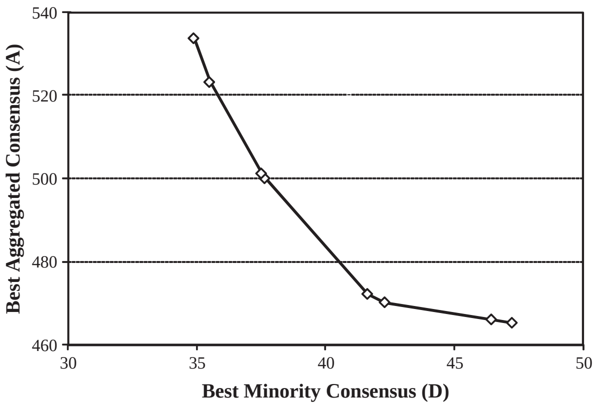

Figure 1. Trade-off curve between minority consensus and majority consensus.

Table I. Consensus values, maximum disagreement (*D*) and aggregated disagreement (*A*).

Consensus values	$m_{12}^{(c)}$	$m_{13}^{(c)}$	$m_{14}^{(c)}$	$m_{21}^{(c)}$	$m_{23}^{(c)}$	$m_{24}^{(c)}$	$m_{31}^{(c)}$	$m_{32}^{(c)}$	$m_{34}^{(c)}$	$m_{41}^{(c)}$	$m_{42}^{(c)}$	$m_{43}^{(c)}$	*D*	*A*
Control parameter λ														
[1, 0.5)	3	3	3	0.33	1	1	0.33	1	0.33	0.20	1	1	47.22	465.19
[0.5)	3	3	3	0.20	0.33	1	0.33	1	0.33	0.20	3	1	46.42	465.99
[0.49, 0.25)	3	3	3	0.20	0.33	1	0.33	3	0.33	0.33	3	3	42.29	470.12
[0.25, 0.12)	3	3	3	0.20	0.33	0.33	0.33	3	0.33	0.33	3	3	41.62	472.13
[0.12, 0.10)	3	1	3	0.20	0.33	0.33	0.33	5	0.33	0.33	3	3	37.64	499.99
[0.10, 0.08)	3	1	3	0.20	0.33	0.33	0.33	5	0.20	0.33	3	3	37.51	501.16
[0.08, 0.05)	3	1.70	3	0.20	0.33	0.33	0.33	5	0.20	1	3	5	35.50	523.16
[0.05, 0)	3	1.70	3	0.20	0.33	0.33	0.33	5	0.14	1	3	5.57	34.89	533.71

matrices. (4) There is a relatively large degree of conflict between the two opposite solutions. Figure 1 aims to quantify this degree of conflict. In any case, a maximum improvement in the balanced direction of 26.11% (i.e. a reduction in the value of variable D from 47.22 to 34.89) implies an impoverishment of 14.73% in the aggregated direction (i.e. an increase in the value of variable A from 465.19 to 533.71), and vice versa.

The associated vector of preferential weights (W_i, $i = 1, \dots, 4$) can be calculated for each of the eight consensus matrices shown in Table I. To undertake this task, and as the matrices are non-reciprocal, the maximum eigenvalue method proposed by Saaty cannot be applied, although for this type of situation a GP method can efficiently derive the associated weights (González-Pachón et al., 2003). The vector of weights derived from the consensus matrices is shown in Table II. It should be noted that the first two consensus matrices lead to the first vector of weights, the next four matrices lead to the second vector of weights and, finally, the last two consensus matrices direct to the last vector of weights. The respective consistency index was calculated with respect to the maximum possible level of inconsistency. For instance, a consistency index of 0.901 means that the aggregated judgements contained in the respective pc matrices are 90.10% consistent (for details see González-Pachón et al., 2003).

Discussion

The need to integrate different types of multiple criteria, as well as the points of view of several stakeholders, into forest management models appears to be the rule rather than the exception nowadays. Stakeholders can express their preferences in different formats. Of these, pairwise comparison systems leading to pc matrices appear to be a very suitable option. In fact, the main practical and theoretical virtue of the pairwise comparison procedure is its simplicity: it takes two parts at a time when it is too difficult to handle the whole. In addition, the procedure used in the paper to aggregate pc matrices has two important advantages: (1) the computational burden is very light: the derivation of the different aggregated pc matrices, and that of the corresponding social weights, lead to goal programming formulations, in which only linear programming models of a moderate size have to be solved; and (2) the different aggregate pc matrices obtained can be straightforwardly interpreted in preferential terms. Thus, there is an aggregated pc matrix that maximizes the aggregated consensus (i.e. point of view of the majority), an aggregated pc matrix that maximizes the balanced consensus (i.e. point of view of the minority) and several potential aggregated pc matrices that represent compromises between these two solutions.

Even though this paper has a methodological orientation, the results could be a useful first step towards implementing a MCDM model for the management of the Matarrucha and El Monte forests. Finally, it should be pointed out that the consensus pc matrices were calculated assuming that the stakeholders wanted to act as a unit. Thus, the 23 pc matrices were aggregated into a single consensus pc matrix, from which the social weights were derived. It may be interesting to explore an alternative case, in which the stakeholders want to act as separate individuals. In this type of situation, instead of building a common aggregate pc matrix, a priority vector will be calculated for each of the individual pc matrices. Finally, the priority vectors can be aggregated using the same type of goal programming-based method.

In conclusion, nowadays many forest management problems require the consideration of several criteria of a different nature as well as the assessment of different viewpoints of several stakeholders. The method adapted and tested in this paper addresses this type of complex problem very efficiently for the following reasons: (1) the computational burden is very low: the method only requires the solution of a limited number of linear programming problems of a moderate size; (2) the level of interactivity is very low: once the initial pairwise information has been obtained, no more interaction with the stakeholders is required; (3) all

Table II. Social weights with respective consistency indices.

	Social weights				
Control parameter λ	W_1	W_2	W_3	W_4	Consistency index
[1, 0.49)	0.500	0.166	0.166	0.166	0.978
[0.49, 0.08)	0.562	0.062	0.188	0.188	0.901
[0.08, 0)	0.395	0.131	0.079	0.395	0.719

the consensuses obtained can be easily interpreted in preferential terms; and (4) the method allows the combination of the two basic social principles of the majority and the minority.

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Appendix 1. Summary of Saaty's fundamental scale (Saaty, 1977).

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one activity over another
5	Strong importance	Experience and judgement strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another, its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation

Appendix 2. The 23 "pairwise" comparison matrices obtained from the respective interviews.

	BIO	NCC	VV	NPV	BIO	NCC	VV	NPV	BIO	NCC	VV	NPV
BIO	1	7	9	3	1	3	5	3	1	9	0.33	0.14
NCC	0.20	1	0.33	0.20	0.20	1	0.33	0.20	0.11	1	0.11	0.11
VV	0.11	0.20	1	0.20	0.11	5	1	0.20	7	9	1	0.11
NPV	0.20	0.33	7	1	0.20	0.33	0.11	1	7	9	7	1
BIO	1	1	7	7	1	3	5	3	1	3	0.20	0.33
NCC	0.20	1	7	7	1	1	3	3	0.20	1	0.14	0.20
VV	0.11	0.14	1	0.14	0.20	0.14	1	1	3	9	1	3
NPV	0.14	0.14	7	1	0.20	0.20	0.33	1	0.33	3	0.20	1
BIO	1	3	0.33	0.20	1	5	0.33	0.14	1	3	0.14	0.14
NCC	0.33	1	0.20	0.14	0.33	1	0.14	0.14	0.20	1	0.20	0.33
VV	3	5	1	0.33	7	9	1	0.33	7	7	1	0.33
NPV	3	5	1	1	9	9	3	1	3	5	0.11	1
BIO	1	5	3	5	1	5	3	3	1	3	7	3
NCC	0.20	1	1	5	0.14	1	0.20	0.20	0.33	1	5	7
VV	0.20	0.20	1	5	0.33	5	1	0.33	0.33	0.14	1	0.33
NPV	0.20	0.20	0.33	1	0.20	3	0.33	1	0.20	0.20	0.33	1
BIO	1	3	5	5	1	3	1	3	1	5	7	5
NCC	0.20	1	3	3	0.33	1	0.20	0.33	0.14	1	3	1
VV	0.33	3	1	1	0.20	0.33	1	5	0.11	0.20	1	0.33
NPV	1	3	5	1	0.33	1	5	1	0.20	3	5	1
BIO	1	0.33	3	5	1	5	1	0.33	1	0.20	5	3
NCC	5	1	4	5	0.33	1	0.33	1	1	1	7	7
VV	0.33	1	1	3	1	3	1	0.20	0.20	0.14	1	0.33
NPV	0.20	0.20	0.25	1	3	5	3	1	0.20	0.20	3	1
BIO	1	3	5	7	1	3	5	5	1	3	5	3
NCC	0.33	1	3	5	1	1	3	5	0.20	1	5	3
VV	0.20	0.33	1	5	0.14	0.33	1	1	3	5	1	0.20
NPV	0.14	0.20	0.33	1	0.33	0.33	1	1	3	5	3	1
BIO	1	3	0.33	3	1	0.33	3	3				
NCC	0.33	1	0.33	0.33	0.33	1	1	3				
VV	0.33	3	1	3	0.11	0.20	1	0.14				
NPV	1	5	1	1	0.20	0.33	3	1				

BIO = biodiversity; NCC = net carbon captured; VV = veneer volume; NPV = net present value.