



A combined multi-criteria approach to assess forest management sustainability: an application to the forests of Eastern Macedonia & Thrace Region in Greece

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Abstract

Sustainable forest management should be pursued in all public forests of the EU countries, as this constitutes a legal requirement within the frame of the FOREST EUROPE policy. However, the forest management sustainability assessment process is a complex task, mainly because it involves integration of multiple environmental, socio-economic and institutional impacts at different spatial scales of different forest management policies, which are considered for implementation at any forest location. Moreover, the conflicts and interests of the various stakeholders related to the forest resources should be included in the assessment process. Much of the on-going research, therefore, focuses on the development of tools that can facilitate the integration of the different type of forest resource impacts and conflicts towards achievement of forest management sustainability. This paper presents a multi-criteria approach, which combined spatial analysis, Geographic Information Systems (GIS), the Analytic Hierarchy Process (AHP), spatially referenced impact indicator models for pairwise comparisons, the fuzzy extent analysis, fuzzy preference programming and the ideal solution concept in order to assess the performance of forest management sustainability at regional level. The combined multi-criteria approach was successfully implemented to the forests of Eastern Macedonia and Thrace Region in northern Greece through the operation of the National Forest Governance Council. Seven forest management policies were subjected to sustainability assessment and an Overall Forest Sustainability Performance Index (OFSPI) was calculated for each one of them. The final ranking of the forest management policies was based on their OFSPI values. Furthermore, sensitivity analysis was conducted to explore robustness of the final solution.

Keywords Fuzzy AHP · Fuzzy extent analysis · Fuzzy preference programming · Spatial analysis · Governance · Sustainable forest management

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1 Introduction

Forests have an important ecological and economic role particularly in the mountain and rural areas of Europe and are managed for different purposes to fulfill various demands of different stakeholders. These demands involve the production of wood and non-wood products and the provision of services, such as recreation, water, biodiversity, soil protection and carbon storage. Simultaneous fulfillment of these demands since the 90s has been pursued in the context of Sustainable Forest Management (SFM), following the seminal UN Conference on Environment and Development in 1992 (UN 1992), which raised the concept of sustainability into a subject of public interest. Therefore, the SFM definition from its traditional meaning of sustained yield for over two centuries in Europe (Farell et al. 2000; Wolfslener et al. 2005) was extended so as to include “stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, generation capacity, vitality and their potential to fulfill now and in the future, relevant ecological, economic and social functions at local, national and global levels” (MCPFE 1993). In the European Union (EU) SFM should also be pursued in line with the new EU Forest Strategy (European Commission 2013).

From the operational point of view at the current state of art, the extant evaluation tools are mainly in the form of criteria and indicators, which have been developed to measure quantitatively or qualitatively aspects of Sustainable Forest Management. In the EU territory the best known such tools have been expressed through the Pan-European (MCPFE) Criteria and Indicators (C&I) within the FOREST EUROPE policy context (MCPFE 2003), which the member states are committed to use in order to monitor and report about sustainable forest management at national level.

However, despite the growing concern since the 90s in ensuring forest management sustainability at different levels, only few studies focusing on integrated forest sustainability assessments have seen publicity (Wolfslener et al. 2005; Lindner et al. 2010; Jalilova et al. 2012; Martinez-Vega et al. 2016; Nilsson et al. 2016; Kazana et al. 2015; Kazana et al. 2017; Martin-Fernandez and Martinez-Falero 2018). The majority of published studies in the context of SFM concerns resource allocation, where SFM often is reflected through sustained yield and/or habitat requirement constraints (Hasle et al. 2000; Kazana et al. 2003; Alfandari et al. 2011; Gomez et al. 2011; Zhang et al. 2011; Gharis et al. 2015; Wei and Murray 2015; John and Tóth 2015; Teclé 2018) or specific decision environments, such as location choices, fire risk modeling or biodiversity evaluation (Kurttila et al. 2000; Shrestha et al. 2004; Mendoza and Prabhu 2004; Kangas and Kangas 2005; Margles et al. 2010; Dursun and Kaya 2010; Kaya and Kahraman 2011; Zandebbarisi et al. 2012; Sharma et al. 2012; Lepetu 2012; Derak and Cortina 2014; Allende et al. 2014; Salehnasab et al. 2016; Birendra et al. 2014; Bilbao-Terol et al. 2016; Mohammadi and Limaie 2018; Mehta et al. 2018). On the contrary, in other fields of applications, such as sustainable development, renewable energy sustainability, supply chain sustainability performance and construction industry a substantial number of published studies provided useful decision tools for overall sustainability assessments (Venema and Calamai 2003; Ertuğrul and Karakaşoğlu 2006; Kaya and Kahraman 2010; Choo and Yu 2013; Santoyo-Castelazo and Azapagic 2014; Li and Zhang 2015; Shewell and Migiro 2016; Isik and Aladag 2017; Cirstea et al. 2018; Ioannou et al. 2018, Malesios et al. 2018; Mohammed 2019; Nechi et al. 2019).

The scarcity of published studies on integrated assessments of forest sustainability performance may be attributed to the multi-level and multifunctional complexity inherent

in the forest sustainability assessment process, which requires (i) a clear definition of the forest decision making environment (spatial scale/spatial entities, decision-making level, stakeholders involved, alternative forest management regimes, time frame), (ii) selection of appropriate impact indicator tools to measure the different types of environmental, socio-economic and institutional impacts at relevant spatial scales and decision making levels, (iii) elicitation of preferences that reflect the interests of the various stakeholders for the forest resources in relation to the different types of impacts and finally (iv) application of an integrative multi-criteria approach to arrive at a measure of overall forest sustainability performance. In Greece, the study reported in the current article is to our knowledge the first effort to provide an overall assessment of forest management sustainability performance at regional level.

Multi-criteria Analysis (MCA) is in general a suitable framework, where relevant indicators can be embedded and integrative forest sustainability assessments are possible to be made. Indeed the Multi-Attribute Decision Making Methods of MCA have been the most applied in this context. Specifically among those the Analytic Hierarchy Process, best known as AHP is the most popular (Kurttila et al. 2000; Shrestha et al. 2004; Wolfslener et al. 2005; Perez-Rodriguez and Rojo-Alboreca 2012; Martinez-Vega et al. 2016; Teclé 2018). The AHP was originally designed by T.L. Saaty in the early 1980s to solve complex problems involving multiple criteria (Saaty 1980). The AHP approach includes three stages. First a multi-attribute hierarchical structure is designed for the decision problem in hand. In the second stage relative preferences of the decision alternatives consideration are elicited by means of pairwise comparison. The input values should be checked for acceptable consistency. In the third stage the output is a ranking, which is prioritized indicating the overall preference of each of the decision alternatives.

One main challenge however that should be properly addressed in the applied field of forest management sustainability assessment is related to the uncertainty of human judgments, as well the vague, subjective, intangible and uncertain nature of most of the forest resource related attributes. Therefore, the AHP in its original form would not be particularly suited to our SFM decision environment under consideration, since uncertainty of human judgments could seriously affect the final results as it has been documented in the literature (Chen and Hwang 1992; Cheng and Molenaar 1999; Buckley et al. 2001; Chwolka and Raith 2001; Leung and Cao 2001; Nie et al. 2001; Ramanathan 2001; Wedley et al. 2001; Lai et al. 2002; Beynon 2005; Kangas and Kangas 2005; Lepetu 2012). In order to improve upon that we incorporated fuzzy analysis in our methodological forest management sustainability approach (Zadeh 1965, Zadeh 1975; Dubois and Prade 1988; Zadeh 1996; De Korvin and Kleyle 1999; Ertugul and Karakasoglu 2006; Jie et al. 2006; Dağdeviren and Yüksel 2008; Dursun and Kaya, 2010; Sharma et al. 2012; Choo and Yu 2013). Furthermore, we introduced in the overall approach fuzzy extent analysis (Chang 1996; Deng 1999) to include the experts' confidence in their fuzzy assessments and the experts' attitude towards risk in combination with the ideal solution concepts (Zeleny 1981). Finally, we used Fuzzy Preference Programming to derive the crisp priorities from the fuzzy comparison matrix with the aim to check upon potential errors from the application of the extent analysis method (Mikhailov 2003; Yuen 2012; Aminuddin and Nawawi 2015).

Within the above combined multi-criteria methodological approach for forest management sustainability assessment we embedded spatial analysis, Geographic Information Systems (GIS) and spatially referenced impact indicator models. We implemented the whole approach to the forests of Eastern Macedonia & Thrace (EMT) Region in northern Greece through the National Forest Governance Council (NFGC) function.

The Region of Eastern Macedonia and Thrace (Fig. 1) is one of the thirteen administrative regions of Greece and it is located in the northeastern part of the country. It borders Bulgaria to the north and Turkey to the east and it covers 14,157 km² corresponding to 10.7% of the total area of Greece. Its population amounts to 608,182 according to the National Census of 2011, which is about 5.6% of the total Greek population. Almost 54% of EMT Region is covered by forests and forest lands of which 90.5% is available for wood supply. Indeed the forests of EMT Region comprise about 34% of the growing stock of the total forest area of Greece. The wood production processes are very well established in the Region's forests, which are managed by the Hellenic Forest Service. Grazing, production of Non- Wood Forest Products (NWFP), forest recreation and hunting opportunities are also among the main concerns of the Forest District Officers, who are responsible for the management of the Region's forests. Finally important for the forest managers of EMT Region are the biodiversity conservation and the protection of forest ecosystems both from abiotic factors, such as wildfires, floods and soil erosion

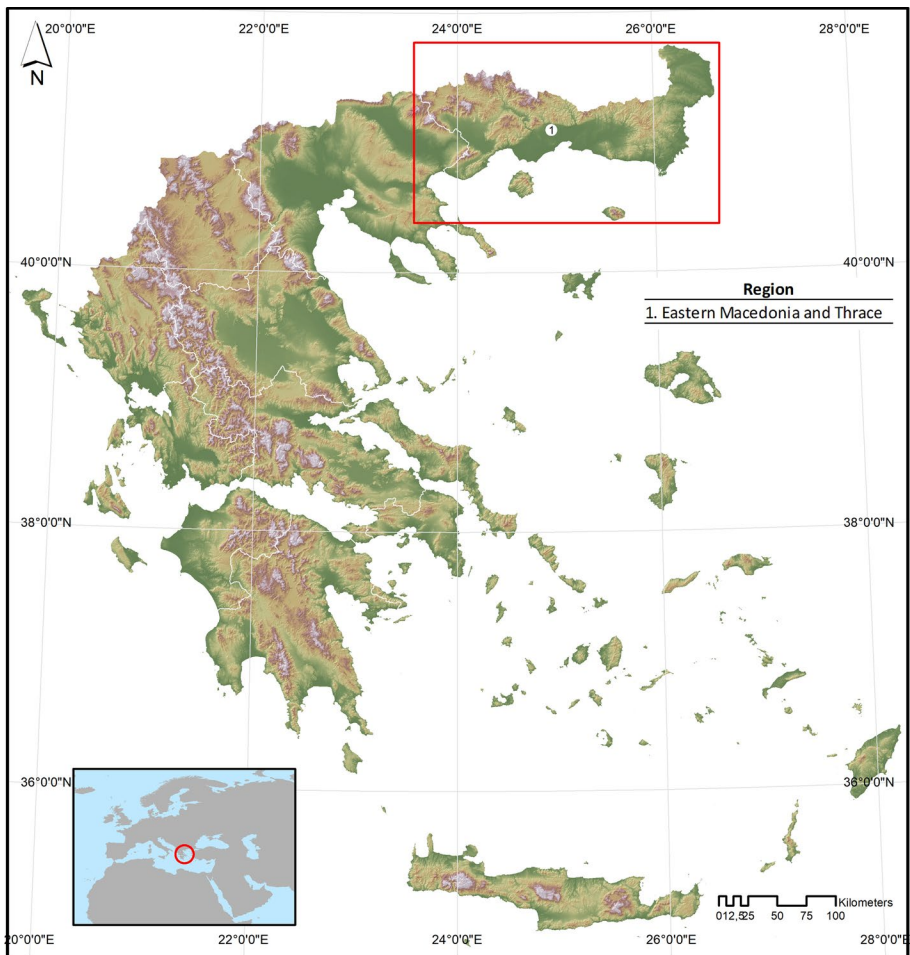


Fig. 1 Location map of the Eastern Macedonia & Thrace Region in Greece

and biotic factors, such as illegal logging, illegal hunting, forest land encroachment and land use change.

The NFGC is an innovative forest governance structure, which was set up and put into operation through INFORM, an EU LIFE project (www.inform-life.gr) to help building an indicator based knowledge system and establishing a national forest policy framework for sustainable management of the country's forests. The NFGC consists of a moderating team (the authors are members of this team), Forest Service top-level staff from Forest District Offices all over the country, scientists of different expertise related to the management of forests and representatives of opinion influencing stakeholders in fields of concern to sustainable forest management, such as representatives of NGOs, the Hunting Association, the Forest Cooperatives, and the Forest Owners' Association.

Specifically, application of the combined multi-criteria approach aims to provide answers to the following questions: (i) to what extent each of the forest management policies to be considered for implementation in the forests of Eastern Macedonia & Thrace Region lead to forest sustainability, (ii) which of those forest management policies could perform better towards forest sustainability and (iii) how should these forest management policies be ranked towards achieving forest sustainability.

2 The combined multi-criteria assessment process of forest management sustainability

The combined multi-criteria SFM assessment process involved three main stages: (i) the definition of SFM policy options and planning assumptions, as well as the preparation of prerequisites in relation to the specific for the forest areas under concern forest management policies, (ii) the selection of suitable at relevant spatial scales impact indicators and assessment of the environmental, socioeconomic and institutional impacts of the forest management policies, (iii) the integrated assessment of the overall forest management sustainability performance for each forest management policy.

2.1 Forest management policies, forest sustainability planning assumptions and prerequisites

Among the main difficulties facing the forest managers when attempt to assess forest management sustainability are the issues related to the spatial dimension of the forest management processes, since different tools particularly in the form of impact indicators should be used at different spatial scales and levels of aggregation. In this context, we identified and mapped using GIS meaningful spatial entities at suitable spatial scales for sustainable management assessment of EMT Region forests in Greece. We formed these entities, so as to reflect the dynamic relationship between the spatial patterns of natural resources and the economic and social activity spatial patterns at the geographic area of concern (Kazaklis et al. 2014). The generic spatial scale system we adopted includes four different hierarchical spatial levels, the landscape region, the landscape system, the landscape type and the ecotope level. At each level relevant spatial entities can be identified and mapped by combining different variables at some specified level of aggregation. Forest management sustainability assessments at the regional level are better suited at the landscape system spatial scale, because at this scale spatial patterns are easier to define, the rate of change pattern is slow and it is therefore more efficient to conduct at this scale impact analysis. Identification

and mapping of the spatial entities at the landscape system level was based on the combination of the geologic substrate and altitude range (main defining variables), as well as the soil types, the climate types, the mean annual temperatures, the mean annual rainfalls, the vegetation types and the land use patterns of the forest territory of interest. Ten spatial entities at the landscape system level were identified and mapped for the forest area of EMT Region in Greece and these are depicted in Fig. 2.

Furthermore, during this stage a series of workshops were organized through the NFGC operation, where the NFGC members analyzed the strategic forest planning environment for forest management policy formulation towards achieving sustainability. SWOT Analysis was used to formulate alternative forest management policies towards achieving forest sustainability (Kazana et al. 2015). A total of seven forest management policies were finally formulated for the forests of EMT Region (Table 1) and these were subjected to sustainability performance assessment.

The NFGC moderators elaborated the planning assumptions and prerequisites of the SFM alternative policies related to the forest area of EMT Region. Based on the spatial entities, which were identified for the Region's forest territory they selected relevant for this spatial scale environmental, socio-economic and institutional impact indicator models from the INFORM toolbox (Kazana et al. 2014). The selected indicators are presented in Tables 2 and 3. The environmental impact assessment indicator models concerned mainly the assessment of the SFM alternative policy impacts on the forest ecosystems, the rangelands, the water and soil resources of the forest territory, the forest recreational resources and the wildlife of the Region's forests (Kazaklis et al. 2014; Kazana et al. 2014).

The moderators set as planning horizon for evaluation of the anticipated environmental, socio-economic and institutional impacts a 10 year period starting from 2012 to 2022. They also prepared impact evaluation templates along with relevant guidelines for the NFGC members, who performed the evaluation.

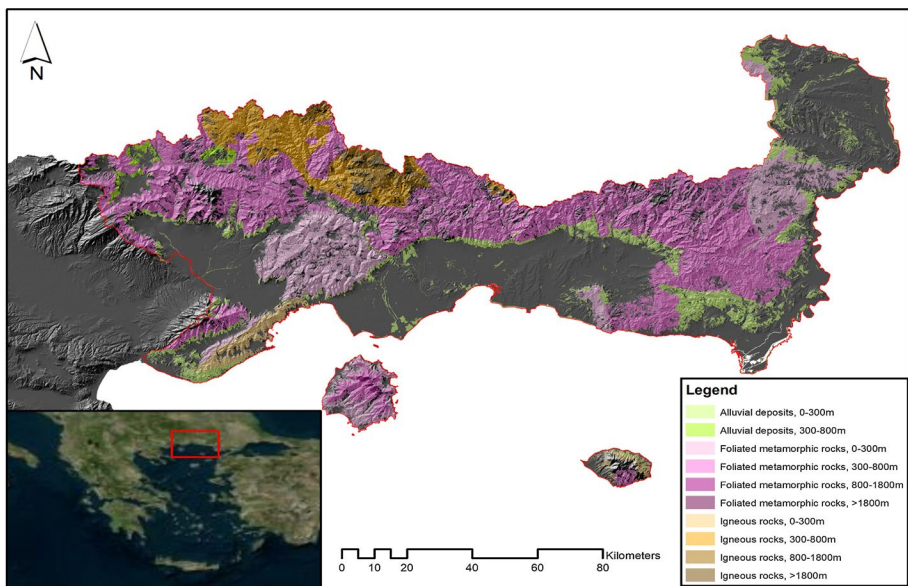


Fig. 2 Forest landscape systems of Eastern Macedonia & Thrace Region in Greece

Table 1 Forest management policies for sustainability assessment in the forests of Eastern Macedonia & Thrace Region, Greece

Code	Abbreviation	Description of SFM alternatives
A1	Wood prod	Improvement of the existing wood stock quantity and quality through appropriate silvicultural treatments for commercial wood production, mainly firewood, technical wood and pulpwood
A2	FREC	Development of forest recreation/ecotourism opportunities
A3	NWFP	Production of Non-Wood Forest Products, mainly honey, aromatic plants and forest fruits
A4	Biodiv	Conservation of flora and fauna biodiversity
A5	Hunting	Provision of avian and mammalian game species hunting opportunities
A6	Prot_abiotic	Forest protection from abiotic factors, mainly wildfires
A7	Prot_biotic	Forest protection from biotic factors, such as illegal logging, illegal hunting, forest land encroachment, land use change

Table 2 Environmental indicators for pairwise comparison of forest management policies towards sustainability performance of Eastern Macedonia & Thrace Region forests in Greece (INFORM toolbox, Kazana et al. 2014)

Environmental indicators (ENV)				
Forestry (FOR)	Rangelands (RANGE)	Water/soil (WAT)	Wildlife (WILD)	Forest recreation (FREC)
1. Pulpwood production	1. Soil/moisture conservation	1. Water quality preservation	1. Avian endangered species protection	1. Landscape aesthetics preservation
2. Firewood production	2. Wildfire prevention	2. Water for household use	2. Mammalian endangered species protection	2. Skiing
3. Technical wood production	3. Landscape aesthetics conservation	3. Groundwater and Spring Water	3. Damage prevention caused by wildlife to trees, bushes, grasslands, agricultural crops and livestock	3. Traditional food products
4. Soil/moisture conservation	4. Flora biodiversity conservation	4. Water for agricultural crops	4. Mammalian game species production in controlled hunting areas	4. Walking-hiking
5. Wildfire prevention	5. Rangeland production conservation related to genetic heritage (forage, livestock races)	5. Water for hydroelectric energy	5. Protection of important for ecotourism avian species	5. Sightseeing of natural and cultural attractions (mountains, national parks, aesthetic forests, caves, etc.)
6. Seed production (collection or seed beds)	6. Herbage production	6. Irrigation infrastructure	6. Wild fauna biodiversity conservation	6. Environmental awareness
7. Landscape aesthetics conservation	7. Browse production	7. Water related biodiversity conservation	7. Mammalian game species production in uncontrolled hunting areas	7. Climbing
8. Air quality preservation	8. Livestock related production	8. Water for biomass production (grass or woody plants)		8. Fishing
9. Water quality preservation				9. Canoeing- Rafting
10. Soil erosion prevention				

Table 3 Socio-economic and institutional indicators for pairwise comparison of forest management policies towards sustainability performance of Eastern Macedonia & Thrace Region forests in Greece (INFORM toolbox, Kazana et al. 2014)

Socio-economic indicators (SECON)	Institutional indicators (INST)
1. Ordinary production (Quantities of produced products)	1. Forest land tenure
2. Forest legislation	2. Revenue
3. Number of jobs	3. Bureaucracy
4. Forest recreation economic value	4. Lack of tools for sustainable forest management assessment and integration in forest management plans
5. Intermediate consumption	5. Lack of funds for management plan studies
6. Product quality	6. Lack of funds for investments
7. New technology	7. Personnel shortage
8. Forest roads traffic	8. Outdated forest management plan specifications
9. Cultural or historical heritage	
10. Increase of forest population	

2.2 Environmental, socio-economic and institutional policy impact evaluation

The methodology and the tools for impact assessment were presented to the NFGC members by the moderators during the first workshop and all the relevant material prepared in stage 1, such as the forest spatial entity maps at the landscape system level, the spatially referenced at the landscape system level impact indicator models and the impact evaluation templates for the pairwise comparisons were provided to them. The NFGC expert members were asked to select the most appropriate for the areas under evaluation environmental, socioeconomic and institutional indicators from the INFORM toolbox provided by the moderators and adapt the baseline indicator model values, where needed. A total of 38 environmental, 10 socio-economic and 8 institutional impact indicator models relevant at the landscape system level spatial scale were finally selected by the NFGC members from the available ones of the INFORM toolbox, in order to assess the different types of impacts of each of the forest management policies on the forest areas of Eastern Macedonia & Thrace Region.

The underlying question for filling in the relevant evaluation tables of the environmental and the socio-economic impact indicators was to what degree in terms of the selected indicator the area under concern would be impacted by each forest management policy. For the environmental impact assessments the measurement scale of the indicator models was from 1 to 20, with 1 meaning a very low impact on the indicator under examination and 20 indicating a very high impact.

For the socio-economic and institutional impact assessments, the measurement scale of the indicator models was from 1 to 5 corresponding to the following degrees of impact: very low potential impacts: 1, low potential impacts: 2, moderate potential impacts: 3, high potential impacts: 4 and very high potential impacts: 5. All partial indicators were aggregated then to form higher level indicators on two directions, that is, gain and loss with regard to specific resources.

2.3 Integrated forest management sustainability assessment

The generalized integrated forest management sustainability assessment includes the following components:

- (i) A number of forest management policies to be assessed in terms of their overall forest sustainability performance, denoted as A_i , where $i = 1, 2, \dots, n$.
- (ii) A set of evaluation indicators, denoted as IND_j , where $j = 1, 2, \dots, m$. These indicators operate at different levels of aggregation that should be decided on a forest study area basis (Kazana et al. 2014).
- (iii) Pairwise comparison assessments, denoted as x_{ij} , where $i = 1, 2, \dots, n; j = 1, 2, \dots, m$. These assessments should be provided by the decision makers (in our study the NFGC members) and represent impact ratings of each forest management policy (A_i) on each indicator (IND_j), thus leading to the determination of a decision matrix for the forest management policies (Kazana et al. 2014) and
- (iv) A weighting vector $W = (w_1, w_2, \dots, w_m)$, called also indicator weights, which represents the relative importance of the evaluation indicators at each level of aggregation with respect to the overall objective of the level of aggregation under concern.

The hierarchical structure of the integrated forest management sustainability assessment process in the AHP frame is depicted in Fig. 3.

The detailed calculations to estimate the impact performance indicators of the forest management policies involved the following:

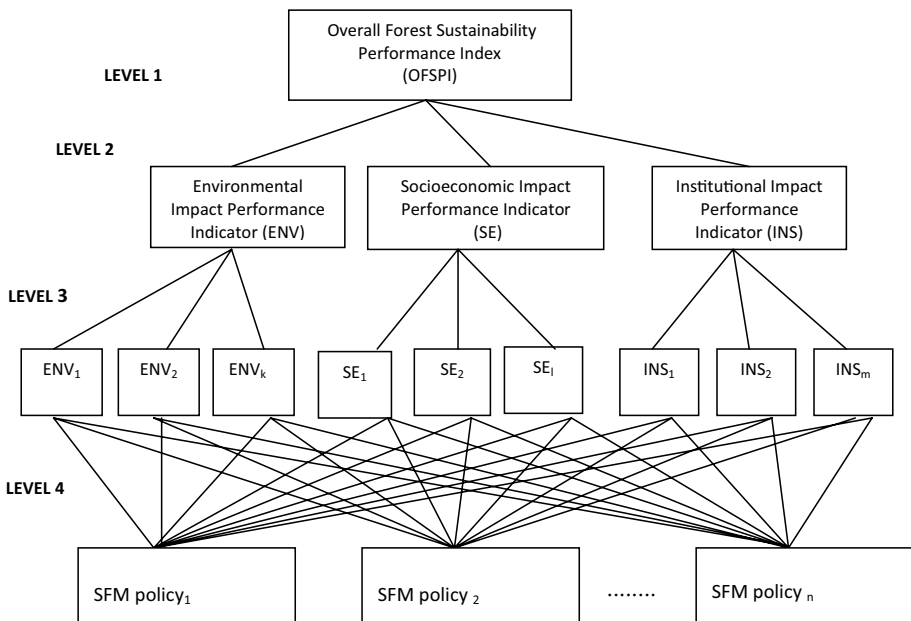


Fig. 3 The hierarchical structure of the SFM policy options integrated evaluation process

The NFGC members’ assessments in order to facilitate the pairwise comparisons were expressed with triangular fuzzy numbers $(\alpha_1, \alpha_2, \alpha_3)$, as presented in Table 3 and membership functions as defined in (1).

$$\mu_a(x) = \begin{cases} (x - a_1)/(a_2 - a_1), & a_1 \leq x \leq a_2 \\ (a_3 - x)/(a_3 - a_2), & a_2 \leq x \leq a_3 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

The value of fuzzy synthetic extent that represents the Overall Forest Management Sustainability Performance was calculated by:

$$S_i = \frac{\sum_j^m \mu_i^j}{\sum_{i=1}^n \sum_{j=1}^m \mu_i^j}, \quad i = 1, 2, \dots, n \tag{2}$$

The decision matrix was determined by using the AHP method and fuzzy numbers as follows:

The indicator importance (W) or forest management policy importance with respect to a specific indicator (IND_j) was determined by a fuzzy reciprocal judgment matrix as:

$$IND_{j \text{ or } W} = \begin{vmatrix} \bar{a}_{11} & \bar{a}_{12} & \dots & \bar{a}_{1k} \\ \bar{a}_{21} & \bar{a}_{22} & \dots & \bar{a}_{2k} \\ \dots & \dots & \dots & \dots \\ \bar{a}_{k1} & \bar{a}_{k2} & \dots & \bar{a}_{kk} \end{vmatrix} \tag{3}$$

$$\bar{a}_{s\ell} = \begin{cases} \bar{1}, \bar{3}, \bar{5}, \bar{7}, \bar{9} & \ell < s \\ 1 & \ell = s, \quad s = 1, 2, \dots, k, k = \text{morn} \\ 1/\bar{a}_{s\ell} & \ell > s \end{cases} \tag{4}$$

where, the fuzzy numbers used in the judgment matrix were those shown in Table 4.

The NFGC members conducted the pairwise evaluation and provided these qualitative assessments, that is, they recorded their cross-impact assessments, using the fuzzy numbers of Table 4.

The NFGC moderators then calculated the corresponding indicator weights (w_j) or the forest management policy performance ratings (x_{ij}) with respect to a specific indicator IND_j as follows:

Table 4 Fuzzy numbers for qualitative cross-impact assessment

Fuzzy number	Membership function
$\bar{1}$	(1, 1, 3)
\bar{x}	(x - 2, x, x + 2) for x = 3, 5, 7
$\bar{9}$	(7, 9, 11)

1: equal impact, 3: small impact, 5: moderate impact, 7: high impact, 9: very high impact

$$x_{ij}orw_j = \frac{\sum_{s=1}^k \bar{a}_{sl}}{\sum_{l=1}^k \sum_{s=l}^k \bar{a}_{sl}} \tag{5}$$

where $i = 1, 2, \dots, n$; $j = 1, 2, \dots, m$ and $k = m$ or n depending on whether the reciprocal judgment matrix was used to assess the performance ratings of the forest management policies or the weights of the indicators involved. Therefore, the decision matrix (X) was determined as:

$$X = \begin{pmatrix} x_{11} & x_{12} & \dots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2m} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mm} \end{pmatrix} \tag{6}$$

where, x_{ij} represented the resultant fuzzy impact performance assessments of the forest management policies A_i ($i = 1, 2 \dots n$) with respect to IND_j .

The weighting vector W for the indicators was calculated by (3) to (5) using again the AHP method and fuzzy numbers as shown in (1) and (2) and Table 4. The NFGC members provided the weight qualitative assessments through the same procedure as described in the previous step (determination of decision matrix). The resultant fuzzy weight of the indicator IND_j ($j = 1, 2 \dots m$) with respect to the overall objective was then

$$W = (w_1, w_2 \dots w_m) \tag{7}$$

The fuzzy impact performance matrix as in (8) was determined by multiplying the decision matrix with the weighting vector.

$$Z = \begin{pmatrix} w_1x_{11} & w_2x_{12} & \dots & w_mx_{1m} \\ w_1x_{21} & w_2x_{22} & \dots & w_mx_{2m} \\ \dots & \dots & \dots & \dots \\ w_1x_{m1} & w_2x_{m2} & \dots & w_mx_{mm} \end{pmatrix} \tag{8}$$

$$Z_a = \begin{pmatrix} \left| \begin{matrix} \underline{z}_{11l}^a & \underline{z}_{11r}^a \end{matrix} \right| & \left| \begin{matrix} \underline{z}_{12l}^a & \underline{z}_{12r}^a \end{matrix} \right| & \dots & \left| \begin{matrix} \underline{z}_{1ml}^a & \underline{z}_{1mr}^a \end{matrix} \right| \\ \left| \begin{matrix} \underline{z}_{21l}^a & \underline{z}_{21r}^a \end{matrix} \right| & \left| \begin{matrix} \underline{z}_{22l}^a & \underline{z}_{22r}^a \end{matrix} \right| & \dots & \left| \begin{matrix} \underline{z}_{2ml}^a & \underline{z}_{2mr}^a \end{matrix} \right| \\ \dots & \dots & \dots & \dots \\ \left| \begin{matrix} \underline{z}_{n1l}^a & \underline{z}_{n1r}^a \end{matrix} \right| & \left| \begin{matrix} \underline{z}_{n2l}^a & \underline{z}_{n2r}^a \end{matrix} \right| & \dots & \left| \begin{matrix} \underline{z}_{nml}^a & \underline{z}_{nmr}^a \end{matrix} \right| \end{pmatrix} \tag{9}$$

The interval impact performance matrix (9) was obtained by determining a value described by Deng (1999) as α -cut value ($0 \leq \alpha \leq 1$) to represent the NFGC members' confidence on their fuzzy assessments regarding the alternative ratings and indicator weights. A larger α value indicates more confidence, meaning that the decision maker's or expert's assessments are closer to the most possible value α_2 of the triangular fuzzy numbers ($\alpha_1, \alpha_2, \alpha_3$). The arithmetic operations on these fuzzy numbers were based on interval arithmetic. The α value in our empirical study was derived as the median of the α values of the NFGC members of the Region of Eastern Macedonia & Thrace and this was equal to 0.6.

The crisp performance matrix (10) was determined by incorporating the NFGC members' attitude towards risk through an optimism indicator λ .

$$Z_a^{\lambda'} = \begin{pmatrix} z_{11a}^{\lambda'} & z_{12a}^{\lambda'} & \dots & z_{1ma}^{\lambda'} \\ z_{21a}^{\lambda'} & z_{22a}^{\lambda'} & \dots & z_{2ma}^{\lambda'} \\ \dots & \dots & \dots & \dots \\ z_{n1a}^{\lambda'} & z_{n2a}^{\lambda'} & \dots & z_{nma}^{\lambda'} \end{pmatrix} \tag{10}$$

where,

$$z_{ija}^{\lambda'} = \lambda z_{ijr}^a + (1 - \lambda)z_{ijl}^a, \quad \lambda \in [0, 1]$$

With λ values equal or close to 1, the experts are assumed to have an optimistic view, favouring higher assessment values. With λ values equal or close to 0.5 the experts are assumed to have a moderate view, while λ values equal or close to 0 indicate a pessimistic view favouring lower assessment values. In our study the λ value was taken also as the median of the λ values of the NFGC members of the Region and this was equal to 0.65.

The normalized impact performance matrix (12) was calculated by using (11).

$$z_{ija}^{\lambda} = \frac{z_{ija}^{\lambda'}}{\sqrt{\sum_{i=1}^n (z_{ija}^{\lambda})^2}} \tag{11}$$

$$Z_a^{\lambda} = \begin{pmatrix} z_{11a}^{\lambda} & z_{12a}^{\lambda} & \dots & z_{1ma}^{\lambda} \\ z_{21a}^{\lambda} & z_{22a}^{\lambda} & \dots & z_{2ma}^{\lambda} \\ \dots & \dots & \dots & \dots \\ z_{n1a}^{\lambda} & z_{n2a}^{\lambda} & \dots & z_{nma}^{\lambda} \end{pmatrix} \tag{12}$$

Then the positive ideal solution $A_{\alpha}^{\lambda+}$ and the negative ideal solution $A_{\alpha}^{\lambda-}$ were determined as in (13) and (14) by selecting the maximum value and the minimum value across all forest management policies with respect to each indicator, given as in 13. The concept of the ideal solution was first introduced by Zeleny (1981) to form the best or desired decision outcome for a given decision situation. Hwang and Yoon extended the concept also in 1981 to include the negative ideal solution to avoid the worst decision outcome and it has been used to solve several practical decision making problems in many parts of the world.

$$\begin{aligned} A_a^{\lambda+} &= (z_{1a}^{\lambda+}, z_{2a}^{\lambda+}, \dots, z_{ma}^{\lambda+}) \\ A_a^{\lambda-} &= (z_{1a}^{\lambda-}, z_{2a}^{\lambda-}, \dots, z_{ma}^{\lambda-}) \end{aligned} \tag{13}$$

where

$$\begin{aligned} z_{ja}^{\lambda+} &= \max(z_{1ja}^{\lambda}, z_{2ja}^{\lambda}, \dots, z_{nja}^{\lambda}) \\ z_{ja}^{\lambda-} &= \min(z_{1ja}^{\lambda}, z_{2ja}^{\lambda}, \dots, z_{nja}^{\lambda}) \end{aligned} \tag{14}$$

The Eqs. (15) and (16) were used then to calculate the degree of similarity between each forest management policy and the positive ideal solution and the negative ideal solution.

$$S_{ia}^{\lambda+} = \frac{A_{ia}^{\lambda} A_a^{\lambda+}}{\max(A_{ia}^{\lambda} A_a^{\lambda}, A_a^{\lambda+} A_a^{\lambda+})} \tag{15}$$

Table 5 Overall environmental, socioeconomic and institutional performance indices of the forest management policies in the region of Eastern Macedonia & Thrace

Forest management policies	Normalized crisp values		
	Overall environmental performance index	Overall socioeconomic Performance Index	Overall institutional performance index
Wood prod	0.51	0.66	0.64
FREC	0.47	0.32	0.33
NWFP	0.33	0.30	0.45
Biodiv	0.39	0.38	0.39
Hunting	0.35	0.26	0.27
Prot_abiotic	0.29	0.15	0.15
Prot_biotic	0.21	0.34	0.18

Table 6 Ranking of forest management policies for Eastern Macedonia & Thrace forests based on the overall forest sustainability performance index

Ranking	Forest management policies	Overall forest sustainability performance index
1	Wood prod	0.57
2	Prot_abiotic	0.42
3	Prot_biotic	0.41
4	Hunting	0.39
5	NWFP	0.37
6	FREC	0.36
7	Biodiv	0.34

$$S_{ia}^{\lambda+} = \frac{A_{ia}^{\lambda} A_a^{\lambda-}}{\max(A_{ia}^{\lambda} A_a^{\lambda}, A_a^{\lambda-} A_a^{\lambda-})} \tag{16}$$

The overall impact performance indicator at the level of aggregation under concern was determined by (17).

$$P_{ai}^{\lambda} = \frac{S_{ia}^{\lambda+}}{S_{ia}^{\lambda+} + S_{ia}^{\lambda-}}, \quad i = 1, 2, \dots, n. \tag{17}$$

The integrated algorithmic procedure described above was repeated at all the relevant levels of aggregation shown in Fig. 3.

The Overall Environmental, Socioeconomic and Institutional Performance Indices for each of the 7 forest management policies subjected to sustainability performance assessment in the Region of Eastern Macedonia & Thrace are presented in Table 5.

The final ranking of the forest management policies on the basis of the Overall Forest Sustainability Performance index in descending order is shown in Table 6. The forest management policy concerning the improvement of the Region’s wood stock so as to further increase the quantity and quality of the produced wood products, such as technical wood, firewood and pulpwood appears as the best performing management policy towards sustainability of the forests of EMT Region. This finding is in line with the current forest

management practices for commercial wood production, as from the environmental point of view the traditional sustained yield constraints are followed through the implementation of the forest management plans, while at the same time the wood production processes in EMT Region are positively related to the local income and number of jobs. The following two forest management policies in the ranking list include the forest protection policies, one concerning protection from abiotic factors, such as wildfires, floods and soil erosion and the other concerning the biotic factors, which refer mainly to practices such as illegal logging, illegal hunting, forest land encroachment and land use change. The overall forest sustainability performance values of both policies are very close to each other, as implementation of these forest management policies is important for safeguarding the Region's forest ecosystems. There is also a positive relation of these two forest management policies with the local economy and particularly the generated income and number of jobs, as temporary personnel is usually hired for implementation of these management policies. In the fourth ranking position in terms of sustainability performance appears the management option concerning the provision of hunting opportunities in EMT Region's forests. The hunting activity is important in the area and positively related also to the local economy as it generates income through the license fees the hunters pay to exercise this activity as well as the high added value to the area. The remaining three forest management policies that is the provision of non-wood forest products, provision of forest recreation/ecotourism opportunities and biodiversity conservation were ranked 5th, 6th and 7th correspondingly with expected close to each other but lower in relation to the other forest management policies overall forest sustainability values over the 10 year assessment period. This may be due to the weaker relation of these management policies with the local economy and particularly the generated income and number of jobs within the existing institutional framework, although we expected the biodiversity conservation to have been ranked higher.

To explore further the results presented in Table 6 we decided to apply also Fuzzy Preference Programming as significant technical errors have been reported in the literature with regard to the extent analysis method when the latter is used for prioritization in AHP and FAHP (Wang et al. 2008; Yuen 2012). Specifically, potential errors have been attributed to the fact that in AHP and FAHP it is impossible to have zero priority due to the axiom $a_{ij} = \frac{w_i}{w_j}$ that is there is no scale for a_{ij} if $w_j = 0$. Therefore, some entries may have undefined values due to dividing zero (Yuen 2012).

Fuzzy Preference Programming (FPP) has been proposed by Mikhailov (2003) as an alternative to convert the fuzzy value of FAHP into crisp value.

The maximum prioritization problem according to FPP can be represented as

$$\begin{aligned}
 & \text{Max } \lambda \\
 & \text{Subject to } (m_{ij} - l_{ij})\lambda w_j - w_i + l_{ij}w_j \leq 0, \\
 & (u_{ij} - m_{ij})\lambda w_j + w_i - u_{ij}w_j \leq 0, \\
 & \sum_{k=1}^n w_k = 1, w_k > 0, k = 1, 2, \dots, n \\
 & i = 1, 2, \dots, n-1; j = 2, 3, \dots, n; j > i
 \end{aligned} \tag{18}$$

If the optimal value λ^* , is positive (the maximum value is one), it means that the initial set of fuzzy judgments is relatively consistent. Therefore, the optimal value λ^* can be used for measuring the consistency of the initial set of fuzzy judgments (Mikhailov 2003; Yuen 2012; Aminuddin and Nawawi 2015).

Table 7 Priority weights for the first level of criteria and final weights for the forest management policies of Eastern Macedonia & Thrace Region forests with use of fuzzy preference programming and consistency measures

Forest management alternatives	Environmental performance (ENV)	Socioeconomic performance (SECON)	Institutional performance (INST)	Overall forest sustainability performance
Wood prod	0.154	0.159	0.157	0.155
FREC	0.134	0.133	0.138	0.139
NWFP	0.138	0.134	0.137	0.129
Biodiv	0.144	0.136	0.145	0.142
Hunting	0.139	0.143	0.134	0.144
Prot_abiotic	0.144	0.147	0.150	0.145
Prot_biotic	0.146	0.147	0.139	0.146
First level priority Weights	0.111	0.481	0.407	
Consistency measures				
CR	0.045	0.017	0.068	0.025
CC(θ)	0.572	0.281	0.646	0.511
OC(ψ)	0	0.003	0.06	0
L	0	0	0	0

CR: consistency ratio, CC: cardinal consistency, OC: ordinal consistency, L: transitivity

Table 8 Final ranking of forest management policies for the forests of Eastern Macedonia & Thrace region based on fuzzy preference programming

Ranking	Forest management alternatives	Overall forest sustainability performance
1	Wood prod	0.155
2	Prot_biotic	0.146
3	Prot_abiotic	0.145
4	Hunting	0.144
5	Biodiv	0.142
6	FREC	0.139
7	NWFP	0.129

We applied FPP using the PriEsT software (Siraj et al. 2015) and we produced different consistency measures (CR, CC, OC) for the first level of criteria. These are shown in Table 7. The final ranking of the forest management alternatives with FPP is presented in Table 8.

The weights for the environmental, socioeconomic and institutional performance of the forest management policies under evaluation in the Region of Eastern Macedonia & Thrace in terms of their contribution to forest sustainability as it is shown in Table 7 were 11.1%, 48.1% and 40.7% respectively and their CR values are within the acceptable levels. According to Table 7 the best contributing to sustainability forest management policy is wood production with a weight of 15.5% followed by the two policies oriented to forest protection from biotic and abiotic factors with weights 14.6% and 14.5% correspondingly. This is compatible with the results of the extent analysis method presented in Table 6,

although the forest protection from biotic factors ranked 2nd and the forest protection from abiotic factors ranked 3rd. Their overall sustainability values however are very close as the ones shown in Table 6. The hunting and biodiversity conservation alternatives were ranked 4th and 5th with weights 14.4% and 14.2% respectively followed by forest recreation (13.9%) and non-wood forest products (12.9%) management policies. The main difference in the final solution resulted from the application of FPP was the ranking place of the management policy concerning conservation of biodiversity, which was ranked 5th instead of 7th as in Table 6. This is closer to our expectation and it can be better interpreted in the context of EMT Region's forest sustainability, as there are several NATURA 2000 sites, as well as other sites under special protection status within the Region's forests. The robustness of the final solution has been also checked with Sensitivity Analysis, which is presented in detail in the following section.

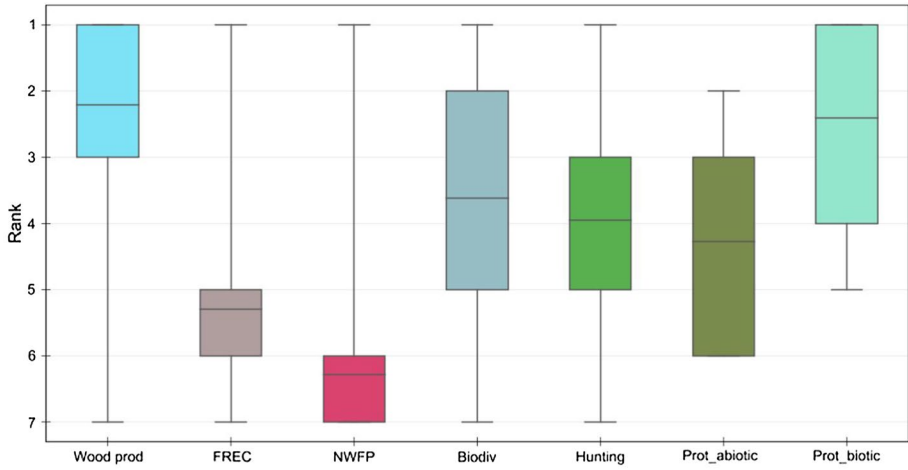
2.4 Sensitivity analysis

Sensitivity Analysis was conducted by using PriEsT in order to explore robustness of the final solution. Figure 4 depicts the ranking of the forest management policies under evaluation for sustainability performance when uniformly distributed random weights were used for the first level criteria (ENV, SECON, INST). The forest management policy concerning commercial wood production has a mean ranking about 2.1 with the best ranking of 1 and the worst as 3. In 50% of the simulation iterations the wood production management policy was top ranked. The forest management policy concerning forest protection from biotic factors had a mean ranking 2.2 very close to that of the wood production one, with best and worst rankings between 1 and 4 respectively. The conservation of biodiversity management policy was ranked between 2 and 3 in 50% of the simulation iterations and for some combinations of weights became top ranked alternative. The other forest management policies were ranked at lower positions for half of the time, although for some combinations of weights they also became top ranked with the exception of the management policy concerning forest protection from abiotic factors, which never appeared top ranked.

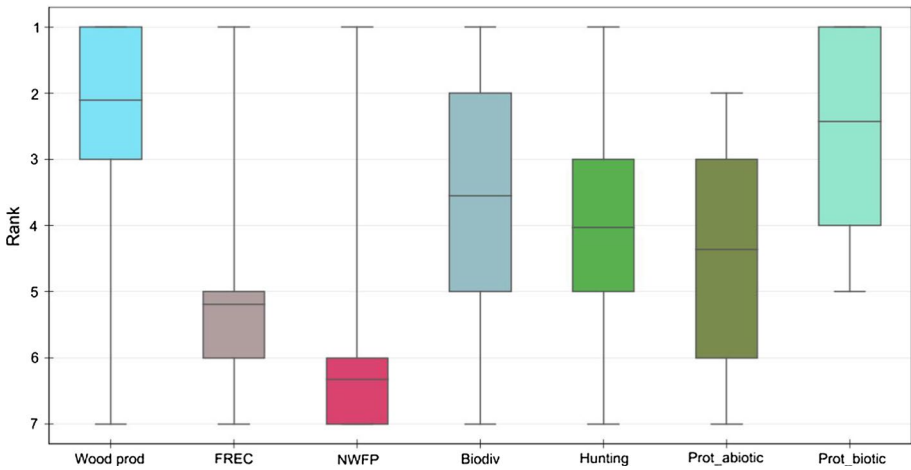
The simulation was performed again replacing all criteria weights with random weights. The results of the simulation were very similar with the previous ones, where only the top—level criteria were used. These are shown in Fig. 4b. The wood production alternative remained top ranked.

To explore the weights that may cause ranking to change the one-at-a-time and mathematical analyses were conducted. An increase in the weight of ENV from 11.1 to 32.2% caused the conservation of biodiversity (biodiv) alternative to become the best contributing management policy to forest sustainability of EMT Region with a priority of 15.3%. An additional increase in the weight of ENV to 37.2% caused the forest protection from biotic factors (prot_biotic) management policy to be ranked 2nd with a priority of 15.1% and the wood production alternative (wood prod) to be ranked 3rd. The wood production management policy was even ranked 4th when the weight of ENV changed to 48.6% causing the protection from abiotic factors to be ranked 3rd with priority of 14.9%. The FREC, NWFP and Hunting management policies were not top ranked with any increase in the weight of ENV.

The one-at-a time sensitivity analysis method of PriEsT when it was implemented for SECON showed that a decrease in the weight of SECON from 48.1 to 37% caused the prot_biotic management policy to be top ranked with a priority of 15.3%, while further decreases in the weight of SECON to 32.1% and 25% caused the prot-abiotic and NWFP



(a) Simulation using random weights for first-level criteria



(b) Simulation using random weights for all criteria

Fig. 4 Ranking of forest management policies in terms of sustainability performance using probabilistic simulation

alternatives to be ranked 1st and 2nd with priorities 15.2% and 15% respectively. On the other hand an increase in the weight of SECON from 48.1 to 90.7% caused the biodiv alternative to be the best performing for forest sustainability alternative with a priority of 17.4%.

Finally, when the one-at-a time method was implemented for INST it showed that a decrease in the weight of INST from 40.7 to 17.9% caused the biodiv management policy to be top ranked with a priority of 16.5%. On the other hand an increase in the weight of INST from 40.7 to 53.7% caused the prot-biotic alternative to be ranked 1st with a priority of 15.4% and the wood production management policy to be ranked 2nd. An additional

increase in the weight of INST from 40.7 to 59.5% caused the prot-abiotic alternative to be ranked 2nd with a priority of 15.2% and the wood production alternative 3rd, while a further increase to 66.3% caused the NWFP alternative to be ranked 3rd followed by the wood production alternative in the 4th place.

Through sensitivity analysis also simultaneous changes were considered on the first-level criteria by using the mathematical analysis of PriEsT in order to identify the most sensitive element. Three sensitivity coefficients, the Operating Point Sensitivity Coefficient (OPSC), the Rank Reversal Probability (RR%) and the Sensitivity Coefficient (SC) were calculated for different combinations of criteria and these are shown in Table 9. OPSC is defined as the shortest distance from the current weights to the edge of the allowable region. It represents the minimum change that that may cause a rank reversal (Chen and Kocaoglu 2008; Siraj 2011, 2012).

The minimum OPSC was 0.081 and corresponded to the combination of the ENV/INST criteria, while the maximum OPSC was 0.141 for the combination of all three criteria ENV, SECON and INST. By choosing the all criteria OPSC, the minimum change of weights necessary to cause a rank reversal was 0.141, which represents a 74% more robust final ranking of the forest management policies under sustainability assessment.

3 Conclusions

The combined multi-criteria approach that has been presented in this article has successfully in a novel way integrated the AHP, the fuzzy extent analysis, the ideal solution concept and Fuzzy Preference Programming with spatial analysis, Geographic Information Systems and spatially referenced impact indicator models to assess forest management sustainability performance. Integrated forest management sustainability assessments are complex tasks because they involve multiple types of impacts, environmental, socio-economic and institutional, different spatial scales of management processes and different levels of aggregation. Furthermore, most of the forest resource related attributes are vague, subjective, uncertain and intangible. Our applied research contributes significantly to the ongoing research efforts of the scientific community for development of methods and tools that could help decision makers to carry out required integrated forest management sustainability assessments, as these are of great importance for the sustainable development of mountain and rural areas.

We implemented this approach to assess the sustainability performance of seven different forest management policies for the forests of Eastern Macedonia & Thrace Region in northern Greece. This made it possible to obtain specific answers to the following questions: (i) to what extent each of the forest management policies to be considered for implementation in the forests of Eastern Macedonia & Thrace Region lead to forest sustainability, (ii) which of those forest management policies could perform better towards forest

Table 9 Sensitivity coefficients

Criteria	OPSC	RR%	SC
ENV/SECON	0.107	81.4	5.387
ENV/INST	0.081	81.4	5.387
SECON/INST	0.123	81.4	5.387
ENV/SECON/INST	0.141	81.4	5.387

sustainability and (iii) how should these forest management policies be ranked towards achieving forest sustainability. The solutions that were produced with both the fuzzy extent analysis and Fuzzy Preference Programming showed that all seven forest management policies that were subjected to sustainability performance assessment contribute to forest management sustainability. Furthermore, the management policy concerning the commercial wood production from the forests of EMT Region in Greece appeared as the best performing in terms of forest sustainability performance. When sensitivity analysis was conducted it was shown that by choosing all criteria that is environmental, socioeconomic and institutional the minimum change of weights necessary to cause a rank reversal was 0.141, which represents a 74% more robust final ranking of the forest management policies subjected to sustainability assessment.

To our knowledge this study is the first effort to assess the overall forest management sustainability performance at regional level in Greece. The combined multi-criteria approach we implemented to the forests of EMT Region made it possible to incorporate the forestry decision makers'/experts' confidence in their fuzzy assessments and their attitude towards risk and it can be used in other similar decision environments for forest management sustainability assessments.

Finally, on the sustainable development mainstream policy side, the work presented in the current article can be used to improve the current FOREST EUROPE framework at the European level by providing a suitable approach to perform integrated forest management sustainability assessments, so as to better monitor the sustainable management of Europe's forests.

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