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A sustainable forest management criteria and indicators assessment using fuzzy analytic hierarchy process

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Abstract Today, resource depletion has become a worldwide issue due to the increasing human population and related consumption. Therefore, the sustainability of renewable natural resources has recently gained great importance. To achieve a more sustainable world, sustainable development is needed. In sustainable development, the sustainable forestry holds an important part because of forests' great importance among the natural resources. Thus, the sustainable forest management (SFM) practices have been vital at this point. The present paper aims to contribute SFM applications and literature with the evaluation and interpretation of the National SFM of Turkey by calculating the importance levels (weights) of latest criteria and indicators (C&I). For this purpose, Fuzzy Analytic Hierarchy Process (AHP), a hybrid approach of fuzzy logic and multi-criteria decision-making, was adopted. This adoption is due to the complex and hierarchical framework of sustainability and the suitability of the method to the subject. The present research is a case study from Kastamonu Regional Directorate of Forestry. Kastamonu holds an important part in Turkish forestry, and it has the potential to represent general condition. This study has shown that the importance attached to environment-related C&I is considerably higher than that of other SFM C&I. Furthermore, Turkey focuses more on the sustainability of wood and wood products rather than other sustainability indicators. The research has also identified that there is a classification problem for SFM indicators. The current C&I should be reviewed and localized.

Keywords Sustainability · Decision-making · Criteria and indicators · Turkey · Forestry

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Introduction

The conventional concept of sustainability, and perhaps the most agreed, is based on the growth that should be planned to meet the current generation's needs without compromising future generations' ability to meet their own needs (Agostinho et al., 2019). Sustainable forestry, as often discussed at the United Nations Conferences on Environment and Sustainability, is assumed one of the most important focal points of sustainable development (Atmiş & Çil, 2013). To ensure sustainable development, a management approach based on sustainability principles is needed.

In forestry, sustainable forest management (SFM) view has been an adopted principle since the eighteenth century (Wiersum, 1995). The definition of sustainability in the forestry sector had a narrow focus emphasising only sustainable wood production when it was first presented. Since then, the notion is still evolving (Santos et al., 2019a, b). Now, it can be described as managing and using the forests and forest lands in a way and at a rate to maintain both the biodiversity, generation capacity, productivity and vitality of forests and their potential local, national and global relevant ecologic, economic and social functions without compromising the needs of now and the future (Mohammadi & Limaei, 2018).

To date, due to its complex nature, several hierarchical frameworks have been developed for the SFM concept (Jafari et al., 2018). These frameworks consist of a number of criteria and indicators (C&I) and are necessary to monitor, measure and assess the management plans (Martín-Fernández & Martinez-Falero, 2018). C&I provide a science-supported framework that can be the basis for policy decisions (Hall, 2001). But, despite the efforts of United Nations, because of SFM's complexity, there is no international consensus on neither the assessment nor the C&I of SFM yet, but for countries and regions, a base framework consisted of 7 criteria and 65 indicators exists (Jafari et al., 2018; Mohammadi & Limaei, 2018; Ness et al., 2007; Reynolds et al., 2007).

Nevertheless, today, one of the most preferred ways of sustainability assessment is the indicator approach. C&I can provide helpful information on the status and trends of sustainable development, and they can be used by decision-makers (Mohammadi & Limaei, 2018). However, to benefit from these frameworks, customization is a must for each country (Jafari et al., 2018). International C&I should not be identical copies, to be implemented at the national level they must be tailored to the national conditions (Durusoy & Türker, 2005).

In Turkey, almost all the forests are owned by the state and managed by General Directorate of Forestry (OGM). The privately owned forest area is less than one-thousandth of the entire forest area (about 18 thousand hectares) (OGM, 2015). Turkey is part of the sustainable forestry process of the Pan-European and Near East. Therefore, OGM blended the C&I adopted in these processes, and the Near East was based on due to its comprehensiveness and overlapping features to Pan-European criteria (Atmiş & Çil, 2013). Since 2004, OGM began to publish C&I for SFM, but the progress is insufficient for today, and recent studies proved that there is a classification problem for SFM indicators. Studies also have revealed that the present C&I are inadequate and not consistent with the local dissimilarities (Akyol, 2009; Anonymous, 2010; Atmiş & Çil, 2013).

It has been observed that, currently, neither in Turkey nor in the world the studies focusing on sustainable forestry have not achieved the desired level yet; hence, the continuation of research efforts that focus on sustainability and forestry is recommended (Atmiş & Çil, 2013; Jafari et al., 2018).

The primary aim of this study is to evaluate and interpret the National SFM by calculating the importance levels (weights) of the latest C&I for future strategies. The methodological approach taken in this study is Fuzzy Analytic Hierarchy Process (Fuzzy AHP) that is a mixed method based on fuzzy logic and multi-criteria decision-making (MCDM).

The decision-making process of SFM is inherently uncertain and complex (Hickey & Innes, 2005). Fuzzy methods are suitable for solving complex and ill-defined problems (Mendoza & Prabhu, 2003). Due to including ecological, economic and social aspects SFM may be considered a complex and versatile problem. A search of the literature revealed few studies which focus on sustainability and MCDM (Calabrese et al., 2019): integrated sustainability into strategic decision-making by using fuzzy AHP (Mohammadi & Limaei, 2018), employed various MCDM approaches for forest sustainability (Dos Santos et al., 2019a), investigated the AHP and decision-making for sustainable development (Giannetti et al., 2019), proposed a model for assessing sustainability with another MCDM method (Mendoza & Prabhu, 2003) and applied fuzzy logic for assessing SFM C&I. Also, several authors employed various MCDM methods for assessing the sustainability of forests (Balana et al., 2010; Rawat et al., 2008; Wolfslehner & Vacick, 2008).

Whilst the majority of the existing literature employed AHP as a MCDM method, this work contrarily and deliberately adopted Fuzzy AHP. Because the traditional AHP is often criticized for falling short to reflect the human thinking style (Chiouy et al., 2011; Şen et al., 2010) and fuzzy sets come in handy at this point. The hybridization of fuzzy logic and AHP helped to cope with the disadvantages of AHP (Aliabadi et al., 2019). This research's novelty arises from the fact that it aims to evaluate the C&I of sustainable management in a less investigated field with a less employed yet more difficult and beneficial method in depth.

The study was conducted in two stages. First, a group of experts were asked to reduce the original declared C&I of OGM. Second, a hierarchical model was created based on group decision and then Fuzzy AHP was employed to analyse the hierarchy and to reveal the relative importance of C&I. For fuzzy AHP, another group of experts were chosen. The selected experts are sustainability-related branch managers in Kastamonu Regional Directorate of Forestry. This research is a case study whose scope is Kastamonu region. However, Kastamonu Regional Directorate of Forestry is the richest region in terms of wealth with 201 million cubic metres of forest (OGM, 2015). Therefore, Kastamonu holds an important part in Turkish forestry and may represent the general condition.

Material and methods

The present paper utilizes the declared C&I of the National Sustainable Forest Management Criterion and Indicators Workshop (2018) held by the Republic of Turkey General Directorate of Forestry (OGM, 2018) which was the most current and reliable data source as of 2021. The workshop was held in Ankara in July 2018, and a total of 141 people participated from public institutions and organizations to non-governmental organizations, from universities to private sector representatives. The workshop consisted of five main sections: the presentations of the working groups, the panel discussion, the handling and decision of the problematic and controversial issues in the sub-working groups and the closing part. The working groups held a total of 13 study meetings in which 140 members actually participated, determined 40 candidate indicators under 6 criteria and prepared the final reports (OGM, 2018).

The study was conducted in two stages. At the first, interviews were made with a group of experts (7) including academics, forest engineers and stakeholders. Whilst academics are people from Kastamonu University, Faculty of Forestry and whose researches and published papers mainly focus on sustainable forestry, forest engineers and stakeholders are experienced people who take part in sustainable forestry activities or sustainable forest management decisions. With the help of a survey, they were asked to reach a consensus in reducing the original criteria and indicators. This reduction was necessary to prevent cumbersome mathematical calculations and to be simple yet explanatory as much as possible. Nominal group technique (NGT) was used to develop a consensus on criteria reduction. NGT is one of the most widely used methods to build consensus (Harvey & Holmes, 2012). It is a decision-making technique structured to elicit opinions and aggregate judgments of groups (ideally consisting of between seven and ten individuals) who have insight into a particular area of interest (Delp et al., 1977; Gallagher et al., 1993; Horton, 1980; Lago et al., 2007). In general, NGT may be useful on the following points: identifying the components of a problem, especially where there are political, social and cultural elements, and identifying and ranking the goals or priorities of any problem (Delp et al., 1977). Due to the overlapping of the properties of the method and the research objectives, NGT was adopted in the present study to develop consensus. Consequent to group decision, the most prominent criteria and sub-criteria were determined as given in Table 1.

At stage two, basing on the determined C&I, the hierarchy was created as following (Fig. 1):

To analyse the hierarchy, Fuzzy AHP method was adopted. The reason behind this adoption was explained in detail in fuzzy analytic hierarchy process section below. For the fuzzy AHP, a second questionnaire was prepared. The questionnaire consists of pairwise comparisons of the criteria and indicators shown in the hierarchy above. The survey was conducted with 5 experts one by one. Each of the experts conducted the survey by comparing the relative importance of one indicator over another. In the present study, for pair-wise comparisons, the fuzzy scale of Chang (1996) was adopted (see Table 2 below). However, in the literature, different fuzzy scales are available, but there is still no consensus on a widely accepted scale (Ishizaka & Nguyen, 2013).

The experts were branch managers selected from Kastamonu Regional Directorate of Forestry. In the beginning of the process, the directorate suggested conducting the survey with branch managers who are working on either closely related subjects or directly sustainable forestry itself. In the directorate, there are

Table 1 Criteria and indicators of sustainable forest management

Criteria	Indicators (sub-criteria)
1—Forest resources and its contribution to the global carbon cycle (C_1)	1.1. Forests and other wooded areas (SC_{11})
	1.2. Carbon stock (SC_{12})
	1.3. Forested area which under management plan (SC_{13})
	1.4. Increment (SC_{14})
	1.5. Forested land of which cadastre is finalized (legally registered)
2—Health, vitality and integration of forests (C_2)	2.1. Silvicultural activities (SC_{21})
	2.2. Using permission and easement (SC_{22})
	2.3. Forest roads and facilities (SC_{23})
	2.4. Monitoring air pollution climate change effects in forests (SC_{24})
	2.5. Human damages (SC_{25})
	2.6. Forests affected by natural factors
	2.7. Grazing damage
3—Production capacity and functions of forests (C_3)	3.1. Increment and production (SC_{31})
	3.2. Non-wood forest products and services (SC_{32})
	3.3. Certified forest (SC_{33})
4—Biologic diversity (C_4)	4.1. Gene sources (SC_{41})
	4.2. Common forest bird species (SC_{42})
	4.3. Common mammal species (SC_{43})
	4.4. Tree species diversity (SC_{44})
	4.5. Threatened forest species (SC_{45})
	4.6. Protected forests (SC_{46})
	4.7. Rejuvenation
	4.8. Naturalness
	4.9. Introduced tree species
	4.10. Dead wood
	4.11. Fragmentation of the forest
5—Protective functions of forests (C_5)	5.1. Soil protection forests (SC_{51})
	5.2. Water basin protection forests (SC_{52})
	5.3 Natural disaster and infrastructure protection forests (SC_{53})
6—Socioeconomic functions of forests (C_6)	6.1. Contribution of the forestry sector to GDP (SC_{61})
	6.2. Financial balance of forestry (SC_{62})
	6.3. The size of the forest-dependent society (SC_{63})
	6.4. The size and quality of employment in the forestry sector (SC_{64})
	6.5. Income transfer from forestry sector to forest villagers (SC_{65})
	6.6. Forest products supply–demand balance (SC_{66})
	6.7. Share allocated from the state budget to the forestry sector
	6.8. Those who benefit from recreation services
	6.9. Research, development, publishing and educational studies
	6.10. Activities of forestry related NGOs
	6.11. Forest and society conflicts

Table 1 depicts the announced original C&I. The sub criteria in bold indicate the reduced sub-criteria according to expert opinion

15 branches and as a matter of course, they are all not related to sustainable management. According to the conversations and examination of the branches, 5 related branch managers were selected. The selected branch managers are all forest engineers. Subsequent to this process, the fuzzy group decision

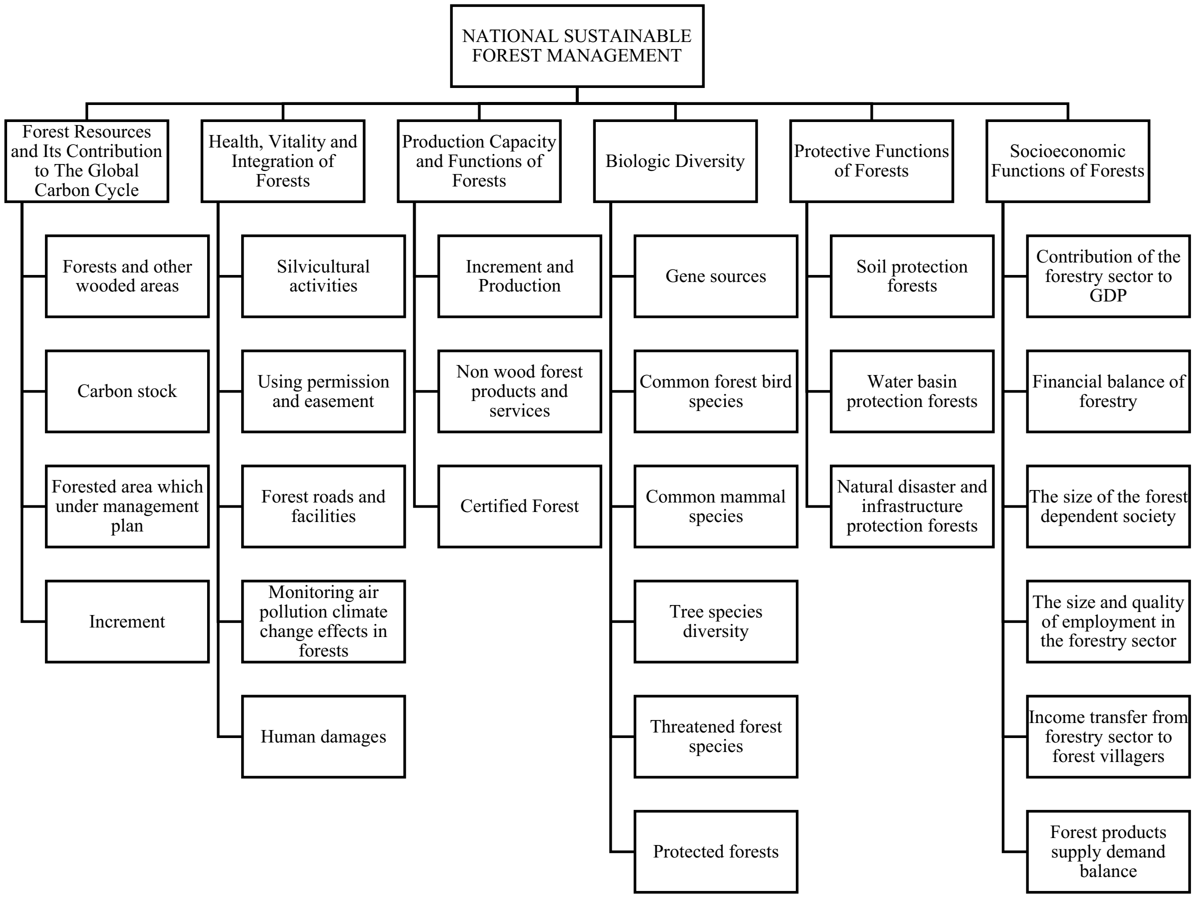

Fig. 1 The national sustainable forest management hierarchy

matrix was obtained by the aggregation of individual judgements.

In the ongoing section, the fuzzy AHP methodology and the obtainment of fuzzy group decision matrix were explained, and the related calculations were given. Before deep-diving into the fuzzy AHP, the fuzzy sets and fuzzy numbers must be understood. Therefore, the basic principles were described below.

Table 2 The fuzzy scale of Chang (1996)

Linguistic variables	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equally important	(1, 1, 1)	(1, 1, 1)
Moderately important	(2/3, 1, 3/2)	(2/3, 1, 3/2)
Important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)
Much more important	(7/2, 4, 9/2)	(2/9, 1/4, 2/7)

Fuzzy sets and fuzzy numbers

In (1965), Zadeh introduced the concept of fuzzy set theory for dealing with vagueness and subjectiveness of human thought (Ip et al., 2012). The word "fuzzy" alludes to the condition in which boundaries of the set of activities or observations are not well-defined (Chen & Hwang, 1992). Fuzzy set theory provides a wider frame than classic set theory (Ertuğrul & Tus, 2007).

Some of the major contributions of fuzzy set theory are its ability to represent vague data and reflecting real-world better (Ertuğrul & Tus, 2007; Naghadehi et al., 2009). Unfortunately, decision-makers generally do not have sufficient data to perform decision analysis. Therefore, whilst modelling decision analysis problems, decision-makers should rely on expert's knowledge and judgment. The fuzzy set theory helps to attain quantitative data in case of imprecision and uncertainty (Huang et al., 2008).

In the absence of full and precise data, fuzzy sets and fuzzy logic are facilitators of common-sense reasoning in decision-making. They are powerful mathematical methods and useful tools for modelling uncertain systems in industry, nature and humanity (Naghadehi et al., 2009).

Fuzzy sets comprise fuzzy numbers in computations, and fuzzy numerical calculations need cumbersome effort. Thus, in the literature, various types of fuzzy numbers are proposed for easy calculation (Aydin & Kahraman, 2010). Generally, in practice triangle and trapezoid, fuzzy numbers are employed (Ertuğrul, 2007). This study applies triangular fuzzy numbers (Ip et al., 2012). Triangular fuzzy numbers are explained below:

An $\tilde{M}$ triangular fuzzy number (TFN) is shown in Fig. 2 below and is simply denoted as (*l, m, u*). The parameters l, m and u, respectively, indicate the smallest possible value, the most promising value and the largest possible value that describe a fuzzy event.

All TFNs have linear representations on their left and right sides such that their membership functions can be described as:

$$\mu\left(x\,|\tilde{M}\right) = \begin{cases} 0, & x < 1, \\ (x-l)/(m-l), & l \le x \le m, \\ (u-x)/(u-m), & m \le x \le u, \\ 0, & x > u. \end{cases} \quad (1)$$

A fuzzy number can always be given by its corresponding left and right representation of each degree of membership:

$$\tilde{M} = (M^{l(y)}, M^{r(y)} = (l + (m-l)y,\ u + (m-u)y) \qquad y \in [0,1] \quad (2)$$

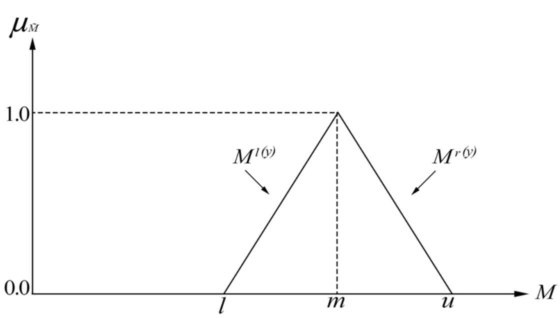

Fig. 2 TFN M̃

where *l(y)* and *r(y)*, respectively, define the left and the right sides representations of a fuzzy number.

Fuzzy numbers' algebraic operations can be found in Srichetta and Thurachon (2012).

Fuzzy analytic hierarchy process

Fuzzy AHP is the extended version of the renowned AHP method (Van Laarhoven & Pedrycz, 1983). Thomas Saaty introduced the AHP in (1980) as a modern instrument to deal with complicated decision-making processes and to assist the decision-makers to determine priorities for the best decisions. Since its development, because of being simple, easy to use and greatly flexible, the researchers studied AHP broadly and employed the method in numerous fields of multiple criteria decision-making (MCDM) (Emrouznejad & Ho, 2017).

As this is a well-established approach, its algorithm is not discussed here. Interested readers can refer to the works of Saaty. In spite of being simple and highly efficient, AHP is frequently criticized due to ignoring the inaccuracy and innate unreliability in perceptions of decision-makers and reflecting their thoughts as crisp numbers. This issue continued until the presentation of fuzzy sets. The hybridization of these methods helped to eliminate the disadvantages of AHP. Fuzzy AHP opened the way of better decisions (Aliabadi et al., 2019).

In fuzzy AHP, the classical AHP has been extended by combining it with fuzzy set theory. In the fuzzy version, fuzzy ratio scales are used for indicating the relative strength of the factors in the corresponding criteria; therefore, the judgement matrix is consisted of fuzzy numbers. So, the final scores of alternatives are represented in terms of fuzzy numbers. The optimum alternative is obtained by ranking fuzzy numbers (Lee et al., 2001).

In multiple criteria-decision-makings under uncertainty, fuzzy AHP has a major function. Plenty of the studies employ this method for quantifying indicators of evaluation. It is broadly exploited by researchers for prioritizing and weighting the criteria and indicators (Aliabadi et al., 2019). Fuzzy AHP is applied extensively in numerous fields such as the following: business, management, manufacturing, industry, government, supply chain, finance, environmental assessment, sustainability systems and risk assessment (Aliabadi et al., 2019; Chiouy et al., 2011; Emrouznejad & Ho, 2017; Lee et al., 2001; Sirisawat & Kiatcharoenpol, 2018).

There have been lots of fuzzy AHP methods used in the literature (Ip et al., 2012). These methods are systematic approaches to the alternative choice and justification problem with using the fuzzy set theory and hierarchical structure analysis concepts (Demirel et al., 2008).

The first form of fuzzy AHP was suggested by Van Laarhoven and Pedrycz (1983), using TFN in the pair-wise comparison matrix. To express the evaluation of alternatives by the decision-maker with regard to each criterion, Buckley (1985) used trapezoidal fuzzy numbers. A new fuzzy AHP method was introduced by Chang (1996). For pair-wise comparison scale, he used triangular fuzzy numbers and employed the method of extent analysis for the synthetic scale values of pair-wise comparisons. In (1997), Cheng suggested a new evaluation algorithm based on the membership function's grade value. Via the application of fuzzy logic mathematics to the classic AHP, Weck et al. (1997) proposed a method. A fuzzy prioritization method was proposed by Mikhailov (2003) for obtaining crisp weights from the matrices of fuzzy comparison through non-linear optimization.

In the present paper, Chang's (1996) extent analysis method will be used. This method is preferred over other approaches because of being relatively easier and its application is similar to the conventional AHP (Şen et al., 2010). In the following, Chang's extent analysis method is explained.

Let $X = \{x_1, x_2, x_3, ..., x_n\}$ be an object set and $U = \{u_1, u_2, u_3, ..., u_m\}$ be a goal set. In Chang's extent analysis, each object is taken, and extent analysis for each goal, g_i, is performed, one by one. Thus, with the signs below, values of $m$extent analysis for each object can be obtained:

$$M^1_{gi}, M^2_{gi}, ..., M^m_{gi}, \qquad i = 1, 2, ..., n$$

where all the $M^j_{gi}(j = 1, 2, ..., m)$ are TFNs. In the following, the steps of Chang's extent analysis were given:

Step 1. Fuzzy synthetic extent value with respect to ith object is described as

$$S_i = \sum_{j=1}^{m} M^j_{gi} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} \right]^{-1} \tag{3}$$

To obtain $\sum_{j=1}^{m} M^j_{gi}$, perform the fuzzy addition operation of m extent analysis values for a particular matrix such that

$$\sum_{j=1}^{m} M^j_{gi} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{4}$$

and to obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi}\right]^{-1}$, perform the fuzzy addition operation of $M^j_{gi}(j = 1, 2, ..., m)$ values such that

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right) \tag{5}$$

and then compute the inverse of the vector in Eq. (5) such that

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right) \tag{6}$$

Step 2. The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as

$$V(M_2 \geq M1) = \sup_{y \geq x} \left[\min(\mu_{M1}(x), \mu_{M2}(y)) \right] \tag{7}$$

and can be equivalently expressed as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1, & if (m_2 \geq m_1) \\ 0, & if (l_1 \geq u_2) \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise \end{cases} \tag{8}$$

where d is the ordinate of the highest intersection point D between μ_{M_1} and μ_{M_2}. To compare M_1 and M_2, the values of both $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are required (see Fig. 3).

Step 3. The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i = (i = 1, 2, ..., k)$ can be described by

$$V(M \geq M_1, M_2, ..., M_k) = V\left[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and... and } (M \geq M_k)\right] = \min V(M \geq M_i), \quad i = 1, 2, ..., k \tag{9}$$

Assume that $d'(A_i) = \min V(S_i \geq S_k)$ for $k = 1, 2, ..., n; k \neq i$. Then, in the following, the weight vector is given as:

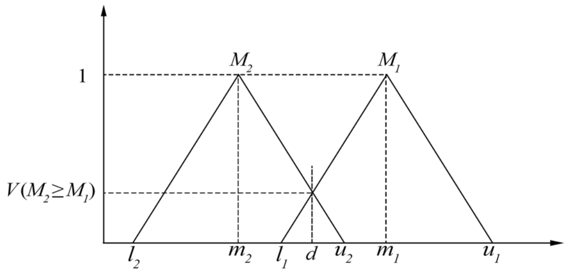

Fig. 3 Intersection point "d" between two fuzzy numbers M_1 and M_2

$$W' = (d'(A_1), d'(A_2), ..., d'(A_n))^T \tag{10}$$

where $A_i(i = 1, 2, ..., n)$ are n elements.

Step 4. Via normalization, the normalized weight vectors are

$$W = (d(A_1), d(A_2), ..., d(A_n))^T \tag{11}$$

where W is a non-fuzzy number.

In general, the fuzzy AHP method consists of the following steps, respectively, development of the problem hierarchy, fuzzy comparison matrices obtainment, fuzzy synthetic extents calculation, fuzzy synthetic extents comparison, the minimum degree of possibilities evaluation and weight vector normalization.

Fuzzy group AHP

In individual and group decision-making processes, the procedures of AHP are applicable (Lai et al., 2002). However, in the group decision-making applications, the individual expert preferences have to be aggregated into a group consensus (Ossadnik et al., 2016). Various aggregation procedures have been presented in the literature (Escobar & Moreno-Jimenez, 2007). Two of the proposed methods have been found to be the most useful in group decision-making applications of AHP: the aggregation of individual judgments (AIJ) and the aggregation of individual priorities (AIP) (Dong et al., 2010). In the present work, AIJ methodology was adopted.

In AIJ, each individual conducts the pairwise comparisons by himself. Then, using (the weighted) geometric mean method, group judgment for each entry of the comparison matrices is obtained (Ossadnik et al., 2016). The geometric mean method is used for obtaining a collective judgement matrix by aggregating individual judgement matrices (Dong et al., 2010). The use of geometric mean operations to aggregate group decisions is common within the applications of AHP towards groups (Meixner, 2009).

The fuzzy AHP is a major extension of the traditional AHP (Coffey & Claudio, 2021; Grošelj & Stirn, 2017). In fuzzy AHP, the use of geometric mean to cope with aggregating and decision-making problems is found to be beneficial by researchers (Chen & Chen, 2005). In this paper, for aggregating the judgements of individuals into a joint decision, geometric mean operations in fuzzy numbers were used based on the equation below. (Emrouznejad & Ho, 2017; Grošelj & Stirn, 2017):

$$l_{ij} = \left(\prod_{k=1}^{k} l_{ijk}\right)^{1/k}, m_{ij} = \left(\prod_{k=1}^{k} m_{ijk}\right)^{1/k}, u_{ij} = \left(\prod_{k=1}^{k} u_{ijk}\right)^{1/k} \tag{12}$$

Application of fuzzy AHP for weighting national SFM criteria and indicators

In the following paragraphs, the aggregated group decision matrix and calculation steps for the main criteria were given. Also, the aggregation operation of experts' judgements on the first criterion was given as an example to demonstrate how the aggregated group decision matrices were obtained (see Table 4). For the sub-criteria, only the calculation results will be presented. The aggregation and calculation steps of the sub-criteria and main criteria are the same and were explained in fuzzy analytic hierarchy process and fuzzy group AHP sections above (Table 3).

To obtain aggregated group decision matrices of all criteria and sub-criteria, the same operation was repeated. The calculations in the ongoing pages were based on the data in Table 4.

Following the creation of fuzzy pair-wise comparison matrix, all criteria weights are calculated with fuzzy AHP. In fuzzy AHP, at first, the calculation of synthesis values must be done. Table 4 was used to calculate these values with respect to main goal using Eqs. (3) to (6):

Table 3 Aggregation of experts' judgements on the first criterion with Eq. (12)

	C_1					
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Aggregated group decision
C_1	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
C_2	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(1, 1, 1)	(0.67, 1, 1.5)	(1.5, 2, 2.5)	(0.85, 1.15, 1.53)
C_3	(0.22, 0.25, 0.29)	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(0.54, 0.76, 1.08)
C_4	(0.67, 1, 1.5)	(1, 1, 1)	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(1.5, 2, 2.5)	(0.85, 1.15, 1.53)
C_5	(0.4, 0.5, 0.67)	(1, 1, 1)	(1, 1, 1)	(0.67, 1, 1.5)	(1, 1, 1)	(0.77, 0.87, 1)
C_6	(0.22, 0.25, 0.29)	(0.67, 1, 1.5)	(1, 1, 1)	(0.67, 1, 1.5)	(1, 1, 1)	(0.63, 0.76, 0.92)

$$S_{c1} = (5.27, 6.46, 8.02) \otimes (0.0222, 0.0273, 0.0332) = (0.12, 0.18, 0.27)$$
$$S_{c2} = (5.62, 7.08, 8.96) \otimes (0.0222, 0.0273, 0.0332) = (0.12, 0.19, 0.3)$$
$$S_{c3} = (4.3, 5.18, 6.33) \otimes (0.0222, 0.0273, 0.0332) = (0.1, 0.14, 0.21)$$
$$S_{c4} = (5.62, 6.89, 8.43) \otimes (0.0222, 0.0273, 0.0332) = (0.12, 0.19, 0.28)$$
$$S_{c5} = (4.9, 5.89, 7.2) \otimes (0.0222, 0.0273, 0.0332) = (0.11, 0.16, 0.24)$$
$$S_{c6} = (4.42, 5.16, 6.1) \otimes (0.0222, 0.0273, 0.0332) = (0.1, 0.14, 0.2)$$

The degrees of possibility of these values were calculated as below (Eq. (8)):

$$V(S_{c1} \geq S_{c2}) = 0.8916, \quad V(S_{c1} \geq S_{c3}) = 1.0000, \quad V(S_{c1} \geq S_{c4}) = 0.9224, \quad V(S_{c1} \geq S_{c5}) = 1.0000, \quad V(S_{c1} \geq S_{c6}) = 1.0000$$
$$V(S_{c2} \geq S_{c1}) = 1.0000, \quad V(S_{c2} \geq S_{c3}) = 1.0000, \quad V(S_{c2} \geq S_{c4}) = 1.0000, \quad V(S_{c2} \geq S_{c5}) = 1.0000, \quad V(S_{c2} \geq S_{c6}) = 1.0000$$
$$V(S_{c3} \geq S_{c1}) = 0.7283, \quad V(S_{c3} \geq S_{c2}) = 0.6214, \quad V(S_{c3} \geq S_{c4}) = 0.6463, \quad V(S_{c3} \geq S_{c5}) = 0.8390, \quad V(S_{c3} \geq S_{c6}) = 1.0000$$
$$V(S_{c4} \geq S_{c1}) = 1.0000, \quad V(S_{c4} \geq S_{c2}) = 1.0000, \quad V(S_{c4} \geq S_{c3}) = 1.0000, \quad V(S_{c4} \geq S_{c5}) = 1.0000, \quad V(S_{c4} \geq S_{c6}) = 1.0000$$
$$V(S_{c5} \geq S_{c1}) = 0.8884, \quad V(S_{c5} \geq S_{c2}) = 0.7782, \quad V(S_{c5} \geq S_{c3}) = 1.0000, \quad V(S_{c5} \geq S_{c4}) = 0.8074, \quad V(S_{c5} \geq S_{c6}) = 1.0000$$
$$V(S_{c6} \geq S_{c1}) = 0.7077, \quad V(S_{c6} \geq S_{c2}) = 0.5967, \quad V(S_{c6} \geq S_{c3}) = 1.0000, \quad V(S_{c6} \geq S_{c4}) = 0.6219, \quad V(S_{c6} \geq S_{c5}) = 0.8238$$

Then priority weights were calculated with Eq. (9):

$$d'(c_1) = min(0.89, 1, 0.92, 1, 1) = 0.89$$
$$d'(c_2) = min(1, 1, 1, 1, 1) = 1$$
$$d'(c_3) = min(0.73, 0.62, 0.65, 0.84, 1) = 0.62$$
$$d'(c_4) = min(1, 1, 1, 1, 1) = 1$$
$$d'(c_5) = min(0.89, 0.78, 1, 0.80, 1) = 0.78$$
$$d'(c_6) = min(0.71, 0.60, 1, 0.62, 0.82) = 0.60$$

Priority weights form $W' = (0.89, 1, 0.62, 1, 0.78, 0.60)$ vector. After the normalization of these values, priority weights respect to main goal are calculated as (0.18, 0.20, 0.13, 0.20, 0.16, 0.12). Priority weights for each criterion and sub-criterion have been indicated in Table 5.

Results and discussion

To determine the relative importance of criteria affecting sustainable forest management, the present paper adopted fuzzy AHP method. Six criteria and twenty-seven sub-criteria were analysed, and the results are displayed in Table 5.

Among the main criteria, "health, vitality and integration of forests" and "biologic diversity" were

Table 4 Aggregated main criteria group decision matrix

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	(1, 1, 1)	(0.65, 0.87, 1.18)	(0.87, 1.25, 1.78)	(0.65, 0.87, 1.18)	(1, 1.15, 1.3)	(1.09, 1.32, 1.59)
C_2	(0.85, 1.15, 1.53)	(1, 1, 1)	(1.08, 1.43, 1.85)	(0.72, 0.84, 1)	(0.78, 1.15, 1.66)	(1.18, 1.52, 1.91)
C_3	(0.54, 0.76, 1.08)	(0.54, 0.7, 0.92)	(1, 1, 1)	(0.72,0.92,1.18)	(0.66, 0.8, 0.98)	(0.85, 1, 1.18)
C_4	(0.85, 1.15, 1.53)	(1, 1.19, 1.39)	(0.85, 1.08, 1.39)	(1, 1, 1)	(1, 1.32, 1.7)	(0.92, 1.15, 1.41)
C_5	(0.77, 0.87, 1)	(0.6, 0.87, 1.28)	(1.02, 1.25, 1.51)	(0.59, 0.76, 1)	(1, 1, 1)	(0.92, 1.15, 1.41)
C_6	(0.63, 0.76, 0.92)	(0.52, 0.66, 0.84)	(0.85, 1, 1.18)	(0.71, 0.87, 1.08)	(0.71, 0.87, 1.08)	(1, 1, 1)

Table 5 Fuzzy analytic hierarchy process results

Criteria	Indicators (sub-criteria)	Local weight	Global weight
Forest resources and its contribution to the global carbon cycle (0.18)	Forests and other wooded areas	0.26	0.0467
	Carbon stock	0.26	0.0467
	Forested area which under management plan	0.27	0.0497
	Increment	0.21	0.0388
Health, vitality and integration of forests (0.20)	Silvicultural activities	0.28	0.0566
	Using permission and easement	0.08	0.0154
	Forest roads and facilities	0.13	0.0264
	Monitoring air pollution climate change effects in forests	0.20	0.0418
	Human damages	0.31	0.0643
Production capacity and functions of forests (0.13)	Increment and production	0.37	0.0468
	Non wood forest products and services	0.32	0.0402
	Certified forest	0.31	0.0398
Biologic diversity (0.20)	Gene sources	0.08	0.0172
	Common forest bird species	0.13	0.0263
	Common mammal species	0.15	0.0316
	Tree species diversity	0.18	0.0374
	Threatened forest species	0.23	0.0479
	Protected forests	0.22	0.0441
Protective functions of forests (0.16)	Soil protection forests	0.26	0.0418
	Water basin protection forests	0.43	0.0685
	Natural disaster and infrastructure protection forests	0.31	0.0493
Socioeconomic functions of forests (0.12)	Contribution of the forestry sector to GDP	0.20	0.0248
	Financial balance of forestry	0.13	0.0161
	The size of the forest-dependent society	0.12	0.0146
	The size and quality of employment in the forestry sector	0.17	0.0206
	Income transfer from forestry sector to forest villagers	0.18	0.0218
	Forest products supply–demand balance	0.20	0.0248

ranked the highest, followed by “forest resources and its contribution to the global carbon cycle”, “protective functions of forests”, “production capacity and functions of forests” and “socioeconomic functions of forests”.

What stands out in this finding is the dominance of environment-related criteria. This dominance may be explained by the fact that the fuzzy AHP analysis is based on the views of branch managers working in the Kastamonu Regional Directorate of Forestry, and their jobs mainly focus on the environmental facets of forests.

As aforementioned in the introduction section, sustainability has three main pillars, and the current SFM guidelines are based on planning programmes which seek to identify economic, environmental and social consequences (Riccioli et al., 2020). The mentioned condition may cause the social and economic functions of forests to be neglected. It can therefore be assumed that the present sustainable forest management planning is not focused on the three pillars equally but on environmental.

This finding is consistent with the study of Jafari et al. (2018). In their study, environmental-related criteria were found the most important and followed by economic and social-related criteria, respectively.

Before turning to the sub-criteria groups, an important point should be underlined: the below interpretations are based on local weights and evaluation of the global ranking of all sub-criteria will be done in the end of this section.

If we now turn to the sub-criteria groups, the ranking in sub-criteria group 1 (under the main criteria: "forest resources and its contribution to the global carbon cycle") is as follows: "forested area which under management plan", "carbon stock" and "forests and other wooded areas", "increment". It can be said that the sub-criteria in group 1 partially has equal importance.

In the sub-criteria group 2 (under the main criteria: "health, vitality and integration of forests"), "human damages" ranked the highest and followed by "silvicultural activities", "monitoring air pollution climate change effects in forests", "forest roads and facilities" and "using permission and easement".

The sub-criteria related to "health and vitality" were found more important than the sub-criteria related to "integration". This result supports the argument that the social and economic functions of forests may be neglected. However, this finding is rather disappointing. It is because Pokharel et al. (2015) concluded that socio-economic issues are highly important and need to be addressed in order to motivate people towards SFM.

"Increment and production" ranked the highest in sub-criteria group 3 (under the main criteria: "production capacity and functions of forests") and followed by "non-wood forest products and services", and "certified forests".

According to the weights, it is apparent that the sub-criterion related to "production capacity" is more important than the others. This result is consistent with the literature. Akyol (2009) distinguished that OGM focuses more on the sustainability of wood and wood products. Similarly, Riccioli et al. (2020) found that the actual SFM policies in Tuscany (which are highly related to the Italy's) aim to support wood production rather than other sustainability indicators. Lindahl et al. (2017) stated that, generally, the production-related criteria have a higher weight in management decisions.

Also, contrary to expectations: despite certification is one of the most important tools for achieving SFM (Akyol, 2009), "certified forests" were found as the least important sub-criterion. A possible explanation for this might be that the "certified forest" sub-criterion may be located under the wrong criteria. Atmiş and Çil (2013) reported the existence of classification problem for Turkey's SFM indicators. Turkey adopted the original form of near east process's C&I without any adaptation. The international C&I should not be identical copies (Atmiş & Çil, 2013). Customization of them is essential for each country (Jafari et al., 2018).

In sub-criteria group 4 (under the main criteria: "biologic diversity"), among the criteria, "threatened forest species" ranked the highest and followed by "protected forests", "tree species diversity", "common mammal species", "common forest bird species" and "gene sources".

Based on Table 5, it is apparent that, in sustainable forest management, in terms of biological diversity: the sub-criteria related to plants have been found to be more important than those related to animals and gene sources.

Sustainable forestry should not only cover forest assets and tree species. Wildlife in forests and other functions of forests should also be essential in sustainable forest management. Mankind has many needs from the forests in form of goods and services (Bekiroğlu et al., 2016). The forest is a forest with all its elements. Therefore, the sub-criteria related to mammals, birds and gene sources should be paid more attention.

The ranking in sub-criteria group 5 (under the main criteria: "protective functions of forests") is as follows: "water basin protection forests", "natural disaster and infrastructure protection forests" and "soil protection forests".

What stands out in here is the importance of water related sub-criterion. When the importance of water to living things taken into consideration, this finding seems reasonable. The current and future generations of mankind need water and water catchments (Atmiş & Çil, 2013; Bekiroğlu et al., 2016).

In sub-criteria group 6 (under the main criteria: "socioeconomic functions of forests"), "contribution of the forestry sector to GDP" and "forest products supply–demand balance" ranked the highest and followed by "income transfer from forestry sector to forest villagers", "the size and quality of employment in the forestry sector", "financial balance of forestry" and "the size of forest-dependent society".

Closer inspection of this sub-criteria shows that, whilst sub-criteria related to economic function came to the fore, sub-criteria related to social function fell behind. Although these sub-criteria are directly related to economic and social indicators, this finding supports the prevailing opinion throughout the research. According to the present study, environmental indicators are the most important in sustainable forest management, followed by economic and social indicators, respectively.

This finding is consistent with that of Atmiş and Çil (2013) who noted that forests' socioeconomic functions are ignored in the SFM indicators of Turkey. The evidence from this study suggests that Turkey should not forget that, in sustainable forest management, the socioeconomic roles of forests are becoming more important. (Higman et al., 2005).

As indicated previously, the global ranking of sub-criteria is as follows:

1-Water basin protection forests (0.0685), 2-human damages (0.0643), 3-silvicultural activities (0.0566), 4-forested area which under management plan (0.0497), 5-natural disaster and infrastructure protection forests (0.0493), 6-threatened forest species (0.0479), 7-increment and production (0.0468), 8-forests and other wooded areas (0.0467), 8-carbon stock (0.0467), 9-protected forests (0.0441), 10-monitoring air pollution climate change effects in forests (0.0418), 10-soil protection forests (0.0418), 11-non-wood forest products and services (0.0402), 12-certified forest (0.0398), 13-increment (0.0388), 14-tree species diversity (0.0374), 15-common mammal species (0.0316), 16-forest roads and facilities (0.0264), 17-common forest bird species (0.0263), 18-contribution of the forestry sector to gdp (0.0248), 18-forest products supply–demand balance (0.0248), 19-income transfer from forestry sector to forest villagers (0.0218), 20-the size and quality of employment in the forestry sector (0.0206), 21-gene sources (0.0172), 22-financial balance of forestry (0.0161), 23-using permission and easement (0.0154), 24-the size of the forest-dependent society (0.0146).

This ranking confirms the previous interpretations, mostly the environmental indicators have higher weights than economic and social indicators.

Conclusions

The main goal of the present research was to investigate and reveal the importance levels of sustainable forest management C&I of Turkey to evaluate and interpret the advantages and disadvantages of present National SFM. Fuzzy logic and one of the multi-criteria decision-making methods (Fuzzy AHP) have been used for this purpose.

This study has shown that the importance attached to environment-related C&I is considerably higher than that of other SFM C&I. The ranking of the importance levels (weights) of C&I from high to low is as follows, respectively, environmental, economic and social. Sustainability has three pillars, and the mentioned case may cause to the negligence of the economic and social functions of SFM.

One of the more significant findings to emerge from this study is that Turkey focuses more on the sustainability of wood and wood products rather than other sustainability indicators. However, obviously, this is not enough for a sustainable forest management practice. In the theory, the sustainability of all the elements in forests must be ensured and be passed on to future generations.

The research has also identified that there is a classification problem for SFM indicators of Turkey. In Turkey, OGM adopted the internationally determined C&I, but these should not be identically copied. Each country should customize the C&I according to their realities. A reasonable approach to tackle this issue could be to review and localize the current SFM C&I by integrating all types of stakeholders to the process.

The findings from this study make several contributions to the current literature. First, there are not many studies in the literature dealing with the measurement of sustainability or calculation of the indicators' importance. Much of the literature concerns the concept of sustainability. A recent literature review concluded that most of the studies dealing with calculation adopted the basic multi-criteria decision methods without fuzzy logic. This is the main novelty that lies in the present paper, measuring the importance of sustainable management C&I in an important natural resource field with fuzzy logic and multi-criteria decision-making approach. Second, the findings are in line with those of previous studies. Therefore, the calculated weights of C&I may be regarded as reference values for the future sustainable forest management plans.

The present study is limited by Kastamonu region, and this is the major limitation of this work. Kastamonu region is small yet represents an important part of Turkey's forestry. Although the findings are found in line with the literature, this fact should not be forgotten. Therefore, the results need to be interpreted with caution. Another limitation of the study is the type of stakeholders involved. Academics, forest engineers and branch managers contributed to the work; however, forest villagers were not be able to reach due to various difficulties.

Focusing on the measurement of sustainability and calculation of indicators' importance would be a fruitful area for further work. More comprehensive research covering different stakeholder types are needed to develop better sustainable management plans.

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Data availability The author confirms that the data supporting the findings of this study are available within the article.

Declarations

Conflict of interest The author declares no competing interests.

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