



Multi-attribute decision making and geographic information systems: potential tools for evaluating forest ecosystem services

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Abstract

• **Key message** Due to social and environmental changes over the last decade, managers use multi-attribute decision-making techniques and geographic information systems to support participatory planning. Several studies have indicated that the combined use improves forest planning by applying a set of key criteria to simultaneously evaluate various ecosystem services.

• **Context** Forest landscapes are essential elements for the provision of ecosystem services and they contribute to human well-being. The identification of management options that consider various objectives and stakeholder interests requires strong decision support tools.

• **Aims** We review the current state of knowledge on the use of decision-making approaches in combination with geospatial technologies, and the criteria most often used to assess supporting and cultural services in scientific literature.

• **Results** The analysis demonstrated that Analytic Hierarchy Process is the most common method used in combination with spatial knowledge due to its simple principles (decomposition, comparative judgment, priority synthesis) and effective work-flow to evaluate potential decision alternatives and support reproducible results. Key criteria used in the analysis are: distance to road, water bodies, slope, and vegetation cover.

• **Conclusion** Easy to use methods allow a broad and participatory engagement of layman in the decision process. More advanced techniques might be used by experts to produce more robust and reliable results. Future research should provide easy access to the spatial information of the key criteria to utilize synergistic effects.

Keywords Forestry · Ecosystem services · MADM · GIS · Review

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1 Introduction

The 2017 United Nations (UN) Forum on Forests launched a new worldwide strategy to promote sustainable forest management and provide a multitude of wood and non-wood forest products and ecosystem services (ES) (U. Nations 2018). The framework aims to maintain and enhance the economic, social, and environmental value of all types of forests for the benefit of present and future generations (FAO 2020). In

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this context, the benefits people obtain from ecosystems are classified by the Millennium Ecosystem Assessment as provisioning, regulating, supporting, and cultural services (Reid et al. 2005).

In a global context, environmental changes caused by carbon dioxide emissions and the related increase in disturbances and natural hazards are influencing the provision of ES by forest management. These changes affect human well-being in many ways. Forests cover approximately four billion hectares worldwide, or about 30% of the total land surface area (FAO 2020). Recent studies confirm that the exponential growth of atmospheric carbon dioxide has driven the increase in global temperatures worldwide, which has led to ecosystem degradation, and deforestation. As estimated by the Food and Agriculture Organization of the UN, the average annual deforestation rate from 1990 to 2015 was 13 million hectares (IUFRO Division 5 and SWST Convention 2017). ES play an important role for human well-being and have been recognized as a fundamental element of the ES framework (Deal et al. 2017; Sandifer et al. 2015). Understanding these interactions and analyzing trade-offs and synergies is of high relevance. Recent technological advances as well as uncertainties related to environmental change are the main drivers in research about forest ES (Yousefpour and Hanewinkel 2016).

One of the challenges for forest managers is to identify anthropogenic pressures with regard to environmental change and select adequate, adaptive measures (Radke et al. 2017). Hence, the complexity of adaptive forest management planning under climate change is increasing, as different alternative options could be promising with regard to the achievement of multiple goals and interests. The managerial problem for forest management requires a rational planning process in complex and dynamic landscapes, which is best achieved by reducing uncertainty related to the choice among alternatives (Muller et al. 2020). The use of forests for cultural ES (e.g., different recreational and spiritual activities such as ecotourism, sport, collection of non-wood forest products) are rapidly diversifying, and types vary across geographic areas and visitor demands. Thus, the participation of the public to advocate their values and interests has become an increasingly important aspect in the decision-making process. In practice, forest planning decisions should be developed in consultation with local inhabitants, recreation users, forest owners, the public, or people belonging to a forest community, as each of them has different preferences regarding the use of forests and other natural resources (Pourghasemi and Gokceoglu 2019). With the need to involve larger groups in discussions, it becomes increasingly difficult to arrive at a consensus.

These complex decision problems and the analysis of trade-offs between different ES, the combined use of multi-attribute decision-making (MADM) techniques and

geographic information systems (GIS) to support planning efforts is recommended (von Detten and Hanewinkel 2017; Malczewski and Rinner 2015). These approaches are increasingly seen as an opportunity to quantify and evaluate the temporal and spatial effects of forest management on multiple ES by spatial analysis (Keenan 2015; Vacik and Lexer 2014). The combined use of MADM techniques, relevant evaluation criteria, and appropriate GIS solutions provide a solid basis for the planning process (Baskent et al. 2020; Fish et al. 2016).

MADM techniques provide several powerful applied mathematical techniques to choose the best management approach based on the goals and preferences of the decision maker. To solve an MADM problem, the weights of the attributes have to be determined, the second step is to normalize the attribute values for each management option, and the third is to aggregate the normalized attribute values into an overall index for ranking the alternatives (Zhang 2014). Through an algorithm, which considers the social or stakeholder preferences in a technical framework, complex decision problems can be addressed (Ishizaka and Nemery 2013).

The potential power of GIS goes beyond producing maps by providing mechanisms for the input, storage, analysis, and use of spatial information. Large criteria sets are often used to evaluate different management approaches as they allow accounting for environmental impacts, stakeholder opinions, and ecological, bioeconomic, risk, and security aspects. While GIS offers the opportunity to analyze the spatial dimension of decision problems, remote sensing data also present additional data sources to support forest planning. A large variety of advanced geospatial technologies and data sources in earth observation are used within GIS for forest management, for example, satellite systems, in-situ observations, unmanned aerial vehicle (UAV) system, mobile laser scanning, multispectral imaging devices, new sensors mounted on mobile devices, and digital camera combined with global navigation satellite system (GNSS) (Hyyppe et al. 2020; Liang et al. 2019). GIS is well suited to analyze different management scenarios, on a cross-multiple spatial and temporal scale (Palomino et al. 2017; Emery et al. 2017).

A combined approach of MADM and GIS techniques can help to minimize trade-offs between multiple ES, and support decision making of short-term forest resource management and long-term strategic planning (Armatas et al. 2018). In this context, supporting ecosystem services are necessary for the provision of all other ES and, therefore, provide a sound basis for the evaluation. The increasing demand for cultural services causes several challenges for forest management because the non-material benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, aesthetic experiences, reflection, and recreation are mostly not considered in the design of forest management

Table 1 Conceptual framework for review of multi-attribute decision making (MADM) and geographic information system (GIS) in forest applications

Context	<ul style="list-style-type: none"> • Integration of ecosystem services into the process of forest management planning; • Environmental issues; • Investment cost; • The participation process.
Intervention	<ul style="list-style-type: none"> • Selection of an appropriate combination of evaluation criteria; • Decision support methods and GIS tools.
Mechanisms	<ul style="list-style-type: none"> • Different practices and instruments of elicitation methods; • Priorities determined for criteria; • Professionals and/or laymen actors involved in the process; • Spatial scale considered.
Outcome	<ul style="list-style-type: none"> • Finding the most relevant MADM method and criteria frequently used in forest management; • Cost performance by the use of MADM and GIS; • Comprehensive understanding in the participatory process by use of MADM and GIS; • Dealing with uncertain and imprecise data.

strategies. However, no comprehensive overview can be found on the criteria used to quantify selected forest ES and the application of MADM in combination with GIS.

We designed this review to contribute to this knowledge gap and evaluate the adoption of new technologies in the field of forestry. Based on an analysis of scientific literature in the use of MADM methods and GIS in forestry over the past 10 years, this study provides (i) an overview about the applicability of different methodological approaches as well as (ii) the most relevant evaluation criteria used to quantify cultural and supporting ES. We review the characteristics of the multi-attribute methods used in combination with GIS as a basis for forest management planning and provide a description of an ideal combination.

2 Material and methods

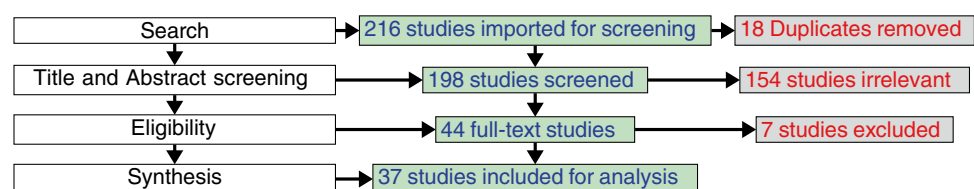
We summarize the key aspects of the review following the CIMO-logic methodology (Table 1) proposed by Denyer et al. (2008). The approach was helpful in the development of more rigorous design propositions; the logic involves a combination of the context of the problem, a suggestion for a certain intervention type, and mechanisms to produce the intended outcome. In this way, we were able to describe the context of the ES used, as well as the GIS and MADM techniques applied to improve the outcomes. We constructed and reviewed a database of scientific papers that employed state-of-the-art techniques combining MADM techniques

and GIS in the field of forest management and planning for the provision of forest ES over the last 10 years. It is an update of previous similar scientific reviews published in 2009, 2013, and 2015, where the case studies in the literature reviewed were conducted between 1989 and 2013 (Ananda and Herath 2009; Hujala et al. 2013; Uhde et al. 2015).

The web-based software 'Covidence' was applied in this review to extract the relevant studies; the detailed steps are shown in the (Fig. 1). The research analysis was initiated in January 2019 using the online keyword search in several databases including Web of Science, Google Scholar, and Scopus.

The identification of relevant studies was based on two steps: the search from primary channels (high quality books; journals; review articles) and from secondary sources (bibliographies; abstract reading), taking into account the following ranges:

- definition of the keywords for the search included 'multi-attribute decision-making method', 'multi-criteria decision making', 'MCM', 'MCA', 'MCDA', 'MCDM', 'MADM', 'MODM', 'Geographic Information System', 'GIS', 'ecosystem services', 'forestry', 'forest recreation/cultural services', 'forest supporting services/conservation';
- use of the Boolean AND operator for combining search terms: Use of multi-attribute decision-making method AND Geographic Information System AND Forestry;

Fig. 1 A descriptive steps of the paper review

- (c) research criteria: advanced search, at least 40% of forest surface areas included in the study application;
- (d) limits: papers published from 2009 to 2019;

A review matrix technique was used to search for scientific studies (author; title; purpose; MADM methods; area studied; number of actors involved; actors fields; criteria used; method of elicitation); 198 research articles were sampled from the literature review, 154 were eliminated in the early stages because the papers were off-topic for this review (e.g., present a majority of agricultural or urban land rather than forest surfaces, different ES except for cultural and supporting ES). From the identified examples, we used 37 case studies for further consideration based on specific selection criteria (e.g., completeness of the methods described, description of the evaluation criteria, context of the study) and mainly on validation of simulation models (e.g., comparison; verification).

These papers were then categorized by authors according to cultural services and supporting services. The cases differed in spatial scale from local, to municipal, regional, and/or national scale and covered a wide range of countries (Fig. 2). A database was built to organize and evaluate the literature and support the qualitative and quantitative synthesis of the studies: number of multi-attribute methods and criteria used, surface of spatial scale, number of participants involved in the questionnaire survey, choice of preference elicitation technique among the criteria, and validation approach for both the spatial analysis model and sensitivity analysis among the criteria (see Tables 2 and 3). The evaluation criteria were clustered according to the two dimensions of the Millennium Ecosystem Assessment classification (Reid et al. 2005). Firstly, cultural services are defined by the non-material benefits, such as recreation, culture, and spiritual aspects. Secondly, the supporting services needed for their production, such as primary production, production of oxygen, or soil formation.

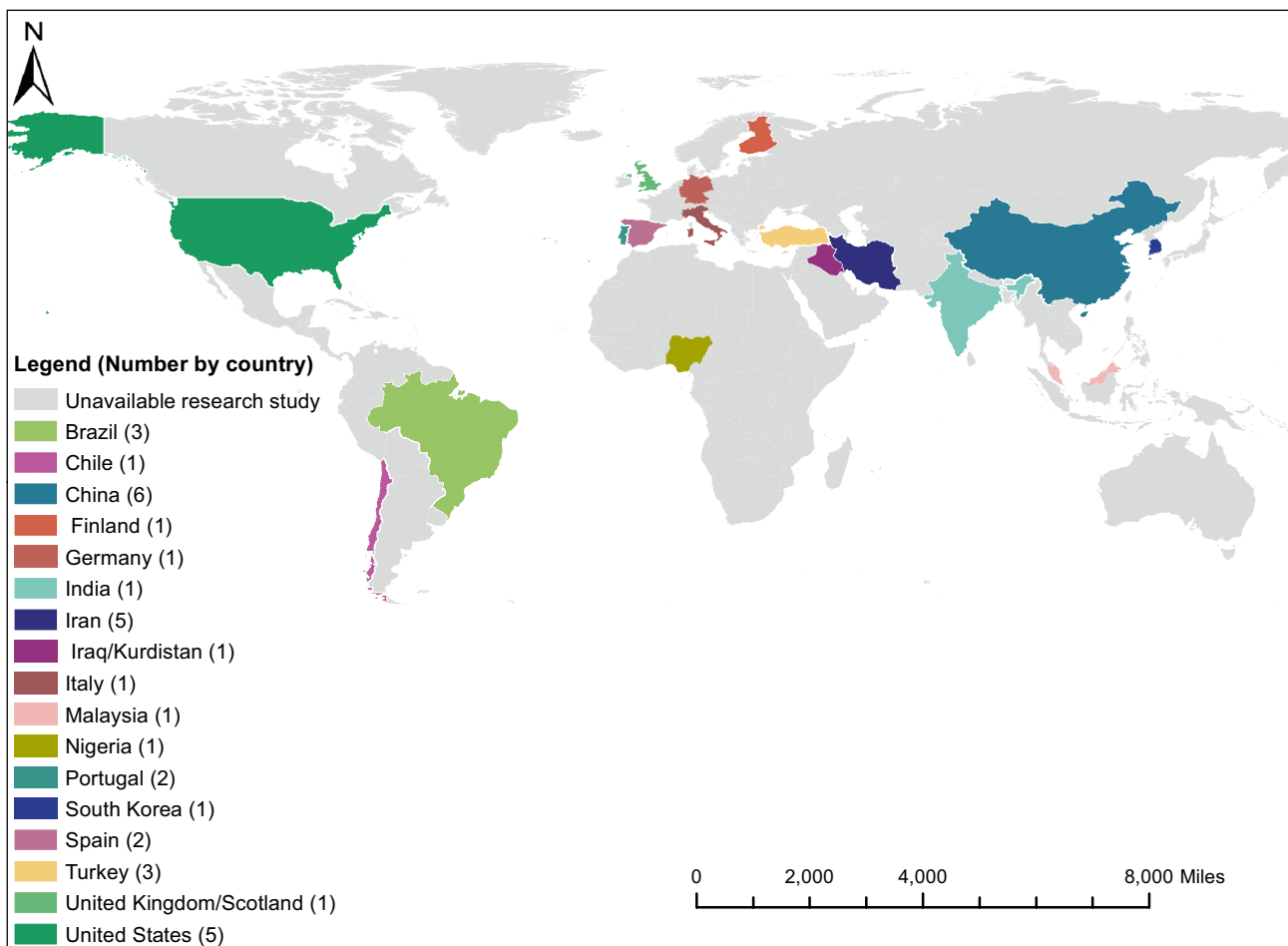


Fig. 2 Geographic coverage of the studied cases using multi-attribute decision-making (MADM) techniques and geographic information system (GIS) applications

Table 2 Overview of recent forest recreation and cultural ES case studies applying MADM and GIS

Study	MADM Techniques	Study region	Description of approach adopted		Study objective	Validation techniques	Results	Simulation model validation	Findings
			No. of criteria	Elicitation methods					
Ustaoglu and Aydinoglu (2020)	AHP	Turkey	17	Expert consultations	Suitability of green space zones	N/A	15,6% of areas highly suitable	N/A	Assessment analysis may help connect green features and allocate future demand for urban green space
Siroosi et al. (2020)	AHP	Northern Iran	10	Questionnaire	Evaluate potential tourism areas	Comparison between multi-criteria evaluation models and ground-based using ROC	Most suitable areas were found close to attraction points	Statistic results scored 0.82 and 0.814 for multi-criteria evaluation-based MLP and LR	Decision aid methods can be merged into mathematical models as linear regression or multi-layer perception process
Yun et al. (2019)	AHP	South Korea	4	Expert consultations, literature review	Evaluate restoration sites	Field survey-conducted to compare models suitability using GPS	49,5% were high and very high suitable zones	Comparison-demonstrated accurate assessment analysis	Presented model could enhance success of reestablishment efforts
Ghorbanzadeh et al. (2019)	ANP-OWA	North-West Iran	4	Questionnaire	Map potential nature tourism areas	N/A	The result showed a high suitability zones for nature tourism	N/A	Technical framework has the possibility of dealing with physical process of nature-based tourism
Yang et al. (2019)	AHP	Hebei Province China	9	Review literature, expert consultations	Evaluate potential visual sensitivity site of a plantation forest landscape	N/A	High visually sensitivity areas were found in recreation areas and along major roads	N/A	Model can quickly support updating data change results
Zheng et al. (2019)	AHP	Tianzhu forest China	5	Ad hoc expert appraisal	Suitability of recreation development for forest conservation	N/A	0,06% of zones adequate for recreational facilities	N/A	Model could be integrated into forest park management systems
Balist et al. (2019)	Fuzzy AHP	Kurdistan Province	15	Expert opinions, literature reviews	Allocate ecotourism zones	N/A	Nearly 664km ² of areas were most appropriate for ecotourism	N/A	Proposed work led to regional scale efficiency map

Table 2 (continued)

Study	MADM Techniques	Study region	Description of approach adopted			Results	Simulation model validation	Findings	
			No. of criteria	Elicitation methods	Study objective				Validation techniques
Olaniyi et al. (2018)	AHP	Nigeria	7	Interviews	Suitability of ecotourism national parks	Image classification accuracy using <i>Kappa</i>	On average both Parks have great ecotourism potential	Overall accuracy results showed $K = 86.00\%$ and 85.63% compatibility	Model can be integrated into ecotourism clusters to realize tourism compatibility
Dagistanli et al. (2018)	WLC-AHP	Turkey	8	Expert panels	Suitability of recreation sites	Image classification analysis using <i>Kappa</i>	33% zones obtained highly suitable scores	Overall classification accuracies greater than $K = 80.00\%$	Integrated model has ability to evaluate visitors demands and tendencies
Merry et al. (2018)	Fuzzy	Jackson county, USA	3	Decision-making group	Suitability of motorized sightseeing recreation sites	Image classification analysis using <i>Kappa</i>	89,639ha were highly suitable zones	Accuracy assessments greater than $K = 70.00\%$	Integrated method suitable in determining key information for regional and national recreation planning
Samira et al. (2018)	Fuzzy-AHP	North Iran	14	Questionnaire	Evaluate potential of ecotourism mapping	Image classification analysis using <i>Kappa</i>	60.00% of basin area was most suitable for recreational activities	Overall accuracy result $K = 83.00\%$	Proposed methodology requires less cost and time
Abdullah and Rafeai (2017)	AHP	Malaysia	5	Literature reviews, expert knowledge	Assess potential of recreational areas	N/A	81.00% of zones were most suitable	N/A	Vegetation cover considered an important criterion for forest ecosystem planning
Aliani et al. (2017)	WLC-Fuzzy	North Iran	16	Questionnaire, literature review	Map ecotourism development	Survey conducted in terrain using GPS	82,891.89ha of sites suitable for ecotourism	Comparison results were 94% in accordance with ground realities	Model could simultaneously consider different criteria to find the best alternative decision problems

Table 2 (continued)

Study	MADM Techniques	Study region	Description of approach adopted			Results		Simulation model validation	Findings
			No. of criteria	Elicitation methods	Study objective	Validation techniques			
Ahmad and Goparaju (2017)	AHP	India	5	Not indicated	Prioritize urban forest sites	Land-use/cover image was compared to the ground truth data using <i>Kappa</i>	27% of sites highly suitable	<i>kappa</i> accuracy 0.87%	Process analysis helps analyze suitable sites for urban forest management
Cuirong et al. (2016)	AHP	China	12	Expert consultations	Evaluate camping zones	N/A	64.09% of areas considered as potential sites for camping activities	N/A	Proposed analysis provides scientific and efficient workflow to evaluate appropriateness of other areas
Gonzalez-Ramiro et al. (2016)	AHP	Extremadura Spain	6	Not indicated	Assessing the potential of rural tourism	N/A	Some municipalities were very suitable for rural tourism	N/A	Proposed tool offers free access to open source that can serve investment users for sustainable development
Erfani et al. (Aug2015)	WLC	Iran	12	Questionnaire	Evaluate ecotourism zoning	N/A	1344.39ha suitable for ecotourism	N/A	Methodology provides weighting of quantitative and qualitative criteria
Store et al. (2015)	AHP	Different regions of Finland	12	Expert group opinions, questionnaires	Evaluate visual sensitivity map	Comparison between expert judgments and predicted sensitivity map applying CC calculus	Areas alongside water bodies and hill zones had high sensitivity rates	Comparison gave similar results with strong correlation coefficient ($R^2 = 0.945$)	Developed methodology useful in terms of cost efficiency and forest management

Table 2 (continued)

Study	MADM Techniques	Study region	Description of approach adopted			Results	Simulation model validation	Findings
			No. of criteria	Elicitation methods	Study objective			
Dhami et al. (2014)	AHP	West Virginia, USA	6	Self-administered questionnaire among visitor preferences	Map forest eco-tourism areas	The most suitable area covered more than half of the total case study zone	Weighted eco-tourism map more accurate than the unweighted one	Framework technique was promising using forest visitor preferences and helpful in terms of tourism development and forest conservation
Zhang et al. (2013)	AHP	Meili Snow Mountain, China	8	Requirement workshops	Prioritize nature tourism sites	Fewer areas for recreational activities	N/A	Proposed approach helped to interact many different stakeholder needs

N/A Not applied, LR Linear Regression, CC Correlation coefficient, GPS Global positioning system, KO Kolmogorov, χ^2 Chi-square

2.1 Decision-making methods in ecosystem management

Roy (1996) defined decision making as: A decision aid and a mathematical tool determining the comparison of different alternatives or scenarios including multiple criteria, often conflicting, in order to guide the decision maker to find optimal choice. Generally, it is a set of behaviors characterized by principles to limit the risk of conflict and eliminate uncertainty (Almeida et al. 2015; Rao 2013). There are various MADM methods applied in forest management planning for providing ES (Uhde et al. 2015); examples include techniques for choosing the best option, ranking options from best to worst including prior or posterior elicitation of preferences (Zyoud and Fuchs-Hanusch 2019). The integration of GIS and MADM techniques has only recently been applied to environmental problems in forestry, including spatial modeling and procedures for site selection (Ezzati et al. 2016; Hayati et al. 2013; Zucca et al. 2008; Snyder et al. 2008). These techniques have also been applied to risk mapping (Eskandari 2017; Lin et al. 2014; Kant et al. 2012), and conservation planning (Vettorazzi and Valente 2016; Gülci and Akay 2015; Zhang et al. 2013; Store and Antikainen 2010; Geneletti and van Duren 2008). A recent review of the literature describes the many emerging tools and practices developed for sustainable forest management (Gülci and Akay 2015).

The methods in multiple attribute utility theory (MAUT) (Arriaza et al. 2002) and multiple attribute value theory (MAVT) (Martin et al. 2000) were among the first introduced in forestry applications. They are based on ranking and interactive methods which construct a utility/value function for each criterion. The weighted linear combination (WLC) and ordered weighted averaging (OWA) determine different possibilities relative to weights for each factor using the aggregation process (Gülci and Akay 2015; Lin et al. 2014). The combination of analytical hierarchy process (AHP) or analytical network process (ANP) with GIS has been widely used in forest management as well. These methods provide a means to measure quantifiable and/or intangible criteria data. Although the methodology of both techniques is similar, the main difference is that the ANP approach is a generalization of the AHP based on a network, not a hierarchy (Ezzati et al. 2016). A few researchers have applied fuzzy methods in forest management planning, particularly the combination of fuzzy AHP integrated with GIS for localization of forest risk mapping (Eskandari 2017; Kant et al. 2012). This extension technique allows an approach to manage the vagueness and uncertainty of certain data.

3 Results

The combination of MADM methods and GIS is currently considered to be the most effective decision support approach to respond to landscape planning problems, and it allows us to improve our knowledge and understanding of natural and socioeconomic factors. Various applications in the field of recreation planning and eco-tourism, as well as forest conservation management, can be found in scientific literature. In this review, a selection of the most prominent examples is given in Tables 2 and 3.

3.1 Use of GIS and MADM methods for cultural ES

The identification of the most appropriate locations for touristic hot-spots or the zoning of the countryside for recreational activities are relevant applications (Table 2). Ustaoglu and Aydinoglu (2020) recently combined a decision-making approach with spatial analyses to evaluate and find suitable green space areas. They used the AHP method to compute the criteria weights, and decision makers selected the most relevant criteria. Yun et al. (2019) also used an AHP and GIS approach to compute the location of potential sites for forest wetland in South Korea, where the goal was to analyze the characteristics of the forest wetland with sixteen criteria. Ghorbanzadeh et al. (2019) assessed nature tourism planning in northern Iran by combining ANP with the OWA method and GIS. ANP models were employed to obtain the relative importance of criteria, while the OWA approach was used to aggregate the corresponding important criteria derived from ANP techniques for the computation of a final potential map. Siroosi et al. (2020) analyzed potential sites for tourism with a GIS-based multi-attribute decision technique. A map was computed with the final model by superimposing ten main factors, which were selected by thirty experts from different fields. Yang et al. (2019) explored the use of AHP combined with GIS to evaluate visual sensitivity of locations within a forest plantation landscape; nine criteria were included to construct a visual sensitivity index, which was based on the proposals of thirty forest experts. Zheng et al. (2019) described an AHP and GIS method to analyze the siting of recreation facilities in forested areas in China, with the aim of promoting nature conservation and restoration. Five criteria were chosen to compute the relative importance weights using the AHP technique. Balist et al. (2019) visualized an ecotourism map using a GIS-based, Fuzzy-AHP multi-attribute method.

Olaniyi et al. (2018) applied AHP and GIS to provide a map of potential ecotourism national zones in Nigeria. The seven criteria identified were based on interviews with eight experts to compute the corresponding criteria weights.

Accuracy assessment of image classification was conducted using a statistical approach, and the results indicated high-model efficiency. Dagistanli et al. (2018) conducted a study using WLC-AHP and GIS to identify recreation locations in Turkey. Merry et al. (2018) presented the suitability of sightseeing sites based on a fuzzy approach with three criteria. This case study considered one of the largest spatial scales with 247,057 ha. Samira et al. (2018) assessed potential zones for ecotourism mapping. The survey collected data from 39 specialists in ecotourism and the environment to extract fourteen criteria, and sub-criteria weights used fuzzy-AHP.

Aliani et al. (2017) determined potential areas for ecotourism development by the use of WLC-Fuzzy and GIS. Fifteen environmental and ecotourism experts were asked to define the main goal and criteria for the study area. Gonzalez-Ramiro et al. (2016) evaluated potential rural tourism sites based on AHP and GIS, including six qualitative and quantitative criteria, mainly from outdoor recreation domains. Store et al. (2015) conducted similar work in a visual sensitivity assessment map applying AHP and GIS. They used 12 sub-criteria which were selected based on thirty expert views; the weights for the criteria were extracted using AHP, statistical modeling, as well as statistical inference techniques. For this purpose, the uncertainty of expert judgments was compared to the predicted sensitivity map, and the correlation coefficient was computed to validate the performance of the model. It was found that both comparison results represented appropriate accuracy assessments. Dhami et al. (2014) performed forest ecotourism mapping by applying the AHP method and GIS. They created of an unweighted ecotourism map based on a naturalness continuum and the production of a weighted ecotourism map based on visitor survey responses.

3.2 Use of GIS and MADM for supporting ES

Very often the combined consideration of protection measures, biodiversity conservation, and management of protected areas requires the use of MADM techniques and GIS. In the context of ecotourism, it is therefore important to have the knowledge about conservation areas, restricted access, as well as the management of rare species (Table 3). Cao et al. (2019) used the WLC method to simulate wilderness site mapping at a national scale; they conducted a survey of twenty-five experts, which they used to design the objective and relevant criteria for their study research. Talebi et al. (2019) presented road network planning based on AHP-Fuzzy evaluation methods with GIS to optimize the environmental impacts of forest areas, situated in Portugal. They conducted field surveys and statistical methods to assess the quality of the simulation. Zhang et al. (2019) proposed AHP in combination with GIS to

find suitable zones for the planting of forest tree species. In a field survey, GPS was used to validate the suitability model. Richter and Behnisch (2019) analyzed a GIS-based AHP technique to select potential green spaces for environmental planning. Tambarussi et al. (2019) computed a fuzzy spatial, multi-attribute analysis for selecting land suitability sites for preservation areas.

Zhang et al. (2013) integrated a participatory process to support zoning of protected and conservation areas applying a combination of GIS and AHP at the regional scale. With semi-structured interviews of 28 stakeholders, three main objectives were identified: conservation, tourism/recreation, and community development. Gülci and Akay (2015) developed a GIS-based MADM using WLC to designate the most suitable ecological passages along a road network in Turkey. They considered nine factors in their model. The rank order of the criteria was established without a pairwise comparison. Fieldwork was conducted using observation activities to monitor the species behaviors and areas. The accuracy results were then computed applying statistical methods. The least cost paths techniques was also used to estimate the best paths for wildlife corridors. Carver et al. (2012) created a WLC and GIS model to map wilderness locations in two national parks in Scotland (Cairngorms; Loch Lomond and The Trossachs). To support wilderness land policy, the preference elicitation was based on attribute weights from the general public (300 residents from national parks, and an additional 1,400 participants from the general public).

Vettorazzi and Valente (2016) evaluated the performance of three MADM methods (WLC, OWA1, and OWA2) and GIS in prioritizing locations for forest conservation of water resources in the Corumbata River basin in Brazil. Fernandez and Morales (2016) applied spatial multi-attribute decision analysis based on arithmetic mean of layers by a non-weighted scheme. Young et al. (2011) determined the use of a GIS and the AHP approach to examine 11 geographic factors influencing the poaching risk for American ginseng (*Panax quinquefolius*), a rare and potentially valuable plant.

3.3 Decision-making method

Our review was able to indicate the number of applications for the different MADM methods (Table 4), which depends strongly on the context of the case study; Asia was the most analyzed region for MADM/GIS forest studies.

20 studies employed the AHP and GIS in our review. 13 publications were found in the area of forest recreation planning and ecotourism, which is probably attributable to its simple and widespread technique (Cegan et al. 2017; Segura et al. 2014). This technique entails manual calculations and less programming skills compared to other methods. The technique was the most used method in terms of significant cost-saving and reducing environmental impact. As the

theory is easy to understand, it can be used by a non-experts in decision making, and a wide array of web-based AHP tools (<https://bpmsg.com>) (Goepel 2018) and several free AHP software programs are available (<https://www.expertchoice.com>) (Garson 1997). In addition, AHP has also proven to be very useful in ecological and conservation planning; it consistently integrates well with spatial modeling across very large areas, ranging from approximately 860 ha to national scale.

The approach can be reused in other studies under similar conditions. However, there were some drawbacks in the implementation of AHP as well. AHP cannot sufficiently address vagueness and uncertainty in all cases. The WLC method was found to be the second most often used MADM method plus GIS in the field of forestry, where it was mostly utilized in the domain of forest supporting ES. The majority of authors who used validation techniques for WLC expressed confidence in the method and data used, yet this technique remains limited in use. We attribute this to the fact that it is compensatory and does not contain a pairwise comparison, but most importantly, the primary difficulty is defining a procedure that adequately converts qualitative evaluations into quantitative values. As an alternative approach, several studies applied hybrid methods in uncertainty and risk scenarios, such as AHP combined with the fuzzy approach in a pairwise comparison to compensate for the classical deficiency with AHP. According to Table 2, researchers who have used this technique have provided a comparison between the proposed model and ground truth, which led to high accuracy regarding robustness of the method (Talebi et al. 2019; Aliani et al. 2017). Compared to those who apply only AHP (Siroosi et al. 2020; Zhang et al. 2019), the difference was noticed where these case study map results were compared to reference maps by applying geostatistical analyses, which is associated to validate the performance of those models (Haidara et al. 2019; Eskandari 2017). This approach also has good potential to solve complex multi-attribute-dependent problems because it allows for global management of uncertainty and imprecise data (Mosadeghi et al. 2015). The MADM method with a fuzzy approach improves the precision of results. Vettorazzi and Valente (2016) also discussed the power of the OWA2 technique by comparing the simulation result with reference data. The method was applied in forest restoration and conservation scenarios, and at 170,000 ha (8 municipal districts), it was one of the larger study areas considered in this research. The OWA approach has restricted capacity to input considerable sets of criteria for forest management planning, and it also involves spatial considerations, which necessitates the use of heuristic optimization techniques (Carver et al. 2012; Kangas et al. 2015).

Table 3 Overview of recent forest conservation and supporting ES case studies applying MADM and GIS

Study	MADM Techniques	Study region	Description of approach adopted		Study objective	Validation techniques	Results	Simulation model validation	Findings
			No. of criteria	Elicitation methods					
Cao et al. (2019)	WLC	China	6	Expert survey	Map wilderness sites	N/A	North Tibet, West Qinghai, South Xinjiang and West Mongolia obtained highest wilderness quality	N/A	Developing technique could be used in setting wilderness conservation and ecological target areas
Talebi et al. (2019)	AHP-Fuzzy	Portugal	9	Expert knowledge	Improve road network planning in forested areas	Comparison between model and ground truth applying χ^2 tests	Seventh scenario alternative was selected as optimal option	No significant differences with 95% level	Process framework could be helpful for management tourism planning
Zhang et al. (2019)	AHP	U.S.A	4	Expert consultations, literature review	Evaluate restoration sites	Field survey conducted to compare model suitability using GPS	49.5% were high and very high suitable zones	Comparison demonstrated accurate assessment analysis	Presented model could enhance success of reestablishment efforts
Richter and Behnisch (2019)	AHP	Germany	3	Workshop	Potential areas of environmental planning for green cities	Visual comparison observed	41% of zones scored medium functional density class	More urban areas presented high protection concerns functionality	Model was useful for better understanding of data and supporting green strategic planning
Tambarussi et al. (2019)	Fuzzy	Brazil	4	Not Indicated	Establish preservation zones	Cross validation performed for this model	Area map indicated it could succeed in future natural zone management	Root mean square error 1.99, mean error 0.0136 respectively	Integrated model could manage quantitative and qualitative variables conservation
Navalho et al. (2019)	AHP	Portugal	6	Participatory technique, expert consultations	Potential sites of forest landscape for protection and conservation	N/A	Result indicates coexistence of several functions	N/A	Developed methodology could be integrated into regional landscape forest planning

Table 3 (continued)

Study	MADM Techniques	Study region	Description of approach adopted			Results	Simulation model validation	Findings
			No. of criteria	Elicitation methods	Study objective			
Valente et al. (2017)	WLC	Brazil	2	Participatory technique	Potential areas for forest restoration	5.22% with high priority sites	N/A	The proposed approach helped provide an environment for movement of fauna between landscapes
Wang and Du (2016)	AHP	China	16	Investigation, questionnaire	Prioritize natural world heritage sites	Only 7.15% of land suitable for monitoring	N/A	Process guarantees success and sustainability of monitoring and management
Vettorazzi and Valente (2016)	OWA	Corumbataí, Brazil	5	Participatory technique	Evaluate site for forest restoration	River basin had 9% high and 10% very high priority for forest restoration areas	Comparison between OWA2 forest restoration map and reference data	Integrated model has ability to control criteria influence on final result through trade-off
Fernández and Morales (2016)	Equal weight	Chile	3	Participatory phase not included	Restore forest plant species sites	Results depended on two species considered and criteria included	N/A	Developing technique could be applied as a complementary approach to available spatial scale conservation planning
Mahan et al. (2015)	Fuzzy	U.S.A	3	Literature, expert opinions	Allocate ecological assessment in National Parks	Overall assessment of landscape component showed a good forest condition	N/A	Proposed process was flexible and dynamic

Table 3 (continued)

Study	MADM Techniques	Study region	Description of approach adopted			Results	Simulation model validation	Findings
			No. of criteria	Elicitation methods	Study objective			
Gülci and Akay (2015)	WLC	Osmaniye, Turkey	9	Literature, expert interviews	Locate ecological road structures	Field survey to compare predicted model using LR and CC calculus	Accuracy results showed a very high correlation coefficient ($R^2 = 0.9958$)	Model provided rapid solutions regarding environmental effects
Derak and Cortina (2014)	AHP	Spain	14	Questionnaire	Evaluate forest plantation for afforestation	N/A	N/A	Approach provides evaluation of ES that could be used in other semi-arid areas
Orsi et al. (2013)	WLC	Italy	7	Expert groups	Wildness suitability sites	Visual comparison between unsupervised classification and predicted map	Data in close concordance in wilderness sites	Integrated model quickly adaptable in different size and characteristics areas
Zhang et al. (2013)	AHP	Meili Snow Mountain, China	6	Requirement workshops	Prioritize nature conservation sites	N/A	N/A	Proposed approach helped to interact many different stakeholder needs
Carver et al. (2012)	WLC-Fuzzy	National Parks, Scotland	4	Attribute weights	Map wilderness area patterns	Equally weighted map used to compare the parks	High rate of robustness and confidence in methods/data used	Model spatially illustrated the human perception of wilderness in terms of conservation planning
Young et al. (2011)	AHP	Shenandoah National Park, U.S.A	11	Questionnaire, workshop	Map rare plant poaching risk	Field observations to compare predicted data using test KO-Smirnov	Observed American poaching incidents were in or near predicted areas	Simulation model has a great potential for policy target and environmental strategies

N/A Not applied, LR Linear Regression, CC Correlation coefficient, GPS Global positioning system, KO Kolmogorov, χ^2 Chi-square

3.4 Evaluation criteria used

Different approaches have been used to elicit the opinions, preferences, knowledge, and experiences of different stakeholders to understand the importance of evaluation criteria and their respective weights. Literature review, interviews, and questionnaires were the most frequently used in the case studies reviewed. The experts involved were generally academic and/or scientific researchers (foresters, environmentalist, ecologists, biologists, conservationists), and/or professionals (forest engineers, forest planners, forest mensurationists, loggers, local government, tourism developers, forest technical personnel). In the majority of studies, the average number of actors involved in the decision process was nearly thirty. The participatory process was frequently based on consultation with decision makers at all levels (local communities, local government, national park planners, tourism promoters, rangers, local residents). These complex multiple interactions between cultural/supporting ES and stakeholder/public group participation have highlighted the need for an efficient participatory process. AHP and WLC both involve a large number of professionals and/or laymen views. MADM combined with GIS seems to be a useful tool to generate a comprehensive understanding of the participatory process related to different field issues; it seeks to achieve different general stakeholders and public priorities, which were integrated in the model to generally simulate landscape mapping for forest land developments. The deployment of new technology in the participatory processes (free online survey integrated in mobile devices, dynamic share and analyze surveys together with decision makers) (Bilge et al. 2016; Erti 2015), the availability of free open source image data and other technology advances (GIS software, MADM software, Geo-statistical software) helped in accelerating rapid solutions in the process of decision making (Bettinger et al. 2016; Mani and Varghese 2018). Despite the technological efforts, the fundamental issues of large spatial scales will remain limited, it takes time when processing huge datasets and update images simultaneously, which cause variation and inaccuracy in the results. Indeed, the regional level provides an adequate scale to ensure efficiency and reasonable processing time.

Figure 3 displays the most commonly used criteria in this study research; distance from a road and water bodies, slope, as well as vegetation cover were the criteria most often used. Our review indicates that proximity to fundamental facilities is essential to supply and cultural services. This indicates that the clusters terrain conditions, environmental characteristics, and infrastructure comprise the most relevant criteria. Most importantly, multiple factors and criteria related to forestry were considered for conservation and sustainable management (tree species, tree canopy disturbance, stand age).

Comparing the number of criteria for the different clusters and ES, it becomes evident that most of the studies have used evaluation criteria to estimate provision of cultural services. Here the distance from water bodies, slope, and the distance from a road were relevant criteria. Based on this review, the presence of water offers a variety of water-based activities for recreational visitors. Distance from a road is considered as a complementary less cost accessibility criterion; it also contributes a major income source for local tourism/economic development to the sites suitable for recreation and/or eco-tourism. Different land-forms and slopes influenced accessibility to nature-related activities, and the soil types with regard to erosion or landslides. The evidence also showed that these criteria were the easiest spatial data to obtain. The majority of studies considered landscape and scenery as dominant criterion and obtained a higher weight score in many cases. Distance from water bodies, slope, distance from a road, elevation, land use, as well as vegetation cover were the most decisive in designating the chosen forest recreational and cultural ES fields. Some criteria were lacking, such as collecting non-timber forest products. The number of trails and parking areas should be integrated in such recreational research studies, and the biodiversity criterion, which is characterized by nature reserves and nature protection areas (European Ecologic Network: Natura 2000), was almost non-existent in the evaluation of cultural services. Vegetation cover and distance from a road were the most cited criteria in the supporting category. Contrary to cultural ES, the road criterion has a series of impacts on forests: the higher the traffic volumes, the higher the risk of disturbance to forest ecosystems and landscapes. Vegetation cover provides many vital services, which is also easily detectable from satellite or aerial images by the Land Cover Classification System; it provides enough information needed in the region of interest (Gregorio 2016). Slope and elevation were dominant criteria in many studies for conservation and supporting ES. Vegetation cover, distance from a road, wildlife habitats, and biodiversity were among the most importance criteria for supporting ES.

Forest management activities require input from different stakeholders to meet the targets of sustainability and they strive to achieve a high level of approval among the general public. The selection of the set of criteria was generally based on professional views, or forest visitor preference (Huber et al. 2019). This review provides an understanding and easy interpretation of the worldview of decision makers in landscape and forestry planning research, and it can facilitate policy makers in decision making regarding the sustainable provision of forest ES.

Sensitivity analyses (Pianosi et al. 2016), and geostatistical methods are indeed highly endorsed in forest modeling and management planning. Also, the importance of uncertainty in fuzzy set modeling has been recognized

Table 4 Summary of most frequently used multi-attribute decision-making (MADM) methods combined with geographic information systems (GIS) in the reviewed case studies, 2009-2019 in the field of forestry

Methods	Number of case studies	Strength	Weakness
Analytic Hierarchy Process (AHP)	20	<ul style="list-style-type: none"> • Widespread application; • Dealing with a range of spatial scales; • Support large number of professionals and/or laymen views; • Reuse in other similar environments. 	<ul style="list-style-type: none"> • Complex technique • Involves conflict between stakeholders; • Supports maximum of 15 criteria inputs; • Original technique does not support uncertainty.
Weighted Linear Combination (WLC)	6	<ul style="list-style-type: none"> • Easy computation; • Recognize full range of data inputs; • Scalable; • Support large number of professionals and/or laymen views; 	<ul style="list-style-type: none"> • Assign random values to criteria weights; • Large number of stakeholder requirement analyses are unclear; • Suspicious in converting qualitative to quantitative values.
Fuzzy (F)/ F-AHP	5	<ul style="list-style-type: none"> • Transferable to other case studies. • Allows handling of imprecise data; • Incorporate multiple pairwise matrix inputs; • Support literature reviews as elicitation technique; • Collect detailed data from a large number of professional opinions; Improves the quality of decisions. 	<ul style="list-style-type: none"> • Complex to develop the model; • Requires a specialist to simulate the model; number of criteria.
WLC-F;WLC-AHP	3	<ul style="list-style-type: none"> • Minimizes human errors. 	<ul style="list-style-type: none"> • Limited performance and efficiency • Misunderstanding stakeholder requirement analysis.
Ordered Weighted Averaging (OWA)/ Analytic Network Process-OWA	3	<ul style="list-style-type: none"> • Flexible and reliable outcomes; • Dealing with a regional spatial scale. 	<ul style="list-style-type: none"> • Incorporate limited criteria inputs; • Involves understanding of spatial considerations.

by other scientific reviews (Uhde et al. 2015; Ananda and Herath 2009). Reviewing modern combinations of MADM and GIS tools to identify the best approaches can enhance the modeling of complex decision problems and accelerate rapid data processing for future planning scenarios (Nyongesa and Vacik 2019; Hujala et al. 2013).

4 Conclusion

This study reviewed a total of 37 papers to evaluate the lessons learned from the combined use of different MADM methods and spatial analysis techniques in forest planning.

In this study, we evidenced that, due to the easy theory and its simplicity, the most often used method used by the layman is the AHP technique. Most of the times, the process has been done using free web-based AHP tools such as AHP Online System or Expert Choice software. The method offers a rapid and reasonable work-flow under limited resources, it provides reproducible results and supports forest planning

at different spatial scales. Contrary to expert users, hybrid methods can be deployed more effectively in forest management. The Fuzzy approach combined with AHP or WLC yielded accurate results and seems to be a robust method, even when applied with a large number of criteria. However, the implementation of this method is often too complex for practical decision making, and it requires a specialist to understand the theory of the algorithm. The finding shows that the majority of MADM methods deal with a range of spatial scales.

Most of the information used in the evaluation can be easily obtained from existing maps or remote sensing data, and no additional field investigations are required to provide the inputs in spatial modeling. However, increasing demands in the provision of forest ES often ask for additional data in order to provide a proper input for the analysis. In this context, forest inventory concepts of the future will have to provide a more solid database, including parameters relevant for biodiversity, aesthetics, or other supporting services. Otherwise, the key and easily obtained criteria such as distance

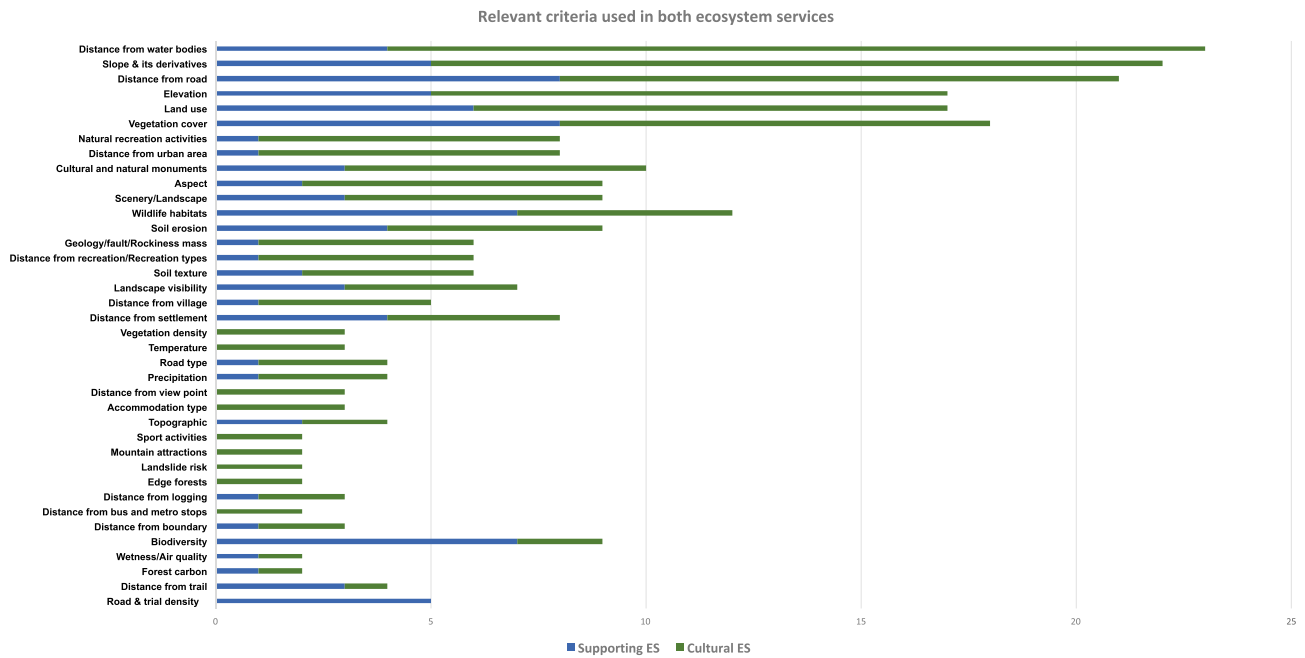


Fig. 3 Most frequently used criteria applying MADM-GIS case studies in forestry and ES

to infrastructure (road), water bodies, slope, and vegetation cover will often continue to serve as a proxy for the evaluation of forest ES. These criteria seemed relevant in this review; they were considered as universal criteria and can be automatically incorporated into other forest ES categories.

An important result of the study is information on the available tools and the most suitable choice to implement MADM-GIS techniques, in order to decide on different forest ES areas depending on the criteria considered, participatory process, and range scales. We discovered the strengths and weaknesses for each method; while some methods are more accurate but focus thoroughly on mathematical theory, others achieve adequate output and are easier to implement.

There are some gaps remaining in the literature. It seems that some insights must be better elucidated for further research and application in the field; improving the interaction and transparency in decision processes between decision makers and stakeholders, providing guidance on efficiency and performance of different MADM approaches taking in consideration a variety of spatial and temporal scale, and concentrating scientific evidence on the effectiveness of different validation techniques that could be integrated directly into the MADM model.

New technologies for data acquisition and its processing in the geospatial domain (e.g., remote sensing data and mobile GIS) enable MADM and GIS to be deployed on mobile phones and tablet devices, accelerating the forest planning and decision-making process. These technologies can also explain individual management decisions better and

more easily to the general public. These creative technologies also seek to involve all stakeholders in participatory planning and work with their often conflicting priorities, find compromise solutions, and meet the demand for different ES.

The methodology provided in this study could help planners to investigate the time effort and costs related to management at multiple temporal and spatial scales. It can strengthen the practice of forest management for a sustainable development and help to reduce biodiversity loss. Our findings highlight the importance of diverse goods, services, and benefits from forests and natural resource systems for landscape conservation to sustain human livelihoods, and to facilitate the understanding and interpretation of decision makers in forest landscape planning research.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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