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Review

Review of indicators for mountain ecosystem services: Are the most frequently used also the best?

Claudia Canedoli [a,*], Noemi Rota [a], Ioannis N. Vogiatzakis [b], Alexia Zanchi [a], Mita Drius [c], Harini Nagendra [d], Emilio Padoa-Schioppa [a]

[a] *Department of Earth and Environmental Science, University of Milano Bicocca, Italy*
[b] *Faculty of Pure and Applied Sciences, Open University of Cyprus, Cyprus*
[c] *Faculty of Education, Free University of Bolzano-Bozen, viale Ratisbona 16, I-39042 Bressanone, Italy*
[d] *Centre for Climate Change and Sustainability, Azim Premji University, India*

A R T I C L E I N F O

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A B S T R A C T

Ecosystem services (ES) assessment is crucial in ecology, with numerous studies seeking to evaluate them. Despite the abundance of methods and indicators, standardization is lacking, hindering comparability and progress in ES understanding and monitoring. This paper reviews indicators used in scientific literature to evaluate mountain ES and then examined whether the most used indicators are also the best. Using ISI Web of Knowledge we searched papers published between 2015 and 2020 containing "ecosystem services" AND "mountains" and we selected 400 papers effectively applying at least one indicator to evaluate ES. For each article, we extracted the following information: type of ES evaluated; indicator(s) used; input data used; type of value-domain (ecological, economic or social); scale of analysis; country; mapping; and management suggestions. From the literature, we extracted a list of 130 most frequently used indicators. The results indicated that regulating services were the most frequently assessed ES, followed by provisioning, cultural, and lastly supporting. The scale of analysis was mainly regional (51%) and local (40%), while studies at national scale were less frequent (9%) and only 2 studies were at global scale. Mountain areas most studied were in Europe (50%) and Asia (31%). Ecological value-domain was the most frequent used (55%), followed by social (26%) and economic (18%). 84% of studies considered only one dimension of the value and few studies combined multiple value-domains (15%). Almost half of studies mapped ES and around one third provided management suggestions. We examined the quality of indicators based on six criteria evaluated by experts in the field: significance, simplicity, cost, replicability, ease of interpretation and policy relevance. Indicators used exhibit significant diversity, and there is no clarity in nomenclature. There are cases where the indicators used represent inadequately the ecological parameters to be measured. Although many indicators score high in some of the properties evaluated, only 13 indicators perform well in all properties. These indicators have a universal value both in terms of semantics, but also in terms of properties and should be promoted for standardization among ES assessments. We envisage the necessity to condense the array of indicators commonly used down to a small set of standardized high-quality metrics.

1. Introduction

Ecosystem services (ES) assessment has become a fundamental subject in ecology leading to the proliferation of studies worldwide over the past 30 years (Costanza et al., 2017). Following the pioneering theoretical and methodological papers by Costanza et al. (2017) and Daily (1997) – as well as significant contributions by Odum and Barrett (1971), Westman (1977), Ehrlich and Mooney (1983), and de Groot (1987) – the ecological scientific literature has covered several themes on ES. A major topic deals with the necessity of conceptual and methodological standardization in the study and quantification of ES. The recognition that standardization in ES description is essential for their assessment and comparisons across studies and regions has led to the adoption of a systematic approach in nomenclature (Paulin et al., 2020). According to the MEA (2005) ES belong to four categories: supporting, provisioning, regulating, and cultural. After MEA the efforts to provide a

* Corresponding author.
E-mail address: claudia.canedoli@unimib.it (C. Canedoli).

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common classification continued and currently there are robust frameworks that have greatly enhanced standardization, like CICES (Haines-Young and Potschin-Young, 2018) and IPBES (Pascual et al., 2017). Although not identical correlations among these different categorizations do exist, meaningful comparisons are possible.

As far as methodology development is concerned, several indicators have been developed to quantitatively measure services for different ecosystems (Maes et al., 2014; Müller and Burkhard, 2012; Chee, 2004). However, there is still a great need to identify common procedures for ES assessment (Czúcz et al., 2018).

Standardized indicators provide a structured framework for data collection and analysis, ensuring that measurements are reliable, reproducible, and accurate. For example, they allow for meaningful comparisons between different ecosystems, regions, or time periods facilitating the identification of patterns, trends, and changes in ecological systems at various scales (Paul et al., 2021). Standardization also allows to minimize biases, errors, and variations in data collection techniques, thereby increasing the reliability of results and supporting robust scientific conclusions. Furthermore, it is essential to provide a consistent baseline for monitoring and in this sense, it is useful to start applying good indicators early in studies. Finally, standardization is critical for public entities (protected areas, municipalities, or administrative bodies) where there is a growing demand for conducting regional and local ES evaluation, and the choice of robust indicators is fundamental for performing reliable estimations and consequently transferring this information into management decisions (La Rosa et al., 2016). Without the use of standardized indicators, comparing and synthesizing data from multiple studies is challenging (Veerkamp et al., 2021).

Mountain ecosystems are fundamental for their capacity to provide a set of critical ES ranging from the provisioning of water, to acting as hotspots for biodiversity and climate regulation. Despite their importance, mountains are among the most threatened ecosystems because of anthropogenic impact as well as climate change, thus deserving compelling attention (Grêt-Regamey et al., 2012), hence this study focused on mountains. We sought to understand the extent to which standard indicators of montane ES have a shared vocabulary and use a standardized approach, enabling the inter-comparability of different research studies. Accordingly, we reviewed the most recent literature on ES assessment in mountain areas. By focusing on one specific type of landscape, i.e. montane ecosystems, we were able to conduct a systematic study, as differences in the type of ecosystems can also lead to differences in the choice and suitability of indicators. Previous studies have highlighted concerns regarding the use of unsuitable indicators in respect of usability, congruence, or other characteristics (Van Oudenhoven et al., 2012; La Rosa et al., 2016). Thus, after conducting a comprehensive systematic review of indicators employed in scientific literature, our inquiry investigates whether the prevalence of certain indicators aligns with their efficacy in evaluating ES.

This study aims to describe, through a review of the scientific literature, the most frequently analyzed ecosystem services in mountain ecosystems, and the indicators used. In doing so, we also describe which type of value-domain is most frequent – ecological, economic, or social – and explore the characteristics of these assessments, including mapping, scale, geographic distribution, and their capacity to provide suggestions or solutions. An innovative aspect of this review is that we selected the most frequently applied indicators for assessing ES in mountain regions and subjected them to expert evaluation for certain quality characteristics. The objective was to determine whether the most common indicators are also the most effective for ecosystem service assessment, providing information for researchers and policy makers.

2. Methods

2.1. Literature search

In January 2021 a keyword-based search was conducted using the ISI Web of Knowledge database thereby including exclusively peer-reviewed journal articles in English (Supplementary Material Table S2). We used the following search keyword string TOPIC: (ecosystem services) AND TOPIC: (mountain) and obtained 1,523 results. They were filtered for the year of publication (from January 2015 to December 2020) because we aimed to identify the most recent indicators and methods, and we obtained 1046 articles. In order not to exclude relevant papers, we included further 9 highly-cited papers published before 2015, resulting in a total of 1055 papers. Highly cited papers are a selection made by the search engine, the threshold is calculated by Clarivate and is defined as the minimum number of citations received by the top 1 % of papers from each of 10 database years. We then screened the abstract of each paper to check if they effectively performed an evaluation of at least one ecosystem service. We selected only those studies that apply at least one indicator to assess ES. Following this screening process, the articles included in the final database and subsequently analyzed in this study were 400. We organized ES using the MEA categories (M.E.A., 2005): provisioning, supporting, regulating, and cultural (Table 1). Although more recent ES classifications do exist, MEA was still the most frequently used in the literature, leading to its use to limit potential errors in the subsequent interpretation. When the ES category reported by authors did not exactly match with the MEA categories, we assigned the indicator to the ES category that best matched; for example, article n. 324 (Supplementary Material Table S1) claims to have evaluated *cultural ecosystem services*, but they recorded only *birdwatching activity*, so their indicator was associated with the *Recreation and ecotourism* ES category. We included in the final database only those articles for which assigning at least one indicator for specific ES was possible.

From each article we extracted additional information about the: type of ES evaluated, indicator(s) used, input data used, type of value-domains (ecological, economic, social; Martín-López et al., 2014),

Table 1
Ecosystem Services categories considered in this study (modified from M.E.A., 2005).

Code	ES Category	ES Type
ES1	Provisioning	Food
ES2	Provisioning	Fresh water
ES3	Provisioning	Fuelwood
ES4	Provisioning	Fiber and minerals
ES5	Provisioning	Biochemicals
ES6	Provisioning	Genetic resources
ES7	Provisioning	Energy
ES8	Regulating	Climate regulation
ES9	Regulating	Erosion prevention
ES10	Regulating	Air Quality and Local Climate
ES11	Regulating	Water regulation
ES12	Regulating	Water purification
ES13	Regulating	Natural hazard protection
ES14	Regulating	Pollination
ES15	Regulating	Biological control
ES16	Cultural	Spiritual and religious
ES17	Cultural	Recreation and ecotourism
ES18	Cultural	Aesthethic
ES19	Cultural	Inspirational
ES20	Cultural	Educational
ES21	Cultural	Sense of place
ES22	Cultural	Cultural heritage
ES23	Supporting	Primary production
ES24	Supporting	Nutrient cycling
ES25	Supporting	Soil formation
ES26	Supporting	Habitat provisioning
ES27	Supporting	Biodiversity

scale of analysis (local, regional, national, global), country and continent (where we have further divided America into North and South), mapping (yes/no) and finally indicated if the paper provides management recommendations based on the ES evaluation (yes/no) (Fig. 1). For the scale of analysis, we defined as "regional" a study area smaller than the nation, and "local" a study area restricted to one or few municipalities. Mapping was marked with "yes" in case authors had effectively provided a mapping output of the ES evaluated. Provision of management recommendations was marked with "yes" when authors explicitly recommended solutions. For example, in the article n. 1005 it is stated that "*By leveraging projections of future species distribution, we highlight areas that may be prioritized in future landscape planning […]*" or, in article n. 958 where authors say "*Overall none of the management alternatives performed best for all ES. PATCH and SLIT regimes at (currently practiced) low intensity appeared as compromise to achieve multifunctionality at small scale. As involved trade-offs among ES can be substantial, partial segregation with priority on specific services in designated zones is recommended.*" (articles number reference in Supplementary Material Table S1).

2.2. Literature analysis

2.2.1. Grouping similar indicators

The indicators were initially documented in the database exactly as they appeared in the original articles (Supplementary Material Table S1). Later, we organized them by grouping together those instances where authors referred to the same indicator using different names. For example, in assessing the provisioning services of fresh water (ES2, Table 1), different papers presented the following indicators: "Water supply", "Water provision", "Water storage, "Water yield", all referring to the same concept; thus, these indicators were grouped under the overarching category labeled 'Water supply'. In other cases, we found the same name that refers to different concepts. For example, in assessing the climate regulation (ES8, Table 1), several authors reported to the indicator: "Carbon sequestration", which it may refer to aboveground organic carbon stock, aboveground *and* belowground organic carbon stock, or soil organic carbon stock. Therefore, we split the indicator "Carbon sequestration" into different categories according to what it actually measures.

2.3. Expert-based evaluation

To investigate whether the most common indicators are also the best for evaluating ES, we conducted an expert-based analysis to evaluate the usability of indicators based on six parameters. We contacted by email 23 experts in the field of ecosystem services evaluation, based on track record or experience in one of the following fields: ecosystem services and mountain ecology (Supplementary Materials Table S6). They were asked to fill out a table where they had to provide their judgment on the suitability of a selection of indicators (that were the most frequently used indicators based our literature review) by answering the questions reported in Table 2. The questions and statements concerned six (6) specific parameters necessary to define the indicators quality: i) significance and representativeness; ii) simplicity; iii) cost; iv) replicability; v) easiness of interpretation; and vi) policy relevance. The six questions were structured into a 5-point scale, where only one answer was possible. After receiving the experts' answers, we calculated the mean value, the standard deviation and the mode for each ES indicator to assess its quality.

2.3.1. Cluster analysis of indicators properties

We used Hierarchical cluster analysis (HCA) using the Ward clustering method, with a discrimination level set at over 60 %. to examine similarities in ES indicators properties and define the number of clusters occurring among those examined. The average values of the six properties for ES indicators, derived from the expert-based analysis, were used in the analysis. To determine the cutoff point, a dendrogram visual inspection was conducted.

3. Results

3.1. Literature search

The complete database of 400 resulting articles and the metadata extracted is reported in Supplementary Material Table S1.

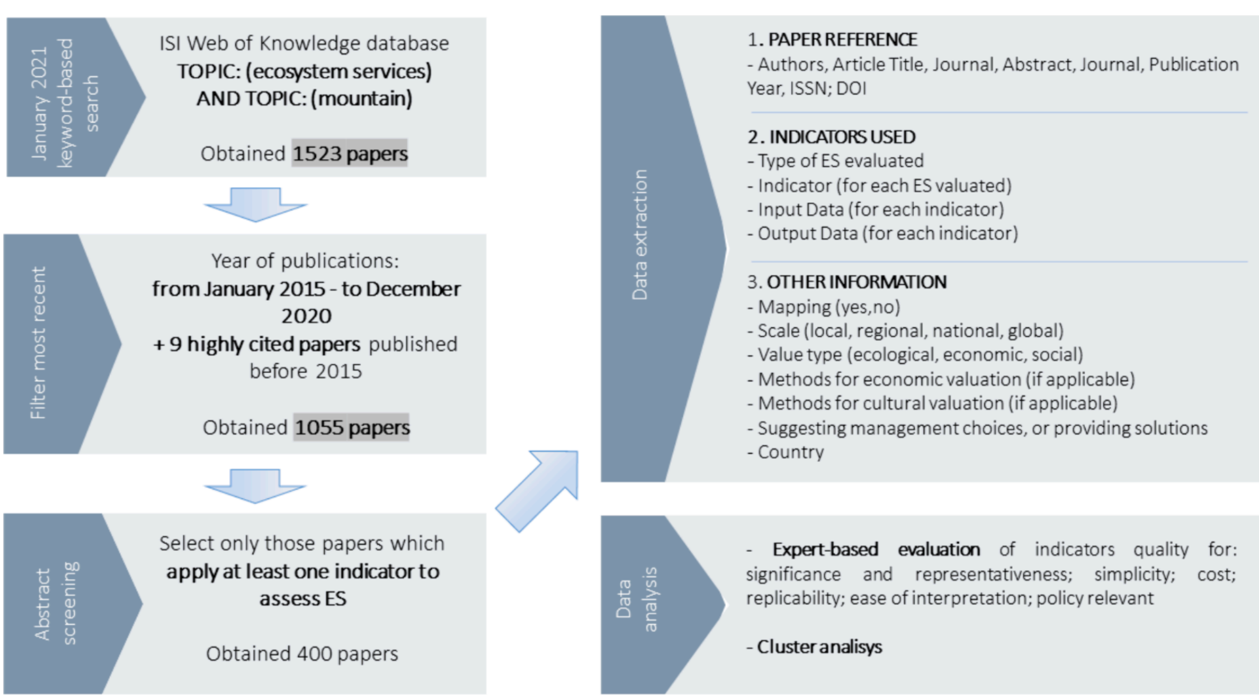

Fig. 1. The figure represents the workflow adopted for this study, detailing the method of bibliography selection for analysis, the information extracted from each article, and the data analysis.

Table 2
Parameters used for the expert-based survey applicable to a single indicator.

	Parameters	Question/Statement	Answer
1.	**Significance, Representativeness**	How well does the indicator reflect conceptually the ES of interest? This represents the compliance with ecological or social parameters to be measured	1. No significance 2. Low significance 3. Medium significance 4. High significance5. Very high significance
2.	**Simplicity**	The indicator is reasonable in terms of methodology, instruments, or analyses needed	1. Very complex (impossible) 2. Complex (not impossible) 3. Relatively simple 4. Simple5. Very simple
3.	**Cost**	The cost to collect data and compute the indicator is reasonable	1. Very high Cost 2. High Cost 3. Medium Cost 4. Low Cost 5. No Cost (Free)
4.	**Replicability**	The indicator is consistently measurable over time, in the same way by different observers	1. No replicability 2. Low replicability 3. Medium 4. Highly 5. Very high replicability
5.	**Ease of interpretation**	Easy to comprehend and interpret for different audiences, also non-experts (like society, or politics).	1. Very difficult (only experts can interpret) 2. Difficult 3. Relatively easy 4. Easy 5. Very Easy (layman may interpret)
6.	**Policy relevance**	The indicator is relevant for all stakeholders in the system studied.	1. Not relevant 2. Limited relevance 3. Quite relevant 4. Highly relevant (majority of stakeholders) 5. Very high relevance (all stakeholders)

3.2. Characteristics of ES assessment

The geographical distribution of studies reveals that most of ES evaluations of mountain areas are carried out in Europe and Asia (50 % and 31 % of cases, respectively) and more specifically in the European Alps (59 % of European studies) and mountain areas of China (61 % of Asian studies) respectively. In North America almost 80 % of studies are carried out in the United States whereas in South America most studies are performed in Brazil and Argentina. In Africa the most studied countries are South Africa and Tanzania, while all studies concerning Oceania have taken place in Australia or New Zealand. Almost all the studies are restricted to a single country (90 %), while only 10 % covered more countries in the study area; of these multi-countries studies 60 % were on the European Alps, a mountain chain spanning across seven countries (Table 3, Fig. 2). For detailed distribution among countries see Supplementary Materials Table S4.

Table 3
Number of ecosystem services' evaluations by continent and percentage of the total.

Continent	No of evaluations	% of total evaluations
Europe	259	50
Asia	160	31
North America	33	6
Africa	31	6
South America	26	5
Oceania	7	1

The level of analysis is mainly regional (51 % of studies) and local (40 %), while studies at national scale are less frequent (9 %) and only 2 studies are at global scale.

In general, the most frequent type of value-domains was ecological (55 %), followed by social (26 %) and economic evaluations (18 %). 84 % of studies performed single evaluations (they consider only one dimension of the value, that is either ecological, economical, or social), a minority of studies (14 %) used two value-domains and only 1 % considered all three dimensions (Fig. 3; Table 4).

ES were mapped by authors in almost half of the studies considered (45 %). 144 papers propose management options or provide solutions for managing ES based on the results of their studies.

3.3. Ecosystem services evaluated

Regulating and provisioning services were the ES categories most frequently evaluated, whereas the most frequent ES among the 27 identified types were climate regulation, food provisioning, recreation and ecotourism, and water regulation (Fig. 4, Supplementary Materials Table S3).

3.4. Ecosystem services indicators

The number of indicators used for each category of ES, and the final number of indicators after the grouping is reported in Table 5. A mean of 14 (s.d. ± 9) of indicators were used for single ES type, after clustering them into major groups.

The complete list of ES indicators identified after grouping is reported along with their frequency in Supplementary Materials Table S5.

3.5. Expert-based evaluation of the quality of ES indicators used

The resulting dendrogram (Fig. 5) illustrates a clustering of the 130 ES indicators into six discrete clusters. The cluster "A" comprises 24 indicators with low average values (mostly less than 3) on all properties evaluated. The cluster "B" comprises 25 indicators with medium values (around 3) on all properties evaluated. There are 27 indicators in the cluster "C", which includes high values in terms of significance but low values (less than 3) in all other properties. The cluster "D" comprises 13 ES indicators, which score high on all properties (ranging from 3.20 to 4.80). The cluster "E" has 24 indicators in total, which scores high on replicability values but medium on all others and finally, the cluster "F" includes 17 indicators, and it scores consistently high value for significance but medium values for the rest of the properties. All six groups have a good mix of indicators from all ES categories examined (Table 6 and S8; for further details see also Supplementary Materials Table S8).

4. Discussion

4.1. Geographical distribution of studies

The geographical distribution of studies reveals that most of ES evaluations of mountain areas globally were carried out in Europe and Asia (respectively half and one-third of cases). In these two continents, the majority of studies come from the European Alps (59 %) and from the mountain areas of China, respectively (60 %). Continents like North and South America, which have extensive mountain areas that cover up to 20 and 30 % of their territory, have been less studied revealing a lack of attention to the study of these geographic areas despite their global importance (Payne et al., 2017). The scarcity of studies in some countries like the developing ones may also be due to a lack of resources being a significant factor (Badr 2018). Papers that consider more than one country in the same study mainly concern European Alps, a mountain chain expanding in several countries, and other papers

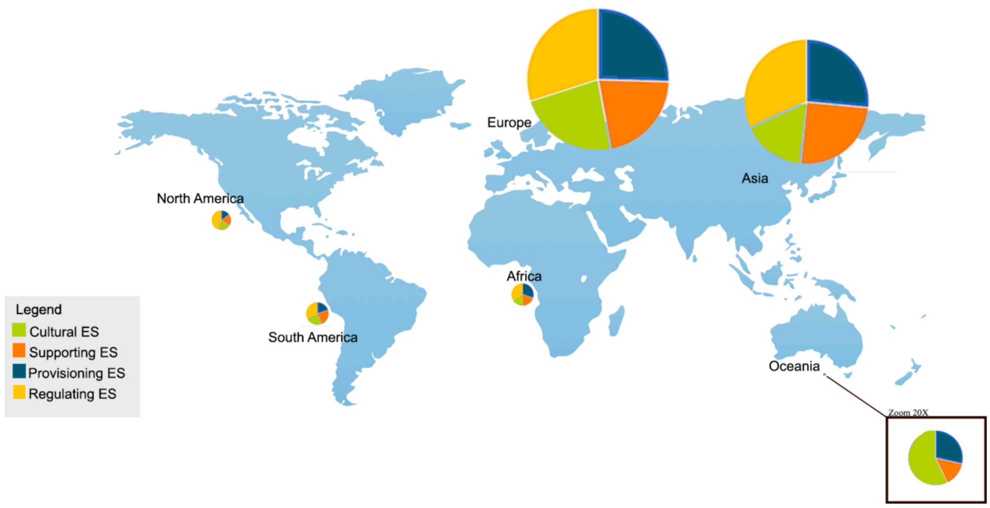

Fig. 2. Geographic distribution per continent of studies on ecosystem services; the size of the pie charts is proportional to the number of studies.

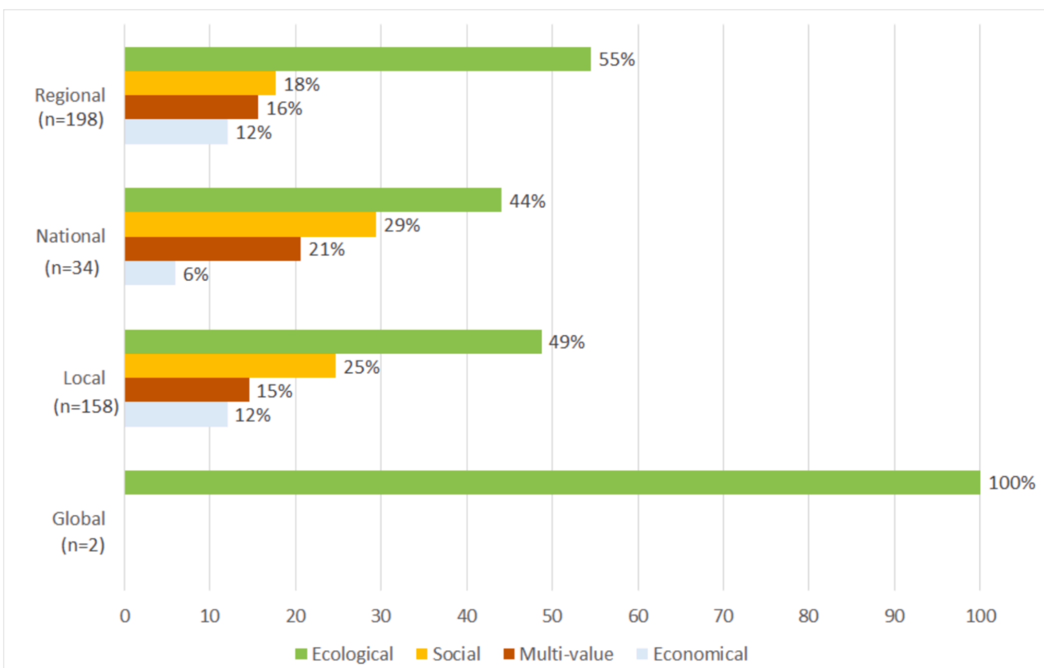

Fig. 3. The graph describes the distribution of value-domain across different levels (the percentage of value types is referred to the total for each scale).

consider different case studies in different countries. The Alps are a good example of a body of research that considers the physical boundary of the mountain areas rather than existing administrative boundaries to evaluate ecosystem services provided by an extended mountain chain (i. e. Schirpke et al., 2019; Vigl et al., 2016). European Alps are part of a community program (the Interreg Alpine Space) which finances cooperation projects aiming at developing transnational solutions for the Alpine region across the borders of the seven Alpine countries, promoting cross-border studies.

4.2. Ecological, economic, or social evaluation

Ecological value-domain are more often applied (55 % of total evaluations) but social value-domain are also common for mountain ES (one-fourth of all evaluations). Less attention is given to economic values. Almost all studies (84 %) use only ecological values, even when they assess more than one ES. Very few authors use in the same paper more than one-value domains (15 %), and when they do so, it is mostly ecological and economic or ecological and social. However, multi-value evaluations are more frequent than economic ones, evidencing that the latter are often accompanied by other value dimensions, rather than being used alone. Only four papers used contemporary ecological, economic and social value-domains in one paper. Considering the ES framework that is embedded with multiple value-domains, capturing and integrating plural perspectives is a recognized need but it is also extremely challenging (Lopes and Videira, 2018) and this could be the reason for such few studies attempting this. In fact, on the basis of value pluralism, one of the primary issues for ES research is to use approaches in which biophysical, socio-cultural and monetary value-domains can be explicitly considered and integrated into decision making processes (Martín-López et al., 2014).

Table 4
The table shows the number of studies that have considered only one value-domain (e.g., ecological only, economic only, social only), or two dimensions, or all three. It also indicates which types of value dimensions have been used.

Number of value domains	no of papers	%	
1 value type	335	84	
2 value type	57	14	
3 value type	4	1	
1 value type	**no of papers**	**%**	**%total**
Ecological	205	61	15
Economic	45	13	3
Social	85	25	6
Total	335		
2 value type	**no of papers**	**%**	**%total**
ecological and economic	24	42	11
ecological and social	21	37	9
economic and social	12	21	5
Total	57		
3 value type	**no of papers**	**%**	**%total**
ecological, economic, and social	4		1

4.3. Mapping of ES evaluations

The potential for the mapping of the reviewed ES indicators is very high, and almost half of the papers effectively conducted ES mapping in their publication. This result highlights the importance of spatial explicit representation of ES, which has an important role in land use planning and landscape conservation, and it is a useful tool for policy and decision-making (Burkhard et al., 2013). A reason for the frequent mapping of ES may lie in the fact that in this way it is possible to study changes in the supply of ES that respond to land use changes and other drivers. Moreover, multiple ES are bundled together in generating trade-offs and synergies in different landscapes, and mapping is essential to highlight these processes (Malinga et al., 2015). It is relevant to highlight the efforts made by more than 35 % of authors to provide explicit solutions and governance suggestions based on their results to better manage ES.

4.4. ES type evaluated

Our review of ES indicators reveals a high proliferation of studies about ES in mountain areas in the past years, with 40 % of them applying at least one indicator to effectively assess ES. Regulating services are the most evaluated category (one-third of the cases), followed by provisioning and cultural services, while the category with less evaluations are supporting services (Fig. 2). The most frequently evaluated ES types identified by this review are climate regulation, food provisioning, recreation and tourism and water regulation. These services are

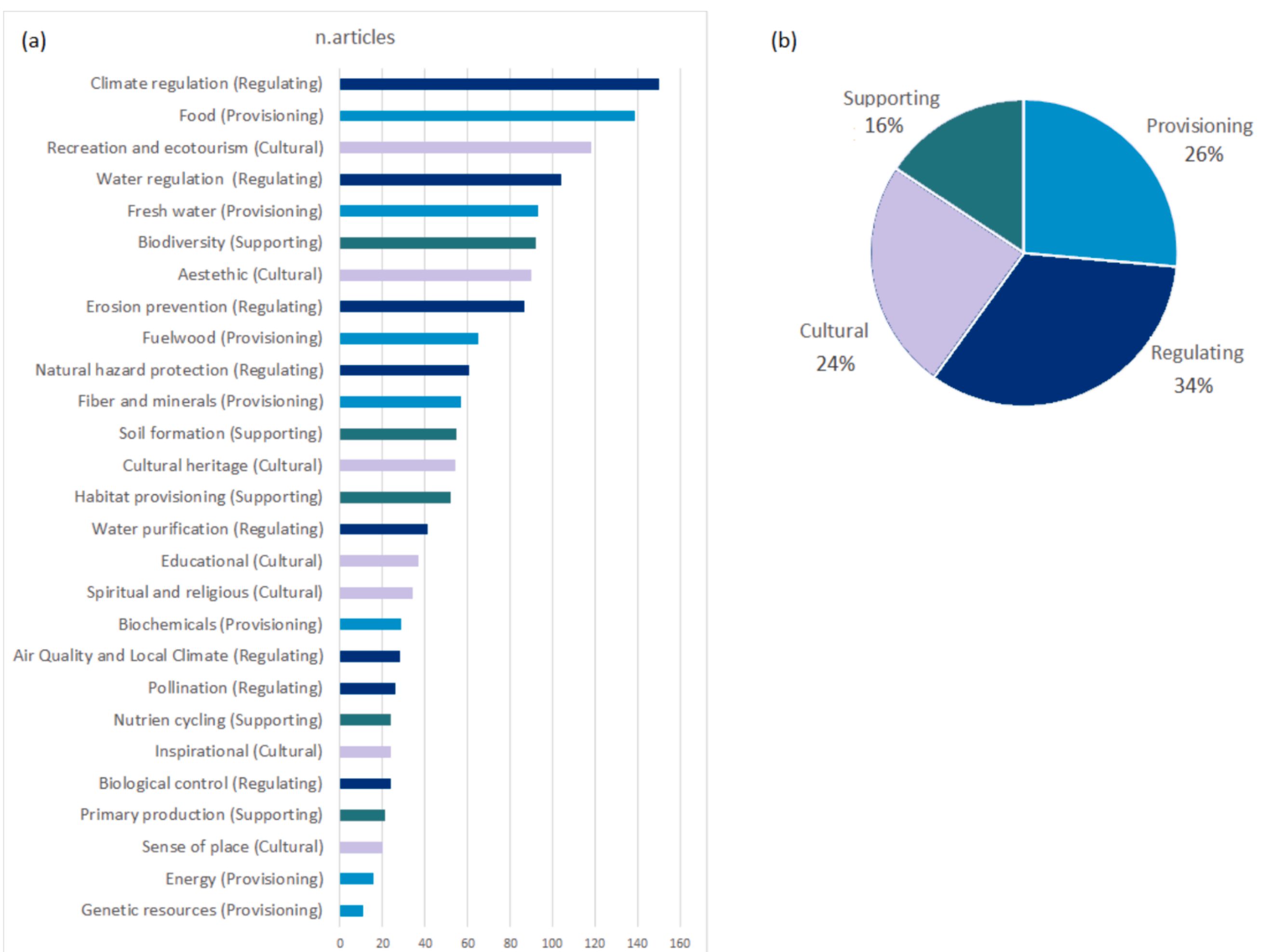

Fig. 4. A) Ecosystem services evaluated in mountain areas and their frequency; b) The distribution of studies for the four main categories of ecosystem services.

Table 5
The table lists the ecosystem services assessed in the studies, and for each one, it indicates: in the first column, the number of indicators used by the various studies considered; in the second column, the number of indicators grouped after our processing (for details on grouping, see the Section 2.2).

Ecosystem services	Number of indicators before grouping	Number of indicators after grouping
Food (Provisioning)	98	**26**
Climate regulation (Regulating)	80	**17**
Recreation and ecotourism (Cultural)	74	**28**
Biodiversity (Supporting)	74	**33**
Water regulation (Regulating)	69	**30**
Aestethic (Cultural)	61	**25**
Fresh water (Provisioning)	51	**15**
Fuelwood (Provisioning)	50	**12**
Natural hazard protection (Regulating)	47	**20**
Erosion prevention (Regulating)	43	**20**
Soil formation (Supporting)	40	**9**
Cultural heritage (Cultural)	32	**15**
Water purification (Regulating)	30	**16**
Fiber and minerals (Provisioning)	25	**8**
Habitat provisioning (Supporting)	25	**16**
Biochemicals (Provisioning)	22	**9**
Nutrien cycling (Supporting)	22	**9**
Educational (Cultural)	21	**9**
Primary production (Supporting)	20	**10**
Spiritual and religious (Cultural)	19	**10**
Sense of place (Cultural)	17	**6**
Inspirational (Cultural)	15	**8**
Pollination (Regulating)	13	**8**
Biological control (Regulating)	12	**9**
Energy (Provisioning)	10	**6**
Air Quality and Local Climate (Regulating)	9	**2**
Genetic resources (Provisioning)	7	**6**

particularly valuable in mountain areas, which can be considered hotspots for such services as highly demonstrated by an extensive body of scientific literature. For example, the carbon stored in soils and vegetation in mountain areas greatly contributes to global climate change mitigation, and more than half of humankind depends on freshwater that is stored and purified in mountain regions (Viviroli et al., 2011). From a societal point of view, mountains are of global significance as key destinations for tourist and recreation activities (Grêt-Regamey et al., 2012), and there is a growing demand for cultural ES and nature-oriented activities (Tenerelli et al., 2016). At the same time, mountain areas are among the most sensitive ecosystems to climate change, resulting in increased vulnerability which may cause a reduction of ES provision level or their complete loss. This dual aspect accentuates the increased scientific interest for investigation on mountain ecosystems. The less studied ES are the provision of genetic resources and the provision of energy. However, mountain areas are ecosystems that contribute to the conservation of unique genetic resources of animals and plants, such as for example the case of the Alpine ibex (*Capra ibex*) in the European Alps (Brambilla et al., 2018) or Stone pine (*Pinus cembra*) in Tatra mountains (Wojnicka-Półtorak et al., 2015), so they are worldwide refuge of species in geological time (Garrick, 2011). Similarly, extensive regions worldwide depend on energy from mountain areas, and these are especially important because of their high-energy potential, especially for renewable forms (Hastik et al., 2015). Energy provision from mountain areas is also associated with land use conflicts because of the need to balance environment exploitation with biodiversity and landscape hotspots, and it is thus crucial to provide trade-off solutions. These services are of high importance in mountain areas and their study should be promoted, as well as those of other services poorly evaluated.

4.5. Lack of standardization in the nomenclature and use of ES indicators

Despite the presence of frameworks for indicator selection that should promote standardization (Van Oudenhoven et al., 2012; De Groot et al., 2012, Haines-Young and Potschin-Young, 2018), our results demonstrate that there is still a high heterogeneity of indicators used for evaluating ES, as well as in the nomenclature used to denote these indicators. Overall, this research field is undergoing significant changes, utilizing various methods that, while showing some similarities, are not always explicitly aligned. Considering that we have found a mean of 14 indicators used for a single ES type, we hypothesize that this heterogeneity could be due to different reasons. First, there could be an objective need to differentiate indicators based on case-study characteristics such as the scale of analysis, land management, data availability, or other site-specific peculiarities. Secondly, the relatively recent proliferation of numerous studies and research projects within the domain of ES assessment has generated a wide range of useful indicators, even for experimentation by the authors of these studies, which must now naturally undergo a process of selection. Despite an initial phase of development and experimentation with various types of indicators being a positive aspect of the research, it is now time to push towards standardizing selected indicators, also employing quality criteria.

We acknowledge that some services due to their nature may have more heterogeneous indicators, like for example hazard protection. In this case, authors used indicators of rockfall, landslide, avalanche, fire, flood, or sandstorm protection, that are strongly dependent on differences in the environmental vulnerability of the study area (i.e. Scheidl et al., 2020; Pais et al., 2020). Some ES, on the contrary, can be described more uniformly even across different areas of study, like in the case of fuelwood or freshwater provisioning (Table 5). In these cases, it should be easier to reduce the number of suitable indicators to few ones. Surprisingly, fewer specific indicators have been developed in mountain areas for those ES considered of primary importance, like provisioning of biochemicals, energy, regulation of air quality and local climate, pollination, and biological control (Table 5).

Cultural services (CES) deserve a separate discussion. Due to their non-material and intangible nature, there are specific challenges associated with their measurement. Moreover, CES rely on human perception, experiences, and cultural values and it is expected that the most frequently used indicator for all CES types is 'people's perception'. The major differences are in the methodology used to collect information about people's perception, which can be questionnaires, interviews, workshops, focus-groups, or participatory GIS. However, in literature we also found other frequent indicators that measure CES through indirect measure related to landscape features or people's activities.

In summary the main issues which pose challenges for the use of ES indicators are related to the:

i) lack of common nomenclature in ES indicators, leading to several names that refer to the same ecological concept;
ii) use of the same names, which may refer to different concepts;
iii) use of the same indicator for different ES.

For example, in the case of climate regulation service, which was overall the most frequent evaluated ES in our literature review, the most common indicators refer to the estimation of carbon stock. However, due to semantic differences in the terminology, it is not clear if the indicator refers to organic/total carbon, aboveground/belowground/both, soil/litter/vegetation, or stock/sequestration, which results in a

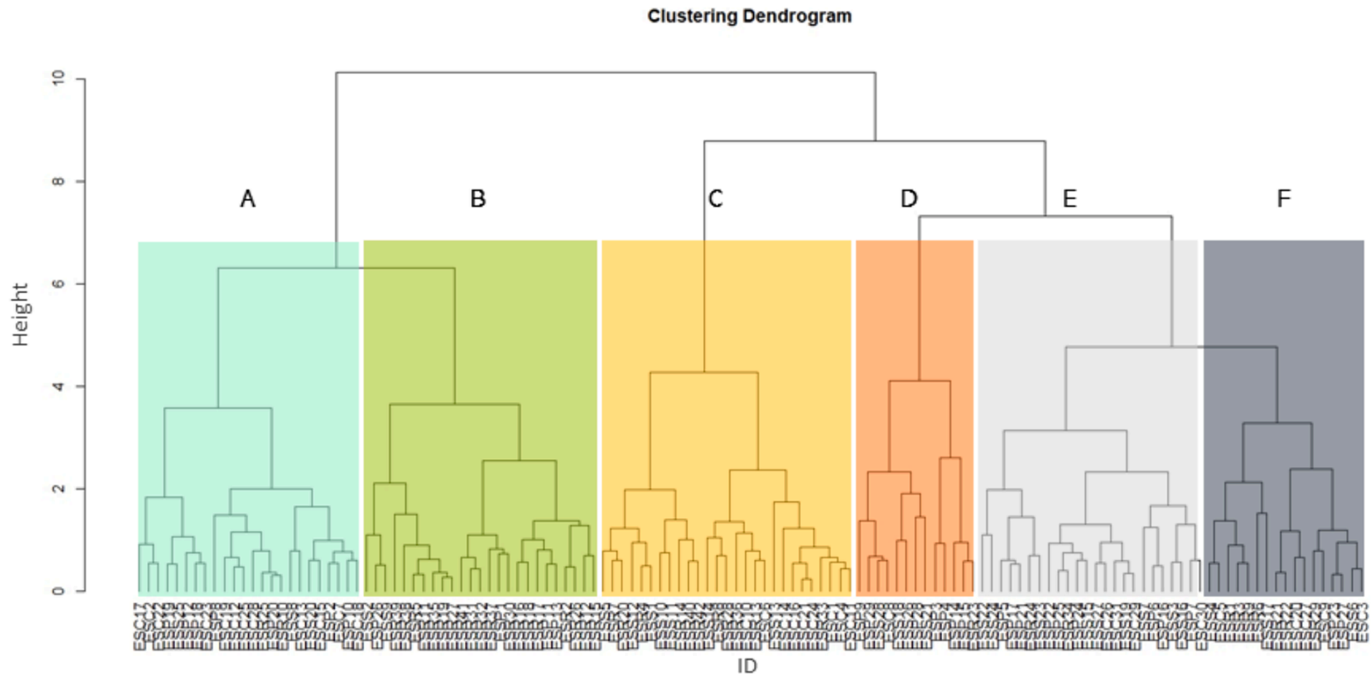

Fig. 5. Resulting dendrogram of cluster analysis (ID are reported in Table 6).

Table 6
Statistics for each component for the six clusters.

Cluster's name		Parameter	Mean	Std. Dev.	Moda
A) "Minimal Metrics"	*N = 24*	Significance	2,99	0,87	3,29
		Simplicity	2,54	0,62	2,39
		Cost	2,66	0,64	2,54
		Replicability	2,93	0,74	3,05
		Interpretation	2,40	0,78	2,32
		Policy	3,00	0,75	3,15
B) "Average Attributes"	*N = 25*	Significance	3,01	0,88	3,24
		Simplicity	2,72	0,60	2,48
		Cost	3,21	0,51	3,17
		Replicability	3,08	0,61	2,92
		Interpretation	3,46	0,72	3,33
		Policy	3,39	0,89	3,44
C) "Significant But Limited"	*N = 27*	Significance	4,41	0,69	4,81
		Simplicity	2,66	0,65	2,36
		Cost	2,58	0,47	2,50
		Replicability	3,37	0,88	3,09
		Interpretation	2,51	0,66	2,61
		Policy	3,65	0,69	3,88
D) "Comprehensive Excellence"	*N = 13*	Significance	4,11	0,81	4,50
		Simplicity	3,97	0,72	4,23
		Cost	3,37	0,47	3,42
		Replicability	4,09	0,63	4,23
		Interpretation	3,93	0,58	3,92
		Policy	3,91	0,72	4,09
E) "Replicability Focus"	*N = 24*	Significance	3,47	0,82	3,95
		Simplicity	3,39	0,85	3,26
		Cost	3,15	0,70	3,36
		Replicability	3,92	0,66	4,10
		Interpretation	3,20	0,75	3,30
		Policy	3,08	0,64	2,95
F) "Significance Consistency"	*N = 17*	Significance	3,85	0,82	3,71
		Simplicity	2,89	0,56	2,76
		Cost	3,31	0,51	3,24
		Replicability	3,51	0,77	3,47
		Interpretation	2,45	0,70	2,50
		Policy	3,15	0,71	3,13

significant difference in its quantification. Reviewing the studies made possible to assess which specific measure was considered, regardless the name of the indicator. For example, the indicator that we have grouped under the name of "Soil organic carbon stock" may be referred to as (in parenthesis the number of the paper) 'Soil carbon' (713), 'Soil carbon content' (821), 'Soil organic carbon storage' (824), 'Carbon storage' (688). Other authors used same or similar names, like 'Carbon stock' (19), 'Carbon content' (947), 'Carbon sequestration' (578), 'Carbon storage' (765), to define 'Aboveground and belowground organic carbon' or used the names 'Carbon stock' (346), 'Carbon Storage'(91), 'Carbon sequestration' (87), 'Carbon storage potential' (803) to define 'Aboveground organic carbon stock'. This semantic ambiguity leads to confusion and lack of clarity. We recommend authors to state clearly in the name of the indicator which ecological measure they are referring to.

In other cases, the same indicator, for example, 'Aboveground biomass', was used to estimate different ES like food provisioning, fuelwood provisioning, climate regulation, primary production, energy provisioning and cultural heritage (i.e. Carvalho-Santos et al., 2016; Knoke et al., 2020; Cabrera and Duivenvoorden, 2020).

4.6. The most frequently used indicators for mountain ES are not always the best

Interpretation ambiguities and inconsistencies can seriously compromise the policy uptake and practical usefulness of the whole ES concept (Nahlik et al., 2012). For this reason, extreme care should be taken in choosing the indicators. Considering the expert interpretation of utility of indicators most frequently used, we focused on six parameters by ranking them based on expert's opinion (Supplementary Materials Table S8) and radar charts were made to visualize the overall quality (see Supplementary Materials Fig. S1). Generally, the lowest mean value refers to simplicity and easiness of interpretation. Simplicity in terms of methodology or analyses needed is on average relatively simple to complex and interpretation by different audiences (also non-expert) of the indicators is on average between relatively easy to difficult. The cost to collect data and compute the indicators is ranked on average reasonable bearing a medium cost. The replicability of the indicators is on average medium–high, and also the relevance for policy is ranked on average quite relevant. Cluster E "Replicability focus" groups a set of indicators that are particularly useful for monitoring due to their high replicability, while still maintaining an average, thus good, value for the other parameters. The significance was on average ranked higher than other quality criteria but always between medium and high, and 38 % of indicators are of high or very high significance. The clusters 'Significant but Limited' and 'Significance Consistency' include indicators that perform very well in terms of significance. However, they differ in other parameters: the first group scores low, while the second group has average values for these other parameters. In these cases, it is preferable to use an indicator from cluster "Significance consistency", assuming the same ecosystem service. Besides the overall average quality for all indicators, there are differences in each one, and some of the most frequently used are of low quality in some aspect. 18 % of indicators were ranked under the medium value (low) for significance. Among these, the indicators ranked of lower quality were *economic value* for services of cultural inspiration, spiritual and religious, and sense of place; and *people's perception* for erosion prevention, pollination, climate regulation, biological control, primary production, and biodiversity. In general, non-cultural services have low value of significance when quantified through people's perception, although this indicator in very frequently used in literature. *Economic value* was also ranked as low for simplicity of application, considering this valuation not easy to assess. Few indicators have a mean high-quality value considering all the quality criteria, the "Comprehensive excellence" cluster. These indicators exhibit high performance, but they represent a small subset (n = 13). Therefore, while they are useful for application, they do not cover all measurable ecosystem services. It is interesting to note that this group mainly includes provisioning services or those related to biodiversity. This is likely because significant measurement efforts have been made in these areas in the past, resulting in reliable and usable indicators today.

Inevitably a compromise exists among different criteria when selecting an indicator. However, we suggest avoiding indicators with low significance, since generating reliable assessments upon which subsequent territorial management policies should be grounded, is crucial. It is possible that the application of relevant evaluation approaches is hindered by data-scarcity, as for several ES we miss basic ecological or social information (Pandeya et al., 2016). The overall quality of indicators for ES should however be enhanced by scientific and technological development.

Cluster analysis demonstrated that ES indicators could be grouped according to their properties with some groups being more useful than others. Although many indicators score high in some of the properties evaluated, actually few perform well in all properties (Table 6, Supplementary Materials Fig. S1). This is the case for indicators in cluster group 4 which represent all four categories of ES and comprise indicators such as water supply, rainfall, biodiversity conservation and visitors' numbers. Since ES are evaluated in bundles (Saidi and Spray, 2018) rather than individually, the value of this finding lies in the identification of ES for assessment on the basis of the quality of indicators as proposed herein with the use of widely accepted properties. These indicators have a universal value both in terms of semantics, science but also in terms of properties and should be promoted for standardization among ES assessments.

4.7. Strength and limitations

A strength of this study lies in its analysis of a significantly high number of scientific articles far exceeding the scope of previous reviews (Hernández-Morcillo et al., 2013; Mengist et al. 2020). In this regard, there is a comprehensive representation of the diversity of studies existing on the assessment of ES in mountain environments. Moreover, it not only identifies which indicators have been utilized but also meticulously categorizes them into "common indicators," thereby overcoming the significant limitation of disparate nomenclature for the same indicator. Finally, the indicators are assessed from the perspective of their quality, considering fundamental parameters. This aspect has facilitated the provision of valuable insights to other researchers or decision-makers regarding the selection of indicators to use in their specific case studies. However, these recommendations are general, and parameters may vary depending on the specifics of the analyzed situations (e.g., costs). Nevertheless, this study has obviously some limitation. Firstly, the analysis is constrained within a specific time frame, as the high scientific productivity on the topic of ES required reducing the number of papers analyzed. Additionally, only English literature was considered for better comprehension; certainly, considering studies conducted in other languages would broaden the range of indicators used. Lastly, the number of experts conducting quality analysis could be increased, which might lead to greater variability in quality judgments.

5. Conclusions

Effective management of ecosystem services advocates the use of methods and indices to implement comprehensive environmental management policies, which are primarily developed and applied in scientific research. Almost half (40 %) of the literature considered quantifies ES by applying indicators, and there is relevant portion of studies which also map ES. Geographically, Europe and Asia are the subject of greater attention from the scientific community, while North and South America, despite their extensive mountain areas, lack sufficient research emphasis. The overall quality of indicators is not very high, but we identify six different clusters with specific characteristics which help users to choose the indicators. For some services, we suggest that greater attention should be paid to the use of indicators that are aligned with the ecological phenomenon being measured.

To conclude, there is a recognized necessity to condense the array of indicators commonly employed in scientific literature for evaluating ES down to a parsimonious set of high-quality metrics. By reviewing the ES indicators which are more frequently employed in mountain areas literature and by analyzing their quality, this study provides useful information to guide appropriate selection.

CRediT authorship contribution statement

Claudia Canedoli: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Noemi Rota:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Ioannis N. Vogiatzakis:** Writing – review & editing, Formal analysis, Data curation. **Alexia Zanchi:** Data curation. **Mita Drius:** Writing – review & editing, Data curation. **Harini Nagendra:** Writing – review & editing. **Emilio Padoa-Schioppa:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared the data in the supplemmentary files.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112310.

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