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A bottom-up practitioner-derived set of Essential Variables for Protected Area management

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ABSTRACT

Assessing the environmental status of Protected Areas (PAs) is a challenging issue. To indicate that status, the identification of a common set of variables that are scientifically sound, and easy to assess and monitor by the PA practitioners, is particularly important. In this study, a set of 27 Essential Variables (EVs) for PA management was selected in a bottom-up process from 67 harmonised variables that describe the status of Ecosystem Functions and Structures, Ecosystem Services, and Threats in PAs. This bottom-up process involved 27 internationally recognised PAs, mostly European, with different level of protection, different extent, and a wide range of human-nature interactions. The EVs were selected by more than 120 practitioners, i.e. PA managers and rangers, as well as scientists, working in terrestrial and aquatic PAs. Across both terrestrial and aquatic PAs, scientists and practitioners largely identified the same variables as important. Data availability for these 27 EVs varied between PAs and av

eraged 67% across all studied PAs. As this set of EVs for PAs is defined through a bottom-up approach considering variables already in use both in management and research, it is more than for previous EVs likely to

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be adopted, applied and developed to record the status and changes in the ecological and socio-economic conditions of PAs and to forecast future changes. Thereby, the EVs for PAs present a common vocabulary and tool to enhance in a uniform way the (inter)national communication, exchange and comparison of information on the status of PAs between policy makers, scientists and PA managers. The perceived status of the EVs, on an average 3.6 on a scale to a maximum of 5, indicates the surveyed PAs are in a moderate to good environmental condition. Moreover, the EVs for PAs form a cost- and time-efficient tool for PA managers to monitor developments in essential elements of their PAs, including the potential for Societal Goods and Benefits (SG&B), and to (pro-)actively tackle the potential threats that may arise in their area. Likewise, for policy makers EVs for PAs may support decision making on ecosystem management, spatial planning, and predictive modelling on the future status and requirements of PAs in their country or region.

1. Introduction

Protected areas (PAs) represent one of the main tools of ecosystems protection and biodiversity strategies and are complex social-ecological systems (SES) (Cumming and Allen 2017; Palomo et al. 2014; Guerra et al. 2019) interacting with, and exposed to, the effects of both natural and anthropic changes and pressures, such as climate change, land use change or recreational use. As a consequence, the management of PAs needs to consider several environmental (e.g. ecosystem functions and structure) and socio-economic (e.g. direct and indirect human activities) variables to assess the PA's status and its changes and possibly to foresee their evolution in order to adopt proper proactive strategies.

In the last decade, the use of the concept of Essential Variables (EVs) has become more and more common in the policy and scientific domains as a tool to support the assessment of the status of, and changes in, the environment and PAs. By providing composite indicators to observe changes in the environment, EVs can support decision-making in environmental policy, spatial planning and ecosystem management. In addition, EVs aim to provide strategic guidance on where to invest limited resources when deciding which variables are to be measured in the myriad of potentially relevant variables. Examples are the Essential Climate Variables, Essential Agricultural Variables, Essential Biodiversity Variables, Essential Variables for Invasion Monitoring, Essential Marine Ecosystem Variables, Essential Geodiversity Variables, Essential Sustainable Development Goals (SDG) Variables, or the Essential Ocean Variables (Pereira et al. 2013; Bojinski et al. 2014; Hayes et al. 2015; Latombe et al. 2017; Reyers et al. 2017; Kissling et al. 2018; Muller-Karger et al. 2018; Jetz et al. 2019; Schrodt et al. 2019; Whitcraft et al. 2019; Zilioli et al. 2019). More recently, efforts have also been made to develop EVs that describe socio-ecological systems (Lehman et al. 2020; Pacheco-Romero et al. 2020), and harmonised indicators of Ecosystem Services (ES) to support decision-making (Van Oudenhoven et al. 2018).

Most of these concepts are established and developed by scientists or policymakers, and thereby mostly in a top-down process, which may turn out to be counterproductive with limited buy-in and uptake if not developed with the active participation of practitioners that are expected to implement these EVs as a tool in their daily work to assess the current status and track the changes in the social-ecological systems they manage (Haase et al. 2018; Guerra et al. 2019; Hummel et al. 2019).

Although these top-down established EVs may be scientifically consistent, the attributes considered in such a derived set of EVs may differ from the attributes required for their day-to-day use by practitioners, which may result in a slow uptake of such new concepts in the management of Protected Areas (PAs) (Fisher and Brown 2014; Hummel et al. 2019).

Similarly, the ES framework is also only slowly adopted by managers so far and rarely addressed in PA management plans (Palomo et al. 2014), As observed by Hummel et al. (2019), only 2 out of 26 surveyed PAs used the concept of ES in the management of their PA, and the majority did not explicitly use the ES framework in their PA management.

Differentiation in the uptake and perception between scientists and PA managers on the most important variables regarding ecosystem functions and ES in PAs was also apparent during a study conducted across 17 PAs throughout Europe (Hummel et al. 2017). PA managers had a more consistent and comparable view on the importance and type of variables, and the scientists deviated strongly from each other as well as from the PA managers.

Therefore, to implement novel approaches to be used by the PA management as well as policy-makers, a stronger bottom-up strategy should be followed in consultation with the practitioners, including their local practices, experiences or interests, and in a way that is understood and approved by them and practical and suitable for their purposes (West et al. 2006; Guerra et al. 2019; Hummel et al. 2019; Morkūnė et al. 2021).

Mutually agreed approaches and metrics are urgently needed, since during the last decades PA managers and policy makers have been under increasing (inter)national pressure to estimate the status of their PA in a practical, scientifically sound and comparable way (Parrish et al. 2003). In addition, (inter)national pressure is also high since PAs are gaining importance in global policies due to the climate and biodiversity crises, with experts of e.g. IPCC and IPBES calling for the protection of at least 30% of the Earth's surface by 2030 (IPCC: Intergovernmental Panel on Climate Change, IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; Dinerstein et al., 2019).

Metrics for the clarification and standardisation of the type of PAs have been initially developed by the International Union for the Conservation of Nature (IUCN) in a system with nowadays six categories (Holdgate 1999; Dudley et al. 2013). However, the system is mainly based on the PA management strategy and less on the actual (environmental or socio-economic) status in the field, and thereby may lead to "paper parks", i.e. PAs that, despite a management plan on paper, are established and maintained with little or no information of the ecological or social reality at the site (Brandon et al. 1998). Although several other systems have been proposed, such as the WWF Rapid Assessment and Prioritisation of Protected Area Management (RAPPAM; Ervin, 2003), the majority of these systems remain top-down, lack the inclusion of effects in the field, require considerable financial or personnel effort, or are not generally applicable for comparisons (Hockings and Phillips 1999; Pomeroy et al. 2004; Stoll-Kleemann, 2010; Hummel et al. 2021).

Wide-scale agreement is central to the buy-in and subsequent use of EVs, to overcome the above-mentioned obstacles, and at the same time to comply with the increasing demand for a comprehensive set of informative metrics on the status of PAs and their management. Therefore, in 2017 and 2018, we interviewed a wide group of managers, rangers and scientists of several PAs. We applied a fixed interview-protocol and a set of harmonised environmental and socio-economic field variables, established in the previous years in co-design with practitioners in the field and scientists (Supplement A, B; Hummel et al. 2018). This protocol allowed us to reduce any mismatches in outcomes and to reach an agreement on a uniform set of variables that are essential to evaluate the status of Ecosystem Functions and Structures (EF), Ecosystem Services (ES), and pressures and drivers of change (Threats).

In this paper we present the results of the surveys. The results presented here are the first coordinated approach to transferring the concept of Essential Variables (EVs) in a comprehensible manner to PAs and their management, following a bottom-up procedure. The outcome is a widely applicable set of EVs showing the best achievable similarity between various scientists and PA managers from a wide spectrum of aquatic and terrestrial systems.

We also provide a first estimate of the data availability for those EVs, and how these data may be used for an indication on the status of EF, ES, and threats in the PAs.

Such a harmonised, bottom-up and agreed-upon, set of variables to capture the status of a PA in a uniform way will pave the way to a common vocabulary to enhance the communication and urgently needed exchange of information between policy makers, international boards, and PA managers and rangers. Moreover, it will yield a practical tool for PA managers to monitor the developments and changes in essential elements in their PAs, including the potential for SG&B, and to (pro-)actively tackle any kind of issues that arise in their area. Additionally, it may support comparisons of PAs on their current status and future requirements at regional, or even global, scale.

2. Material and Methods

2.1. Variables and PAs

The present study is based on surveys carried out with practitioners and researchers from 27 internationally recognised PAs, such as UNESCO Natural Heritage sites and National Parks, across Europe, as well as one PA from Israel and three African PAs (Table 1, Fig. 1).

The order in time of the surveys is schematically shown in the flowchart of Fig. 2.

In the preparatory phase, a first set of variables describing EF, ES, and Threats in PAs was derived from the results of inventories held in 2015 with 15 scientists and 12 managers from 16 PAs, and some workshops in the following year, as reported by Hummel et al. (2018), and of which the results are given in Supplement A.

Variables on comparable aspects were combined and harmonised to ensure that indicators from different realms, i.e. terrestrial and aquatic, could be captured under the same conceptual term. For example, the term “animals of economic use” was used for meat production in agriculture or cattle grazing, as well as for aquaculture or fishing (Hummel et al. 2018). In this way, the set of originally 396 obtained variables was collapsed to a total of 67 harmonised variables (i.e. more than 4 out of 5 variables could be combined; Supplement A).

Using the list of harmonised EF, ES, and Threat variables resulting from the previous step, we carried out several surveys in 2017 to query PA managers, rangers, and scientists regarding the importance they attached to each, in order to identify the most important variables, i.e. the Essential Variables (EVs) for Protected Areas (PAs) as perceived by them (see Supplement B; see for a further description of the survey also Hummel et al. 2018).

The surveys were carried out at the PA locations (Table 1) and included an introduction of the project, a field visit, and a 6–8 h long interview (only for Kruger, due to logistical constraints, the survey was carried out electronically). The PA managers and rangers were requested to evaluate the importance of all harmonised variables regarding the EF, ES, and Threats in their PA using the Likert scale (Likert 1932). The Likert scale is one of the most common and reliable ways of measuring perceptions and opinions in the social, psychological and economic sciences (Joshi et al. 2015; Taherdoost 2019). In each PA, the PA management was asked to give one score per variable whereby 0 indicates the variable is not existing or of no importance at all, and 5 indicates that the variable is of the highest importance in the PA. Examples and specifications of each harmonised variable were given during the surveys to enhance the understanding and meaning of the variables (Supplement B).

In an additional inventory, scientists connected to a PA, but not employed by the PA, e.g. from a nearby related university studying the area, were also asked to score each variable.

All surveys followed the same predefined interview protocol (Supplement B) and set of harmonised variables (Supplement A). Around 80 PA managers and rangers and 35 scientists from the 27 PAs participated in the surveys of 2017.

Table 1
Overview of the Protected Areas (PAs) surveyed, including country of the PA, realm type of PA (Terr = terrestrial, Aqua = aquatic), year of survey (”2015 prep” = surveys in 2015 used to prepare harmonised set of variables, see Hummel et al. 2018 and Supplement A; “2017 EV” = surveys in 2017 for indication of variable importance and EVs, using Supplement B during surveys; “2018 EV-eval” = surveys in 2018 for evaluation of EV status, using Supplement C), participant’s profession (m = PA managers and rangers, s = scientists), and Protection status (NP= National Park, RP= Regional Park, UBR= UNESCO Biosphere Reserve, N2k= Natura, 2000 site, UWH= UNESCO World Heritage).

PA name	Country	Type of PA	2015 prep	2017 EV	2018 EV-eval	Protection status
Appia Antica	I	Terr		ms	s	RP
Bavarian Forest	D	Terr		m		NP, N2k
Camargue	F	Aqua	ms	m		RP, UBR, N2k
Castelli Romani	I	Terr		ms		N2k
Curonian Spit	LT	Aqua	ms	m	m	NP, N2k, UWH
Danube Delta	RO	Aqua	s	ms	s	UBR, N2k, UWH
Doñana	E	Aqua	ms	ms	s	NP, N2k, UBR, UWH
Etangs Palavasiens	F	Aqua		m		N2k
Gran Paradiso	I	Terr	ms	m	m	NP, N2k
Har Ha Negev	IL	Terr		m		NP, UWH
Hardangervidda	N	Terr	ms	m		NP
Kalkalpen	A	Terr	ms	ms	ms	NP, N2k, UWH
Kruger	ZA	Terr		ms	s	NP, UBR
La Palma	E	Terr	m	M	m	NP, N2k, UBR
Lake Ohrid	NMK	Aqua		ms	s	NP, N2k, UWH
Lake Prespa	NMK	Aqua		ms	m	NP
Montado	P	Terr		ms	s	N2k
Nemunas Delta	LT	Aqua	m	m		N2k, RP
Oosterschelde	NL	Aqua	s	ms	s	NP, N2k
Peneda-Gerês	P	Terr	ms	m	s	NP, N2k, UBR
Pieniny NP	SK	Terr		ms	ms	NP, N2k
Reunion	F	Terr		m		NP, UWH
Samaria	GR	Terr	ms	ms	s	NP, N2k, UBR
Sierra Nevada	E	Terr	s	ms		NP, N2k, UBR
Swiss NP	CH	Terr	m	ms	s	NP, UBR
Wadden Sea	NL	Aqua	ms	ms	ms	NP, N2k, UBR, UWH
Westerschelde	NL	Aqua	s		s	N2k

2.2. Analyses of variable importance

In the first EcoPotential surveys in 2015, before harmonisation of protocols and variables, strong differences were found in the responses between scientists and PA managers, and between the various domains of the PA, i.e. terrestrial versus aquatic (Hummel et al. 2017, 2018). Therefore, even though the variables and survey protocol were fully harmonised, all data obtained in 2017 were first tested for differences in outcomes between scientists versus practitioners (PA managers and rangers) and for differences between realms (terrestrial versus aquatic). To this end, a principal component analysis (PCA) with cluster analysis was performed following Metsalu and Vilo (2015).

In the further analyses, the importance level of the variables as perceived by the PA managers and scientists was analysed in two ways, whereby multiple surveys from the same PA, i.e. the one of the PA management and the one of the scientists, were treated as independent

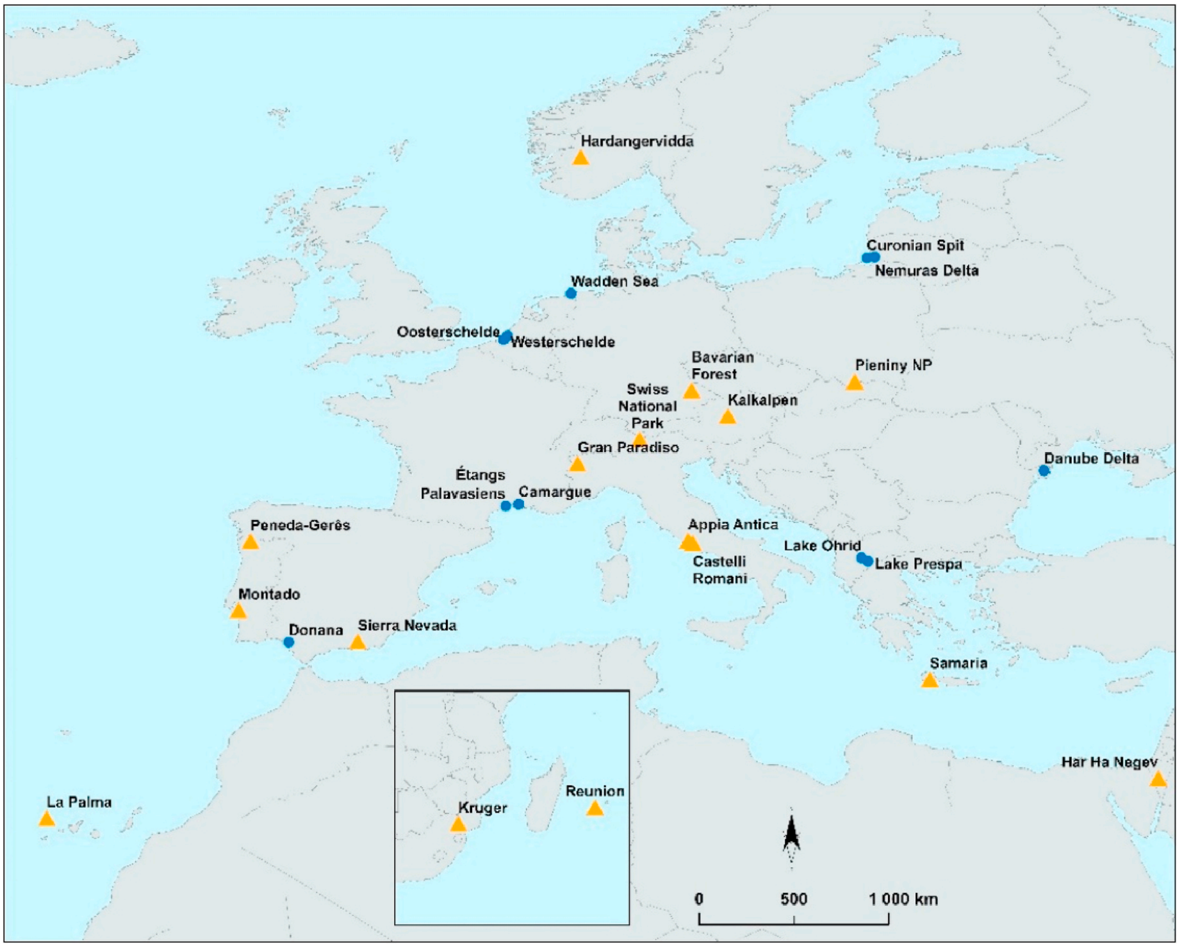

Fig. 1. Overview of PAs surveyed in Europe and beyond. Orange triangle = Terrestrial; Blue circle = Aquatic. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

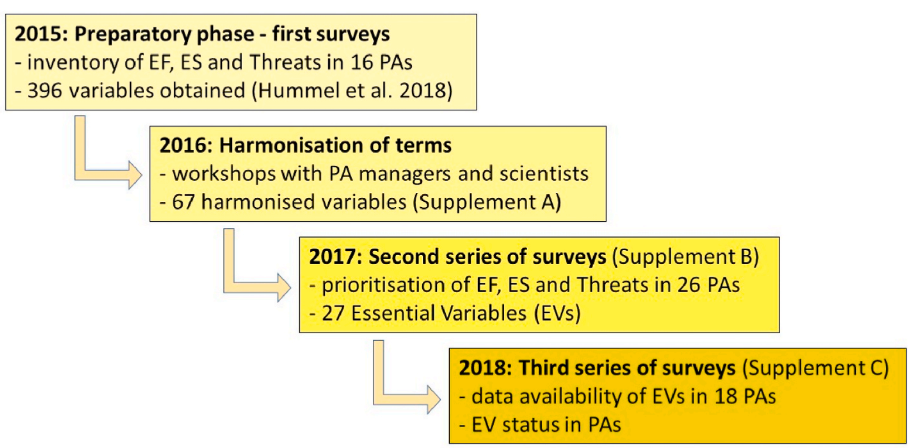

Fig. 2. Flow-chart on the sequence of surveys and selection and harmonisation of variables (EF = Ecosystem Functions and Structures, ES = Ecosystem Services, Threats = Pressures and drivers of change, EV = Essential Variables, PA = Protected Area).

observations:

- First, the number of times a variable was scored at a level of 4 or 5 (very important) was counted.
- Second, the average scores (and the standard deviation and error) for each variable were calculated. In addition, the average scores were calculated for each group (i.e. EF, ES, and Threats). Since each group showed a different average importance level (3.5, 2.9 and 2.6 for EF, ES and Threats, respectively), the ratio of the average for each individual variable to the average of the group the variable belonged to was also calculated.

In order to be assigned as an Essential Variable (EV), the score of a variable had to meet the two following criteria:

- 1) the variable had to be mentioned at least in 50% of the cases to have an importance of 4–5, and
- 2) the variable needed to have an average score over all PAs of at least 2/3 of the maximum (5), i.e. to have an average value of 3.4 or higher, and/or to be at least equivalent or higher than the group average (ratio is 1.0 or higher).

2.3. Survey on data availability and PA status

Using the most important variables identified during the surveys of 2017, i.e. the tentative list of EVs, the participants of the earlier surveys were requested to indicate in a follow-up survey in 2018 the degree of data availability for each tentative EV. In case participants indicated that these data were available and could be interpreted, they were also asked how they perceived the status of their PA (its situation or quality) using these data. An example of the survey is given in Supplement C. In total, 21 surveys were returned by PA managers and scientists from 18 PAs (Table 1), including 16 European PAs and 2 African.

For the question on data availability, the scientists and PA managers could fill in for each EV "Yes = available" or "No = not available or no information". In case of differentiating answers per PA (i.e. when there was more than one replying participant from the PA) a "Yes" prevailed over "No".

The total number of scores on data availability for each EV always summed up to 18, equal to the number of participating PAs. The total number of scores on data availability for each PA always summed up to 27, equal to the number of available EVs. Relative scores, i.e. percentage availability, were then calculated for each variable or group of variables (i.e. EF, ES and Threats) over all surveyed PAs, as well as for each PA over all variables.

For the indication of the perceived status per EV in the PA, the PA managers and scientists were asked to give for each variable for which information was available, a score using the standard 5-point Likert scale (Likert 1932).

The rating was ranging from 1 to 5 as follows:

- 1 = the actual situation is very far from the desired situation, e.g. the environmental situation as measured with the specific variable indicates the PA is highly impacted or even degraded, or there is an unacceptable socio-economic situation impacting the PA negatively;
- 2 = the situation is still far from the desired situation, but there is hope for improvement;
- 3 = the situation is not good and not bad, i.e. almost acceptable but improvement can/should be made;
- 4 = the situation is good and almost, but not completely, the desired situation;
- 5 = the situation is very good, i.e. the desired situation or optimal reference level as measured with the specific variable is reached.

In case there was more than one participant from a PA, their scores were averaged and rounded up.

The ratings were averaged over all PAs per EV, as well as across all EVs per PA, to indicate the average status of EVs in and across PAs.

Finally, the participants were asked to indicate up to three possible methodologies or proxies used to obtain information or data on the EVs. These methodologies were classified as obtained through *in-situ* (field or monitoring) methodologies and those obtained by using remote sensing tools.

3. Results

3.1. Similarity in perception of variable importance between scientists and PA managers from different realms

The perceived importance of variables showed no apparent differences with regard to the profession of the survey participants (PA management or scientist) nor with regard to the realm of the PA (aquatic or terrestrial) (Figs. 3 and 4). All PCA clusters, based on possible variations due to profession or realm, overlap each other strongly. This holds for the overall range of data (Fig. 3) as well as for the specific groups of variables, i.e. the EF, ES and Threats (Fig. 4). As such, the previously recognised mismatch between scientists and PA managers in scoring the perceived importance of variables (Hummel et al. 2018), as well as a clear differentiation between the variables mentioned for the terrestrial and aquatic realms, was not observed anymore.

Therefore, for further analyses on the individual variables, EVs, data availability, and on the use of the data for the EV-status, no distinction was made between data obtained from scientists or PA managers, nor between data from terrestrial and aquatic origin, i.e. all those data-sets have been merged into one data-set.

3.2. Importance of variables: selection of Essential Variables

The importance of variables on EF, ES, and Threats in PAs as indicated by managers and scientists ranged for each group from hardly important to very important (Table 2). Considering the importance ratings of the 67 variables, a group of 27 variables was identified as the most important, i.e. indicated in more than half of the PAs as being very important (marked 4 or 5 at a scale of 0–5, and with an average value over all PAs higher than 3.4 and/or ratio-score ≥1). These crucial variables are nominated as Essential Variables (EVs) for PAs, of which 10 belong to the EF, 9 to the ES, and 8 to Threats.

All the EVs for EF are environmental, i.e. biotic or abiotic, with biodiversity, habitat suitability, and land- and sea-scape identified as the top three (Table 2). Among the ES some of the EVs are also of socio-economic nature (i.e. anthropogenic), with leisure activities being the most important ES, alongside to environmental variables, such as charismatic landscape and biodiversity conservation. Among the Threats for PAs most EVs are anthropogenic, such as tourism, bad management, and change in land use.

3.3. Availability of data for Essential Variables

The availability of data on the EVs in PAs was shown to be reasonably high (Fig. 5), being 67% on average and almost equal for the various groups (EF: 66%, ES: 71%, Threats: 65%).

Though judged very important, for a few EVs a notable low availability of data is mentioned, such as for the "Gene Pool" and for "Bad Management" (Fig. 5).

Among the various PAs, the availability of data could vary strongly from 22 to 93% (Fig. 6). The situation for the Aquatic PAs is on an average slightly better (77%) than for the Terrestrial PAs (59%).

3.4. Status of Essential Variables in Protected Areas

The rating of the status of EVs in the majority of PAs shows a moderate to good level for all EVs (Fig. 7). Only in a minority of PAs the EV status is in a mediocre state.

When viewing the status of EVs from the perspective of each surveyed PA, it is clear that the low scores for EVs are mainly concentrated in a few PAs (Fig. 8). In a majority of PAs, the EV status is moderate to very high, indicating an acceptable to very good, i.e. desired, environmental and socio-economic situation in the PA.

On a scale of 1 (very bad) to 5 (very good) the status over all EVs in all PAs was on an average perceived to be at a level of 3.6, i.e. being almost at a desired good environmental and socio-economic situation in the surveyed areas but some improvements can still be made.

The average perceived status for EVs in PAs tended to be judged at a slightly higher level in case the data availability was higher (Fig. 9).

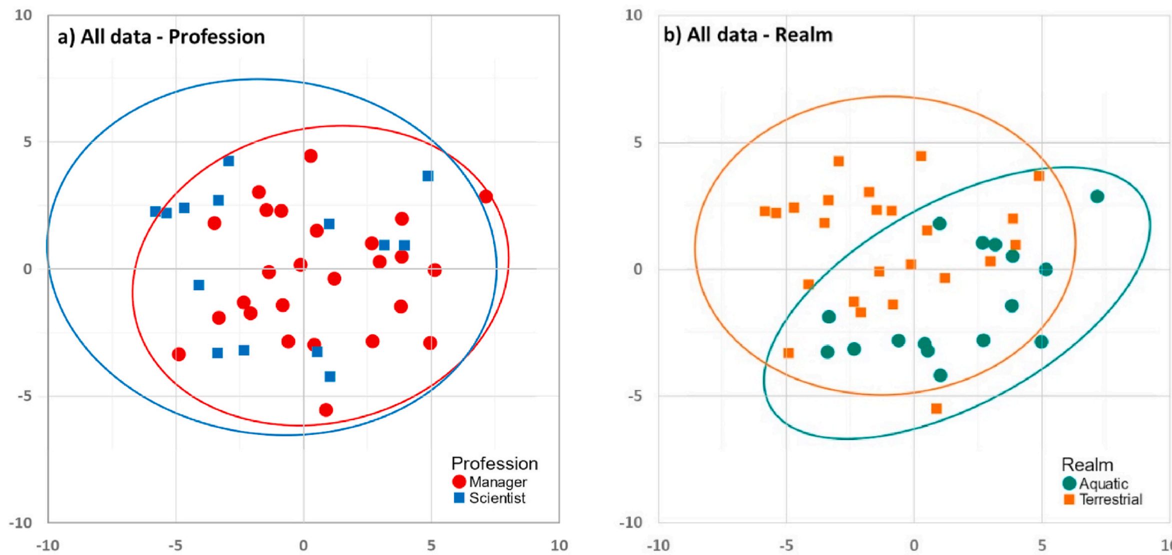

Fig. 3. Cluster analysis of variable importance (n=67) mentioned by PA managers and scientists (a; n=40) of the surveyed aquatic and terrestrial Protected Areas (b; n=26): Unit variance scaling is applied to rows; Nipals PCA is used to calculate principal components. X and Y axis show principal component 1 and principal component 2 that explain 16.4% and 9.7% of the total variance, respectively. Prediction ellipses are such that with probability 0.95, a new observation from the same group will fall inside the ellipse.

3.5. Methodological approach used for measuring Essential Variables in Protected Areas

Data obtained through *in-situ* (field, monitoring) data collection are more often used to indicate the status of EVs in PAs than of remote sensing data collection (Table 3). Out of 522 entries on methodologies used to observe and measure EVs in PAs, 78% of the applied methods are based on *in-situ* and just 22% rely on remote sensing tools.

Among the EVs that utilize remote sensing tools, most of them relate to large scale geographical observations, such as the EF Habitat Suitability and Land- and Sea-scape, and the Threats causing Change in Land Use and Habitat Loss. On the other hand, all ES in PAs are mainly observed with *in-situ* methods, and only rarely through remote sensing.

4. Discussion

4.1. Practitioner involvement and bottom-up harmonisation

At the start of the EcoPotential project, a clear differentiation was observed between scientists and PA managers in identifying and scoring the perceived importance of environmental and socio-economic variables (Hummel et al. 2017). Maas et al. (2021) also showed divergent practitioner and scientist perceptions of biodiversity, ES, and decision-making in the agricultural sector and Pittman et al. (2021) showed such discrepancies for marine management, biodiversity conservation and restoration issues in seascape ecology. A differentiation between scientists and practitioners about their perceptions of important variables can thus be rather common. To overcome such different views and to promote collaboration, Maas et al. (2021) and Morkūnė et al. (2021) demonstrate the urgent need for enhanced communication platforms and cooperation between scientists and key stakeholders. Similarly, we can ascribe the absence of a significant mismatch between scientists and PA managers in the present study, performed two years after the first EcoPotential studies, to the effectiveness of the intermediate communication and information campaign among partners in the EcoPotential project. In the interim years, scientists and managers worked together intensively within the EcoPotential project to collaboratively define consensual PA narratives of ecological conditions and conservation challenges to bridge gaps in their relative perspectives regarding these variables (Provenzale et al. 2020). Such collaboration thus had a tangible, identifiable impact on the views of the participants.

Substantial differences between the terrestrial and aquatic realms were also no longer observed, which may also be reflective of the harmonisation efforts for all variables as well as the fixed data collection protocol used during the surveys.

In the end, a jointly agreed set of harmonised variables to characterise the environmental situation and socio-economic connections in the PAs was achieved. This harmonised set of variables could be further condensed to a set of Essential Variables (EVs), the most important parameters to characterise the PAs, and as envisaged, consistent for all interviewed stakeholders from all aquatic and terrestrial systems involved.

These EVs for PAs may therefore be used as an efficient jointly agreed and harmonised tool to exchange and compare information between PAs, at regional or global scale, and to evaluate the environmental situation in a PA regarding its major ecological functions, ES that it may deliver, and common Threats that may occur in the area.

The PAs explored in this study, as part of the EcoPotential project, are very representative for the conditions of the European network of PAs and also for the overall climatic conditions and biogeographical regions of Europe in terms of climatic and biogeographic data, such as mean solar radiation, mean evapotranspiration, PA size, and mean temperature (Beierkuhnlein et al. (2016). We may therefore assume the results of this study to be valid for the wider range of PAs in Europe.

4.2. Essential Variables

In comparison to some other Essential Variables approaches, the selected set of EVs for PAs is less restricted to specific environmental parameters as e.g. for Essential Biodiversity Variables (Pereira et al. 2013), neither is it limited to some specific domain, as the Essential Ocean Variables (Muller-Karger et al. 2018). Informative systems should capture not only information confined to specific variables as biodiversity but also knowledge on, for example, the dynamics of ecological processes and related anthropogenic effects (Guerra et al. 2019). In that sense, the EVs for PAs presented here, which include a more comprehensive set of environmental and socio-economic variables, are applicable to a broader range of areas and conditions than earlier EVs.

Though some proposed EV concepts may cover a wider array of parameters than the EVs for PAs presented here, they are mostly

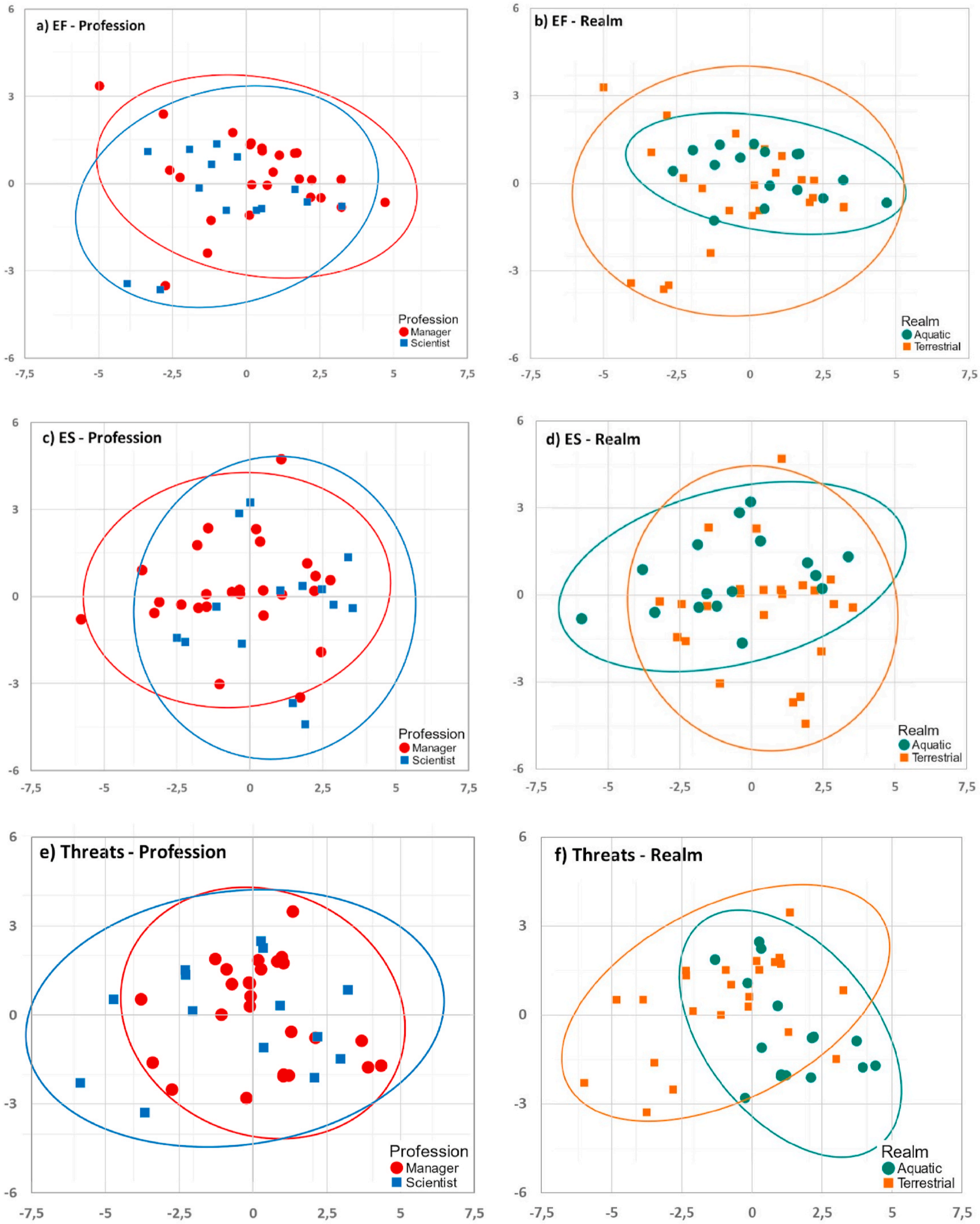

Fig. 4. Cluster analysis of the variable importance for Ecosystem Functions and Structures (EF; n=17), Ecosystem Services (ES; n=25), and pressures and drivers of change (Threats; n=25) mentioned by PA managers and scientists (a,c,e; n=40) for the surveyed aquatic and terrestrial Protected Areas (b,d,f; n=26): Unit variance scaling is applied to rows; Nipals PCA is used to calculate principal components. X and Y axis show principal component 1 and principal component 2 that explain for the EF 29.3% and 13%, respectively, for the ES 18.8% and 13.4%, respectively, and for the Threats 21.4% and 11.8%, respectively, of the total variance. Prediction ellipses are such that with probability 0.95, a new observation from the same group will fall inside the ellipse.

concepts proposed in a top-down approach by policy makers or academic experts without the input of practitioners, such as the EVs for socio-ecological systems (SES; Pacheco-Romero et al., 2020). These SES include social aspects as 'governance' and 'human population dynamics' that might also have an effect on PA management, the demand for ES, or Threats. Though there are indirect connections between SES variables and the selected EVs for PAs, e.g. 'governance' with Bad Management, and 'human population dynamics' with Leisure Activities (as ES) or Tourism (as a Threat), these SES variables were not mentioned as separate issues of direct concern by PA managers in our surveys, and thereby remained outside the scope of the practical management of an area, and consequently also outside our more concise list of EVs.

To the best of our knowledge, no previous study has involved practitioners throughout the complete process of establishing EV concepts. A comparable attempt was provided by Turak et al. (2017) whom also involved practitioners, together with scientists and experts, during a 1-day workshop to evaluate their proposed list of Essential Biodiversity Variables on their feasibility and applicability, yet involved practitioners thus only for a restricted part of the development process and for a confined EV concept.

Table 2

Importance of variables in PAs as indicated by PA managers and scientists. The frequency of high scores on importance of variables in PAs and the average importance scores are indicated as COUNT and SCORE respectively. The selected Essential Variables (EVs) are in colours and bold. Selected EVs should have a high COUNT and a high SCORE (i.e. a grey cell under COUNT as well as under SCORE). Threshold levels on grey-color-codes, for the COUNTs at ½ (50%; light grey) and ¾ (75%; dark grey) of the number of surveys giving the variable a score of 4 or 5, and for SCOREs at 2/3 (67%; light grey) and 4/5 (80%; dark grey) of maximum score (5). For the Type of Essential Variables: "Env"= Environmental, i.e. biotic or abiotic, variable, "Soc-Ec" = Socio-Economic, i.e. anthropogenic, variable; the typology of the variables is dependent on the origin of the variable, to prevent loss of causality. For example: the ES aquaculture is categorised as biotic since the object in aquaculture is of biotic origin, and the ES materials of economic use as abiotic since the materials are of abiotic origin, though the benefit from both can be considered to be socio-economic, because both are an economic activity. If both would have been categorised as socio-economic, the origin of the variable (abiotic or biotic) would be lost, and with this the possible connections and implications for the supporting (functions in the) (eco)system.

	COUNT		**SCORE** Value	**SCORE** Ratio			**Type of EV**
N = number of surveys; x = score	**N (x=4+5)**		**Avg x**	**x / avg**	StD	SE	(for EVs)
Colour coding used	N=31-40		4.0-5.0	>1.3			
Colour coding used	N=20-30		3.4-3.9	1.0-1.3			
Ecosystem Functions and Structures							
Biodiversity	37		4.7	1.3	1.1	0.2	Env
Habitat Suitability	36		4.5	1.3	1.0	0.2	Env
Land- and Sea-scape	31		4.1	1.2	1.5	0.2	Env
Population Dynamics	31		4.0	1.1	1.6	0.3	Env
Hydrodynamics	27		3.8	1.1	1.6	0.3	Env
Gene Pool	27		3.7	1.1	1.6	0.2	Env
Climate Dynamics	26		3.6	1.0	1.5	0.2	Env
Primary Production	25		3.7	1.1	1.4	0.2	Env
Weather	22		3.5	1.0	1.5	0.2	Env
Element Cycling	21		3.4	1.0	1.5	0.2	Env
Carbon Cycle	20		3.3	0.9	1.5	0.2	
Food-chain Energy Transfer	18		3.3	1.0	1.8	0.3	
Secondary Production	18		3.3	0.9	1.5	0.2	
Nutrient Regulation	17		3.2	0.9	1.7	0.3	
Sediment Characteristics	14		2.9	0.8	1.7	0.3	
Water Surface Characteristics	11		2.3	0.7	2.0	0.3	
Raw Materials	4		1.8	0.5	1.6	0.3	
Average	**23**		**3.5**				
Ecosystem Services							
Leisure Activities	39		4.6	1.6	0.7	0.1	Soc-Ec
Charismatic Landscape	38		4.6	1.6	0.7	0.1	Env
Biodiversity Conservation	36		4.6	1.6	1.1	0.2	Env
Education and Research	36		4.4	1.5	1.0	0.2	Soc-Ec
Charismatic Species	34		4.1	1.4	1.6	0.2	Env
Habitat for Feeding and Breeding	30		4.1	1.4	1.5	0.2	Env
Spiritual Significance	25		3.7	1.3	1.4	0.2	Soc-Ec
Animals of Economic Use	22		3.4	1.2	2.0	0.3	Env
Climate Regulation	22		3.2	1.1	1.9	0.3	Env
Water Regulation	17		3.1	1.1	2.1	0.3	
Hydrological Regulation	16		3.2	1.1	1.7	0.3	
Food Provision for Animals	16		3.2	1.1	1.7	0.3	
Flood and Coastal Protection	16		2.8	1.0	2.1	0.3	
Prevention of Erosion	15		2.8	1.0	1.9	0.3	
Food Provision for Humans	15		2.7	0.9	1.9	0.3	
Sedimentological Regulation	14		2.4	0.8	2.1	0.3	
Waste and Toxicant Mediation	12		2.5	0.9	2.0	0.3	
Pollination	12		2.5	0.9	1.7	0.3	
Plants of Economic Use	10		2.4	0.8	2.0	0.3	
Transport Facilitation	7		1.7	0.6	2.1	0.3	
Hunting	7		1.4	0.5	2.1	0.3	
Fire Protection	5		1.5	0.5	2.1	0.3	
Materials of Economic Use	5		1.2	0.4	1.9	0.3	
Energy Production	4		1.4	0.5	1.8	0.3	

Raw Materials	1		0.8	0.3	1.4	0.2	
Average	**18**		**2.9**				
Threats							
Bad Management	23		3.4	1.3	2.0	0.3	Soc-Ec
Change in Land Use	22		3.2	1.2	2.1	0.3	Soc-Ec
Tourism	21		3.5	1.3	1.6	0.2	Soc-Ec
Disturbance (anthropogenic)	21		3.4	1.3	1.6	0.3	Soc-Ec
Exotic Species	21		3.3	1.3	1.7	0.3	Env
Overexploitation	21		3.3	1.3	2.0	0.3	Soc-Ec
Change in Species	20		3.3	1.3	1.8	0.3	Env
Habitat Loss	20		3.3	1.3	1.9	0.3	Env
Illegal Human Activities	19		3.3	1.3	1.9	0.3	
Climate Change	17		3.3	1.3	1.6	0.3	
Pollution	14		2.9	1.1	1.8	0.3	
Hydrological Changes	14		2.2	0.9	2.3	0.4	
Fire	14		2.1	0.8	2.3	0.4	
Landscape Disturbance	12		2.5	1.0	2.1	0.3	
Civil Engineering	12		2.2	0.8	2.2	0.4	
Diseases	11		2.7	1.0	1.6	0.3	
Agriculture	11		2.4	0.9	2.1	0.3	
Eutrophication	11		2.4	0.9	2.0	0.3	
Harmful Algae	9		1.6	0.6	2.3	0.4	
Sediment Dynamics Changes	8		2.0	0.8	2.0	0.3	
Fisheries	8		1.8	0.7	2.2	0.4	
Encroachment	7		1.8	0.7	2.0	0.3	
Predation	7		1.8	0.7	2.1	0.3	
Extreme Weather	4		1.6	0.6	1.6	0.3	
Increased Salinisation	4		1.0	0.4	1.9	0.3	
Average	**14**		**2.6**				

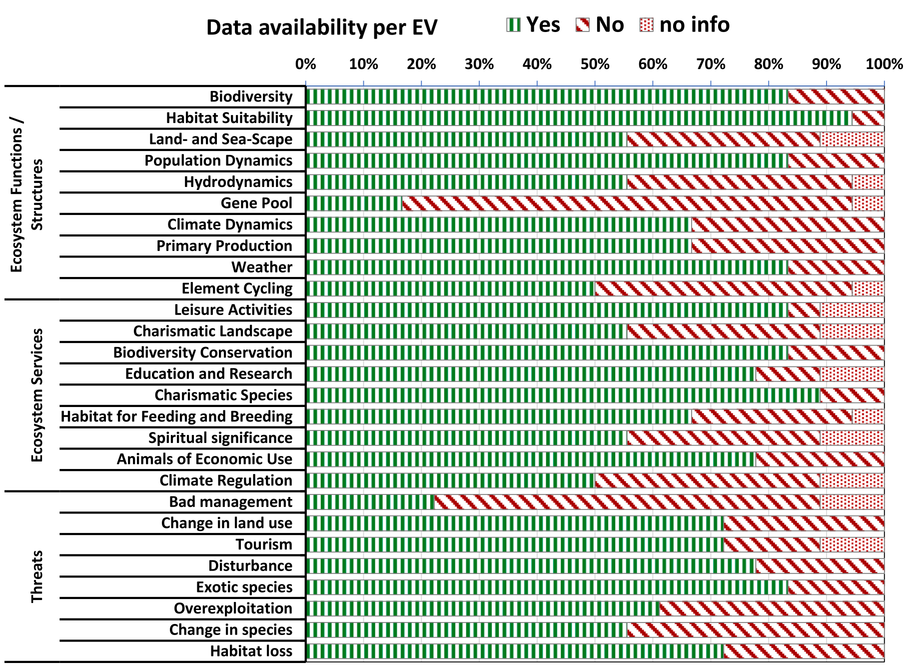

Fig. 5. Data availability for Essential Variables (EVs) in Protected Areas (PAs) (averages in % over 18 PAs).

We found a high level of agreement among participants about the importance of variables. Although the meaning of most variables is rather unambiguous, the interpretation of a few variables was dependent on the specific context of the PA.

For example, "Bad management" was perceived as very important in many PAs. Yet, the definition of what constitutes "good" management depends on the goals of the PA and on the affected stakeholders, and is thereby, to a certain degree, subjective. Similarly, tourism can sometimes support conservation efforts by providing more sustainable livelihoods (e.g. Arcos-Aquilar et al. 2021) and as such be indicated as an

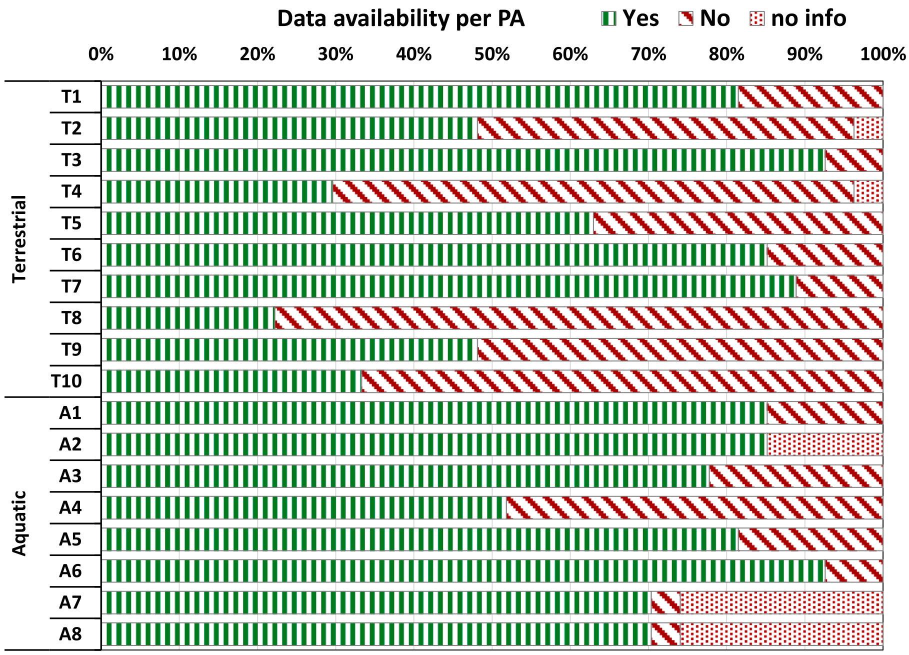

Fig. 6. Data availability of Essential Variables (EVs) in Protected Areas (PAs) (averages over 27 EVs; T= Terrestrial PA, A= Aquatic PA; for privacy reasons no names of PAs are provided).

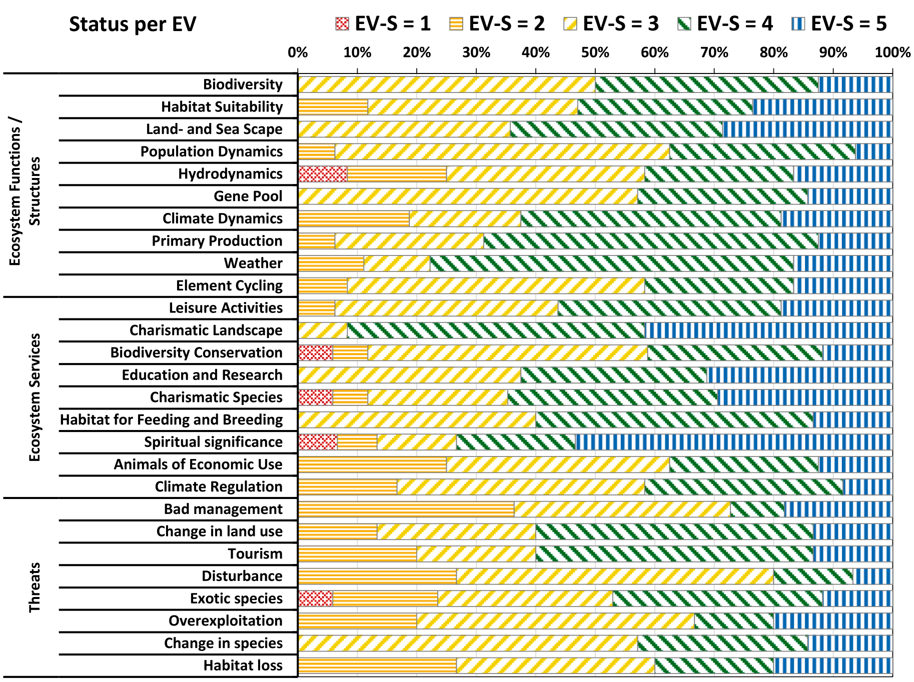

Fig. 7. Rating of the status of the EVs (EV-S) in the surveyed PAs. The status was perceived as 1 = the actual environmental of socio-economic situation as measured with the EV is very far from desired (highly impacted/degraded), 2 = the situation is still far from the desired situation, but there is hope for improvement, 3 = the situation is neither good nor bad, i.e. almost acceptable but improvement can/should be made, 4 = the situation is good and almost, but not completely, the desired situation, 5 = the situation is very good, i.e. the desired situation or optimal reference level is reached.

important EV under ES in our study (i.e. Leisure Activities), while increasing tourism can also be a threat through causing ecosystem degradation and disturbance of wildlife (e.g. Schirpke et al. 2020) and as such it becomes an important EV under Threats.

A proper interpretation and valuation of these more ambiguous EVs depends on the specific area under study and trade-offs associated with the specific activities, and thus has to be carried out with care.

4.3. Data availability

Information and data for most EVs is mainly determined through *in-situ* observational methods. This may be because *in-situ* methods are relatively easy to apply and interpret to obtain essential environmental information on the PAs. During the majority of the interviews, Remote Sensing (RS) was judged by the PA management to be technically too complicated and of no added value to the regular *in-situ* methods to monitor their PA. Nevertheless, improvements in satellite technologies and analytical capabilities, and increasing accessibility of openly available remote sensing products, might create greater potential for easier and wider use of remote sensing for some of the suggested EVs, especially in the larger PAs (a few examples are Pettorelli et al. 2016; Braun et al. 2018; Carvalho-Santos et al. 2018; Finer et al. 2018; Rossi

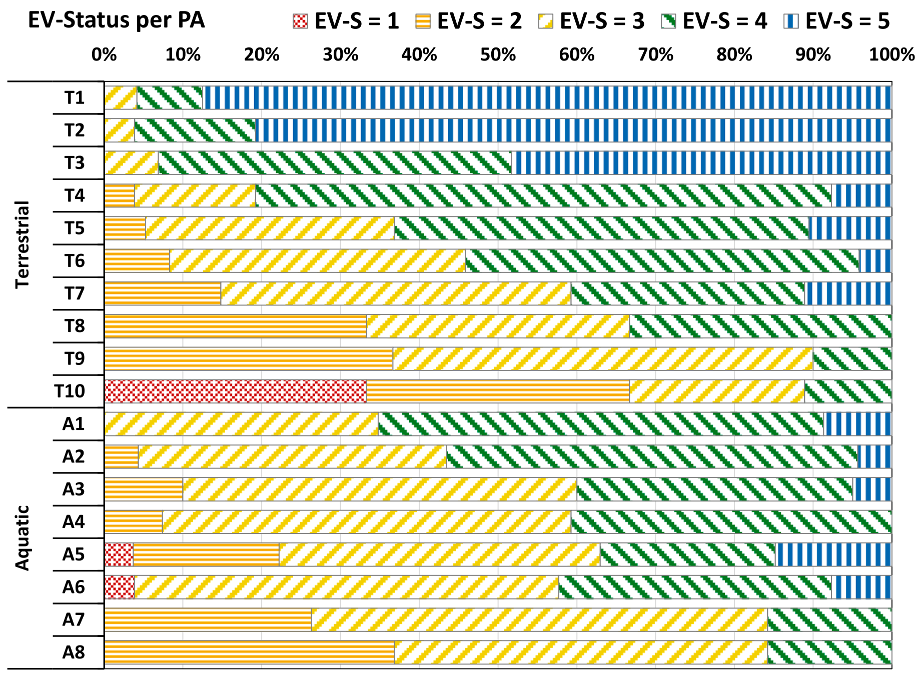

Fig. 8. Rating of the status of the EVs (EV-S) in the surveyed PAs (T = Terrestrial PA, A = Aquatic PA; for privacy reasons no names of PAs are provided). For an explanation of status levels see Fig. 7 or the Material and Methods section.

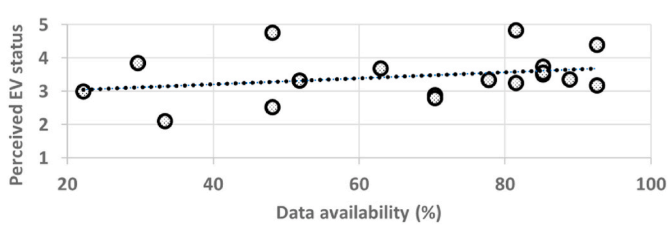

Fig. 9. Relation of the average perceived EV status in the surveyed PAs and the average data availability in those PAs (r = 0.37, linear relationship, status log transferred, data availability in %; p=0.12).

et al. 2020; Skidmore et al. 2021).

It was striking that, though judged very important, for some EVs a very low data availability was observed, such as for Gene Pool and Bad Management.

The reason for the low data availability for Gene Pool may be that collection of this data depends on sophisticated and expensive methods, which are not directly accessible in many PAs. With the emergence of fast and easier to use molecular methods this EV might at the short term become more instrumental.

Bad management was interpreted to represent inadequacy of the PA management to fulfil all the needed activities and actions in the PA to realise its objectives (e.g. biodiversity conservation). The cause was often discussed in length, and included elements such as e.g. lack of funding, restrictive decisions and regulations enforced by external policy and political organisations, disproportional influence of divergent stakeholders, non-implementation of legal penalty measures, or poor supervision. Owing to the high frequency of respondents citing “bad management” as a major threat, this EV was considered very important. However, it is also a vague and highly subjective variable that is difficult to express in a direct way with only one factor. This may explain why factual data on Bad Management are lacking. Further research should find concrete parameters to more accurately define and directly appraise what is meant by Bad Management.

4.4. *Status of PAs*

The presented set of EVs may provide a helpful mechanism to assess and understand the actual and potential status of a PA in terms of the quality status of the EF and ES in the PA and the pressures imposed on them. From the present study, it can be concluded that for the European PAs explored here, the actual environmental condition on the basis of the identified EVs was perceived as being good, almost as desired with some improvements still to be made.

Such a good quality status is also a proper basis for the eventual provision of ES from the PAs, since it is imperative that the quality status of those specific EVs should be sufficiently high to allow for sustainable delivery of Societal Goods and Benefits (SG&B).

The average perceived status for EVs in PAs tended to be judged at a higher level in case the data availability was higher (Fig. 9). This indicates that better knowledge of the issues at stake in a PA may coincide with an improved perception of its status, or conversely it may mean: unknown makes unloved.

The status of EVs for PAs should not be mistaken with the Protection Level Index of a PA, since the EVs are a general indication of the perceived environmental status and of the socio-economic, i.e. anthropogenic, impact on the ecosystem of the PA. For an indication of the Protection Level several other, often external, parameters should be taken into account as managerial, economic, and cultural variables, as was proposed by Hummel et al. (2021) for some of the surveyed PAs. As such, the EVs, or elements of the EVs, may be embedded as an environmental component in the Protection Level Index.

Protected areas are gaining importance in global policies due to the climate and biodiversity crises (IPCC, IPBES), with experts calling for the protection of at least 30% of the Earth’s surface by 2030 (Dinerstein et al. 2019). However, existing PAs include a wide diversity of management goals, objectives, and levels of success. The PAs in this study range from the strictly protected Swiss National Park (IUCN level Ia), where the main goal is to exclude human interference in the ecosystem, to multifunctional landscapes such as Appia Antica in Italy (IUCN level V), which is managed for providing a wide variety of ecosystem and cultural services. A harmonised set of EVs, of use for all those PAs, adopted by practitioners as well as scientists, and equally applicable to

Table 3
Type of observation used for Essential Variables (EVs) in Protected Areas (PAs) (n = number of methods indicated to measure EVs in PAs; in situ = *in-situ* field observation tools and methods (% of n), RS = remote sensing techniques and methods (% of n)).

Essential Variables	n	in situ	RS	Protected Areas	n	in-situ	RS
Ecosystem Functions and Structures				Terrestrial PAs			
Biodiversity	31	90.3	9.7	T1	40	73.8	26.3
Habitat Suitability	25	34.0	66.0	T2	27	85.2	14.8
Land- and Sea-scape	11	22.7	77.3	T3	43	76.7	23.3
Population Dynamics	31	61.3	38.7	T4	11	45.5	54.5
Hydrodynamics	17	94.1	5.9	T5	18	72.2	27.8
Gene Pool	3	100.0	0.0	T6	37	73.0	27.0
Climate Dynamics	22	59.1	40.9	T7	41	79.3	20.7
Primary Production	13	65.4	34.6	T8	6	100.0	0.0
Weather	33	86.4	13.6	T9	21	66.7	33.3
Element Cycling	13	96.2	3.8	T10	12	83.3	16.7
EF totals	**199**	**70.1**	**29.9**	**Terr. PA totals**	**256**	**74.8**	**25.2**
Ecosystem Services				**Aquatic PAs**			
Leisure Activities	19	97.4	2.6	A1	41	78.0	22.0
Charismatic Landscape	18	91.7	8.3	A2	56	84.8	15.2
Biodiversity Conservation	27	94.4	5.6	A3	23	80.4	19.6
Education and Research	29	100.0	0.0	A4	13	73.1	26.9
Charismatic Species	15	100.0	0.0	A5	35	74.3	25.7
Habitat for Feeding and Breeding	22	86.4	13.6	A6	31	82.3	17.7
Spiritual significance	10	95.0	5.0	A7	34	79.4	20.6
Animals of Economic Use	19	100.0	0.0	A8	33	78.8	21.2
Climate Regulation	14	71.4	28.6				
ES totals	**173**	**93.6**	**6.4**	**Aquat. PA totals**	**266**	**78.9**	**21.1**
Threats							
Bad management	7	100.0	0.0				
Change in land use	21	9.5	90.5				
Tourism	24	100.0	0.0				
Disturbance	22	45.5	54.5				
Exotic species	23	93.5	6.5				
Overexploitation	15	86.7	13.3				
Change in species	17	100.0	0.0				
Habitat loss	21	42.9	57.1				
Threats totals	**150**	**69.0**	**31.0**				
General Total	**522**	**77.6**	**22.4**	**General Total**	**522**	**77.6**	**22.4**

terrestrial and aquatic areas, as introduced in this study, will help tackle this complexity and provide a basis for monitoring the changes in the status of the various types of PAs.

5. Conclusions

The outcomes of the surveys on the importance of variables describing ecological functions, ES, and threats in Protected Areas (PAs) are highly representative and of direct general use. Outcomes were found to be consistent for scientists and practitioners, such as PA managers and rangers, as well as for terrestrial and aquatic areas.

Because of their general applicability in the majority of PAs, the joint and general agreement on their importance and their ease of use and interpretation, the Essential Variables (EVs) selected here may form an ideal basis for further studies and comparisons on the current status and future developments and changes of the environmental quality, ES, and threats in any kind of PA in the aquatic and terrestrial realms.

On basis of this set of EVs, the status of the surveyed European PAs is judged to be at a rather good level, yet there is still room for improvement.

Since this set of 27 Essential Variables (EVs) for Protected Areas (PAs) has been determined in a bottom-up procedure with PA practitioners, the EVs may also form the preferable basis for further actions and management by PA managers and regional or national policy makers, when addressing the quality and requirements of current and future PAs. As such the here presented set of EVs for PAs may be a helpful tool for:

- relevant, scientifically sound, information characterising the environmental status of PAs, with specific focus on the ecosystem functions of an area, the ES that the area may deliver, and the pressures imposed on them.
- quick and easy, thereby cost- and time-efficient, monitoring in time of developments and changes in essential elements of the PA.
- global comparisons on the current status and future developments and changes of the environmental status, ES, and threats in any kind of PA, in the aquatic as well as terrestrial realms.
- enhanced communication and exchange of information between policy makers and practitioners on basis of a common vocabulary.
- PA managers and rangers to align priority issues to be (pro-)actively tackled in their area and/or to focus their efforts.
- policy makers to support decision making on ecosystem management, spatial planning, and predictive modelling on the future status and requirements of PAs in their country or region.
- providing an indication on the potential for sustainable delivery of Societal Goods and Benefits (SG&B), in case the quality status of the system in general, and of the potential ES in particular, is sufficiently high to allow for it.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2022.100179.

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