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Original Research Article

Hunters as citizen scientists: Contributions to biodiversity monitoring in Europe

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ABSTRACT

Monitoring biodiversity characteristics at large scales and with adequate resolution requires considerable effort and resources. Overall, there is clearly a huge scope for European hunters, a special and often overlooked group of citizen scientist, to contribute even more to biodiversity monitoring, especially because of their presence across the entire European landscape.

Using the Essential Biodiversity Variables (EBVs) framework we reviewed the published and grey literature and contacted experts to provide a comprehensive overview of hunters' contributions to biodiversity monitoring. We examined the methods used to collect data in hunter-based monitoring, the geographic and taxonomic extent of such contributions and the scientific output stemming from hunter-based monitoring data.

Our study suggests that hunter-based monitoring is widely distributed across Europe and across taxa as 32 out of the 36 European countries included in our analysis involve hunters in the monitoring of at least one species group with ungulates and small game species groups which have the widest hunter-based monitoring coverage. We found that it is possible to infer characteristics on Genetic composition, Species population, Species traits and Community composition with data that are being routinely collected by hunters in at least some countries. The main types of data provided are hunting bags data, biological samples including carcasses of shot animals and non-invasive samplings and Observations for counts and indices.

Hunters collect data on biodiversity in its key dimensions. Collaborations between hunters and scientists are fruitful and should be considered a standard partnership for biodiversity conservation. To overcome the challenges in the use of hunters' data, more rigorous protocols for sampling data should be implemented and improvements made in data integration methods.

1. Introduction

Global biodiversity is undergoing severe declines (Díaz et al., 2019). This situation has led the international community to take action to alter this trend by setting policy frameworks and objectives. For example, the Aichi Biodiversity Targets set by

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the Convention on Biological Diversity (UN General Assembly, 1992) and the United Nations Sustainable Development Goals (UN General Assembly, 2015) are globally accepted frameworks which set targets for progress toward a more sustainable world. Biodiversity monitoring is an essential component of measuring progress towards these goals. However, monitoring biodiversity at large scales and with adequate resolution requires considerable effort and resources and represents a logistical challenge for researchers. This is one driver behind the recent enthusiasm about involving of the public in the data collection process (Silvertown, 2009).

Citizen science, here defined as the involvement of citizens in scientific research and knowledge production, has repeatedly demonstrated its ability to gather massive amounts of data at a spatial scale unattainable by research teams and biodiversity management structures such as state authorities and other societal groups active in biodiversity monitoring (Silvertown, 2009). Even though some citizen science projects are able to provide data the quality of which equals expert-based data, most citizen science biodiversity programs focus solely on species abundance and distribution, limiting its use for assessing some international biodiversity targets (Kosmala et al., 2016; Chandler et al., 2017). Other concerns about citizen science include observational biases such as 'false absences' or misidentification or uneven spatial and temporal coverage. This raises concerns when making inference using this kind of data, despite the fact that advances in modelling based on such data are currently being made (Hochachka et al., 2012). The extent to which citizen science dataset are biased depends on both the sampling regime used in citizen science programs and the expertise of the recorder which can reduce some of the biases mentioned (e.g. bird watchers data are less clustered around urban areas; Geldmann et al., 2016; Isaac and Pocock, 2015).

Here we study the monitoring of biodiversity characteristics by volunteer citizen scientists taking the special, and often overlooked, case of European hunters. For the purposes of this review we focus on the monitoring activities that hunters engage in that are specific to their hunting activity. We do not include other citizen science activities that they might engage in outside of hunting. Hunters collect data during their activity both voluntarily through cooperation with veterinary or other research institutes, and as a parts of compulsory programs when countries' hunting regulations mandate such reporting through hunting statistics or the collection of other data (see for instance http://artemis-face.eu/ for an overview of the European hunting bag regulations; Mörner et al., 2014). To a large extent hunter collected data is formally institutionalised into wildlife management structures that are intended to support sustainable harvest. Virtually the entire European landscape is utilised for some form of hunting, and most hunting systems are tied to some form of property rights that ensure a broad distribution of hunters across the whole landscape (Linnell et al., 2015). These factors combined make Europe's estimated seven million hunters a potentially valuable resource for citizen science data collection (www.face.eu/).

In this study we use the Essential Biodiversity Variables (EBVs) framework to categorise the different types of data coming from hunter-based monitoring and hence assess their contribution to biodiversity monitoring. EBVs are a set of variables that aim to represent biodiversity across its key dimensions (space, time and biological organisation) and that can accurately document biodiversity change (Kissling et al., 2018). EBVs are being defined and refined by GEO BON, a global biodiversity network that contributes to effective management policies for biodiversity. They provide a first level of aggregation computed from the raw data and can be used to compute more complex biodiversity indicators that can be used to measure the achievement of policy goals (Pereira et al., 2013). GEO BON has divided the EBVs into 21 candidates grouped among 6 classes (i.e. genetic composition, species population, species traits, community composition, ecosystem functioning and ecosystem structure, www.geobon.org/ebvs).

We aim at providing a comprehensive overview of hunters' contributions to biodiversity monitoring in Europe, and review the methods used to collect data in hunter-based monitoring. We also examine the geographic and taxonomic extent of such contributions and the scientific output stemming from hunter-based monitoring data.

2. Method

2.1. Systematic literature search

The first step of the review process was to define the scope of research that focuses on the research question (Booth et al., 2016). In the present study we aimed at identifying which Essential Biodiversity Variables are possible to derive using hunter-based monitoring. We initially developed a list of keywords listing the actor (i.e. hunter or hunting team), the full list of EBVs as defined by GEO BON, the taxonomic scope and the geographic scope. The refinement of this list was done in an iterative fashion, running the list of keywords through Scopus and Web of Science Core Collection and adding new keywords that emerged, and then re-running the search until we reached a plateau in the number of papers returned by the databases (for the full list of keywords see Document A1 in Appendix).

Before any screening the search string returned 1335 papers that we exported to create a dataset. The dataset was initially reduced to 962 papers after screening for duplicates. The search returned many papers that were outside the scope of our study and that concerned anthropological studies on hunter gatherers, studies on hunter-based monitoring outside Europe, or sociological studies on hunters such as hunters' perception of management decisions or hunters' willingness to contribute to species monitoring. We excluded these studies after screening for titles and abstracts and reduced our dataset to 493 papers. If doubts remained regarding the potential contribution of a paper to our study, we kept it in our dataset for final screening. We finally screened the paper's full text and rejected studies in which hunters' contribution was unclear such as if hunters were only mentioned in the acknowledgement of the papers or if it was unclear how hunter-based monitoring was used to compute the EBV. After this final step we retained a total of 277 papers (Figure A1 in Appendix). The screening process was facilitated using the R package 'revtools' (Westgate, 2019).

2.2. Non-systematic literature search

The non-systematic search of our study was divided into two parts; a targeted search on Web of Science Core Collection and Scopus and a search in the grey literature. Literature collection databases such as Scopus and Web of Science only screen through the title, the abstract and keywords. Because hunters' contribution to data collection is in some cases only mentioned in the method section of peer reviewed papers, we expected the systematic literature search to return incomplete information. To be able to include such sources of information, we used 'snow-ball sampling' (Goodman, 1961), whereby we sampled the references found in the systematic literature search searching for certain authors or countries that we suspected were commonly using hunters' as their main data providers. This added 89 additional unique papers to our dataset.

Secondly, we manually accessed a sample of the proceedings of the International Union of Game Biologists (IUGB). This sample was restricted to the volumes available from our own institutional archives and, did not constitute the whole collection. The included volumes spanned a time period ranging from 1957 to 2011. In total we analyzed 14 out of the 35 existing proceedings. Some of the articles were written in a language that no authors in this paper were able to read (i.e. Russian or German) and were directly excluded. We selected papers based on the inclusion and exclusion criteria previously defined and the search in the IUGB resulted in the addition of 92 papers to the dataset.

2.3. Expert knowledge

To further complete our search of hunters' contribution to wildlife monitoring, we requested information from our contact network of experts, wildlife managers and national hunting associations in different European countries. The list of informants was primarily based on the authors' professional networks, but in some cases we were redirected to more competent contacts they personally knew. We first asked for information related to any hunter-based monitoring programs or other monitoring schemes involving hunters in their respective country and if they could provide documentations (i.e. scientific papers or other documents such as official reports or links to websites), for which species and which method was used. A total of 28 contact persons returned 89 inputs including 23 published papers used to complete our dataset.

2.4. Classification of EBVs

Following the recommendations given by Stewart et al. (2005) and based on the pre-defined keywords, we compiled a database of inputs found in different sources i) a systematic search of the peer-reviewed literature, ii) a non-systematic gathering of literature, including 'snow-ball' search of the scientific and technical grey-literature (which included our own knowledge and libraries), and iii) a survey among our professional networks (i.e. experts in wildlife management or wildlife research, and among national hunting associations).

For each input provided we documented the country, the species, the EBVs computed from the data collected by hunters, the methods used by hunters to collect the data and the source of the case. If there was any doubt about the EBV computed we referred to the 'Measurement and scalability' section of each EBV candidate on the GEO-BON website (https://geobon.org/) to find the EBV that most closely proximated the data collected by hunters (e.g. if jaw bone length was measured, we deduced the EBV candidate 'morphology' was used, although with the implicit understanding that this was ultimately used as a metric to monitor demography/life history). To facilitate the analysis and interpretation we pooled species into five broad functional species groups: "ungulates", "large carnivores", "waterfowl", "other birds" and "small game" (including lagomorphs and medium sized carnivores, Table A1 in Appendix for the full description of each group). We aggregated the diverse data

Table 1
List of criteria to classify hunters' data collection methods.

Method	Criteria
Bag	If the EBV was calculated from data taken from official harvest numbers
Camera trap	If the EBV was calculated from data collected through camera traps operated by hunters
Carcass	If the EBV was calculated from the carcass of the shot animal including any invasive samples
Direct Observation	If the EBV was calculated from hunters' direct Observations of a species
Indirect Observation	If the EBV was calculated from hunters' indirect Observations of signs such as snow tracking, faeces sampling, observations of dens
Questionnaire	If the EBV was calculated from data coming from any sort of questionnaires, including written or digital questionnaires, distributed to hunters
Ringing	If the EBV was calculated as a result of the ringing of animals by hunters, this include birds rings or animal tags
Other	If the EBV was calculated from data collected through any sort hunters' cooperation such as direct interview with hunters, non-invasive sampling or bringing shot ringed or tagged animals

collection methods into eight categories based on the criteria shown in Table 1, namely “Bag”, “Camera trap”, “Carcasses”, “Direct Observations”, “Indirect observations”, “Questionnaire”, “Ringing” and “Others”.

3. Results

3.1. Geographic and taxonomic extent of hunter-based monitoring

Our study suggests that hunter-based monitoring is widely distributed across Europe and across taxa (Fig. 1). We found that 32 out of 36 countries involve hunters in the monitoring of at least one species groups. With respect to the species group present in those countries we found that 16 countries use hunter-based monitoring for all potential species groups (UK, Ireland, the Netherlands and Iceland do not host any populations of large carnivores). In four countries (Albania, Kosovo, Macedonia and Liechtenstein), we did not find any published evidence of an organised hunter involvement in the monitoring of game species.

Based on our review, ungulates and small game are the species groups which have the widest hunter-based monitoring coverage, as nearly all European countries (80% for ungulates and 86% for small game; Fig. 1) involve hunters in the monitoring of these species. Even though geographically widespread, we found that waterfowl and large carnivores are the groups which receive less attention from hunter-based monitoring coverage as 63% and 66% respectively of European countries use some sort of hunter-based monitoring for these groups (Table A2). We did not find any hunter-based monitoring scheme for large carnivores in countries such as France or Lithuania, even though they have population of large carnivores (Linnell and Cretois, 2018).

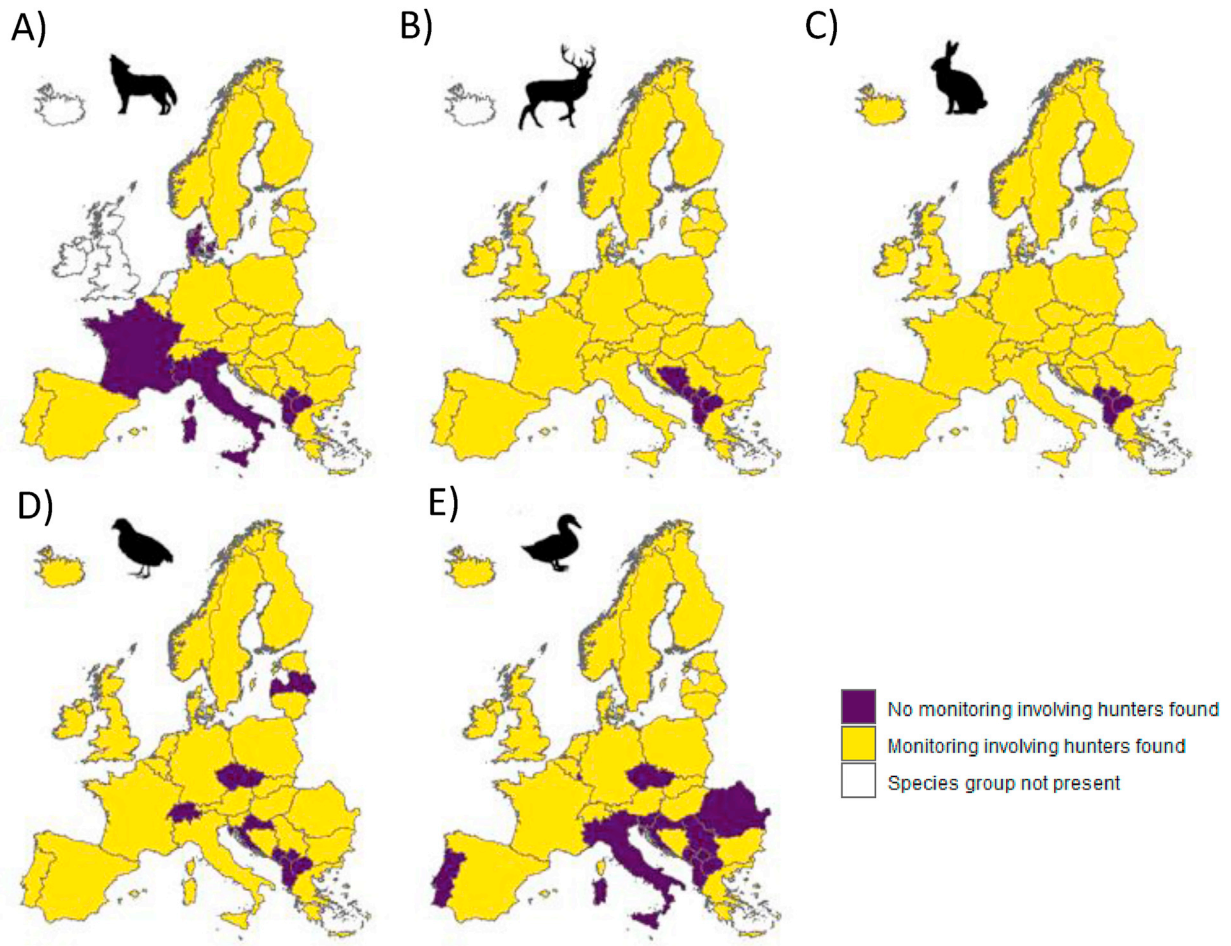

Fig. 1. Geographic extent of hunter-based monitoring per species group. A) Large carnivores, B) ungulates, C) small game, D) other game birds and E) waterfowl.

Table 2
Use of monitoring methods to infer different Essential Biodiversity Variables. (X) representing the finding of a source documenting the use of the method to infer the EBV, (–) if no sources have been found.

EBV class	EBV candidate	Bag	Cam	Carcass	D	I	Help	Questionnaire	Ringing	Other
Genetic composition	Allelic diversity	–	–	X	–	X	–	–	–	X
	Co-ancestry	–	–	X	–	–	–	–	–	–
Species population	Population abundance	X	X	X	X	X	–	X	–	X
	Species distribution	X	X	X	X	X	–	X	–	X
	Population structure	X	–	X	X	X	–	X	–	X
Species traits	Morphology	–	–	X	–	X	–	X	–	–
	Movement	–	–	X	–	–	X	–	X	X
	Phenology	X	–	X	X	X	–	–	–	–
	Physiology	–	–	X	–	X	–	X	–	X
	Reproduction	X	X	X	X	X	–	–	–	X
Community composition	Species interaction	X	–	X	X	X	–	–	–	X
	Taxonomic diversity	–	–	X	–	–	–	X	–	–

3.2. *Diversity of biodiversity characteristics recorded by hunter-based monitoring*

Overall, we found that a wide range of biodiversity characteristics are being derived from hunter-based monitoring programs (Fig. 2). In fact, our study suggests that researchers and wildlife managers infer characteristics on Genetic composition, Species population, Species traits and Community composition with data that are being routinely collected by hunters. We did not find any evidence of hunter-based monitoring schemes directly gathering information on Ecosystem function and Ecosystem structure.

Other game birds and small game were the taxonomic groups for which hunter-based monitoring was the most diverse, with 79% of the species centric EBV candidates being monitored in at least some countries (if we exclude the 7 EBV candidates of the EBV classes Ecosystem function and Ecosystem structure). Hunter based monitoring for other groups of species was less diverse, with 64% of EBVs being recorded for ungulates and 57% for large carnivores and waterfowl (Table A2).

For all species groups, all characteristics concerning their population (i.e. species distribution, population abundance and structure) were recorded except for ungulates, for which we did not find any inputs explicitly documenting the monitoring of their distribution. Nevertheless, it has been argued that species distribution can be inferred from species abundance (Kéry and Royle, 2015), hence it is an implicit by-product of other monitoring. Characteristics at the individual level were also very well monitored by hunters, and examples of monitoring of traits such as physiology, morphology and reproduction were found for all species groups. Even traits that are normally hard to obtain with traditional citizen science such as species phenology and movement were monitored by hunters for 4 out of the 5 species groups.

Our results also suggest that studies use hunters' data for monitoring of genetic composition through studies on allelic diversity and studies on co-ancestry for large carnivores, ungulates, small game and other game birds on samples collected by hunters. It should, however, be noted that we did not find evidence of hunter-based monitoring for the EBV candidates population genetic differentiation and breed and variety diversity for any taxon, although tissue samples from animals shot and non-invasive scat samples are often used by geneticists to study these topics.

3.3. *Methods used to obtain species characteristics*

Hunters contribute to the collection of data relevant for monitoring in many ways, which vary greatly with respect to data volume, coverage and quality (Table 2). The main types of data provided include;

Hunting bags: Information on the numbers of individual animals of different species that are killed by hunters is recorded in most countries, although the spatial resolution of the information varies. Under assumptions of more or less similar effort and similar quotas, between year variation in the numbers of animals shot is being used to infer broad scale spatio-temporal changes in abundance and thus species demographic attributes (e.g. Aebischer, 2019; Massei et al., 2015), especially if combined with secondary data sources (Moleón et al., 2008, 2013; van der Jeugd and Kwak, 2017). As well as being used to follow single population trends, the analysis of such data from multiple populations is used to map changes in distribution and elucidate the relative impacts of multiple drivers of population change (Hagen et al., 2014; Grøtan et al., 2005; Reimoser et al., 2014). We also found that hunting bag data are being used to infer species interaction characteristics through studying fluctuations in small game hunting bags (Smedshaug, 1999).

Biological samples including carcasses of shot animals and non-invasive samplings: Shot animals are used to yield a wide variety of information relevant for monitoring. For mammals, this demographic data is made even more valuable when animals can be aged from tooth sectioning. Data on age and sex can be used to infer population structure and survival rates via analyses like life-tables or population reconstruction (Nilsen et al., 2012; Solberg et al., 1999) and for spatial population structure (Swenson et al., 1998; Kojola and Laitala, 2000). Data on reproduction can be obtained from the analysis of reproductive organs. Body weights and measurement of jawbones or femurs are used to infer body size and condition. Bird wings are used to infer age and sex of animals killed (Pöysä and Väänänen, 2018). Tissue samples are also collected for disease

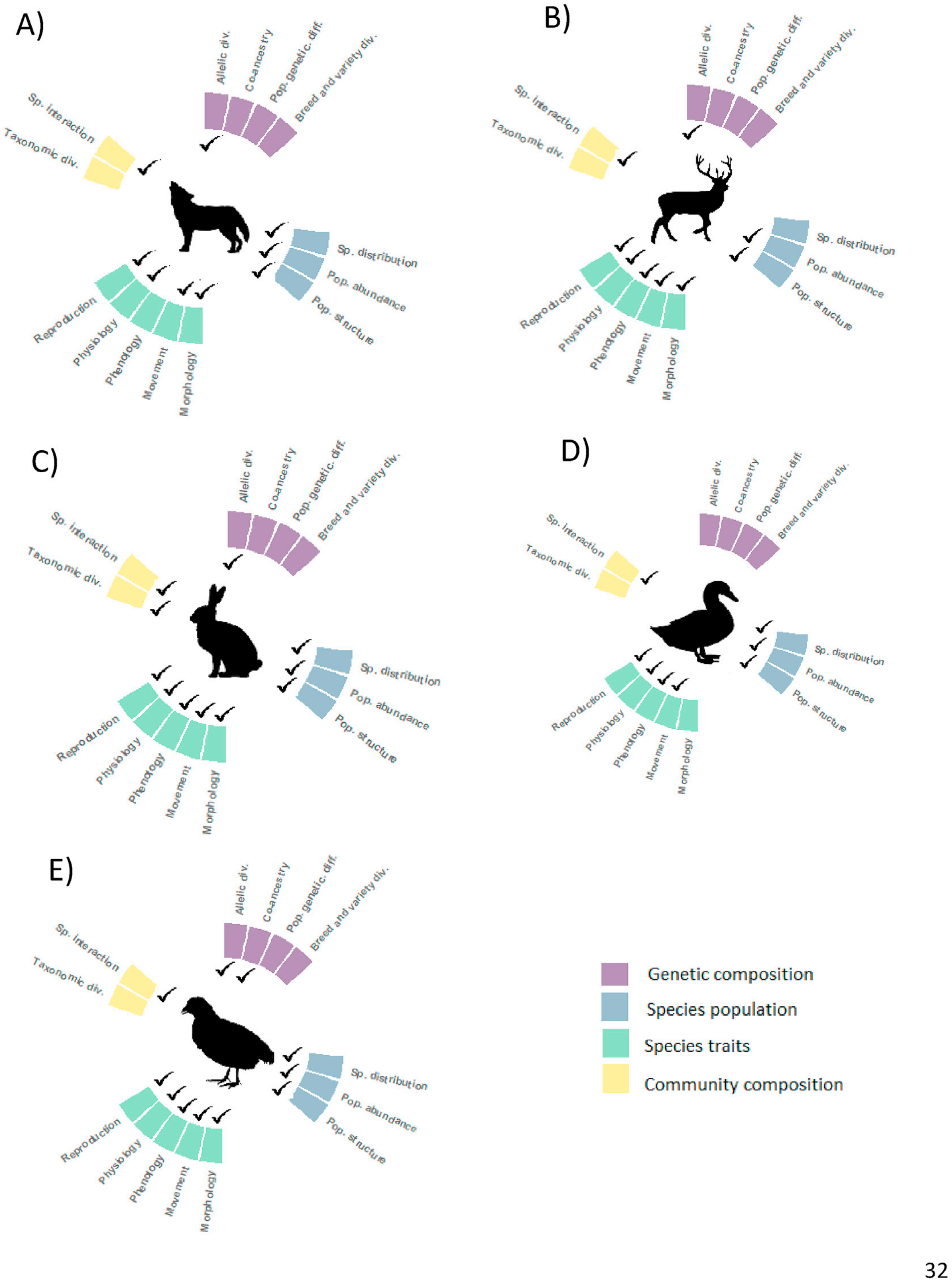

Fig. 2. Diversity of EBV monitored through hunter-based monitoring. A) Large carnivores, B) ungulates, C) small game, D) other game birds and E) waterfowl. A tick indicates if the Essential Biodiversity Variable has been found in our review. Colors represent the Essential Biodiversity Class. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and parasite screening, ecotoxicology screening, or for genetical analysis (Garbarino et al., 2017; Jelenko and Pokorny, 2010; Tallmon et al., 2004). The rise in non-invasive DNA methods has opened a whole new avenue for collaboration as hunters can collect samples such as faeces for use in population census. For example, the collection of bear scats for DNA based census depends on hunters in Norway, Sweden, Slovenia and Croatia who annually collect thousands of samples (Kindberg et al., 2011; Skrbinšek et al., 2019).

Observations for counts and indices: Hunters also observe many animals while hunting or tending to their hunting areas. These observations, whether direct or indirect, are used to obtain very valuable data on abundance, distribution and structure if there is a robust design and analysis. For example, in Scandinavia the number of moose and bear observations per hunter per hunting day during the hunting season constitutes a robust index of relative abundance (Ericsson and Wallin, 1999; Kindberg et al., 2011; Solberg and Saether, 1999; Swenson et al., 1994). French roe deer hunters report numbers of roe deer seen along transects (Vincent et al., 1991). Hunters in much of Scandinavia and Finland also take part in structured distance sampling-based surveys of abundance of ptarmigan and forest-living grouse (Lindén, 1996). Bear hunters in Slovenia and Croatia record data on sex ratio and reproductive rates of bears observed on feeding stations (Reljic et al., 2018) as well as using simultaneous observations to produce relatively robust minimum counts of the size of the bear population (Bordjan et al., 2019). Hunters all across the Nordic and Baltic countries submit records of lynx and wolf tracks (and increasingly camera trap images) that are used to produce minimum counts of lynx and wolf populations (Linnell et al., 2007, 2010).

Other types of data: Hunters also collect other type of data used to infer a wide range of characteristics regarding their species of interest. Questionnaires and interviews are used for disease detections through documentation of what hunters observe on the hunting ground such as scabies infestation for red fox, hair loss in moose, or inferring species distribution or abundance based on their experience and past Observations (Gortázar et al., 1998; Llaneza and Núñez-Quirós, 2009; Madslien et al., 2011). Hunter cooperation with researchers and management authorities also includes their willingness to help ring birds or tag mammals, and return the carcass of shot ringed and tagged animals (Guzmán et al., 2017; Jensen, 1973).

3.4. Origin of the information

Overall, we found that more than 70% of the diversity in EBV monitoring was documented in both the systematic and unstructured literature search for large carnivores, other game birds, small game and ungulates (Fig. 3). The result is slightly more contrasted for waterfowl as this number goes down to about 60%. Inputs from the unstructured search generally brought as much or more information than the systematic search for large carnivores, small game, ungulates and waterfowl (respectively contributing to 20, 18, 10 and 25%) and didn't add any unique information for small game.

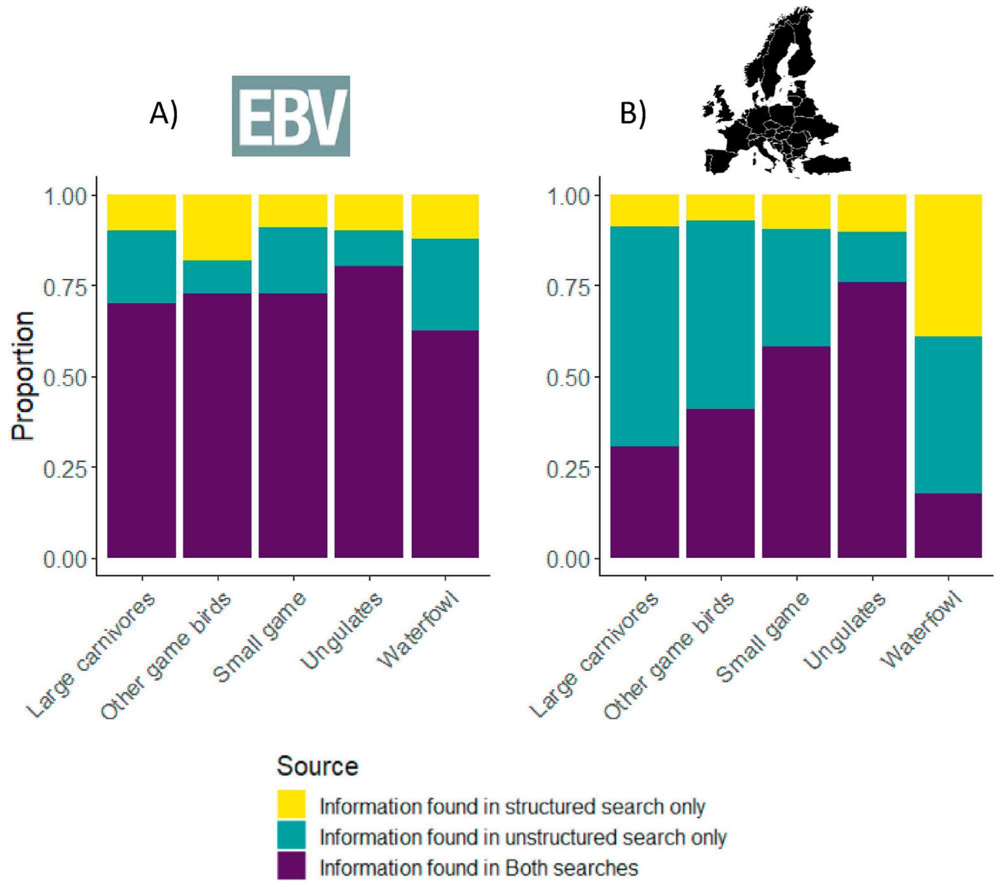

Fig. 3. Proportion of unique information yielded by the systematic search, unstructured search and both sources with regards to A) EBVs and B) Countries.

Regarding geographic extent we found that the unstructured search provided a large amount of unique information for other birds (40%), waterfowl (31%), small game (25%) and large carnivores, for which other sources contributed to 50%. The use of a structured search only yielded more information than the unstructured search for waterfowl and ungulates (respectively 47 and 21% of total information).

4. Discussion

Our study highlights the taxonomic and geographical potential hunter-based monitoring holds, with evidence of nearly all European countries (32 out of 36) using hunter-based monitoring for at least one species group. Moreover, in about half of Europe (including the Scandinavian and Baltic countries) there were examples of hunter-based monitoring to monitor of all species groups. We found that the overwhelming majority of hunter-based monitoring programs focus on multiple aspects of the EBVs grouped under species characteristics (i.e. species population, species traits, genetic composition and species community). However, we found that not all countries use hunter-based monitoring for all species groups and some gaps remain. More specifically, we did not find any evidence of hunter-based monitoring in many of the Balkan countries. Concerning species groups, waterfowl is less monitored by hunters than any other groups. This could possibly be due to the A lack of literature about the use of hunter-based monitoring due to a lack of acknowledgement of hunters' work from the scientific community or due to language barriers could be two other reasons for these gaps given that some of our data has been found only through experts' inputs. Up to 35% of the conservation literature is not written in English (Amano et al., 2016) and given the diversity of languages in Europe we did not expect to get the full picture of the contribution of hunters in biodiversity monitoring through the systematic search of the literature. There is almost certainly a major geographic and species-specific bias in the extent to which hunter derived data is analyzed and published by scientists in English. In fact, the emails sent to wildlife managers and hunting associations added a significant number of inputs in our dataset which were not documented in academic databases through the form of scientific papers or grey literature. This result highlights that we would have dramatically underestimated the extent to which hunters take part in monitoring across Europe without the input of experts. It is almost certain that there are more examples that our search was not able to uncover. The scale of our study (i.e. pooling species into groups and studying hunter based monitoring at country level) might also hide certain fine scale particularities. Even though there is monitoring of a certain EBV in ungulates in a given country, this does not mean that all harvested ungulates are monitored, nor that the whole country is included. As such, our review gives a broad overview of the potential and some examples, but it may not give a full picture of how widespread the use is.

4.1. Particularities of hunter-based monitoring

Our results have highlighted the particularity of hunters as citizen scientists due to their access to certain forms of data. Even though highly controversial in some countries in Europe (Fischer et al., 2013), we have shown that hunting delivers data that can be beneficial to researchers and management authorities through the submission of body parts (ovaries, jaw bones, femurs, wings, tissues) from the carcass of harvested animals from which certain species characteristics would have been otherwise unobtainable.

Hunting data can provide a unique time series in some countries and we have found studies using roe deer antlers over a 67-year period to study change in environmental pollution (Kierdorf and Kierdorf, 2000), or studies using 30 years of bag data (Jansson and Pehrson, 2007). Even though the hunting season is normally limited to only certain periods (i.e. hunting seasons, depending on the taxa and the countries' regulations), some programs make hunters monitor species characteristics throughout the entire year. For instance, the Finnish wildlife triangle is carried out once during summer and once during winter, allowing the creation of time-series dataset useful for ecological research.

Hunting grounds are also widely spread across almost the entire European continent, and even most protected areas are usually open to hunting (Linnell et al., 2015). Hunting is an opportunity for monitoring the status of species population in these areas as hunter-based monitoring has the potential to supplement traditional citizen science which is highly biased towards environments with easy access such as human infrastructures, or nature reserves (Tiago et al., 2017).

Hunters monitor characteristics primarily on species they hunt and hence species they can recognise easily (i.e. for most countries in Europe, getting a hunting licence requires passing examinations, including assessments of species knowledge). This feature is especially important when making inference from hunters' data as species misidentification is presumably less of an issue than in other citizen science data. Hunters' data are also characterised by their institutionalisation. Most European countries oblige hunters to report their harvest to estimate the relative population of game species and to set quotas for the following year. This system involves hunters directly in the management loop, motivating the data collection. Unfortunately, this degree of institutionalisation does not always extend to scientific analysis and publication, with much information remaining within management organisations where it is not readily available.

4.2. The challenges with hunter-based monitoring

There are however several challenges regarding the use of hunter-based monitoring.

Institutionalising the data can potentially lead to some extent of misreporting. Hunters might report a higher harvest rate or a higher number of Observations to artificially boost population numbers, increasing the quota for the following year

(Popescu et al., 2016) or to pretend that they are active on their concession and that they follow the wildlife management plan. This can lead to growing population of game species leading to an increasing human-wildlife interface and resulting in more damages to properties. The same issues could also lead to over-reporting to hide a real decline. Even when misreporting is not purposeful, the discrepancies between population indexes resulting from hunting game bags and other more systematic methods can result in mistrust in data provided by hunters from both institutions and other stakeholders, potentially increasing the negative perception of hunters.

Moreover, because each country has its own reporting system, misreporting can be facilitated depending on the system. For instance, some of the very structured monitoring programs are able to report data that provide precise indices of the variation of game populations over large areas (Ueno et al., 2014; for a selected sample of these programs see Box 1). However, many programs across Europe are much less structured (i.e. they do not follow a robust sampling scheme) and are based on hunter reports of total numbers of animals believed to occur on their hunting grounds, which are then aggregated at other administrative levels. These procedures have poorly described methodology, no robust measures to prevent multiple counts of the same individuals and are highly prone to misinterpretation or even potential abuse (Popescu et al., 2016). At best they may provide a rough relative index of temporal change in abundance (Bragina et al., 2018) and an indication of broad scale distribution. However, despite their somewhat ad hoc nature their utility in guiding sustainable hunting practices over the last 50 years in many areas must be acknowledged. There is potential to add value to these systems if the underlying concrete Observations can be separated from the interpretation, and if some transparent structure can be placed onto both the observation and interpretation processes (e.g. ENETWILD consortium et al., 2018).

Finally, hunting based monitoring programs potentially encounter similar biases as any other citizen science programs. For instance, hunter-killed birds rarely constitute a random subset of a population as juveniles or older birds are more likely to be shot, resulting in age biases in hunting bags (Madsen, 2010). Geographical biases also exist with hunting-based monitoring because of different regional management practices, making some hunting areas more popular than others which render abundance indices less reliable (Ranta et al., 2008). Nevertheless, obtaining accurate measures of game characteristics is possible using rigorous methods and standardised protocols such as the collection of 'indicators of ecological change' as done in France for ungulates (Morellet et al., 2007). Recent statistical developments regarding the integration of different data sources and types also allowed the researcher to combine hunters' bag statistics with other sources to overcome some of the biases inherent to hunting bag data (Isaac et al., 2019; Rutten et al., 2019).

5. Conclusion

With limited resources and requests from governments to monitor diverse biodiversity characteristics at large scales, there is a growing need for scientists and wildlife management authorities to use cost effective methods to collect data. Our study

Box 1
Examples of highly structured hunter-based monitoring schemes

Norwegian moose monitoring program: Besides reporting the harvest, Norwegian moose hunters are asked to report all moose observed during the hunting season on a standardised form (Solberg and Saether, 1999). This system was started in a few municipalities in the late 1960s and extended to cover the entire country during the 1980s. On a daily basis, the leader of each moose hunting team records the number, sex (male, female, unknown) and age (calf, adult, unknown) of all moose observed by the team members but removes individuals that with certainty are observed by more than one member of the team. In addition, they record the number of members that are hunting each day of the hunting season. Data are later reported to the municipality wildlife board and the national deer register (www.hjorteviltregisteret.no/) and used to generate various indices of moose population density and structure for use by the wildlife management (Solberg and Saether, 1999). In addition, hunters in a selection of monitoring sites are required to submit jawbones, ovaries and body weight information of the animals harvested. These data go back to the 1980's.

Danish bird wing survey: This survey consists of collecting wings from bird shots during the hunting season and is based on voluntary contributions from hunters across Denmark. Every year thousands of wings are forwarded and are used to infer survival, population abundance and structure of the Danish game birds. More information can be found on the website of Aarhus university (http://fauna.au.dk/en/hunting-and-game-management/wing-survey/)

Finnish wildlife triangles: The Finnish Wildlife Triangle scheme was developed by the Finnish Game and Fisheries Research Institute in cooperation with the Hunters' central organization in 1988. It provides a wide range of information on species population distribution, abundance and structure for 30 wildlife species. This scheme is highly structured and consists of equilateral triangles with 4 km sides distributed across the whole Finnish landscape. These transects are travelled in winter where tracks in the snow are counted, and during the summer when species seen are counted. Annually the census is carried out for 800 to 1000 triangles and involve 7000 volunteers, mainly hunters (Pellikka et al., 2005).

shows that collaborations between hunters and scientists can contribute to biodiversity monitoring in nearly all its key dimensions, except for habitat indicators. Nevertheless, hunter based monitoring is not a panacea as geographical and taxonomical gaps exist in the information brought by hunter based monitoring in Europe, possibly due to the low acceptance for the use of hunter-based monitoring within some conservation circles because of the societal and ethical challenges hunting is now facing (Fischer et al., 2013).

Furthermore, apart from some very structured programs, the unsystematic nature of hunting-based monitoring poses challenges concerning the use of these data. Statistical developments in data integration as well as more rigorous protocols for data collection when using hunting-based monitoring is needed to unlock further the potential that hunters' data holds.

Authors' contribution

All authors participated in the conception and design of the study. BC collected and analyzed the data. BC and JDCL drafted the manuscript with the help of all authors. All authors gave final approval for publication.

Data availability statement

The R script and the full dataset used to carry out the analysis are both made available to ensure full reproducibility and can be found at DOI 10.17605/OSF.IO/GKAZM. The dataset lists all the papers from the structured and unstructured searches as well as the answers from the authors' contacts. The distribution of data from expert consultations of was done under full consent from the respondants.

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.gecco.2020.e01077.

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