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Ecosystem services and disservices associated with vultures: A systematic review and evidence assessment

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ABSTRACT

Nature's contribution to people (i.e. ecosystem services) is becoming integral to conservation science and policy, yet our knowledge is restricted to only a few services and taxa. Vultures (family: Accipitridae and Cathartidae), most of which are threatened with extinction, have been touted for delivering regulation and maintenance services via their capacity to rapidly consume organic matter. As such, their appellation as "nature's clean-up crew" has become very popular. However, a comprehensive evaluation of the supporting evidence for such appellation was absent from the published literature. We performed a systematic review and evidence assessment to quantify the global contribution of vultures towards over 20 ecosystem services and disservices. Our analysis determined a critical imbalance in the scope and focus of published research. In contrast to the birds' popularised image as cleaners of the environment, we found only weak evidence to support any regulation and maintenance services for vultures. Moreover, studies on regulation and maintenance disservices were prominent. The only ecosystem services supported by strong evidence were cultural, although even these were evidenced by a limited number of studies. Finally, we unveil major knowledge gaps in the ecosystem service and disservice literature on a taxonomic and spatial scale related to vultures. Our analysis highlights the urgent need to quantify the net contribution of vultures to people.

1. Introduction

The ecosystem services (ES) framework plays an integral part in biodiversity conservation programmes, and is frequently used for identifying objectives in environmental management and policymaking (Daily and Matson 2008; Fisher et al. 2009; Perrings et al. 2011). The capacity of birds to provide a variety of ES has received significant consideration (Wenny et al. 2011; Whelan et al. 2008), including roles in pest control (Jirinec et al. 2011), pollination (Sekercioglu et al. 2016), ecotourism (Sekercioglu 2002) and waste disposal (DeVault et al. 2016). Regarding the latter role, vultures, the only obligate scavengers among the vertebrates, represent one of the best-known examples from across the whole animal kingdom (Buechley and Sekercioglu 2016; DeVault et al. 2016; Gangoso et al., 2013).

Vultures and other terrestrial scavengers are often described as important components of ecosystems, and as ES providers (O'Bryan et al. 2018). Vultures (family: Accipitridae and Cathartidae) are able to consume, and thus recycle, substantial amounts of organic waste (Grilli et al. 2019). This ecosystem function, when put in action, translates into ecosystem services, such as decomposing waste, which represent nature's actual contribution to people (Gangoso et al., 2013). Moreover, when the waste disposal service hinders the transmission of diseases, this results in another ecosystem service, that is, disease control. Typically, conservation marketing campaigns focused on vultures

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prominently flag the birds' role as "nature's clean-up crew". This image of vultures as the cleaners of the environment has been adopted and utilized, among others, by conservation NGOs, becoming very popular and widely accepted within the conservation community and the public. However, there is limited scientific evidence demonstrating the extent to which vultures remove carcasses that may be reservoirs of disease (van den Heever et al. 2021). As a result, a cautionary approach when inferring associations between vultures and key ES has been recently recommended by experts (IUCN Vulture Specialist Group 2020).

Vultures have experienced the most dramatic population declines among all animal taxa during the past few decades. Across all 23 vulture and condor species of the world, most of the Old World vultures (87 % of 16 species; family Accipitridae) are globally threatened or near-threatened (Botha et al. 2017). Conversely, most of the New World vultures, also including condors, are not currently threatened (5 out of 7 species; family Cathartidae; Santangeli et al., 2022; McClure et al. 2018). Toxicosis related to direct or indirect poisoning, is the prevalent driver of threat among all vultures of the World (Santangeli et al., 2016; Brink et al., 2021; Didarali et al., 2022; McClure et al. 2018; Ogada et al. 2016). Vultures' ES are commonly used in conservation marketing to raise awareness of the value of these species and leverage their conservation. Therefore, it is crucial to base the role and value associated to vultures on scientific evidence, in order to leverage funding and conservation attention in the long run. Moreover, a general understanding of ecosystem disservices (EDS) can also be vital for informed decision-making and reducing the risk of mis-information spread (Lyytimäki and Sipilä 2009).

Ecosystem disservices are typically referred to as ecosystem functions that are perceived as negative for the well-being of humans (sensu Lyytimäki and Sipilä 2009). Theory and practice on EDS have been far less prominent in the scientific literature than that of ES (Lyytimäki and Sipilä 2009). Nonetheless, EDS have not been without scientific consideration (e.g., Alemu et al., 2021; Blanco et al., 2020; Shackleton et al., 2016) or scrutiny (e.g., Villa et al., 2014). Moreover, the argument for balancing considerations given to ES and EDS when valuing nature, including stating clear and transparent definitions for each, has also been made (Shapiro and Báldi 2014; Schaubroeck 2017). As such, whilst the incorporation of both ES and EDS has been encouraged within relevant research and assessment frameworks (Blanco et al. 2019; Schaubroeck 2017; von Döhren and Haase 2015), such holistic approaches are rarely implemented.

By determining the net contributions of vultures (and nature in the wider sense) to humans, their value can be better understood and appreciated at the policy level. Moreover, information on the net contribution of vultures to people is of particular importance to justify (or change) the way vultures are often presented to the public in media campaigns aimed at increasing their conservation, i.e. the "nature's clean-up crew" type of image. Importantly, given that the costs of disservices are typically immediate, e.g. vulture-aircraft collisions, while the benefits from ecosystem services manifest in the longer term (Shapiro and Báldi 2014), it is even more relevant to quantify any unbalance in research effort between the ecosystem services and disservices with relevance to vultures.

Research on vulture ES/EDS has been recently accumulating, but a comprehensive review or synthesis of the current understanding and evidence-base is still generally lacking. The Convention on Migratory Species Vulture Multi-species Action Plan (Botha et al. 2017) lists 17 essential actions that should be urgently implemented to contribute to the conservation of Old World vultures. Quantifying vulture's contribution to people was among those listed actions (Action 11.3.1.).

Therefore, this systematic review aims to synthesise and evaluate the existing evidence of the ES/EDS associated with vultures, develop a framework combining the approach proposed by Salafsky et al. (2019) to define and quantify evidence in conservation, with the standards for systematic reviews (Moher et al. 2015) to answer the following questions: (1) What role do vultures have as ES/EDS providers? (2) What is the strength of the evidence identified for these roles? (3) What are the gaps and biases in scientific literature on vultures' ES/EDS? Answering the above questions is timely and relevant, as it can facilitate a better understanding and use of the evidence supporting ES/EDS, point to research gaps that need to be filled, and ultimately increase the effectiveness of vulture conservation and attract increased societal support.

2. Materials and methods

A systematic review of the literature was performed (step 1) and each ES/EDS was scored according to the scientific evidence supporting it (step 2). The studies identified in step 1 were also used to highlight current knowledge gaps (step 3). Each of the three analytical steps is detailed below and step 1 and 2 are graphically represented in Figure S1.

2.1. Systematic literature review

A systematic review of the literature was performed to identify and filter relevant documents using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Moher et al. 2015). The keywords (full list in Supplementary Table S1) included a full list of scientific and common names of vulture species derived from various sources: the R package taxize (Chamberlain and Szöcs 2013), the Integrated Taxonomic Information System (Itis 2020), the Encyclopedia of Life (Eol 2020) and the Global Raptor Information Network (Grin 2020). Keywords identifying potential ES were extracted from the text description of individual ES present in the Common International Classification for Ecosystem Services (CICES) classification spreadsheet v5.1 (Haines-Young and Potschin-Young 2018). Because CICES classification includes 90 specific ES categories applicable broadly across all ecosystems of the world, we performed an a priori selection of those specific ES categories that could be potentially relevant to vultures. When performing this a priori selection of ES categories, we tried to be as inclusive as possible in order to avoid excluding some ES that could be relevant for vultures. That is, when we had doubts whether a specific ES could be relevant to vultures, this was included for study. Through this initial ES selection, we excluded all abiotic ES, as these are not relevant to vultures, as well as other clearly irrelevant biotic ES (e.g. cultivated terrestrial plants for nutrition, materials or energy) and finally selected 23 ES and corresponding EDS (see Table 1). Due to the lack of a recognized EDS classification system, no pre-existing EDS terminology was available for use in database searching. Therefore, terms considered to be in opposition to CICES ecosystem services were used e.g. a "provision" can be contrasted by a "cost". Thus, EDS were considered as nature's actual or perceived negative impacts to humans, and as antagonists to CICES ecosystem services. Search strings (Table S1) were then run through Web of Science and Google Scholar to identify records published in English from 01/01/1970 to 31/12/2020. In order to fit the 250 character limit, searches on Google Scholar were split by replacing the species term of interest. Record identification on Google Scholar terminated at 100 hits per search (excluding patents and citations), thus reducing irrelevant literature and unrealistic screening time.

Results were ordered by relevance and the packages revtools (Westgate 2019) and litsearchr (Grames et al. 2019) within R statistical software (R Development Core Team 2017) were used for: importing RIS files, merging columns, de-duplicating items (based on title/DOI) and screening abstracts through a user-friendly interface. Packages allowed de-duplication to occur automatically, reducing human error. Abstracts and titles appeared randomly and without author affiliations to avoid a biased selection. Data collection and analysis was subdivided into four phases: Identification, screening, eligibility and inclusion (see details in Table S2). The selected criteria targeted primary (i.e. original) studies published as peer-reviewed documents (journal articles, PhD theses and edited books/book chapters). Each document on ES/EDS provided by vultures identified in the final set of studies was assigned to the corresponding CICES category.

Table 1
Summary description of the 23 Ecosystem Services/Ecosystem Disservices (ES/EDS) classes, derived from the Common International Classification for Ecosystem Services (CICES) classification, considered in this study. The table shows the specific CICES classes, given using a simple descriptor and the original CICES code, and grouped by the three main ES / EDS groups. Examples of each are taken from the relevant identified literature resulting from the systematic review. Empty cells in the two example columns depict the absence of any ES or EDS study found for the specific category. See Tables S7 and S8 for more details on each study identified from the literature search and its relevance to each ES/EDS category.

Main group	CICES simple descriptor	CICES code	Example ES	Example EDS
Provisioning	Food from wild animals	1.1.6.1	25 % of traders sold vultures for consumption (Saidu and Buij 2013).	
	Materials from wild animals	1.1.6.2	1,251 traders, hunters and healers benefit annually from vulture trade (McKean et al. 2013).	
	Breeding & genetic information	1.2.2.3	Identification system based on STRs markers for Andean Condor can be applicable to individual discrimination and monitoring programs (Paz-y-Miño et al. 2015).	
	Livestock raised in housing and/or grazed outdoors	1.1.3.1		Vultures were observed pecking cows and their neonates during 34.1 % of all recordings (Toledo *et al.* 2013).
	Damages/risks posed by vultures	1.3.1.1		75.1 % of Turkey vulture collisions with aircrafts resulted in damage (DeVault, Blackwell, et *al.* 2016).
Regulation & maintenance	Decomposing wastes	2.1.1.1	The individual food intake (252 g/day) of vultures suggests that the surveyed population removes 1,000 tons of organic material/year (Grilli et al. 2019).	
	Reducing smells	2.1.2.1		
	Controlling pests and invasive species	2.2.3.1	The absence of vultures was associated with longer carcass decomposition time, more facultative scavengers present and spending more time at carcasses (Ogada, Torchin, et al. 2012).	
	Controlling disease	2.2.3.2	Several pathogens are destroyed in the digestive tract of vultures (Houston and Cooper 1975).	61 % of vulture faeces collected were positive for Salmonella (Blanco 2018).
	Ensuring the organic matter in our soils is maintained	2.2.4.2	Soil microbial communities associated with vultures exhibited greater phylogenetic clustering in bacterial communities (Ganz et al. 2012).	
	Controlling the chemical quality of freshwater	2.2.5.1		
	Regulating our global climate	2.2.6.1	Supplanting the natural removal of dead livestock by scavengers with carcass collection and transport to processing plants meant the emission of 77,344 metric tons of CO2 eq. to the atmosphere per year (Morales-Reyes et al. 2015).	
	Regulation of food chains	2.3.2.4	Vultures may aid other scavengers to locate carcasses, possibly causing trophic cascades if absent (Kane and Kendall 2017).	
Cultural	Watching plants and animals where they live	3.1.1.2	85 % of visitors came to the nature reserve in order view vultures (Becker et al. 2005).	
	Researching nature & studying nature	3.1.2.1	Andean condors depend heavily (98.5 %) on non-native herbivores. The abundance of invasive and native herbivores can be determined by studying vulture diets (Lambertucci et al. 2009).	Vultures may have impacts on bodies left exposed and complicate (or render impossible) the identification of corpses (Beck et al. 2015).
	Nature helping people identify with their history or culture	3.1.2.3	Important species for the Aymara people, with personal and symbolic value. Historic socio-environmental factors have changed the cultural value and traditional ecological knowledge of vulture (Jacques-Coper et al. 2019).	
	The beauty of nature	3.1.2.4		
	Using nature as a national or local emblem	3.2.1.1	Marginal value of vultures at the Gamla reserve = 34,438 NIS. Marginal vulture value at the Hai-Bar reserve = 316,440 NIS (Becker et al. 2007).	Vultures are often seen as ugly birds with negative morphological features and behaviours (Stara et al. 2016).
	The things in nature that have spiritual importance for people	3.2.1.2	In just 3 burials, >430 vultures were observed (MaMing et al. 2016).	Vultures are symbols of darkness and death (Gupta et al. 2020).
	The things in nature used to make films or to write books	3.2.1.3	Based on non-material indices, vultures had the second highest cultural value compared to other scavenger species (Aguilera-Alcalá et al. 2020).	
	The things in nature that we think should be conserved	3.2.2.1	The majority of study respondents reported the need to conserve vultures for their socio-ecological importance (Mdhlano et al. 2018).	
	Things in nature that we want future generations to enjoy/use	3.2.2.2		
	Perception of vultures	3.3.1.1	Over two-thirds of households liked vultures, stating that they were harmless and useful for locating dead livestock (Craig et al. 2018).	Most people perceived the Andean condor as an injurious species (Arnulphi et al. 2017).

2.2. Evidence quantification supporting ES/EDS

The evidence supporting vulture ES/EDS based on the final set of selected studies was assessed by adapting the framework recently proposed by Salafsky et al. (2019), see schematic representation in Figure S2. Specifically, evidence evaluation was performed by addressing the following three key questions:

(i) Does the study provide evidence supporting an ES/EDS? A confidence level of the ES/EDS were generated from criteria in Table S3 by considering the nature, strength and type of evidence. The nature of

evidence was either: supporting evidence (+) which increased the case of the ES/EDS, evidence that failed to support the case of the ES/EDS (-), which decreased the case of an ES/EDS, or mixed evidence (+/-) that included a balance between evidence that supported and failed to support the case of an ES/EDS. The strength of evidence was classified as either strong or weak. Strong evidence convincingly supported an ES/EDS. On the other hand, weak evidence partially supported an ES/EDS. The type of evidence was also divided into two types; direct or circumstantial evidence. Direct evidence adequately assessed an ES/EDS without external evidence/inferences, whereas circumstantial evidence required a combination of the study's own evidence and external evidence/inferences to assess the ES/EDS. At the end of this first evidence assessment step, a study either received a final evidence score of 4 (if the nature and strength of the evidence were very high, coupled with direct or sufficient circumstantial evidence – dark green cell "very confident" in Table S3) or 1 (if the nature and strength of the evidence suggest the project failed to support any evidence for the presence of an ES/EDS – red cells "not confident" in Table S3). For all the remaining cases (light green and yellow cells in Table S3) where there was uncertainty in the confidence level and more information was required, the following step (ii) was required in order to assign a final evidence score based on external evidence support.

(ii) Does external evidence (i.e. evidence coming from external sources other than the focal study) support the ES/EDS (Tables S4 & S5)? If the study in question did not provide sufficient information to clearly support/refute an ES/EDS during the above step (i), its relevance to other literature (any relevant research identified during the literature search) was assessed. The reliability of its evidence was also determined by assessing the experimental design and reproducibility (Table S4). Rows on Table S4 were numbered such that a simple calculation (Equation S1 in Supplementary Material) established the weight of the evidence based on its relevance and reliability. From the outcome describing the weight and direction of the evidence, the overall support of the ES/EDS from the external evidence was determined (see Table S5).

(iii) Is external evidence relevant to site conditions? In this final step, the relevance of data coming from other studies is compared to the assessed evidence on a particular ES/EDS. External evidence on ES/EDS conducted with similar methodologies/conditions would be more relevant when assessing a specific study, therefore obtaining a higher score. The end-result of the process (Tables S3-6) provided a final evidence evaluation, indicating a score from 1 to 4, whereby 4 = evidence confidently supports an ES/EDS, 3 = evidence supports an ES/EDS but may need monitoring, 2 = additional investigations required, and 1 = evidence does not support ES/EDS.

2.3. Biases in vultures ES/EDS research

Gaps or biases in the information regarding the ES/EDS provided by vultures were assessed at the taxonomic and spatial level (e.g. reporting the number of studies per species or per country), as well as at the level of major and specific ES / EDS categories (e.g. the total number of cultural ES).

3. Results and discussion

3.1. ES/EDS associated with vultures

The systematic review identified 10,779 documents after duplicates were removed, 251 of which passed the abstract screening process for full text exploration. A total of 130 documents met the eligibility criteria, yielding information regarding a variety of potential ES/EDS provided by vulture species (Table 1, Fig. 1). Studies indicate that vultures may have a role as ES/EDS providers across all three major groups of services (cultural, regulation and maintenance, provisioning) and across many of the specific ES/EDS categories (Tables S7 and S8).

Overall, we found more studies on ecosystem services focused on cultural than other services, whereas for disservices, we found more studies focused on regulation and maintenance than other groups. Interestingly, we found stronger evidence for cultural and provisioning services and disservices as compared to regulation and maintenance, but differences between specific categories of ES and EDS were also apparent.

3.2. Provisioning

The majority of identified studies addressing the provisioning services associated with vultures focused on direct uses of vulture body

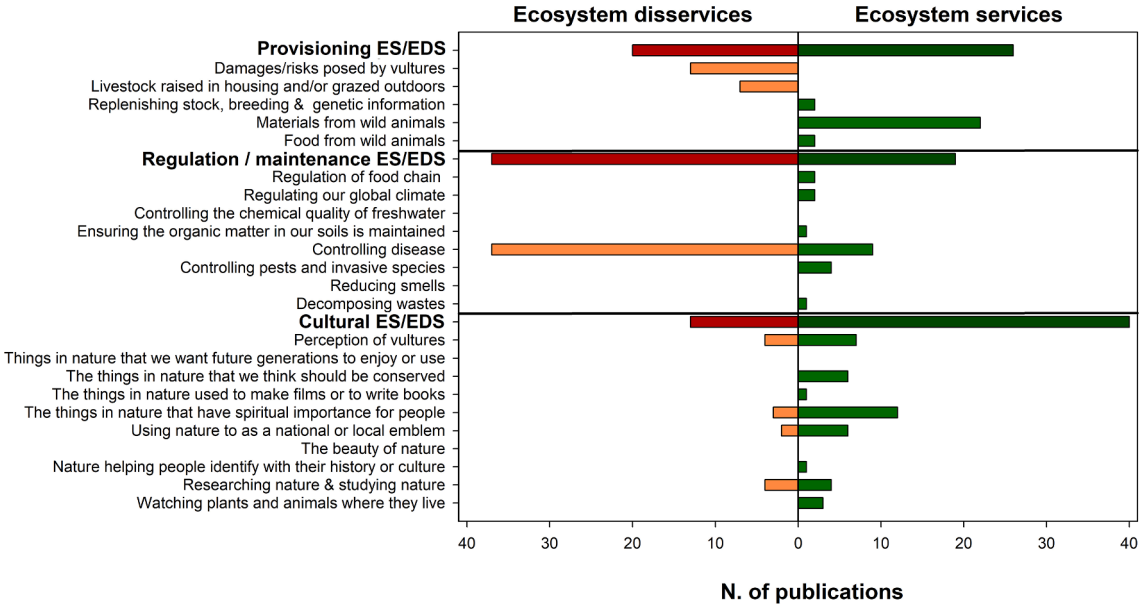

Fig. 1. The number of studies identified from a systematic review of the literature on vulture ecosystem services (ES; green bars) and disservices (EDS; orange bars). The total number of studies for each of the three major groups (provisioning, regulation and maintenance, cultural) is shown with dark green (ecosystem services) and dark red (ecosystem disservices).

parts. Vultures are traded in bushmeat and fetish markets across several African countries, which is a service largely contributing to their decline (Table S7). Apart from bringing economic profit to local vendors, consumers use vulture body parts for various purposes including bushmeat, belief-use practices and personal ornamentation; 40 % of traders interviewed in Northern Nigeria sold vulture parts for healing and 25 % for consumption (Saidu and Buij 2013). Questionnaires administered in South African markets revealed that approximately 1,251 traders, hunters and traditional healers benefit annually from the trade of vultures, while 59,000 consumers per annum psychologically benefit from using vultures (McKean et al. 2013). Although not all communities use vultures for medicinal purposes, and some even consider these practices outdated (Craig et al. 2018), medical benefits of their use have been demonstrated in some cases (Jacobo-Salcedo et al., 2013).

Several studies demonstrate the value of vulture genetic material for maintaining populations, which is listed as an ecosystem service under CICES (i.e. animal material collected for the purpose of maintaining or establishing a population; Haines-Young and Potschin-Young 2018). An identification system from the use of short tandem repeats was used for individual discrimination and estimates of genetic diversity to monitor Andean Condors (*Vultur gryphus*; Paz-y-Miño et al. 2015). These studies may represent a portion of the existing services and opportunities vultures bring to humans invested in vulture conservation or management.

On the other hand, other aspects of human livelihoods may be negatively affected by vultures, thereby indicating the presence of ecosystem disservices. Studies on negative provisioning services (i.e. EDS) exclusively focused on two specific disservices, damage or risk posed by vultures to the aviation industry (i.e. collisions with aircrafts; DeVault, Blackwell, *et al.* 2016), and supposed impacts of vultures on livestock (i.e. vultures presumed to kill calves; Toledo *et al.* 2013). Vulture-aircraft collisions may have an economic impact and cause loss of human life. Methods for reducing bird-strikes could be encouraged, such as sound fields (Swaddle and Ingrassia 2017), habitat management (Barras and Seamans 2002), changes in food availability (Moreno-Opo and Margalida 2017) or adjustments in the spatio-temporal planning of aircraft traffic to avoid key vulture areas at their peak of flight activity (Arrondo et al. 2021). Moreover, reports and perceptions of vultures as livestock predators have been spreading fast in the recent years, largely amplified by social media (Lambertucci et al. 2021). Most negative perceptions in this regard are however largely unsubstantiated, as predation events have rarely been proven with high certainty (Duriez et al. 2019). To this end, the outcome of the evidence assessment of the present study indicates that additional investigations are required in order to demonstrate, or refute, the existence of this potential EDS associated with vultures. Given the above uncertainties and the clear momentum of this issue among the livestock farming communities, there is an urgent need to systematically collect the evidence for this potential ecosystem disservice associated with vultures (Lambertucci et al. 2021) and address any misinformation spread through social media. This evidence-base would then allow the designation of appropriate management strategies, including awareness campaigns among interested stakeholders, to prevent conflicts with vultures on livestock farms before they escalate and culminate in vultures being intentionally killed.

The above cases of ecosystem disservices associated with vultures clearly indicate the high relevance of focusing research and conservation efforts not only on ecosystem services, but also on disservices. Previous studies have also highlighted that managing for ecosystem disservices may represent a better return on the investment compared to managing exclusively for ecosystem services to enhance human wellbeing (Shackleton et al., 2016).

3.3. Regulation and maintenance

Research focusing on regulation and maintenance services associated with vultures was largely focused on controlling disease services, with fewer studies focusing on other services, including decomposing waste (Fig. 1). Vultures are capable of consuming large quantities of organic material (Mateo-Tomás et al., 2017). Such disposal service was recently quantified for the total population of one vulture species, the Turkey vulture *Cathartes aura*, and could reach up to 700 million USD per year in economic value to humans (Grilli et al. 2019) in the Americas. Carcass consumption by vultures also reduces the release of green-house gas emissions through avoided carcass transportation and incineration (Morales-Reyes et al. 2015). It has been suggested that vultures may also be involved in pest and disease control by rapidly disposing of organic matter that would otherwise attract mammalian scavengers, including feral dogs, at the same place. Such a congregation could facilitate contacts and interactions among mammals (Ogada et al. 2012), potentially boosting transmission among them as well as to other species, such as domestic animals and humans (Markandya et al. 2008).

The role of vultures as disease regulators is potentially supported by studies considering the pathogens filtered by the vultures' digestive tract (Houston and Cooper 1975; Roggenbuck et al. 2014). However, a few studies also identified potential ecosystem disservices related to pathogens, showing that vultures may act as reservoirs, amplifiers and disseminators of important pathogens e.g. *Salmonella* (Blanco 2018; Blanco et al. 2019). Despite this concern, a recent study provided no evidence that vultures would act as disease amplifiers and disseminators, e.g. by re-infecting livestock, suggesting that this vulture function may not necessarily translate into an ecosystem disservice (Blanco and Díaz de Tuesta, 2021). Additionally, one study demonstrated the beneficial impacts of vulture guano (i.e. excrements) on soil bacterial communities, and suggested its acidity may (at least partially) counteract the vultures' role as disease vectors (Ganz et al. 2012).

3.4. Cultural

While most identified studies on the cultural services associated with vultures focused on spiritual services, other services, such as existence value and perceptions of vultures were well represented and supported by strong evidence. Clear examples of these cultural services are represented by the sky burials, funeral practices where human corpses are left for vultures to eat in Tibet (MaMing et al. 2016). Our results also broadly align with a recent study showing that vultures are among the top ranked scavengers in providing non-material contributions to people in Spain (Aguilera-Alcalá et al. 2020). However, negative spiritual relationships, thereby highlighting ecosystem disservices, may also exist, as vultures can be represented as symbols of darkness and death in some cultures (Gupta et al. 2020). Perceptions vary depending on the interactions and cultural connections people have with these birds. In Namibia, two-thirds of people surveyed liked vultures, often describing them as harmless and useful for locating dead livestock (Craig et al. 2018). Other communities, such as the ones living in proximity to the northern Gonarezhou National Park in Zimbabwe, understand vultures' importance and are willing to conserve them (Mdhlano et al. 2018). Conversely, most of the interviewed people in the San Juan province in Argentina perceived condors as injurious species (Arnulphi et al. 2017). This may be due to the physical features of vultures, often seen as ugly birds with morphological features and behaviours which are unattractive to many people (Stara et al. 2016). These contrasting outcomes clearly highlight the dichotomous nature of the human-vulture relationship. While some people and cultures may assign positive cultural values to vultures, others carry opposite feelings.

Vultures are also a tourist attraction, such as the case of the Gamla Nature Reserve, Northern Israel, where vulture watching was estimated in 2005 to be potentially worth over 1 million USD annually (Becker et al. 2005). Vultures are often important emblems for these reserves and can be of significant cultural and economic value for the region (Becker et al. 2007).

Vultures also show characteristics that enable scientific investigations or the creation of traditional ecological knowledge (representing ES according to CICES; Haines-Young and Potschin-Young

2018). By studying the diet of Andean condors in North-western Patagonia, authors were able to determine the abundance of native and exotic herbivores (Lambertucci et al. 2009). Conversely, some studies reported that forensic investigations are hindered by scavengers consuming carcasses and dispersing body parts in need of examination, i.e. an ecosystem disservice (Beck et al. 2015). Research on vultures has the potential to help communities identify with their local/national history and culture. For example, the current cultural expressions of condors in Northern Chile are a result of important socio-environmental historical events (Jacques-Coper et al. 2019). In the latter case, the Andean condor (*Vultur gryphus*) has been established as an identifying icon for most Andean communities. Studies also demonstrate the value of vultures for researching and studying the natural world.

3.5. Evidence supporting vultures' role as ES/EDS providers

The strength of the evidence varied largely across the identified CICES groups (Fig. 2). Overall, the highest average evidence scores were obtained from studies on provisioning and cultural ES. Disservices belonging to these two groups also had a relatively high evidence score. By contrast, studies on the regulatory functions provided by vultures had a lower average evidence score (Fig. 2).

3.5.1. Provisioning

The average evidence score (weighted by the number of publications) at the group level was slightly higher for provisioning ecosystem services than disservices (mean = 3.54 and 3.10 for ecosystem services and disservices, respectively). Among the provisioning classes, some ecosystem services were supported by very high evidence scores (e.g. materials from wild animals, replenishing stock, breeding and genetic information) or relatively high evidence scores (e.g. food from wild animals). Similarly, strong evidence supports two ecosystem disservices in this group, namely damage to human infrastructures and livestock.

3.5.2. Regulation & maintenance

The average weighted score was slightly lower for ecosystem services than disservices relating to regulation and maintenance (mean = 2.05 and 2.84, respectively). Strong evidence shows the ability of vultures to consume organic waste and the associated climatic benefits (Fig. 2). It is unclear whether vultures contribute to disease and pest control, as the average evidence score for studies testing this was very low (below the value of two in both cases). Our results also support a recent review of bacterial, viral and mycotic microorganisms present in vultures which found no evidence that vultures may spread diseases to humans or other species, but found evidence of their ability to prevent disease spread via the removal of organic matter (Plaza et al. 2020). Similarly, within an African context, another review concluded that the contribution of vultures to the economics of human and livestock health remains largely unquantified (van den Heever et al. 2021). Ultimately, such uncertainty in the role of vultures in controlling disease was also highlighted by a recent note of the IUCN Vulture Specialist Group (2020) that explicitly cautions against making statements regarding an unequivocal role for vultures in limiting disease transmission.

The poor evidence strength for vultures' association with disease regulation may also stem from challenges in accurately quantifying this relationship, most notably the intricacies and multidimensionality of dealing with disease transmission, and overlaps or contrasts between mammalian and vulture ecologies. Overall, existing research on vulture disease regulation and transmissions is largely limited or conflicted in nature, often has limitations, and overlooks the complexity of epidemiological interactions (e.g. the specificity of diseases, as well as the ecology and transmission of diseases), requiring further work to determine the role of vultures in disease transmission or regulation. Moreover, we note that challenges for demonstrating a disease control

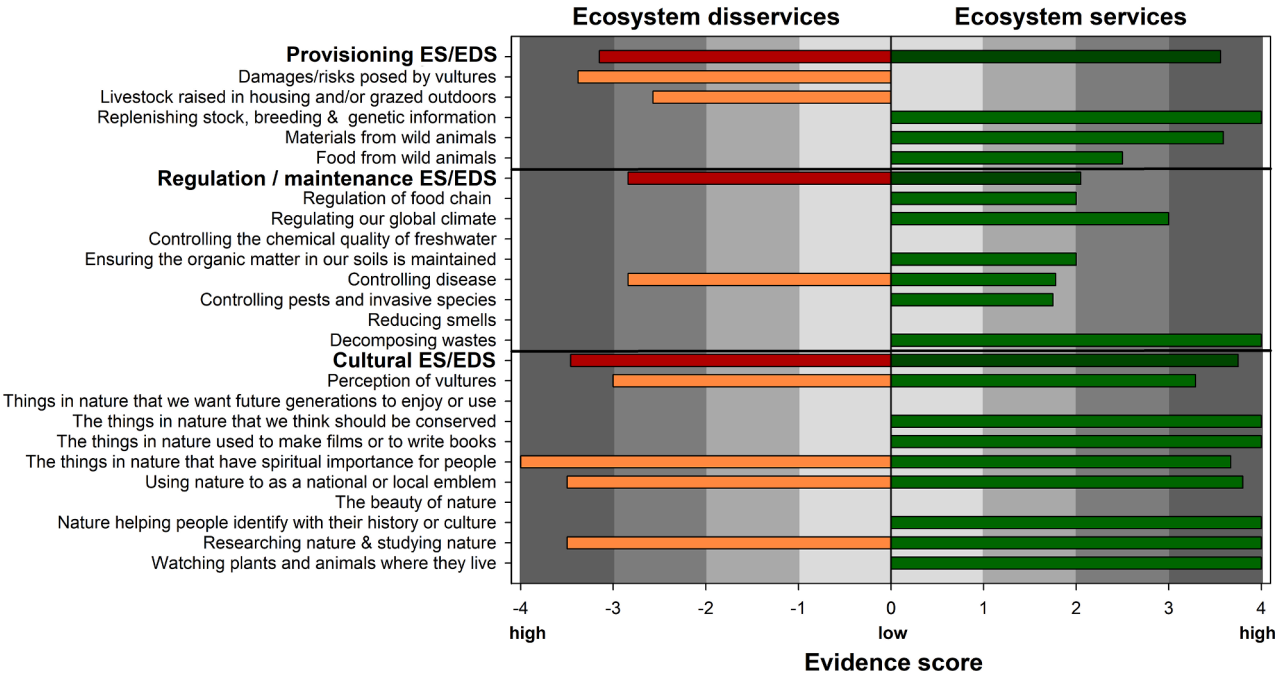

Fig. 2. The strength of the evidence in support of the association between vultures and each specific ecosystem service (ES; green bars) or ecosystem disservice (EDS; orange bars) considered for study (see Table 1). Strong evidence for an ES is represented by positive values close to four, and strong evidence for EDS by negative values close to minus four. Evidence was quantified using the multi-criteria and multi-step framework for evidence evaluation (see methods for more details) whereby a score from 1 (evidence does not support ES/EDS) to 4 (evidence confidently supports ES/EDS) was derived for each paper, and the average of scores for each ES/EDS category was then drawn. For visualization, we present ES with positive and EDS with negative scores. A missing bar depicts ES/EDS categories with no publications, and thus no evidence score. The average evidence score for each of the three major groups (provisioning, regulation and maintenance, cultural) is shown with dark green (ecosystem services) and dark red (ecosystem disservices), derived from the average evidence score of the single ES and EDS categories weighted by the number of publications supporting the evidence.

ecosystem service may be higher than those experienced when demonstrating a disease control ecosystem disservice. The latter would only require the collection and analysis of pathogen-containing fomites of vulture origin, for example, vulture faeces (Blanco 2018). This potential imbalance in quantifying ecosystem services with their corresponding disservice may also explain the apparently stronger evidence seen for a disease control disservice compared with ecosystem services found in our analyses (Fig. 2).

Overall, given the challenges to demonstrating the presence or absence of regulation and maintenance services associated with vultures, e.g., demonstrating the disease control service, it is not surprising that the overall strength of the evidence in support of these services is much weaker than that of, e.g., cultural services (see Fig. 2).

Other regulatory functions had a low evidence score, such as soil quality and food chain regulation (Fig. 2).

3.5.3. Cultural

Average weighted scores were similar for ecosystem services and disservices relating to cultural services (mean = 3.75 and 3.46, respectively). The strength of evidence across all cultural services was relatively high (e.g. watching wild vultures where they live). Similarly, studies revealing any cultural disservices provided by vultures had strong evidence scores (e.g. spiritual role of vultures). As discussed above, these potential cultural services associated with vultures have been well demonstrated and quantified, at least locally (MaMing et al. 2016; Aguilera-Alcalá et al. 2020; Becker et al. 2005; García-Jiménez et al., 2022).

3.6. Gaps and biases in scientific literature on vultures ES/EDS

We found strong taxonomic and spatial biases in the research focused on the ES and EDS associated with vultures. At the level of the three major groups, we show that most studies on ecosystem services associated to vultures related to cultural services (n = 40), with less studies related to provisioning (n = 27), and regulation and maintenance (n = 19; Fig. 1). Conversely, most studies on ecosystem disservices focused on regulation and maintenance (n = 37), while fewer focused on provisioning and cultural services (n = 20 and 13, respectively; Fig. 1). For the ecosystem services, at least 17 specific categories had at least one study addressing them. However, most studies were concentrated on three specific ecosystem services, namely provision of materials from wild animals, spiritual importance and disease control (Fig. 1), while all other specific ecosystem services had less than seven studies. Most studies on ecosystem disservices associated with vultures were related to disease control, and to a lower degree damage and risk posed by vultures, as well as conflict with livestock husbandry. The other four specific cultural ecosystem disservices had fewer than five studies, and all the rest of the ecosystem disservices, including most of those in the regulation and maintenance group, had no studies (Fig. 1). Overall, major research gaps are particularly evident for services such as regulation and maintenance, for which vultures have become an icon (DeVault et al. 2016). Especially striking was the low number of studies focused on controlling pests and disease, or reducing waste, as assumptions regarding provision of these services by vultures have been extensively used in campaigns aimed at vulture conservation. This in turn translates into an evidence-base in support of the ecosystem services and disservices associated with vultures which is at most weak, and often correlative, as the Markandya et al. (2008) case demonstrated.

We also identified large taxonomic biases in the ecosystem service and disservice research, with a few vulture species, namely the Eurasian griffon, turkey and black vulture over-represented in comparison to most other less studied species, such as the Asian and South American vultures (Fig. 3). Similarly, a spatial bias in the research on the ecosystem services and disservices associated to vultures was apparent, with countries in East Africa and South East Asia having the least number of studies (Fig. 4).

Overall, regions of extremely high priority for vulture conservation, such as East Africa and the majority of the Sahel region (Santangeli et al., 2019), are largely lacking studies on the ecosystem services and disservices associated with vultures. Similarly, such studies largely neglect most of the vulture species occurring in Latin America and, surprisingly, in Asia, such as the case of the Indian Griffon vulture (*Gyps indicus*). These biases and limitations greatly hamper any inferences regarding the broader connections between vultures and key ecosystem services and disservices. As such, there is a need for caution when considering the role vultures play in the ecosystem and their relative contribution, both positive and negative, to human wellbeing.

3.7. Study limitations

The results of this study, as those of most systematic reviews, may be subject to publication bias, where positive results are more likely

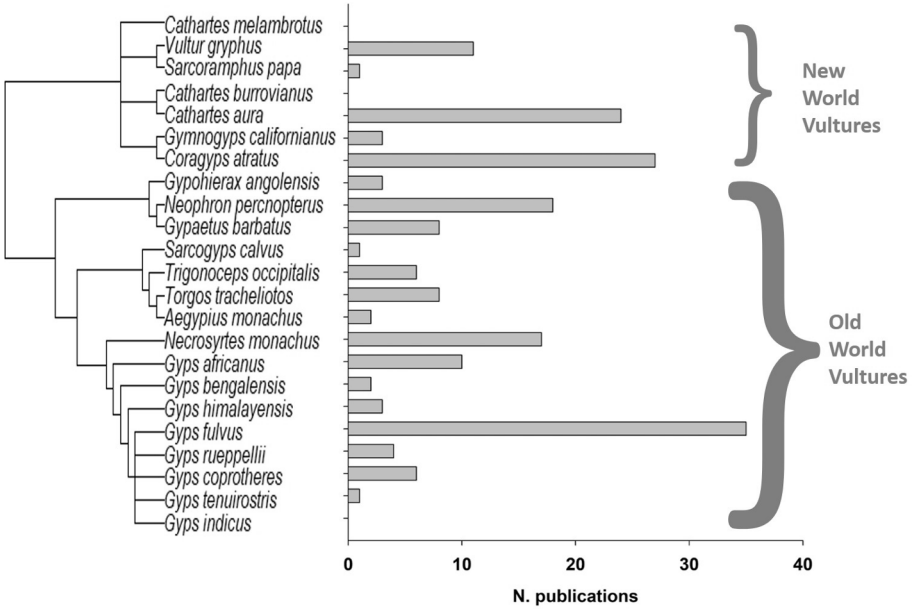

Fig. 3. The total number of documents per species on ecosystem services and disservices identified through the systematic literature review. Seventeen studies are not represented as no particular species were mentioned. The phylogenetic tree is shown on the left and is used for illustration purposes only. The tree was downloaded from www.birdtree.org, and was built by reaching a consensus among 10 000 posterior trees. See Jetz et al., 2012 for technical details about the source of these data on bird phylogeny.

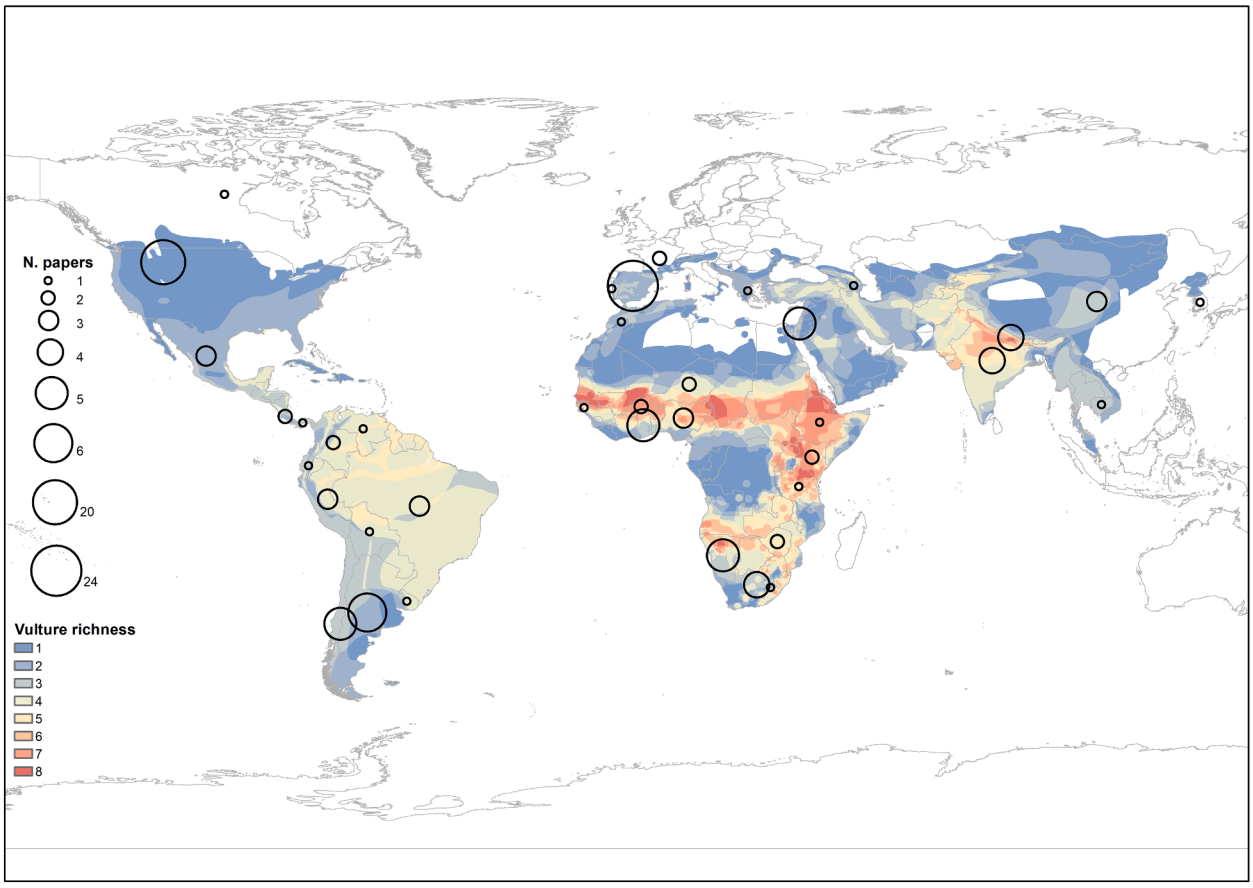

Fig. 4. The distribution of global vulture richness (color gradient) and the total number of identified studies on vulture ecosystem services and disservices by country (empty circles). Nine studies were not included either due to a large geographical coverage (including multiple countries) or the study region not being specified.

published (Egger et al. 2008), and language bias, since we only focused on English literature (Konno et al. 2020); both of which must be considered when interpreting resultant findings. However, with this caveat in mind, the insights gained from this review provide a novel and up to date representation of the ES / EDS associated with vultures, and the gaps and biases therein.

3.8. Future work

The results of this systematic review highlight several knowledge gaps that will require considerable research efforts before we can convincingly assign key ecosystem services or disservices to vultures. While challenging, the above knowledge gaps can be filled by developing interdisciplinary research projects that would embrace and benefit from existing knowledge and tools from across the broad sphere of social, psychological and ecological sciences, as well as from anthropology, ecological economics, and the veterinary and medical sciences. Specifically, we call for semi-natural experimental studies to quantify the potential positive and negative contributions of vultures with regard to regulation and maintenance services. This could be achieved by monitoring a suite of parameters, including carcass presence and persistence, meso-predators, diseases and their transmission, livestock and human diseases and associated health consequences and costs, in comparable areas with and without vultures. A multidisciplinary approach (Kelly et al., 2019; Kremer et al., 2016) including the veterinary, medical, ecological and ecological-economics sciences would unveil the indirect and direct mechanisms that mediate the regulation and maintenance services and disservices attributed to vultures. For provisioning as well as the cultural services, we suggest that gaps are addressed by embracing anthropological as well social, psychological, ecological and ecological-economics sciences. Having the contribution of these different disciplines will be key to garnering a holistic understanding of how humans perceive vultures and how they may make use of them, or how they may be negatively affected by them. This could be achieved by adopting qualitative and quantitative tools, such as questionnaires and analytical approaches, from the social sciences, for example. The evidence-base that such studies would yield could be extremely important to also mitigate threats (e.g. overexploitation) and emerging conflicts (such as those occurring on agricultural lands in several parts of the world).

4. Conclusions

Our findings highlight a large imbalance in the research quantifying links between vultures and ecosystem services and disservices. Such imbalance is not only apparent at the taxonomic and spatial level, but also across the multiple ecosystem service and disservice categories. We show that the evidence base supporting the association between vultures and key ecosystem services and disservices is lacking or weak for most specific service categories, the one exception being cultural services which were largely supported by strong evidence albeit from a limited number of studies. There is an urgent need for research to document the capacity for vultures to provide ecosystem services and disservices so that the benefits of these birds can be finally quantified and compared to the costs, and ultimately determine their net contribution to people.

Filling the above knowledge gaps is imperative for leveraging the ecosystem value of vultures at the international policy level and raising momentum for evidence-based policy decisions in favour of their conservation, such as the ban of diclofenac and other NSAIDS in South Asia. Moreover, it will expedite the incorporation of vulture ES/EDS data into

management plans working towards the sustainable development goals (https://www.sdgs.un.org/goals) and within the One Health programme (https://www.who.int/news-room/q-a-detail/one-health). Assessments of the net contribution of wildlife species to people (often based primarily on tangible costs and benefits) can be instrumental in driving conservation policy and will be similarly important for vulture conservation. However, we also advocate for wider recognition of one key cultural service, that is, the existential value of vultures, whereby justification for vulture conservation should not be limited to their capacity to provide tangible services for people. As a group of uniquely evolved species, vultures necessitate conservation as part of global efforts to halt biodiversity loss, for the sake of all species, including humans.

5. Ethics statement

No ethical approval was required for this study.

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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Authors' contributions

All authors contributed to the conception of the study and to the editing and refining of the concepts and text. All authors have read and approved the final manuscript. TC and AS lead the writing and produced the figures and tables. TC lead the literature review and analysis part, with significant input from KWT and AS.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2022.101447.

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