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Review

Limited accessibility and bias in wildlife-wind energy knowledge: A bilingual systematic review of a globally distributed bird group

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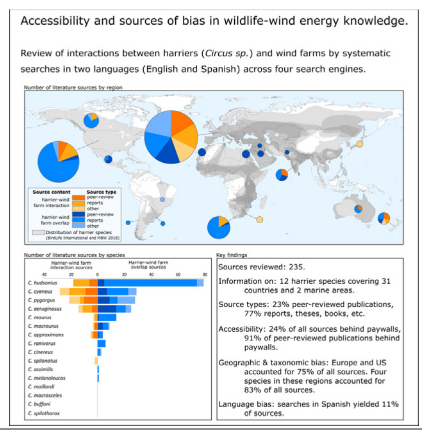
HIGHLIGHTS

- Wildlife-wind energy (WWE) knowledge is key to inform best environmental practice.
- WWE knowledge was explored with a systematic review of a cosmopolitan bird genus.
- Bilingual searches in four databases yielded 235 sources covering 31 countries.
- Availability, accessibility and bias constrain WWE knowledge and best practice.
- Implementing open practices can help align wind energy and conservation priorities.

GRAPHICAL ABSTRACT



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ABSTRACT

Wind energy is a key component of climate action strategies aimed at reducing our dependence on fossil fuels. Despite providing environmental benefits, there are increasing concerns surrounding the impact of wind farms on wildlife, with research indicating that effects on wildlife can be highly variable between species, regions, and sites. In light of this variability and the accelerating growth of the wind energy sector globally, a comprehensive understanding of wind farm effects on wildlife and ease of access to this knowledge are pivotal to inform best practice if wind energy is to become a truly sustainable source of energy. This review evaluates interactions between a globally distributed bird genus (harriers, *Circus* sp.) and wind farms to assess broader patterns in wildlife-wind energy knowledge accessibility and bias. A systematic review of grey and peer-reviewed literature across two multidisciplinary and two field-specific databases in two languages (English and Spanish) yielded 235 relevant sources, covering 12 harrier species and 31 countries. Findings indicate that harriers are considered to have high sensitivity to wind farms, with greatest impacts expected from habitat effects rather than from turbine collisions. In the broader wildlife-wind energy context, this study underscores (i) the predominance of grey literature and of sources solely documenting species-wind farm overlaps; (ii) limitations in grey literature availability and peer-reviewed publication accessibility; (iii) lack of standardized research and monitoring practices; and (iv) evidence of language, taxonomic, and geographic bias in literature sources. Overall, findings demonstrate that limited accessibility to wildlife-wind energy knowledge risks widening the research-implementation gap. Widespread implementation of open practices that allow researchers and practitioners to build on existing knowledge (e.g. national and international online repositories and databases, knowledge sharing and collaborative initiatives, open access publications) is crucial if ongoing wind energy development efforts are to be successfully aligned with conservation priorities.

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Contents

1. Introduction

Development of renewable energy sources plays a key role in efforts to mitigate human-induced climate change by reducing carbon emissions while meeting increasing energy demands (Sawin et al., 2018). Wind energy production in particular is the fastest growing renewable energy sector globally, with accelerated expansion expected in the coming decades (GWEC, 2018). Although widely perceived as an environmentally friendly energy source, the rapid increase in wind energy developments has led to growing concerns about the impact of wind farms on the environment (Dai et al., 2015), biodiversity (Rehbein et al., 2020) and effects on wildlife in particular (Schuster et al., 2015). Construction of wind farms can result in habitat loss and degradation, displacement of wildlife, direct mortality of birds and bats through collision, and population-scale consequences for wildlife through cumulative effects (Kuvlesky et al., 2007; Schuster et al., 2015). Despite increased research attention on wildlife-wind energy interactions in recent decades, substantial uncertainty still surrounds the environmental effects of these developments (Katzner et al., 2019).

Ecological impacts of wind energy have been found to be greatest on birds and bats (Northrup and Wittemyer, 2013; Schuster et al., 2015), with effects on birds in particular becoming the focus of research and monitoring efforts (Drewitt and Langston, 2006; Marques et al., 2014; Powlesland, 2009). Direct mortality of birds through collision with turbines is one of the major concerns associated with wind energy development (Marques et al., 2014), and although wind turbines are estimated to cause less fatalities than collisions with other man-made infrastructures (e.g. buildings, power lines, traffic) (Loss et al., 2015), collision rates are highly variable, site- and species-specific and can be locally high (Thaxter et al., 2017). As a result, ecological and population consequences of collision mortality are also highly variable (Herrera-Alsina et al., 2013; Thaxter et al., 2017), with no simple or broadly applicable mitigation strategy (Marques et al., 2014). Research on other impacts of wind farm construction such as habitat loss (Farfán et al., 2017; Fernández-Bellon et al., 2019; Shaffer and Buhl, 2016), displacement due to disturbance and habitat change (Dohm et al., 2019; Pearce-Higgins et al., 2009), or barrier effects for migratory birds (Cabrera-Cruz and Villegas-Patraca, 2016; Masden et al., 2009) has also found highly variable effects. The lack of uniformity in responses across different species underlines the importance of understanding the responses of individual species (or groups of similar species) to wind farms, in order to develop a comprehensive understanding of the underlying mechanisms which can then inform best practice aimed at minimizing and mitigating any such effects.

In the context of the accelerated growth of the wind energy sector, stakeholder accessibility to wildlife-wind energy knowledge is key to effectively inform different phases of the wind farm planning and development process. Collating information on the impacts of wind energy developments is not, however, straightforward (Stewart et al., 2007). Firstly, wind energy-related research and monitoring studies exist mostly as unpublished grey literature that does not undergo a peer review process and has limited availability. The largest source of wildlife-wind energy grey literature stems from work done for Environmental Impact Assessment reports (EIAs) which are required in most countries before wind farms can be granted planning permission (Glasson et al., 2013), and thus generate a vast amount of research and monitoring data worldwide. However, due to lack of motivation for dissemination and to client confidentiality clauses, EIAs often remain unpublished (Stewart et al., 2007). Secondly, despite a growing body of published research on the topic, this work is not always readily available to practitioners as it is often behind paywalls. Finally, the difficulty of accessing information from different parts of the world is compounded by language barriers (Amano et al., 2016). This is particularly true for grey literature as EIAs are often prepared in different languages across the world, complicating the search, access, and interpretation of EIAs for non-native speakers.

Here I use a systematic review of the interactions between wind farms and a group of birds with global distribution (harriers, *Circus* sp.) to evaluate broader patterns of wildlife-wind energy knowledge accessibility and bias. Harriers are particularly suited to assess broader patterns in wildlife-wind energy knowledge for several reasons. Firstly, their global distribution, use of open habitats, and conservation status often makes harriers important species in the wind farm planning and EIA process (BirdLife International and HBW, 2018; Whitfield and Madders, 2006a). Secondly, although early assessments considered harriers to have low sensitivity to displacement and susceptibility to collisions (Whitfield and Madders, 2006a), more recent work has questioned these findings (Stanek, 2013), exemplifying the uncertainty surrounding wind farm effects on wildlife (Katzner et al., 2019). Thirdly, a systematic review with a concise taxonomic focus is representative of searches for information conducted by practitioners (i.e. stakeholders focus on particular species that are considered by local legislation and regulations), thus presenting an ideal opportunity to assess broader patterns in stakeholder access to wildlife-wind energy knowledge. Finally, the ecological similarity between all harrier species (Simmons and Simmons, 2000) makes it possible to investigate genus-wide patterns and provides a global perspective which would not be possible for species or groups with a more restricted distribution. Review results were maximized by performing systematic searches for peer-reviewed and grey literature across two general and two field-specific databases. Performing searches in English and in Spanish (the language overlapping with the largest number of harrier species globally) expanded search content and enabled assessment of the potential bias of single-language searches. The specific aims of this study were to (i) gain insight into the availability of and accessibility to wildlife-wind energy knowledge with particular focus on assessing geographical, taxonomical and language-related sources of bias, and (ii) collate information and identify patterns and gaps in existing knowledge of the interactions between harrier species and wind energy developments.

2. Methods

2.1. Study species

Harriers are diurnal birds of prey of the Accipitridae family belonging to a genus of worldwide distribution (*Circus*) comprised of 16 species, some with overlapping ranges (BirdLife International, 2019). They are distinctive, medium-sized raptors, with broadly similar ecological traits: all species are dimorphic and ground-nesting, characterized by their slow, low foraging flights over open habitats (e.g. marshes, grasslands and moors), where they hunt small mammals and birds (Simmons and Simmons, 2000). Eleven harrier species are experiencing global population declines, and three are listed on the IUCN Red List of Threatened Species (BirdLife International, 2019). Furthermore, many of the species not considered to be globally threatened are of conservation concern at country or regional scales (Del Hoyo et al., 2019). Loss of natural habitats represents the main conservation threat to harriers worldwide. Specifically, the loss and transformation of nesting and foraging habitats caused by agricultural intensification, drainage of wetlands and marshes, and land use changes to grasslands. Persecution and poisoning are also considered to be serious threats to some species in some regions (BirdLife International, 2019).

2.2. Literature searches

The systematic search to collate available information on harrier-wind energy interactions from both peer-review and grey literature followed Pullin et al.'s (2018) guidelines on systematic reviews in conservation. Specifically, I used a range of Boolean search terms to search four databases: the ISI Web of Knowledge (URL https://webofknowledge.com) as a source of peer-reviewed literature; Google Scholar (URL https://scholar.google.com) as a source of both peer-reviewed and unpublished grey literature; and two field-specific repositories of wind energy-related knowledge: the Tethys (URL https://tethys.pnnl.gov/knowledge-base-wind-energy) and the AWWIC (American Wind and Wildlife Institute Information Center; URL https://awwic.nacse.org) databases. Tethys is a knowledge database supported by WREN, an initiative aimed at facilitating international collaboration between stakeholders and knowledge sharing of environmental effects of wind energy (Copping et al., 2017), while AWWIC is a database of publicly available literature on wind energy and wildlife in North America (AWWI, 2019). Following Coppes et al. (2019), search terms were selected to cover all harrier species (i.e. '*Circus*', 'harrier') and terms relevant to wind energy developments (i.e. 'wind', 'energy', 'turbine', 'farm'). The following six combinations of these terms were used to perform searches in ISI Web of Knowledge and Google Scholar: '*Circus* AND wind* AND energy*', '*Circus* AND wind* AND turbine*', '*Circus* AND wind* AND farm*', 'harrier* AND wind* AND energy*', 'harrier* AND wind* AND turbine*', 'harrier* AND wind* AND farm*'. As Tethys and AWWIC only hold wind energy-specific literature, searches on these databases were restricted to the terms '*Circus*' and 'harrier*'. Similar systematic searches were performed in Spanish. For searches in Spanish I used terms relating to harrier species (i.e. '*Circus*', 'aguilucho') and terms relating to wind energy (i.e. 'energía', 'parque', 'eólico/a', 'aerogenerador') in the following combinations: '*Circus* AND energía* AND eólic*'; '*Circus* AND parque* AND eólic*', '*Circus* AND aerogenerador*', 'aguilucho* AND energía* AND eólic*'; 'aguilucho* AND parque* AND eólic*', 'aguilucho* AND aerogenerador*'. Searches in Spanish of Tethys and AWWIC simply used the terms '*Circus*' and 'aguilucho*'.

All searches were performed between September 2nd and 4th 2019 using web browsers in 'private' mode to prevent the influence of previous browsing history or location on search results. Language was set to Spanish for searches in this language (this option was only available for Google Scholar searches). Some searches yielded more than 40,000 results. However, the first 200–300 results are considered to be adequate for systematic reviews of grey literature (Haddaway et al., 2015) and preliminary examination of search results indicated a drop-off to near-zero in frequency of relevant results beyond the first 150 results. Therefore, only the first 250 search results (sorted by 'relevance') were assessed for searches exceeding 250 search results.

2.3. Initial selection of search results

For each search (total of 32 searches in two languages across four databases) literature sources were selected according to relevance. To determine source relevance, I searched the entire text for the words '*Circus*' and 'harrier'. If these terms were mentioned in relation to existing or prospective wind energy developments the source was considered to be relevant. Duplicate sources (i.e. sources assessed in a previous search) were ignored in subsequent searches. Sources in languages other than English or Spanish were also assessed using the Google translate (URL https://translate.google.com/) option for translating full documents. For sources where the full text was not available, (e.g. only citation information available), searches were performed for the source on all other search databases and on the general Google search engine (URL https://www.google.com/). If the source remained unavailable, relevance was determined based on the title and abstract.

2.4. Further searches, classification of sources and review of information

Once all searches and initial selection of relevant sources were completed, information on harrier-wind energy interactions from each source was reviewed. References to previous studies and bibliographies of all relevant sources were searched for further relevant literature. Sources that referenced another study but provided no new information were discarded in favour of the original source. Sources reviewing multiple studies to arrive at new conclusions were retained as relevant sources (e.g. sensitivity buffers based on review of home range studies). Throughout this process, sources were filtered based on version history: in some cases, multiple EIA reports for the same development, or a conference paper later published as a peer-reviewed article had been collated. In these cases, I reviewed all documents, and where the latest version contained all the relevant information, only this was retained.

The final selection of relevant sources in both languages was categorized according to content, type and accessibility. Content categories distinguished 'interaction' sources (providing new information on the interactions between a harrier species and wind energy developments) from 'overlap' sources (simply reporting the of a harrier species in areas with existing or proposed wind energy development). Source type categories included 'peer-review', 'report', and 'other' (unpublished theses, conference abstracts, and book chapters). Accessibility categories included 'paywall' (sources behind a paywall or only available for purchase, e.g. peer-reviewed publications and book chapters), 'paywall & free' (sources simultaneously hosted by publishers behind paywalls and on free repositories by authors or institutions), 'free' (sources freely available online), and 'not available' (sources for which only citation details were available).

Due to changes in taxonomy, harriers in North (*C. hudsonius*) and South America (*C. cinereus*) were until recently considered subspecies of the European *C. cyaneus* (Oatley et al., 2015). Therefore, sources from North and South America discussing "*C. cyaneus*" or "hen harrier" were considered to refer instead to the corresponding sister species in that region.

3. Results

3.1. Search results: source type and accessibility; taxonomic, geographical and temporal distribution

Systematic searches yielded a total of 235 relevant harrier-wind energy literature sources, many with information on more than one harrier species (see Supplementary Materials for full list of sources and details). Most sources were found through searches in English (n = 208), with searches in Spanish yielding 27 additional relevant sources (Table 1). The majority of relevant sources in both languages were found through Google Scholar searches (Table S1). Of the 235 relevant sources collated, nearly one third (31%) covered new information on interactions between harrier species and wind energy, while the rest solely documented the presence of harriers in areas of existing or proposed wind farms. Relevant sources were dominated by reports (60%), followed by peer-reviewed publications (23%), theses (9%), conference papers (6%) and book chapters (2%). As 181 of the literature sources reviewed corresponded to reports and other sources that have not gone through a peer-review process, these are clearly distinguished in the rest of the manuscript, with references in the text to sources other than peer-reviewed publications preceded by "*in reports and other sources*" in the corresponding citation.

Fifteen percent of all sources were behind paywalls, and a further 9% were simultaneously hosted behind publisher paywalls and on free-access repositories or institutional websites. Paywalls only existed for peer-reviewed publications, book chapters, and some conference papers. Ninety-one percent of peer-reviewed publications were behind paywalls, with only 9% (n = 5) available as open access on publisher websites. An additional 18 sources considered to be potentially relevant were not available online and were not included in the total count of relevant sources. Table S2 provides a breakdown by species, country and source type and lists references of all sources collated (n = 235) and of sources not available online (n = 18).

Relevant sources covered 12 harrier species across 31 countries and two marine regions. Four harrier species (*C. hudsonius*, *C. cyaneus*, *C. pygargus*, and *C. aeruginosus*) accounted for the vast majority of literature sources (83% of all sources, 86% of sources containing new information on interactions with wind energy; see Figs. 1 and 2). The geographic distribution of sources was also uneven, with Europe and the US alone accounting for 75% of all sources (Fig. 2). Most sources collated date from 2000 onwards (Fig. 3). Peer-reviewed publications on harrier-wind energy interactions only appear frequently from the late 2000's onwards. Although reports are frequent since the early 2000's, their numbers appear to peak between 2009 and 2014.

Literature sources containing new information on harrier-wind energy interactions covered the following topics: species' range overlap with and sensitivity to wind energy (n = 10 sources); flight behaviours, avoidance, collision risk, and mortality (n = 53 sources); displacement and effects on breeding, foraging, and migration (n = 19 sources); population scale effects (n = 6 sources). Detailed notes on these studies (key findings, methods, source type, and full references) are available in Tables S3–S6.

Table 1
Number of literature sources on harrier-wind farm interactions reviewed in this study (n = 235) by content, source type, accessibility, and search language. 'Interaction' refers to sources containing new information on harrier species' interactions with wind energy; 'Overlap' refers to sources solely documenting presence of a harrier species in areas with existing or proposed wind farms; 'Paywall & free' refers to sources hosted simultaneously by publishers behind paywalls and on free repositories by authors or institutions.

	Content		Total
	Interaction	Overlap	
By source type			
Peer-review	25	29	54
Reports	30	111	141
Other			
Theses	5	17	22
Conference papers	8	5	13
Books/chapters	5	0	5
By accessibility			
Paywall	23	11	34
Paywall & free	6	14	20
Free	44	137	181
Not accessible	–	–	18[a]
By search language			
English	72	136	208
Spanish	1	26	27

[a] Note that sources that were not accessible (n = 18) were not counted in the total number of literature sources reviewed (n = 235). Full details on all sources are available in the Supplementary material.

3.2. Range overlap and sensitivity

The presence of harriers in areas with existing or proposed wind energy developments was widely documented for 12 of the 16 harrier species (Fig. 2). For three species (*C. aeruginosus*, *C. cyaneus*, *C. pygargus*), studies at a national scale in some European countries have assessed the degree of spatial overlap between harrier species ranges and wind farms. Albeit using different methods, these studies found wind energy developments in 7–28% of the range occupied by harriers (Bright et al., 2008; Busch et al., 2017; Tellería, 2009; Wilson et al., 2017).

Assessments of the sensitivity of harriers to wind energy have been carried out for seven species and are based on reviews of existing information. Due to lack of better information, these studies often relied on different forms of inference to determine each species' sensitivity or sensitivity buffers around nests or roosts. With the exception of Madders and Whitfield (*in reports and other sources* 2006), who rated *C. aeruginosus*, *C. cyaneus*/*hudsonius* and *C. pygargus* as having "low" and "low-medium?" sensitivity to displacement, most authors coincide in considering different harrier species (*C. aeruginosus*, *C. spilonotus*, *C. maurus*, *C. cyaneus*, *C. macrourus*, *C. pygargus*) to have a "high" sensitivity to wind energy developments (Bright et al., 2008; *in reports and other sources* Bright et al., 2009; Percival, 2003; Ralston-Paton et al., 2017; Sands, 2015; Ura et al., 2017).

3.3. Flight behaviours, avoidance, collision risk and mortality

Although several of the studies reviewed report that the majority of harrier flights occur below 20 or 30 m (*in reports and other sources* Whitfield and Madders, 2006b; Bergen et al., 2012; Ura et al., 2019), some of these flights are still within the rotor sweep of smaller turbine models (Table 2). Furthermore, some studies suggest that visual estimations of harrier flight heights are subject to considerable inaccuracy (*in reports and other sources* Stanek, 2013; McCluskie et al., 2017). Average flight heights of 33–41 m have been recorded for *C. cyaneus* with the use of inclinometers, with variations in height linked to habitat, aspect and slope (*in reports and other sources* McCluskie et al., 2017). On the other hand, a recent study using high resolution GPS tags deployed on *C. pygargus*, found that over 50% of flight time was below 10 m, and only 7% was spent at rotor sweep heights of 45–125 m (Schaub et al., 2019).

Evidence of wind turbine avoidance by harriers is varied. Small-scale avoidance has been reported in proximity of turbines (50–250 m) for

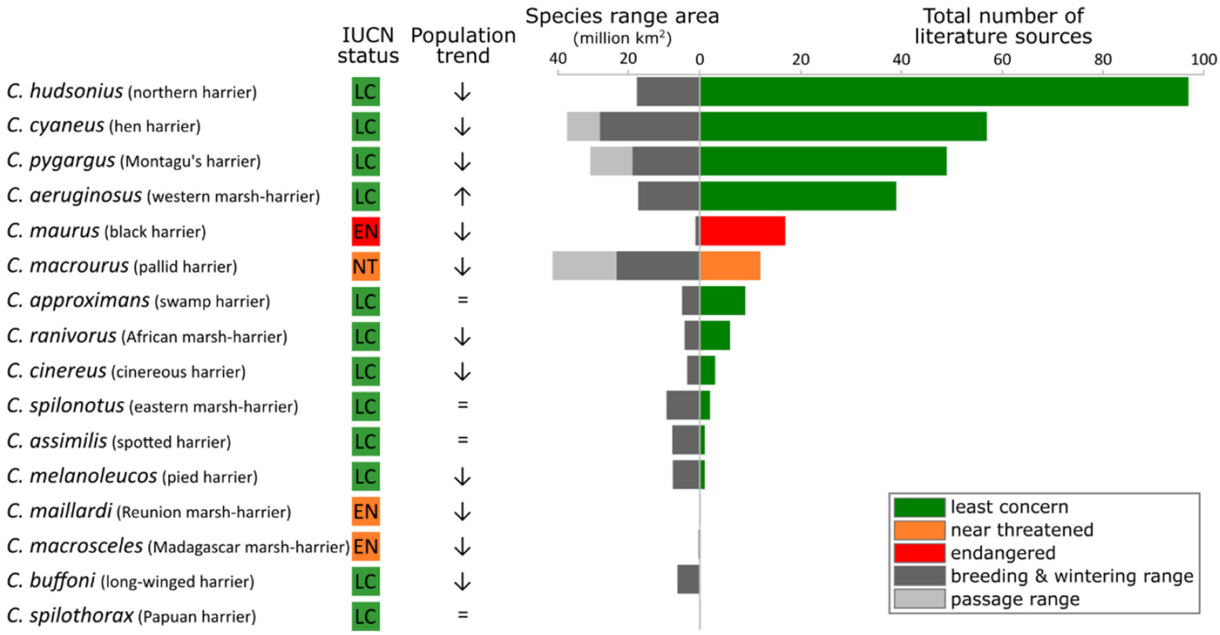

Fig. 1. Diversity of harrier species, their IUCN conservation status, population trend (increasing, decreasing, or stable), and their distribution range area (left) compared to the number of sources reviewed in this study for each species (right). Ranges indicate areas occupied by breeding and wintering birds (dark grey) and areas used during passage by migratory species (light grey). Number of sources distinguish different IUCN categories by colour. Data on IUCN status and population trends from BirdLife International (2019), data on species range areas from BirdLife International and HBW (2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

C. cyaneus and *C. hudsonius* (Pearce-Higgins et al., 2009; Smallwood et al., 2009; Smallwood and Karas, 2009; Garvin et al., 2011; *in reports and other sources* Forrest et al., 2011; Haworth and Fielding, 2012). Smallwood et al. (2009) reported that, when close to turbines, harriers switched to "travel flights" and that these types of flights occurred more frequently than in areas further from turbines. Conversely, Grajetzky and Nehls (*in reports and other sources* 2017) found no avoidance of turbines by *C. pygargus* using visual observations of flying birds. A more recent study using high-resolution GPS tags on the same species reported turbine avoidance rates of 93.5% (Schaub et al., 2019). Data from offshore wind energy is similarly conflicting, with reports of avoidance of turbines and wind farms by migrating harriers at different spatial scales (*in reports and other sources* Jensen and Blew, 2014), but also of non-avoidance (*in reports and other sources* Krijgsveld, 2014), and even of attraction to wind farms (*in reports and other sources* Skov et al., 2016, see Section 3.4).

There is considerable variability in the way collision risk estimates are calculated and reported in the literature (e.g. per turbine, per wind farm, per *n* wind farms, per MW), making direct comparisons complicated (Tables 3 and S4). Reported estimates are generally below 0.005 collisions/turbine*year, although one modelling study rates collision risk as 'high' (*in reports and other sources* de Sousa Soares, 2014) with up to 12–23 collisions/year predicted across seven wind farms in one review of multiple assessments (*in reports and other sources* Buij et al., 2017). The quality and quantity of flight data are key for accurate collision risk estimates (*in reports and other sources* McCluskie et al., 2017), leading some authors to develop methods to estimate collision risk based on energetics when flight data are lacking (Furness et al., 2016).

Reports on harrier wind turbine collision mortality are frequent in the literature, but generally from isolated studies (Table S4). The most comprehensive assessments of the extent of harrier mortality are by Dürr (*in reports and other sources* 2019) and Allison and Butryn (*in reports and other sources* 2019) who collate wind farm bird mortality data for Europe and the US respectively. Dürr (*in reports and other sources* 2019) reported 129 harrier mortalities over a period of 30 years in Europe (63 *C. aeruginosus*, 11 *C. cyaneus*, 55 *C. pygargus*), representing 0.9% of all bird and 2.6% of all raptor fatalities documented. Fatalities of *C. aeruginosus* and *C. pygargus* in particular have been linked to mortality associated with juveniles and migrating birds at migratory bottlenecks (Hernández-Pliego et al., 2015; Martín et al., 2018). In the US, Allison and Butryn (*in reports and other sources* 2019) report 19 harrier mortalities (all corresponding to *C. hudsonius*) over a 15-year period, representing 0.3% of all bird and 2.5% of all raptor mortalities documented. Elsewhere, mortality reports include *C. approximans* (nine fatalities at eight wind farms in Australia (*in reports and other sources* Smales, 2014) and 12 fatalities over two years at a 62-turbine wind farm in New Zealand (Bull et al., 2013)) and *C. maurus* (five fatalities at two wind farms (*in reports and other sources* Ralston-Paton et al., 2017)).

Where mortality reports stem from systematic carcass searches, some studies calculate mortality rates. Similar to collision rate estimates, there is considerable variability in how these values are calculated and reported (Tables 3, S4). Mortality rates appear to be in the range of values estimated for collision risks (Smallwood and Karas, 2009; Martín et al., 2018; *in reports and other sources* Smallwood, 2010), although one study reports 0.23–0.45 fatalities/turbine*year for *C. approximans* (Bull et al., 2013).

3.4. Displacement of breeding, foraging, and migrating harriers

Displacement effects of wind energy have been studied for four harrier species (*C. aeruginosus*, *C. cyaneus*, *C. hudsonius*, *C. pygargus*). Harriers have been recorded nesting successfully within 500 m of turbines (*in reports and other sources* Bergen, 2001; Fielding et al., 2011; Robson, 2011; Haworth and Fielding, 2012). Most studies have found little or no evidence of displacement of breeding birds (Hernández-Pliego et al., 2015; *in reports and other sources* Forrest et al., 2011; Grajetzky and Nehls, 2017; Joest et al., 2017; Rasran and Thomsen, 2017), but Madders and Whitfield (*in reports and other sources* 2006) suggest that displacement of nesting may occur within 200–300 m of turbines. Beyond location of nests, only two of the sources reviewed assessed wind energy effects on breeding output, but both were limited by small sample sizes. In a study of 84 nests, Fernández-Bellon et al. (2015) found apparent reductions in nest success within 1 km of turbines, albeit with only 9 nests within this distance band. O'Donoghue et al. (2011) reported reduced harrier productivity

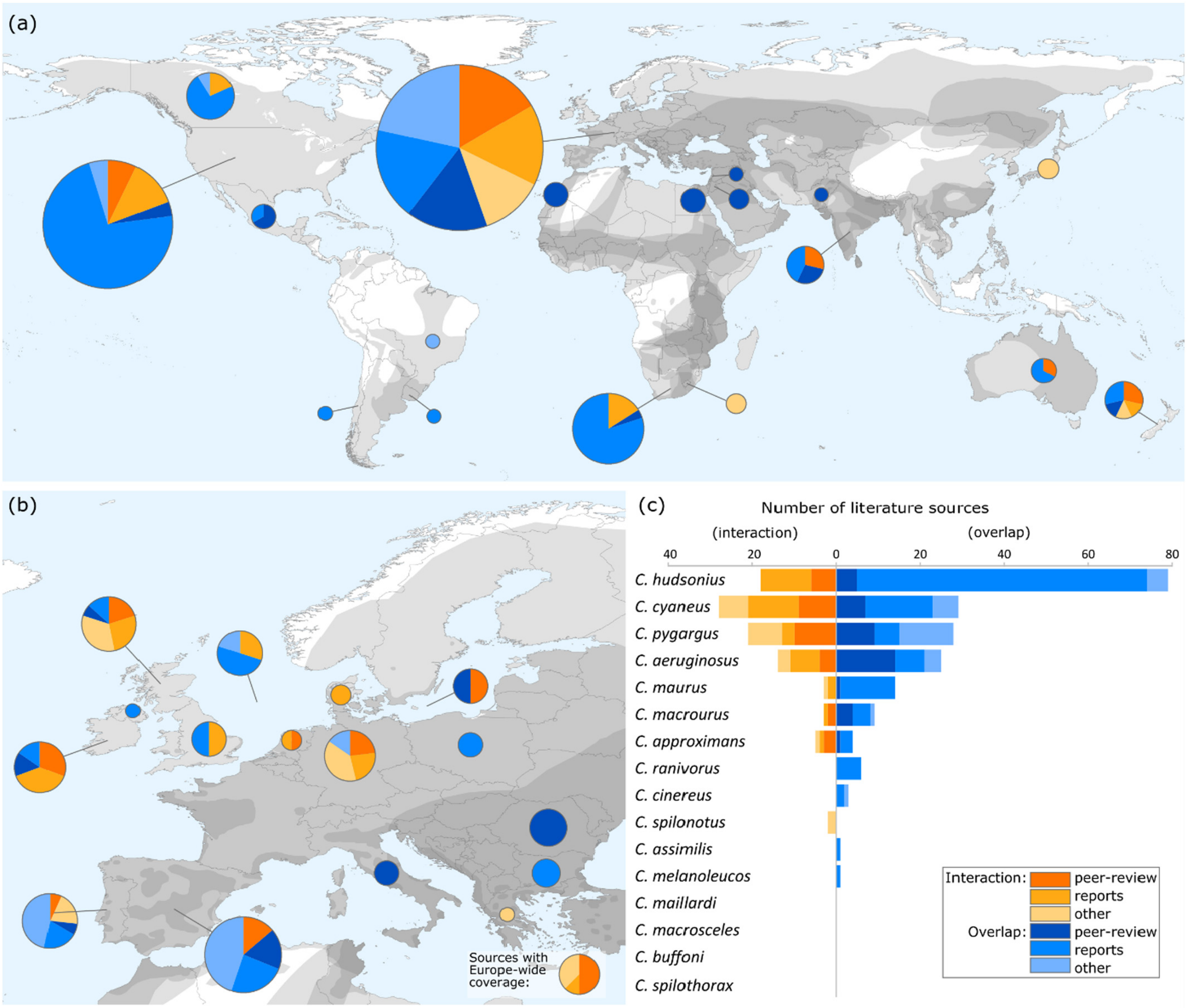

Fig. 2. Distribution of harriers (*Circus* sp.) and of literature sources on harrier-wind energy interactions reviewed in this study (n = 235) at (a) global and (b) European scales; and (c) number of different types of sources by harrier species. Maps show ranges of different harrier species in grey, darker areas indicate overlapping species (BirdLife International and HBW, 2018). Circular graphs indicate relative number (size) and proportion of 'interaction' sources in orange (sources containing new information on harrier species' interactions with wind energy) and 'overlap' sources in blue (sources solely documenting presence of a harrier species in areas with existing or proposed wind farms). Note that European sources are pooled in map (a) and broken down by country/region in map (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

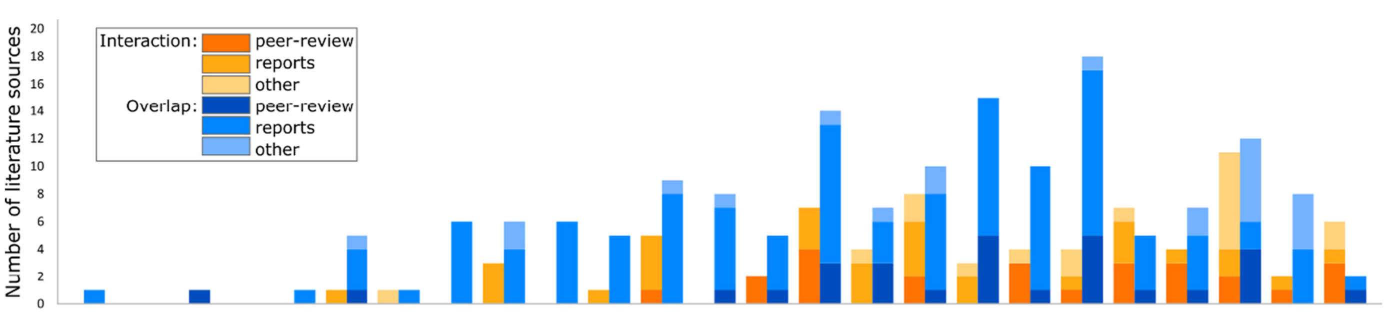

Fig. 3. Temporal distribution of literature sources on harrier-wind energy interactions reviewed in this study (n = 235). Bars indicate the number of 'interaction' sources in orange (sources containing new information on harrier species' interactions with wind energy) and 'overlap' sources in blue (sources solely documenting presence of a harrier species in areas with existing or proposed wind farms) published in a given year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Harrier flight heights in relation to wind turbines reported by the literature sources reviewed (further information on harrier flight behaviours from these and other studies is available in Table S4). Methods include visual observations (V), rangefinder (R), inclinometer (I), GPS tags (G); sample sizes are given as number of observations of harriers (obs.) or as hours of flight observations (hrs); source types include peer-reviewed papers (PR), reports (R), conference papers (C), theses (T), and book chapters (B).

Species	% flights at rotor height	Rotor sweep	Method	Sample size	Country	Source type
C. aeruginosus	46%	21–141 m	VR	36 obs.	Denmark (offshore)[a]	R
	31.9%	50–225 m	VR	46 obs.	Denmark[b]	R
C. spilonotus	28–70%	10–30 m	VR	na	Japan[c]	C
C. maurus	57%	20–150 m	V	na	South Africa[d]	R
	33%	36–171 m	–	na	South Africa[e]	R
C. cyaneus	3.6%	50–225 m	VR	12 obs.	Denmark[b]	R
	55%	na	VI	4 h	Scotland[f]	T
	11.8%	25–125 m	V	27 h	Ireland[g]	R
C. hudsonius	11%	na	V	169 obs.	US[h]	R
	10%	42–118 m	V	29 obs.	US[i]	PR
	18%	32–124	VR	149 obs.	US[j]	PR
	50%	35–130 m	V	25 obs.	US[k]	R
C. pygargus	7%	21–100 m	V	130 h	Germany[l]	B
	7.1%	45–125 m	G	944 h	Netherlands[m]	PR

References:
[a] Jensen and Blew (2014).
[b] Therkildsen and Elmeros (2015).
[c] Ura et al. (2019).
[d] Percival (2016).
[e] Ralston-Paton et al. (2017).
[f] Stanek (2013).
[g] Wilson et al. (2015).
[h] Johnson et al. (2000).
[i] Garvin et al. (2011).
[j] Wulff et al. (2016).
[k] Enk et al. (2010).
[l] Grajetzky and Nehls (2017).
[m] Schaub et al. (2019).

following wind farm construction, but this study was based on long-term monitoring of a single nest.

Displacement studies assessing changes in flight patterns and foraging indicate that displacement can occur within close proximity of turbines (Garvin et al., 2011; *in reports and other sources* Johnson et al., 2000; Whitfield and Madders, 2006a; Forrest et al., 2011), that birds may use different habitats in wind farm and non-wind farm areas (*in reports and other sources* Wilson et al., 2015), and that such effects may be long-lasting (8+ years (Dohm et al., 2019)). The underlying mechanisms of such flight or foraging displacement remain largely unexplored, with few studies focusing on wind farm effects on harrier prey species. One study found no differences in passerine densities between wind farm and control areas (*in reports and other sources* Robson, 2011), while another indicated that wind farm effects on passerine densities appear to be guild-specific and mediated by changes in land use in proximity to turbines (Fernández-Bellon et al., 2019). At a broader scale, barrier effects have been described at onshore wind farms (*in reports and other sources* Hötker et al., 2006) and for migrating birds approaching offshore wind farms (*in reports and other sources* Jensen and Blew, 2014) although other studies have reported that migrating harriers are attracted to offshore wind farms (*in reports and other sources* Skov et al., 2016). However, details on the causes or the nature of such effects are scarce in these sources.

3.5. Population-scale effects

Studies evaluating population-scale effects of wind energy on harriers have been mostly based on predictive population modelling (Buij et al., 2017; Haworth and Fielding, 2012; *in reports and other sources* Hötker et al., 2006; Masden, 2010), with only two studies assessing observed trends from long-term population monitoring (Wilson et al., 2017; *in reports and other sources* Joest et al., 2017). The latter found

Table 3
Estimated of Harrier collision risk with wind turbines and mortality rates reported by the literature sources reviewed. Source types include peer-reviewed papers (PR) and reports (R). Where original reported values were given as 'per wind farm' or 'per MW', these were converted to 'per turbine' using available information in the reference. All converted values are denoted by '*'; original reported values are available in Table S4.

Species	Collision risk (estimated collisions/turbine*year)	Source type	Mortality rate (fatalities/turbine*year)	Source type
C. aeruginosus	–		0.0037*[e]	PR
C. approximans	–		0.23–0.45[f]	PR
C. maurus	0.0033*[a]	R	–	
C. cyaneus	0.0000025* (*winter*)[b]	R	–	
	0.0024* (*summer*)[c]	R	–	
C. hudsonius	–		0.0009–0.0016*[g]	R
C. macrourus	0.0043*[d]	PR	–	
C. pygargus	0.0022*[d]	PR	–	

References:
[a] Percival (2016).
[b] Gittings (2018).
[c] Wilson et al. (2015).
[d] Pande et al. (2013).
[e] Martín et al. (2018).
[f] Bull et al. (2013).
[g] Smallwood (2010).

declines (Wilson et al., 2017) and no effects on breeding numbers (*in reports and other sources* Joest et al., 2017) in relation to wind energy. However, both studies caution of statistical limitations in their work due to limited sample sizes. Studies modelling the response of populations to increased collision mortality parameters reported projected drops in population persistence (*in reports and other sources* Buij et al., 2017) and population numbers (*in reports and other sources* Hötker et al., 2006), although other studies report that such population level effects are “highly unlikely” (*in reports and other sources* Haworth and Fielding, 2012). More elaborate modelling approaches (spatially-explicit individual based models) reported projected population declines associated with existing wind energy developments, and increased declines for scenarios where more wind farms were constructed (*in reports and other sources* Masden, 2010). These effects would be mediated by changes to habitat, rather than collision rates, and were maximized if turbines were located within 1 km of nests.

4. Discussion

This systematic review on harrier-wind energy interaction reveals a high degree of overlap between wind energy developments and different harrier species at a global scale, while also highlighting issues that are representative of the broader field of wildlife-wind energy research. Availability and accessibility to peer-reviewed and grey literature remains a major obstacle for the development of wind energy in a manner compatible with conservation priorities. Limited transfer of wildlife-wind energy knowledge widens the research-implementation gap (Knight et al., 2008), and calls into question the value of research and monitoring studies that are not widely available to researchers and practitioners (Fuller et al., 2014; Gossa et al., 2015). These issues are further compounded by lack of standardized research and data collection practices, by geographical and taxonomic biases in research focus, and by language barriers. Despite covering a larger number of sources (n = 235, 31 countries) than other taxa-specific (Coppes et al., 2019; Rees, 2012), bird (Marques et al., 2014; Smith and Dwyer, 2016; Stewart et al., 2007), or wildlife (Kuvlesky et al., 2007; Northrup and Wittemyer, 2013; Schuster et al., 2015) reviews on wind energy interactions, this study found considerable variability in the reported effects of wind energy on harriers. This study also highlights how harrier-wind energy knowledge is biased towards collision fatality studies in detriment of habitat and displacement studies, mirroring the state of affairs in the wider wildlife-wind energy literature (Allison et al., 2019).

4.1. Searches, availability and accessibility to wildlife-wind energy knowledge

Google Scholar yielded the highest number of relevant sources in this study, albeit also returning the highest number of search results and thus requiring more time and effort to filter and identify relevant sources (Table S1). Despite requiring less filtering time (i.e. fewer search results), wind energy-specific repositories (Tethys and AWWIC) only contributed a relatively small fraction of all relevant sources.

Reports were the predominant type of literature sources found by systematic searches (60% of all sources). In fact, the abundance of reports is likely to be underestimated here, due to their limited online availability. While most peer-review publications are indexed online, this is not the case of environmental impact assessment reports (EIAs), despite their widespread use in the wind farm planning process (Glasson et al., 2013). Furthermore, chronological distribution of the sources reviewed indicates a temporal lag in the online availability of EIAs compared to other sources (Fig. 3), suggesting that these are slow to be made public. For these reasons, it is difficult to precisely quantify the existing EIA literature, but it is clear that this body of knowledge could contribute significantly to wildlife-wind energy research if it was made available for meta-analysis, reviews, etc.

Searches in a second language (Spanish) yielded little additional information to this review. This is surprising as six of the 16 harrier species are found in Spanish-speaking countries, many of which have extensive wind energy developments (GWEC, 2018). The low number of relevant results in Spanish searches is easily explained for peer review publications, as most studies are generally published in English, rather than in the native language of the authors or the study location (López-Navarro et al., 2015). However, it is surprising that searches in Spanish did not yield a comparable number of EIA reports to searches in English. This seems to indicate that reports in other languages (or at least in Spanish) are simply not made available online as frequently as they are in English. It is worth noting that some languages do have extensive wildlife-wind energy literature, both as peer-reviewed publications and as grey literature (e.g. German, see Illner, 2011). However, for non-speakers, searching for and interpreting such literature remains difficult.

Another important hurdle for accessing wildlife-wind energy knowledge are paywalls. Only 9% of peer-reviewed publications reviewed here were open access. This is a serious issue as peer-review publications provide the most detailed and systematic knowledge on wildlife-wind energy interactions (Tables S3–S6). Accessibility to peer-review publications is key if developers, policymakers and other stakeholders are to use this knowledge to inform best practice (Fuller et al., 2014).

Accessibility to wildlife-wind energy knowledge is also hampered by the lack of standardization of research and monitoring practices. The use of different study designs and research approaches precludes comparison of results between studies, sites and species (Conkling et al., 2020). Standardization of research and monitoring practices is thus essential if findings are to meaningfully contribute to a global understanding of the effects of wind energy on wildlife.

4.2. Geographic and taxonomic bias in wildlife-wind energy knowledge

Literature on harrier-wind energy interactions showed significant geographic and taxonomic bias, consistent with biases in the wider wildlife-wind energy literature (Marques et al., 2014; Northrup and Wittemyer, 2013). Europe and the US accounted for 75% of all sources reviewed, while the four species found in these areas (*C. hudsonius*, *C. cyaneus*, *C. pygargus*, and *C. aeruginosus*) accounted for 83% of all sources reviewed. While this may appear to suggest that the species with the most widespread distribution generate most literature, this is not necessarily so (Fig. 1). *Circus macrourus* is one of the four most widely distributed harrier species, but was only covered by 12 sources reviewed, most corresponding to reports. On the other hand, *C. maurus* has a much smaller global range, but was covered by 17 literature sources. Altogether this suggests that taxonomic bias is likely a consequence of geographic bias (i.e. species occurring in areas where more literature is produced receive more attention).

In turn, geographic bias towards Europe and North America is only partly related to rates of wind energy development (which are widespread across the globe (GWEC, 2018)), but is likely a consequence of several other factors. Firstly, ecological and conservation research efforts are biased towards high-income regions, specifically Europe and North America (Lawler et al., 2006; Roberts et al., 2016). Secondly, as a result of geographical differences in legislation (Copping et al., 2017; Glasson et al., 2013), more wind farm EIA studies are carried out in these regions, resulting in higher rates of EIA research and publications (Yanhua et al., 2011). Thirdly, accessibility to information from some countries reflect broader concerns regarding the transfer of scientific knowledge between east and west (Doi and Takahara, 2016). Finally, due to other geographic disparities (e.g. access to online repositories, open research practices, involvement in international initiatives), it is likely that the same regions which already produce the largest amount of literature, are also better placed to make use of online repositories and open access options (Sinclair et al., 2018; Walters and Linvill, 2011). This is exemplified by the Tethys repository, where 93% of all geo-tagged wind energy content corresponds to literature from Europe and the US (WREN, 2019) and by the existence of AWWIC, a North America specific repository (AWWI, 2019).

4.3. Harrier-wind energy interactions

This systematic review demonstrates a global overlap between harrier species' ranges and wind energy developments. Sensitivity of harrier species to wind energy is generally considered to be high, with largest impacts expected from habitat effects rather than from collisions. Despite this, most work to date has focused on flight behaviours, with relatively little research on breeding and foraging displacement or on the potential underlying causes (e.g. wind farm effects on breeding output or on prey communities).

Collision and mortality rates reviewed here (Tables 3 and S4) suggest that harriers are at lower risk from mortality than other raptor species (see Marques et al., 2014 and references therein). Existing long-term data sets on bird mortality at wind farms in Europe and the US suggest that harriers account for 0.3–0.9% of all bird fatalities and 2.5–2.6% of all raptors. However, harriers can be at high risk at some sites (Bull et al., 2013; Hernández-Pliego et al., 2015; Martín et al., 2018; *in reports and other sources* McCluskie et al., 2017). This variability is likely associated with site-specific factors (Marques et al., 2014), although there are suggestions that collision rates for harrier species have been largely underestimated in the past (*in reports and other sources* McCluskie et al., 2017). New technological developments which improve flight path and height data collection will contribute to more accurate avoidance rate and collision risk estimates (e.g. Schaub et al., 2019), and allow for evaluation of patterns specific to sex, age, or migratory behaviours.

Studies assessing displacement effects of wind energy on harriers are limited. There appears to be little evidence for displacement of breeding birds, but most studies report constraints from small sample sizes. Furthermore, effects on breeding output remain largely understudied. Displacement of flying and foraging birds has received more attention (partly due to its relevance to assess avoidance behaviours and collision risk), suggesting that harriers do indeed avoid areas in close proximity of turbines (Dohm et al., 2019; Pearce-Higgins et al., 2009; Smallwood et al., 2009). Reduced passerine prey in these areas may perhaps be an underlying mechanism of such behaviours (Fernández-Bellon et al., 2019), though further work is required to understand the effects of wind energy developments on harrier prey populations.

Population-scale effects of wind energy are equally poorly understood. Few studies have assessed population trends in relation to wind energy developments, and these have been unable to draw clear inferences between harrier demographics and wind farms (Wilson et al., 2017; *in reports and other sources* Joest et al., 2017). Modelling approaches have also been used to assess population-scale effects of wind energy, predicting population-scale consequences of increased mortality due to collisions (*in reports and other sources* Hötker et al., 2006; Buij et al., 2017). More elaborate modelling studies have also found negative effects of wind energy for harrier populations but have linked these to habitat effects rather than to collision mortality (*in reports and other sources* Masden, 2010).

5. Conclusion

This review underscores the urgent need for promoting open practices in wildlife-wind energy research and monitoring that should be encouraged and implemented by different stakeholders, including governments, policymakers, developers, environmental consultants, and researchers. This review highlights three types of knowledge that would benefit from such open research and publication practices: EIA reports, peer-reviewed publications, and wildlife-wind energy data.

EIA reports represent the largest source of wildlife-wind energy knowledge, and thus making them available and accessible to stakeholders should be a priority. This can be encouraged by governments and policymakers by making publication of these reports in international online repositories (e.g. Tethys) part of requirements of the wind farm planning process. As non-peer-reviewed sources of information, increasing their availability can facilitate subsequent incorporation of data from EIA reports into peer-reviewed studies. For its part, peer-reviewed knowledge should similarly strive to increase availability and accessibility to all stakeholders. As peer-reviewed publications are not subject to regulation, it is up to researchers themselves to promote open-science approaches. Where open access is not a viable option, researchers should routinely make copies/preprints of publications freely available online in repositories used by practitioners (e.g. Tethys, AWWIC), as well as on academic or institutional repositories. Standardized approaches for research and monitoring, and for collation and centralization of data can also improve our understanding of wildlife-wind energy interactions, facilitate data sharing, and prevent misreporting the effects of wind energy (see for example how Wang et al. (2015) misreport collision mortality rates, massively understating values reported by Dürr (2019)). Initiatives to standardize collation of data (e.g. collision fatality databases by Dürr (2019) and by Allison and Butryn (2019)) can benefit from government and institutional support (e.g. funding, online hosting services) and from expanding to cover other geographical areas, as well as to other aspects of wildlife-wind energy interactions.

In the specific case of harrier-wind energy interactions, this review highlights several avenues for future work. Research incorporating the application of new technologies to understanding flight behaviours can help reduce uncertainty surrounding visual observations of flight heights and tracks. Displacement, likely the largest impact of wind energy development on harriers, requires more attention. Research should aim to include studies on displacement (e.g. changes in nest locations and flight patterns in response to wind farms) but also on other habitat effects (e.g. effects on breeding output and prey populations). Another largely unexplored approach is maximizing the value of existing data collected for other purposes, for example by taking the opportunity to use population-monitoring data (from national surveys, etc.) to study and disentangle the effects of wind energy developments on harriers at the population scale. Finally, this review underscores the amount of data that has been amassed on harrier species specifically in relation to wind energy in the last decades. Despite this, many studies report sample size limitations. Collaborative studies, involving different stakeholders and sources of data, may be the only way to address such limitations, and can be an important first step towards promoting open research practices.

Declaration of competing interest

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