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RESEARCH ARTICLE

Biodiversity, Planning and Development

Biodiversity biases in research and practice: Lessons from the Irish onshore wind sector

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Abstract

1. Alongside increases in renewable energy developments associated with climate change mitigation efforts, there has been increasing recognition of the role of biodiversity in mitigating and adapting to climate change. Environmental Impact Assessment Reports (EIARs) document potential impacts of proposed new developments on a broad range of environmental factors, including biodiversity, and propose actions to alleviate those impacts. More recently, addressing trade-offs between developments of infrastructure for climate mitigation and biodiversity impacts in EIARs is becoming increasingly important. However, biodiversity may be measured in many ways, impacts may be taxon-specific and there can be survey biases towards particular species and taxonomic groups. It is, therefore, important to consider what is included in EIARs, and to understand the extent to which the taxonomic focus of EIARs aligns with published scientific research evidence.
2. Here, we systematically review both ecological surveys conducted in EIARs of granted windfarm applications in Ireland between 2000 and 2021 and the scientific literature examining the impacts of onshore windfarms on biodiversity.
3. We found that EIARs in the early 2000s examined a considerably more diverse range of animal and plant groups than the scientific literature at that time. This divergence in focus diminished through time as both EIARs and the scientific literature captured a more diverse range of taxa. However, taxa and impacts with low prominence in the scientific literature were also surveyed less frequently in EIARs, highlighting that understudied taxa and biodiversity impacts are at risk of being underestimated or undetected at the development stage.
4. *Practical implication*. We conclude that explicit comparison of the two-way link between scientific literature and EIARs can aid in identifying knowledge gaps and assessment of the broader impacts of renewable energy developments, helping both to inform appropriate mitigation for biodiversity impacts and to inform policymakers.

KEYWORDS
biodiversity, ecological surveys, renewable energy, science-practice gap, wind energy

1 | INTRODUCTION

Globally, there is a critical need to substantially reduce emissions of greenhouse gases to mitigate the impacts of unimpeded climate change (IPCC, 2023). At the same time, we are faced with an accelerating biodiversity crisis and need equally urgent action to prevent further biodiversity loss (IPBES, 2016). Accordingly, there is increasing appreciation that we must avoid putting further pressure on biodiversity as we act to mitigate climate change (Gorman et al., 2023). The transition to renewable energy sources is critical to meeting emission reduction targets to mitigate climate change (Potrč et al., 2021). Though renewable energy installations are known to have negative consequences for some species (Rehbein et al., 2020), some of these impacts can be effectively mitigated throughout the development, operation and decommissioning stages (Gorman et al., 2023). Mitigation measures should be identified and planned for in the early stages of a new development. Planning documents are often the first assessment of the potential impact of a proposed development. As such, they play a significant role in decision-making and can also inform post-planning management actions (Glasson et al., 2012).

Wind energy generated from onshore turbines is one of the most widely used sources of renewable energy around the globe (Gielen et al., 2019). Globally, the wind energy sector has been expanding rapidly (International Energy Agency, 2022) requiring land-use change to accommodate new renewable infrastructure. The development of windfarms can, however, have negative (e.g. Arnett et al., 2015; Helldin et al., 2012) as well as positive (e.g. Pustkowiak et al., 2018; Xu et al., 2019) consequences for terrestrial biodiversity, if appropriate management and mitigation measures are in place. Wind turbines themselves can affect above- (Arnett & May, 2016; Schuster et al., 2015) and below-ground biodiversity (Łopucki et al., 2018; Velilla et al., 2021). Associated infrastructure, such as roads and substations, contribute to the overall impacts of wind energy generation. The biodiversity impacts of windfarms vary throughout the stages in their lifespans (i.e. construction, operation and decommissioning). For example, research has shown that habitat displacement can occur during windfarm construction. This can be short term for some species (da Costa et al., 2018) but, for others, such impacts can last throughout the operational phase as a consequence of, for example, operational noise (Klich et al., 2020; Łopucki et al., 2017). Habitat alterations surrounding turbines can also have positive impacts on biodiversity, introducing heterogeneity and resulting in increased pollinator populations (Pustkowiak et al., 2018). During the operational phase, collisions of volant species with turbines, particularly birds and bats, have been highlighted at windfarms across the globe (Arnett & May, 2016), with negative consequences for populations (Duriez et al., 2023) and ecosystems (Thaker et al., 2018). In addition to direct impacts on biodiversity, windfarms can have broader environmental impacts through modifying, for example, the microclimate (Armstrong et al., 2016), water quality (Heal et al., 2020) and peatland stability (Lindsay & Bragg, 2005), with knock-on consequences for biodiversity.

Effective mitigation of the negative effects of wind farms on biodiversity requires a comprehensive understanding of potential impacts. Appropriate action at the development and planning stages provides the best opportunity to avoid many potential negative impacts (Dai et al., 2015). For example, early windfarms in the United States of America were subject to large numbers of bird collisions post-construction due to poor siting and a lack of pre-construction impact assessment data (Smallwood & Thelander, 2008). This led subsequent windfarm developments to include bird surveys in the siting stages of planning (Wang & Wang, 2015). Later, bats were also included in surveys due to the identification of collision impacts during operational surveys for birds at windfarms (Kuvlesky et al., 2007). Applying knowledge gained during planning and operational surveys can, therefore, be critically important for protecting biodiversity. Avoidance is best practice for reducing impacts of renewable energy on biodiversity. Knowing what species are present on sites and how they might be impacted is essential (Arnett & May, 2016).

Environmental Impact Assessment (EIA) is a global systematic process that utilises project descriptions and environmental baselines to predict and identify potential impacts of developments, while also encouraging public consultation (Glasson et al., 2012). EIAs are a tool to aid management decisions for a wide range of developments and they are also used to develop environmental management plans post-planning in some countries (Glasson et al., 2012). All European Union (EU) Member States are required to produce an Environmental Impact Assessment Report (EIAR) when a construction project or new development is likely to have a significant effect on the environment due to its size and nature (Council Directive 92/43/EEC, CONSIL, 206 OJ L, 1992). In the case of onshore windfarms, an EIAR is required when a development is over 5 MW capacity or consists of five or more turbines (Section 172 Planning and Development Act, 2000 [Government of Ireland]). In some circumstances, where deemed to have potential impact on the environment, a windfarm planning application that is below the above thresholds may still require an EIAR at the request of the planning authority (Articles 103,120 Planning and Development Regulations, 2001 [S.I. No. 600/2001]). EIARs must assess the potential for impacts on biodiversity as well as several other components of the environment, such as land, soil, water and cultural heritage. There has, however, been significant criticism surrounding the EIA process, in terms of its success at both predicting and mitigating impacts (Jay et al., 2007), and the extent of its inclusion in the decision-making process (Loomis & Dziedzic, 2018).

European Union legislation, together with findings of scientific research, informs the biological and environmental surveys that are included in EIARs to identify potential impacts on biodiversity at a proposed development (Drayson et al., 2017). The EIA Directive (2014/52/EU) references that biodiversity should be incorporated into the assessment, with specific reference that there should be a focus on species and habitats included in the Habitats Directive (Directive 92/43/EEC) and Birds Directive (Directive 79/409/EEC). Reviews of EIARs have found that many species may be omitted from EIA surveys (Drayson et al., 2017) and, moreover, that the magnitude of impacts is often underestimated (Briggs & Hudson, 2013; Lintott et al., 2016). The presence of undetected or unconsidered

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TABLE 1 Boolean operators and search terms used in our systematic literature review on biodiversity impacts and wind energy. The Boolean operator 'OR' was used between synonymous search terms for wind energy. The Boolean operator 'AND' was used between these search terms and taxonomic search terms. Taxonomic search terms are organised by our focal taxonomic groups.

Boolean operator	Search term (windfarms)	Boolean operator	Taxonomic group	Search term
OR	Wind farm	AND	Bats	Bat
	Wind farms			Bats
	Windfarm			Chiropteran
	Windfarms		Birds	Bird
	Wind energy			Birds
	Onshore wind farm			Avifauna
	Onshore windfarms		Herpetofauna	Herpetofauna
	Onshore wind energy			Reptiles
				Amphibians
			Invertebrates	Invertebrate
				Invertebrates
				Insect
				Insects
			Mammals	Mammal
				Mammals
			Vegetation	Vegetation
				Plant
				Plants

species and/or impacts at a site can lead to a lack of mitigation for these species and impacts, contributing to biodiversity decline (Davy et al., 2021). Evidence of impacts and—critically—scientific understanding of mechanisms of impact is, therefore, very important to ensure EIARs appropriately identify the potential for impact at early stages so that appropriate mitigation can be put in place.

Here, we investigate the relationship between scientific research on the biological impacts of windfarms and biodiversity assessments in EIARs, with a view to identifying the extent to which taxa included in EIARs correspond to those identified as impacted in published research, using the wind energy sector as a case study. We expect that, if taxa and/or impacts were understudied in the scientific literature, and not protected under legislation, they would also receive poorer survey effort during windfarm development. To address this, we first conducted a review of scientific articles that examined the impacts of onshore windfarms on biodiversity across six focal organism groups (i.e. bats, birds, herpetofauna, invertebrates, mammals and vegetation). We then conducted a systematic search of available EIARs in Ireland over a >20-year period and assessed variation in the linkages between both sets of data. We focused on the Republic of Ireland as it is one of the leading countries in generating capabilities for onshore wind energy in Europe (SEAI, 2023).

2 | MATERIALS AND METHODS

We surveyed the global scientific literature by systematically searching for papers that examined the impacts of onshore windfarms on biodiversity from 2000 to 2021 (inclusive), using Clarivate's Web of Science database and Google Scholar. We used the search terms 'biodiversity impacts', 'wind farm(s)', 'wind energy', 'onshore wind farms' and used the following categories to group focal organisms: bats, birds, herpetofauna, invertebrates (categorised separately into above-ground, below-ground and volant), mammals and vegetation. These categories were based on the typical headings used in Irish EIARs. A full list of search terms is provided in Table 1. We also recorded the primary cause of impact in each study (e.g. direct collision, vibration, etc.), were reported.

In tandem, we conducted a systematic search of available windfarm EIARs in Ireland. Planning applications are submitted on a local (county-scale) basis. There are over 300 windfarms in the Republic of Ireland (Wind Energy Ireland, 2023), thus providing an ample and searchable dataset. Biodiversity or ecology chapters of EIARs are a standard EU planning document under the Environmental Impact Assessment Directive (Directive 2011/92/EU, as amended by Directive 2014/52/EU). The Directive requires that projects deemed likely to have significant effects on the environment produce an assessment to identify and assess direct and indirect significant effects of a proposed development on biodiversity, with particular attention to the species and habitats protected under the Habitats (Directive 92/43/EEC) and Birds Directives (Directive 79/409/EEC). As part of the planning application, these documents are publicly accessible and provide an opportunity to understand potential impacts that may be prioritised in early development. Mitigation measures and other protection measures may be put in place by operators following operational surveys. However, survey data collected during the

TABLE 2 Definitions of the survey methodology used in ecological EIAR chapters to survey across six focal taxonomic groups (i.e. bats, birds, herpetofauna, invertebrates, mammals and vegetation).

Nature of survey	Definition	Example(s)
None	No surveys conducted for the focal taxonomic group/no mention in EIAR	—
Scoping	Taxonomic group mentioned, information on species presence was attained using remotely obtained data	Public databases were searched for records and/or for determining likely habitat suitability from remote imagery and understanding of species ecology
Opportunistic	No planned or focused surveys conducted but the presence or evidence of presence of taxa was noted during site visits	Opportunistic recording of presence of tracks/signs of focal group(s) when on site during targeted surveys of other groups
Field-based	Specific, targeted surveys conducted for the focal taxonomic group	Vantage point surveys for birds of prey. Acoustic recorders placed on site to identify bat presence

operational phase is at the discretion of individual windfarms and is often not publicly available; hence, we focused our data collection efforts on pre-planning ecological EIAR chapters.

We collected EIARs on windfarm planning applications from every county in Ireland, using the terms 'wind farm', 'windfarm' and 'wind turbine' in search of eplanning.ie, a platform that facilitates the search of Irish planning documents through relevant county council websites. We restricted our results to onshore windfarms where planning permission had been granted (including both conditional and unconditional permission) from 2000 to 2021. For each EIAR, we reviewed the chapters pertaining to biodiversity and/or ecological survey information and collected data on the taxonomic groups that were surveyed and the survey methodology. Survey methodology was grouped into one of four categories (see Table 2 for category descriptions).

2.1 | Data analyses

We quantified the diversity of the taxonomic groups reported in the literature and EIARs using Shannon's Diversity Index (Shannon, 1948). We used a linear model with an interaction term (year × source) to test whether diversity varied over time between the two data sources. Our linear model was based on the null hypothesis that the diversity of the taxonomic groups was the same between the two sources over time. The model was fit using the lm() function in R version 4.2.2 (R Core Team, 2022). Model assumptions were checked using residual diagnostics. Data were visualised using the 'ggplot' (Wickham, 2016) and 'ggrepel' (Slowikowski, 2023) packages in R version 4.2.2.

3 | RESULTS

Our global literature search identified 124 scientific articles relating to the impacts of onshore windfarms on biota from 2000 to 2021 (Table S1). There were no geographical search restrictions, and published literature was found across five continents (Figure 1a), with most from Europe (48%, 59/124 papers; Figure 1b). Eighteen papers (15%) incorporated results from multiple countries. A full list of studies and their geographical locations is provided in Table S1.

Within the scientific research identified in our survey, seven general categories of impact were described across our focal taxonomic groups: collision with wind turbines, habitat alteration and loss, proliferation of invasive species, increased stress (via, e.g. increased levels of stress hormone cortisol, or corticosterone), reduced reproductive output, alterations to food webs (e.g. species impacted due to a change in food web or a cascading impact across the food web) and behavioural changes. Early studies (2000–2007) of potential windfarm impacts accounted for just under 10% of the total number of papers in our survey, with studies focusing primarily on collision impacts on birds and invertebrates, and behavioural change in mammals. Collision was the most recorded type of impact in our review overall (52% of studies, 64/124 papers) and research grew notably in this area from 2008 onwards (Figure 2a). This is reflected in a surge in the literature on impacts on volant taxonomic groups, such as birds and bats, from 2008. Habitat alteration was also a common impact category studied in the literature from 2008 onwards (32% of studies, 36/112 papers from 2008 to 2021). This focused largely on birds, but there were also some studies on mammals and vegetation. More recently, a wider variety of impacts were studied across a greater range of taxa (Figure 2a). From 2016, all six of our focal taxonomic groups were consistently represented in the literature. Moreover, these studies also incorporated a broader diversity of impacts. Though studies of collision impacts remained a priority in studies from 2016 to 2021 (49% of studies, 36/73 papers), focusing primarily on bats (56% of studies of collision impacts, 20/36 papers), research into all five of the other categories of impact together made up the remainder of these more recent studies (51%, 37/73 papers).

Our survey identified 336 granted windfarm applications, of which 138 (41%) provided an EIAR with an uploaded and accessible ecology chapter. A total of 622 surveys were reported in those applications, with substantial variation among them in the taxa prioritised (Figure 2b). The reasoning for surveying vegetation provided in most EIARs was to provide context on the landscape of the proposed development, in the absence of an Irish national land cover map prior to 2023. Field-based surveys were the most common methodologies

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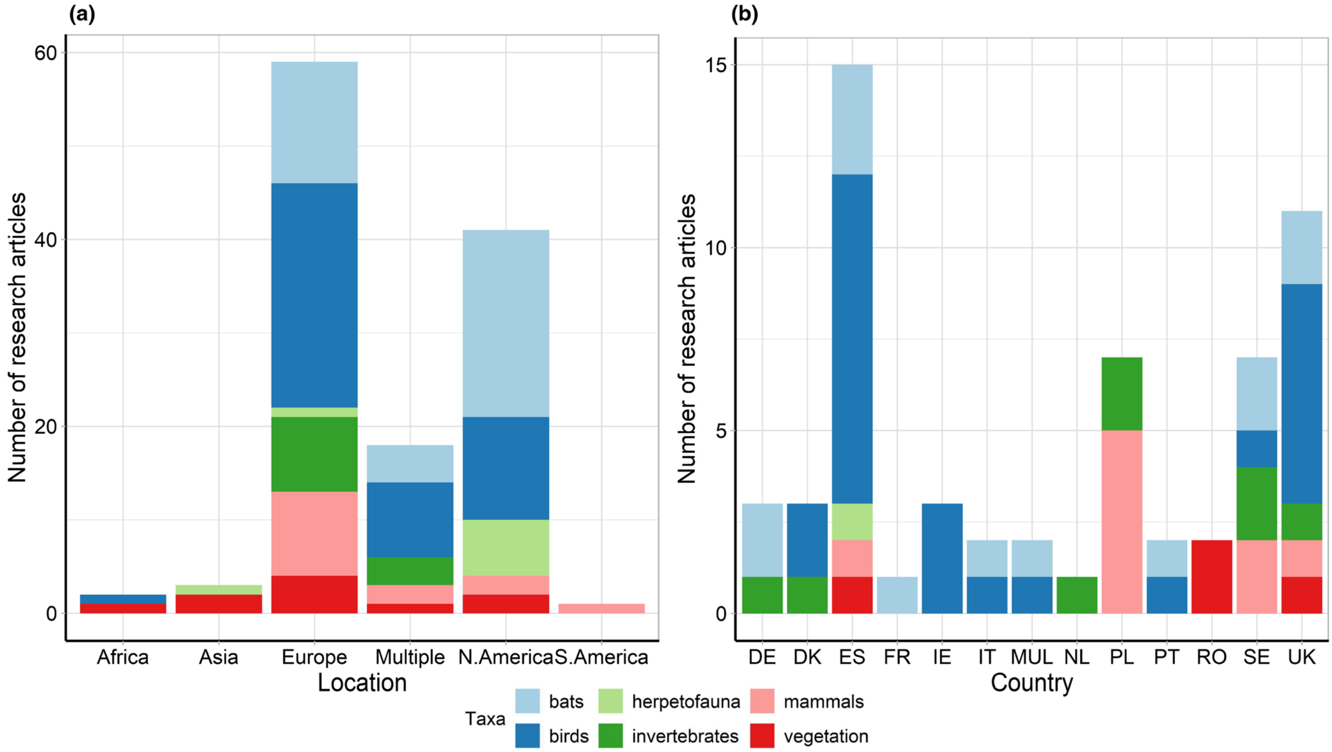

FIGURE 1 Geographical spread of published scientific research relating to impacts of onshore windfarms on biota from 2000 to 2021 across continents (a) and countries in Europe (b). Multiple (MUL) refers to research that includes results across multiple countries or regions: DE—Germany; DK—Denmark; ES—Spain; FR—France; IE—Ireland; IT—Italy; NL—Netherlands; PL—Poland; PT—Portugal; RO—Romania; SE—Sweden; and UK—United Kingdom. We highlight results for Europe as this is the region in which our case study on EIARs is from. Ireland had only three scientific research publications identified in our survey relating to onshore wind impacts on biodiversity, all of which focused on birds.

used (57% of reports, 354/622 surveys), followed by opportunistic (33%, 205/622 surveys) and scoping (10%, 63/622 surveys) methods. Early EIARs had an uneven distribution of survey methods across taxa but this distribution is changing and becoming more even over time. Recent EIARs are implementing field-based surveys more widely and equitably across groups, with field-based methods accounting for 47% (20/43) of surveys from 2000 to 2003 but 81% (17/21 surveys) by 2020–2021.

Birds were surveyed in all EIAR chapters reviewed predominantly using field-based methodologies (86%, 119/138 surveys). Field-based surveys were dominated by a focus on vegetation and birds with occasional inclusion of other groups until 2010, when all six of our focal taxonomic groups started to become more represented in EIARs. Herpetofauna were the taxonomic group surveyed most using opportunistic methods (88%, 71/88 herpetofauna surveys), in addition to mammals (65%, 87/134 mammal surveys). There were 49 surveys of invertebrates and the majority of these were also done using opportunistic methods (67%, 33/49 invertebrate surveys). Although invertebrates were originally further categorised into volant, above-ground and below-ground groups, there were insufficient studies and papers to analyse each group separately, and some surveys did not specify which group was included. Scoping surveys were the most inconsistent methodology used in EIARs, and from 2017 onwards, no scoping surveys were reported. Bats were the taxonomic group surveyed most frequently using scoping methodologies in Irish EIARs (30/55 bat surveys).

The taxonomic focus of both the scientific literature and EIARs has changed considerably over time (Figure 3a,b). From 2000, the taxonomic coverage of both scientific literature and environmental impact assessment has increased notably, with consistent and more evenly distributed taxonomic coverage in EIARs relative to scientific research, while the latter also shows notable year-to-year variation in focus (Figure 3). The taxonomic diversity included in both the scientific literature and in EIARs has increased significantly over time ($t = 3.4$, $p = 0.001$; Table S2). However, the rate of this increase differs between these data sources (interaction between Data Source and Year: $t = 4.47$, $p < 0.001$; Table S2; Figure S1), with taxonomic diversity increasing more steeply over time in the scientific literature compared to the EIARs, though from a lower baseline (Figure 3c).

4 | DISCUSSION

While the global scientific literature and EIARs from Ireland both diversified over time in relation to the taxa and range of impacts included, this diversification took place much earlier and more comprehensively in EIARs. Both datasets were, however, similar in the

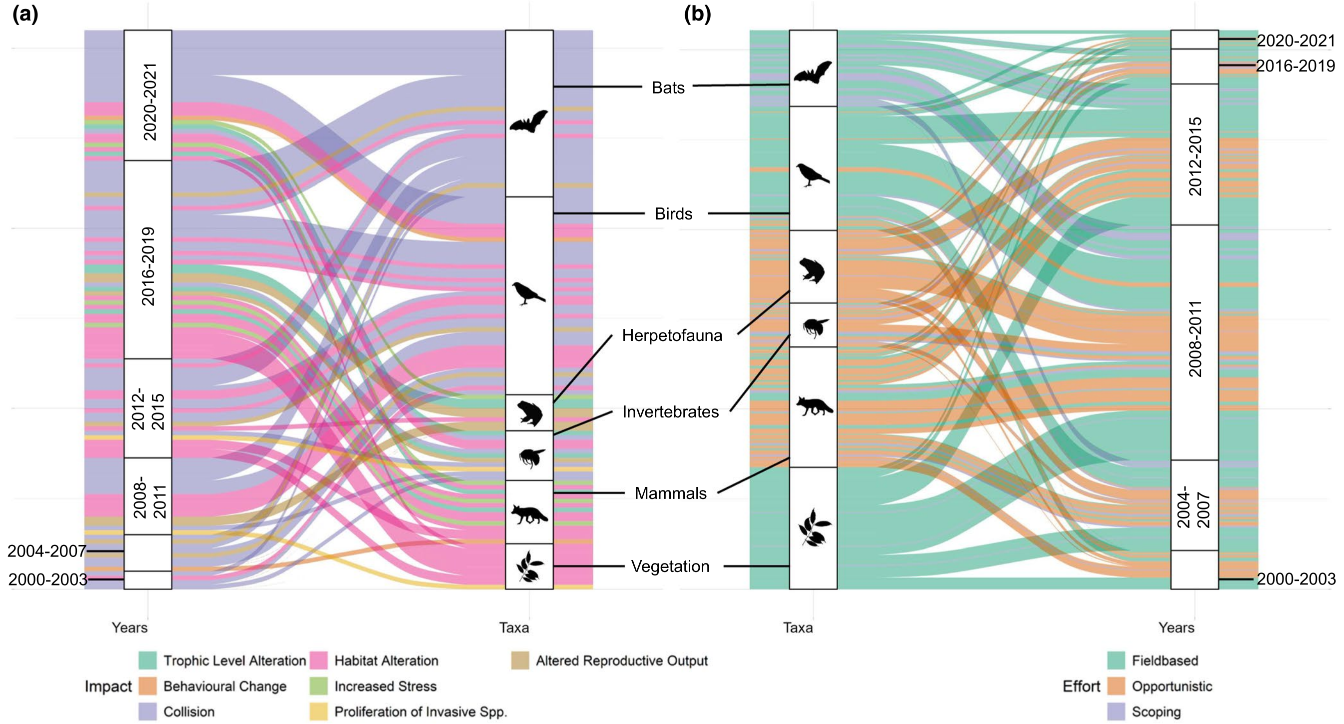

FIGURE 2 Variation over time (2000–2021) in studied taxa and impacts of onshore windfarms on biodiversity from the global scientific literature (a) and the taxa targeted in Irish EIARs through different survey methods (b). Segments on the vertical axes represent categories (years and taxonomic groups) and are proportional in size to the number of published studies ($n=124$) or surveys ($n=622$). In both plots, the number of research articles and EIARs has increased through time. In the scientific literature (a) the number of research articles focusing on birds and bats is greater than that of other taxonomic groups, while in EIARs (b), the number of surveys is more consistent across the taxonomic groups.

taxonomic groups that were most or least frequently included; birds were the most frequently included group in both datasets, while invertebrates and herpetofauna were included least frequently. This adds support to our initial expectation that if a taxonomic group or impact is well studied in the literature, it will also be well represented in ecological surveys for EIARs. Conversely, where a group or impact remains understudied in the literature over time, it also tends to receive less attention in ecological surveys.

Our finding that EIARs from the early 2000s had greater taxonomic coverage than the scientific research at that time indicates that there are other drivers of inclusion for ecological surveys in EIARs. As well as scientific research, legislative requirements, ecological knowledge and established survey guidelines are also key drivers of inclusion of species in EIARs (Briggs & Hudson, 2013). Guidelines developed by the Chartered Institute of Ecology and Environmental Management (CIEEM), which are cited in many Irish windfarm EIARs, have been a driver of change since their first publication in 2006 (Drayson et al., 2015). These guidelines make reference to the importance of published scientific information and promote its inclusion in the EIAR process (CIEEM, 2018). Despite this, EIARs often contain survey methodology that is not up-to-date with the standard in the scientific literature (Singh et al., 2020). The reasoning for this could be a lack of standardised methodologies for biodiversity surveys (Gontier et al., 2006), unclear and broad requirements of the EU Habitats Directive (Council Directive 92/43/EEC) and/or resource constraints within the ecological consultancy setting (Treweek, 1996). While both policy and guidelines are influential drivers of taxonomic inclusion in EIARs (Briggs & Hudson, 2013; Drayson et al., 2015), both will benefit from incorporating up-to-date scientific research.

This study is limited somewhat in spatial context in that the EIARs reviewed were restricted to Ireland, though they are compared against the global literature and restricting our analyses to European scientific literature does not change our conclusions (Figure S2). Language barriers, resource constraints and variable accessibility of EIARs led to us restricting our EIAR review to Ireland. Our search of the scientific literature returned only three studies from Ireland, all of which studied impacts on birds. Even so, the Irish EIARs were more diverse in the number of taxonomic groups included compared to the global literature, which aligns with the findings of EIAR surveys from both France (Bigard et al., 2017) and England (Drayson et al., 2017). This indicates that differences in taxonomic coverage and diversity between EIARs and scientific research have been underestimated in our reviews. Regions with higher species richness than Ireland, which is relatively low in biodiversity (Cerqueira et al., 2015), may have higher diversity in their EIARs compared to the Irish reports. The EIARs were also more consistent in what was studied over time compared to the global literature, where attention focused primarily on birds and bats, with occasional inclusions of other taxonomic groups.

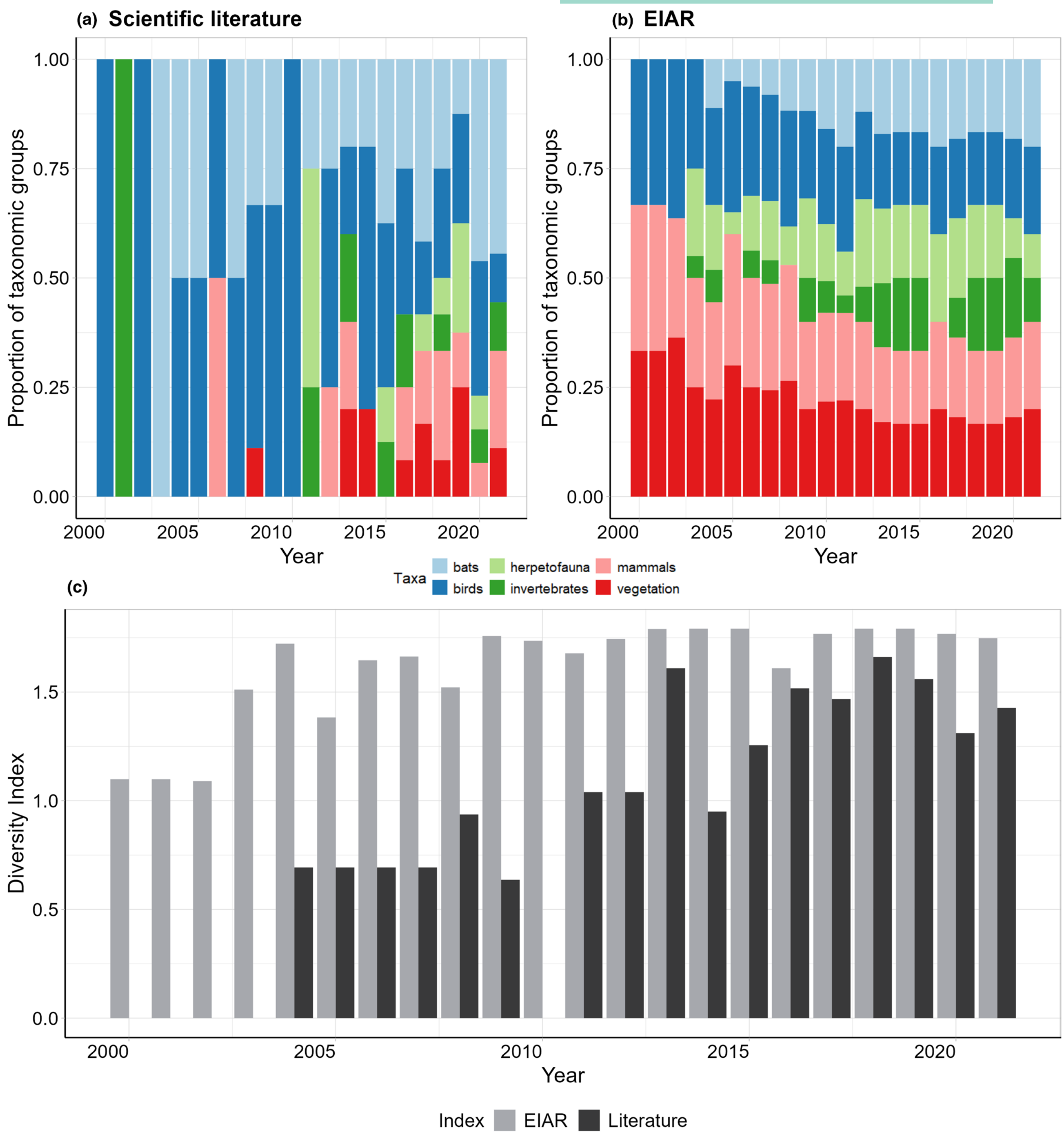

FIGURE 3 Relative taxonomic focus of scientific literature (a) and EIARs (b) over time (2000–2021), and the (Shannon) diversity of the taxonomic focus in the scientific literature and EIARs (c). Only one taxonomic group was found to have been studied in our literature survey for the years 2001, 2002 and 2010, and thus diversity was zero in those years.

These findings of our scientific literature review are consistent with the taxonomic bias observed more broadly in conservation (Clark & May, 2002; Tkach & Watson, 2023; Toomey et al., 2017), research funding (Adamo et al., 2022; Mammola et al., 2020) and ecology (Bonnet et al., 2002; Culumber et al., 2019). Birds and, to a lesser extent, mammals tend to be over-represented in the literature relative to their species richness, whereas herpetofauna and invertebrates are typically underrepresented (Bonnet et al., 2002; Mammola et al., 2023). Thus, in addition to collision being an obvious and serious impact for the onshore wind energy sector, explaining much of the focus on volant animals, the dominant focus on these groups also reflects in part more general biases in biodiversity research (Adamo et al., 2022; Mammola et al., 2020; Troudet et al., 2017). Reviews have described a minimal reduction in bias over time (Clark & May, 2002; Fabian et al., 2019). This contrasts somewhat with our finding that the taxonomic diversity is rising relatively rapidly over time, particularly compared to EIARs. Regarding impacts studied, publication bias may contribute to the larger volume of scientific literature on direct, obvious mechanisms of impact (e.g. collision) where a significant effect is more likely (Koricheva, 2003; Rosenthal, 1979), compared to indirect impacts (e.g. habitat loss, behavioural changes), which can be harder to identify and attribute to the windfarm specifically, or due to the difficulty in measuring such impacts.

Ireland has greatly increased its reliance on wind energy since its first windfarm development in 1992 (Wind Energy Ireland, 2023), with capacity increasing steadily over time (SEAI, 2023). Thus, it provides a meaningful case study of rapid increase in demand for EIARs over the past 20 years. Growing demand for wind energy has led to the expansion of windfarms into a range of habitat types across Ireland (Hallan & González, 2020), and this provides an opportunity for new species that may need to be included in EIARs. Variation in taxonomic diversity across years in EIARs could be representative of the environmental context in which approved windfarms were set, and the changes in such contexts over time. Additionally, Ireland is a member state of the EU, and must, therefore, follow legislation and directives regarding planning permission for large developments, which applies to all member states. The EIAR process is also a common development assessment globally (Morgan, 2012). There are, however, some results from the EIARs that reflect the context of the study's setting. For example, vegetation was frequently surveyed in EIARs to provide landscape context for the EIAR, rather than to examine potential impacts to vegetation caused by infrastructure unless it was specified explicitly for a species present within the proposed development listed on the Floral (Protection) Order 2022 (S.I. 235/2022) or was within a habitat listed in Annex I of the Habitats Directive (Directive 92/43/EEC). This further highlights how, if an impact is not obvious, it can be overlooked even if there is scientific evidence for impact (Urziceanu et al., 2021).

Legislation can, however, play an important role in inclusion in impact assessment (Bigard et al., 2017). We could not account for the legal status of species in our data analysis due to the broad taxonomic groupings used, and the difficulties in quantifying the number of species of certain groups in Ireland (e.g. invertebrates). However, we can see that our findings of birds and mammals occurring more frequently in EIARs reflect the proportions of legal status across Ireland's 232 protected species (European Environment Agency, 2020). Birds had the highest proportion of protected species, accounting for 74% of protected species in Ireland, primarily due to the impact of the Birds Directive (Directive 79/409/EEC) (European Environment Agency, 2020). Mammals had the next greatest share of protected species (14%), and all of Ireland's nine bat species are protected under the Habitats Directive (Directive 92/43/EEC) (European Environment Agency, 2020). Invertebrates, specifically arthropods, account for less than 1% of Ireland's protected species (European Environment Agency, 2020). This aligns with our finding that invertebrates are typically not represented in EIARs. Other studies have documented similar gaps between scientific information, policy and application (Bigard et al., 2017; Knight et al., 2008). Our findings are not, therefore, unique to Ireland, and similar outcomes would be expected in other countries.

Though we quantified the breadth of taxonomic focus in EIARs, we could not quantify robustly how the survey effort for each taxonomic group specifically changed over time. This was because EIARs varied in consistency of reporting on survey effort and, in many cases, survey effort could not be determined. Though taxonomic coverage of EIARs increased over time, the survey methodologies employed remained largely consistent (Figure 2b). Mammals and invertebrates, for example, remained primarily surveyed using opportunistic methods, even as the number of surveys increased. Bats were the exception, as early reports primarily surveyed through scoping. Legislative protection and increasing knowledge of their ecology in Ireland (Roche et al., 2007) have led to increased employment of field-based assessment methods. Additionally, the use of technology is becoming an increasingly popular method of surveying elusive species such as bats (Gibb et al., 2019; Stephenson, 2020), and continuous improvement of open-source identification software (e.g. BirdNET; Kahl et al., 2021, NEAL; Gibbons et al., 2023) can improve the implementation of surveys for such species in planning assessments.

Scientific understanding has been described as a limiting factor for improving ecological EIARs (Briggs & Hudson, 2013; Drayson et al., 2017). Similar relationships, described as the 'science-practice gap', have been well documented in other areas, including landscape ecology (Opdam et al., 2001), land management (Burbidge et al., 2011) and nature conservation in general (Knight et al., 2008). Many tools, frameworks and methods have been suggested to better incorporate science into practice, and make it more accessible for practitioners (Bertuol-Garcia et al., 2018; Cooke et al., 2021). Such recommendations are, however, from practitioners' perspectives, often ineffective or unproductive (Hulme, 2014). In the context of our study, the general perception of the science-practice gap emphasises that the link between scientific research and planning assessments is a one-way relationship, in which scientific findings form the basis for inclusion in ecological planning assessments. In this view, research that is not disseminated to a large audience or that is difficult to access will not be incorporated into EIARs easily. Instead, taking a different perspective and approaching the knowledge transfer between scientific information and EIARs as a two-way feedback loop can enable the identification of gaps in both knowledge and implementation, ultimately aiding alignment of both. Such a two-way view, in which science informs inclusion in planning assessments and planning surveys reciprocally inform research needs, could contribute to overcoming the 'science-practice gap' by encouraging open communication between researchers and practitioners and facilitating knowledge sharing (Gorman et al., 2024). A two-way link is beneficial not only to acknowledge both general gaps but also specific mechanisms of impact. Often impacts on a taxonomic group tend to be neglected when the mechanism behind a potential impact is cumulative, nuanced or less discernible (Gontier et al., 2006). For example, collisions tend to be obvious because there is often direct evidence attributable to the presence of wind turbines. However, impacts such as behavioural change or changes to reproductive output are more nuanced and can often have numerous factors contributing to them. Going further, the development of a two-way link between researchers and practitioners can contribute to going beyond understanding impact into developing and co-designing solutions to mitigate and avoid potential impacts to enhance the coexistence of biodiversity and wind energy.

Developing and maintaining a two-way link between scientific research and practitioner action will require transparency, data sharing and open communication. Barriers to maintaining such relationships have been identified in similar fields and include the inaccessibility of scientific publishing to practitioners, while other formats of dissemination are often not acknowledged in scientific publishing culture (Fabian et al., 2019). Additionally, there is often little time available for both practitioners and scientists to assign to communicating and sharing information in current formats and, according to practitioners, scientific research often does not align with their actual knowledge requirements (Cvitanovic et al., 2016). More inclusive collaboration between industry, practitioners and scientists is clearly needed. An open, accessible platform for knowledge sharing where both scientists and practitioners can upload and share knowledge and findings would aid in bridging the communication gap. Currently, there are databases for both scientific research on wind energy and wildlife impacts (e.g. American Wind Wildlife Institute, n.d.; Tethys, n.d.) and for practitioner knowledge on the topic (e.g. CANWEA, n.d.), highlighting that there is a willingness to participate in knowledge sharing. Currently, however, these and similar initiatives are separate (i.e. either for EIAR data only or scientific articles) and not aligned, furthering the one-way perspective on scientific research and practitioners' knowledge. Combining databases and making data sharing efficient and standardised could provide an essential connection between all parties and ensure knowledge sharing is a two-way link. Such a platform could also support decision-support tools and host communication platforms so that knowledge gaps are identified, and research needs met. Given that legal protection status is a key driver of inclusion in EIARs, policy can play an important role in contributing to solving this science-practice gap.

Ultimately, our study shows that the scientific literature and EIA practice have both diversified in the breadth of their taxonomic coverage and impacts included over time but are not yet fully coherent. Taxa and impacts that were least prominent in both groups are at risk of remaining understudied or undetected over time. Identifying knowledge gaps through enhanced collaboration between scientists, practitioners and stakeholders is essential to ensure correct mitigation is in place to ensure meaningful and impactful solutions that simultaneously address both the biodiversity and climate crises.

AUTHOR CONTRIBUTIONS

Emma King and Ian Donohue conceived the ideas and designed the methodology; Emma King collected and analysed the data; Emma King and Ian Donohue led the writing of the manuscript. Courtney E. Gorman, Jane C. Stout and Yvonne M. Buckley assisted with drafting the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data collected and code produced are accessible and have been archived along with the analysis code on Github at https://doi.org/10.5281/zenodo.17288734 (King, 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Scientific literature of windfarm impacts on biodiversity included in the literature review and subsequent comparison with the Environmental Impact Assessment Reports. Asterisks highlight studies located in the same country as the EIAR case study (Ireland).
Table S2. Results of linear model for Shannon Diversity of EIARs and Scientific literature over time.
Figure S1. Linear trends in the diversity of both the scientific literature (purple line) and EIARs (blue line) over time (2000–2021).
Figure S2. Relative taxonomic focus of European scientific literature (a) and EIARs (b) over time (2000–2021), and the (Shannon) diversity of the taxonomic focus in the scientific literature and EIARs (c). Only one taxonomic group was found to have been studied in our European literature survey for the years 2001, 2002 and 2010, and thus diversity was zero in those years.

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