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Review article

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Impacts of onshore wind energy production on biodiversity

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Abstract

Wind is increasingly used as a renewable source of energy worldwide. However, harvesting wind energy can have negative consequences for biodiversity. In this Review, we summarize the growth of onshore wind power, its impacts on species and ecosystems, and how those impacts are assessed and mitigated. Across the construction, operation and decommissioning stages, wind facilities are associated with wildlife fatality and behavioural change as well as alteration, loss and fragmentation of terrestrial and aerial habitat. These negative consequences can be mitigated by avoiding construction of wind turbines at sensitive sites, detecting and deterring wildlife, curtailing turbines to reduce fatalities, and replacing lost habitats. Uncertainty about wildlife populations and their demographic parameters, the rate and extent of build-out of onshore wind energy, and best practices for mitigation, as well as variability in regulatory requirements by country or region, all contribute to the difficulty of predicting the consequences of this technology for biodiversity. Scenario-based modelling that incorporates population- and community-level consequences to biodiversity from varying degrees of wind energy development – including the cumulative effects of multiple facilities – is key to addressing this uncertainty.

Sections

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Key points

- Wind energy is a growing source of electrical power, but it can have negative effects on biodiversity.
- Asia has the most wind energy, followed by Europe and then the USA; the rest of the world supports <10% of installed capacity of wind energy.
- Biodiversity impacts from wind energy can occur at all stages of a wind facility's life cycle — including planning, construction, operation and decommissioning.
- Although fatalities are perhaps the best-known impact from wind turbines, turbines can also alter the behaviour of wildlife and cause loss, alteration and fragmentation of habitat.
- Mitigation of these impacts can include strategically placing turbines to avoid negative interactions (avoidance), encouraging wildlife to steer clear of turbines (deterrence) and replacing animals or habitats lost to turbines (compensation).
- Despite many uncertainties regarding wind energy's impacts, the available evidence can inform scenario-based modelling to assess both the consequences of this energy source for biodiversity and how its implementation compares to potential impacts from climate change.

Introduction

Electricity generation through operation of utility-scale wind turbines ('wind power') is expanding rapidly worldwide[1]. Although wind power can offset or mitigate carbon emissions and potentially reduce the consequent effects of climate change on organisms[2], it can also kill flying organisms (such as birds, bats and insects), change behaviour, physiology and demography, and alter ecosystems[3]. With this conflict in mind, the Convention on the Conservation of Migratory Species of Wild Animals of the United Nations Environment Program called for the conservation needs of migratory species to be integrated into national climate and energy policies and into regulations governing the planning of new energy infrastructure[4].

Given the risks to wildlife and that the regulatory implications of wildlife fatalities can impede or restrict efforts to construct and operate wind power facilities, attention has turned to identifying ways to mitigate harmful effects[5,6]. Actions such as informed macro- and micro-scale siting of wind power facilities, curtailment (suspending turbine operations when activity is highest for vulnerable species), detection and deterrence of volant (flying) wildlife, and compensatory mitigation measures (offsetting negative effects via restoration or protection in other areas) aim to reconcile biodiversity conservation and energy production. However, these tools have been applied inconsistently[7–10].

A growing body of research illustrates that the effects of utility-scale wind energy production can be far reaching and sometimes have large and unexpected consequences for biodiversity[11–13]. Furthermore, achieving renewable energy targets will require converting large areas of land to support wind power facilities[14], and new wind facilities are often located in remote and high-biodiversity areas[15]. In the face of an ongoing biodiversity crisis[16], understanding the impacts across the extensive land areas required for wind turbines demands a nuanced consideration of multiple factors that extend beyond ecology and draw from diverse fields, including economics, climate science and sociology. For example, bat fatalities at wind turbines are rarely put into the context of economic losses caused by losing important ecosystem service providers[17–20]. Impacts of wind energy on biodiversity are also rarely assessed in the context of net outcomes or scenario-based comparisons[21]. Likewise, regulatory and political considerations often determine impacts of renewables on biodiversity, and a host of factors, including transboundary considerations, climate change denial, changing perceptions of the value of biodiversity and its protection[22], and economic considerations (that vary in developed and developing countries), all can influence perceptions of how wind turbines affect biodiversity.

In this Review, we document the current state of onshore wind power and its projected worldwide growth, followed by a summary of the current understanding of the various ways wind power affects biodiversity. We focus on four main categories of effects: changes in ecosystems, changes in weather that affects those ecosystems, changes in wildlife behaviour, and fatality. Finally, we discuss the mitigation hierarchy that is, or could be, used to reduce or offset negative effects. Throughout the Review, we discuss how variability in legal and regulatory environments affects outcomes of impacts and mitigation[23,24]. We conclude with thoughts on future directions and on how policy and regulatory considerations could influence the effects of wind power on biodiversity.

History and projected growth of wind energy

The first windmills for electricity generation were built in Denmark and the USA at the end of the nineteenth century[25]. The sudden rise in oil prices following the oil crisis in the 1970s incentivized investment in renewable energy sources[25]; this investment resulted in the construction of the world's first large-scale wind facility, in California (USA) in the late 1980s[26], and an increasing role of wind in the global energy sector. By the year 2000, Europe accounted for more than 70% of the global wind market, followed by North America and, to a lesser extent, Asia and the Pacific[27]. Growth in wind power historically was slower elsewhere, with few facilities outside these regions. However, by 2009, Asia developed enough wind power that it had equalled North America's installed capacity[26].

In the past two decades, wind power has experienced rapid development worldwide[28], with, as of June 2025, an estimated 17,960 operating onshore wind power facilities with a total capacity of ~1,000 GW (ref. 29). Asia has the largest installed capacity, with 50.5% of world production from >6,300 facilities, mostly concentrated in China (Fig. 1). Europe is next, with 22.1% of world production from >6,900 facilities, mainly in Germany, followed by Spain[30]. North America has 19% of installed capacity, mainly in the USA (~1,400 facilities). Central America, South America and the Caribbean contribute about 5.8% of the world's wind power capacity (~1,100 facilities). Growth in wind power has been slower in Oceania and Africa, which generate about 1.5% (~126 facilities) and 1.1% (~99 facilities) of global wind energy production, respectively[29].

These current trends can be extrapolated to future projections using the current operational capacity ratio (that is, current capacity/(current capacity + prospective capacity)). The development of the onshore wind industry over the next 5 years is expected to be driven mainly by China, Europe and the USA[31] (Fig. 1). In addition, the Central and South America region has a growth rate of 35%, with marked progress largely due to Brazil, which remains the leading regional country in onshore wind capacity owing to its rapid development over the past decade.

Wind power is anticipated to have a central role in the global production of energy during the ongoing transition from fossil fuels to renewable sources[28,29,32]. The Paris Agreement climate change treaty of 2015 and the 28th United Nations Climate Change Conference[33] called for the tripling of global wind power capacity by 2030 (ref. 31), with similar targets at national and supranational levels[34]. Under the current scenario of implemented energy, climate and industrial policies, onshore wind power generation is projected to grow from 5% of global power generation in 2022 to 10–15% by 2050. This projection would increase to more than 50% of global power generation by 2050 under a zero-emissions policy scenario[28].

The declining monetary cost of wind energy generation projected in coming years, fuelled by policy support, is expected to facilitate further growth[28]. This growth is particularly important for many lower-income countries, where high initial investments and economic constraints are major barriers to growth of renewable energy[35] and where research on impacts of renewable energy is less well developed (Fig. 1e,f). In this sense, emerging economies such as Southeast Asia, Central Asia and the Middle East and North Africa are expected to accelerate the growth of the onshore wind sector from 2026 onwards. China, Europe and the USA are projected to remain the largest market leaders in the near term, accounting for 80% of total production by 2028, while Central and South America will see steady growth in new installations, driven primarily by Brazil, Chile and Colombia[31].

Life cycle impacts of wind energy on biodiversity

The development and operation of a wind power facility is a multiphase process, involving, at a minimum, planning, manufacturing of turbines, construction, operation and decommissioning

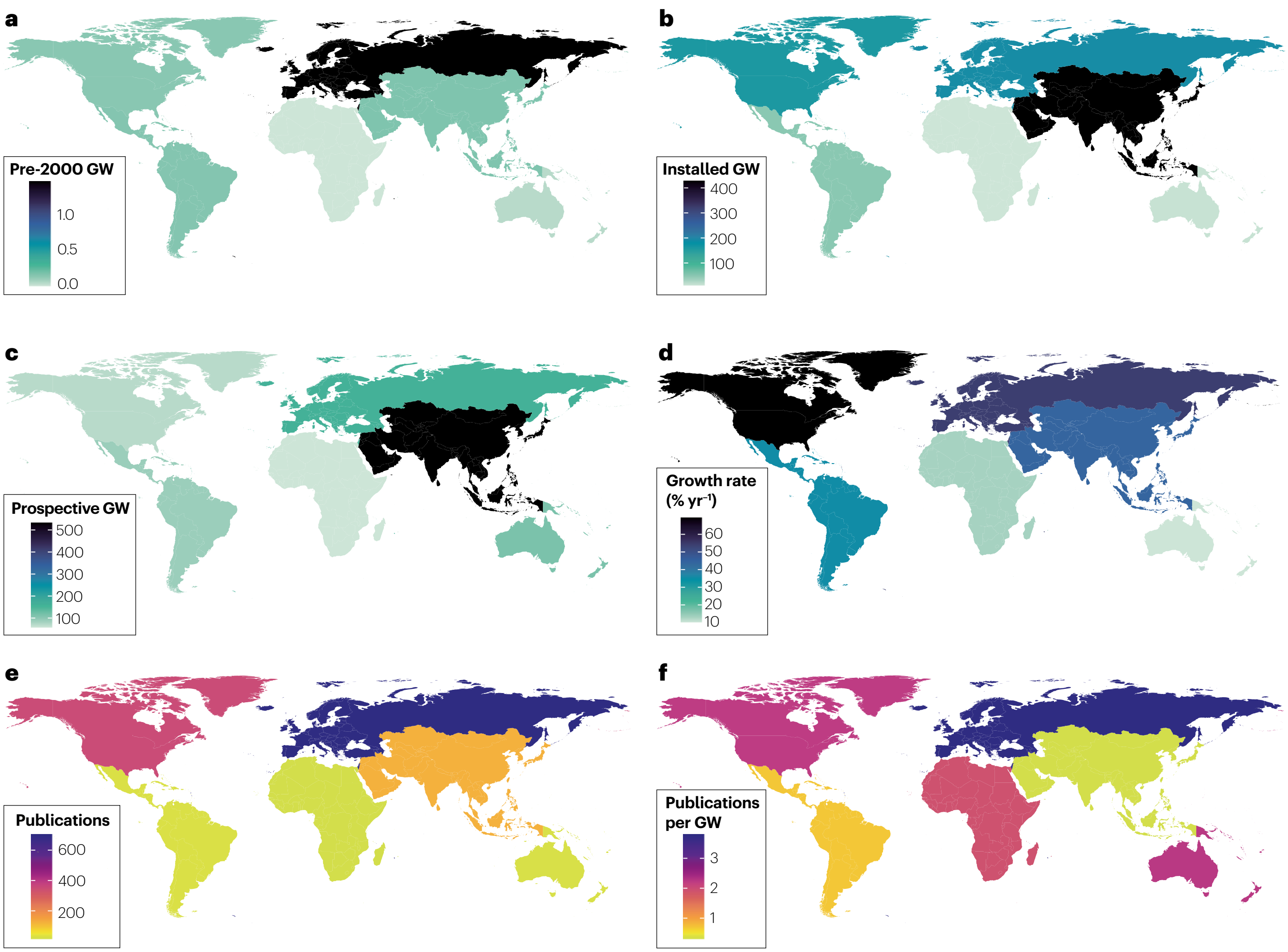

Fig. 1 | Onshore wind energy globally. a, Gigawatts (GW) installed before the year 2000. **b**, GW installed through 2024. **c**, Prospective (planned and under construction) GW. **d**, The current rate of growth (growth rate = operational GW/(operational GW + prospective GW) × 100). **e**, The number of publications per region on wind–wildlife interactions. **f**, The number of publications per installed GW wind energy per region. Wind energy data in panels **a**–**d** are derived from Global Wind Power Tracker[29] and are resolved to the level of continents. See the Supplementary Information for methods on deriving the number of publications per region.

Table 1 | Range of documented or potential biodiversity impacts of wind energy facilities across life cycle phases

Process	Planning	Manufacturing	Construction	Operation	Decommissioning
Terrestrial habitat alteration and loss	U	P	D	D	U
Aerial habitat alteration	U	P	P	D	U
Weather change	U	U	U	D	U
Carry-over effects of weather changes	U	U	U	D	U
Behaviour — avoidance	P	U	D	D	P
Behaviour — attraction	U	U	P	D	P
Fatality — turbine collision	U	U	U	D	P
Fatality — vehicle strike	P	U	P	D	P
Fatality — infrastructure	U	U	D	D	P
Overall documentation	Limited	Limited	Moderate	Extensive	Limited

D: documented effect (see main text for applicable reference(s)); P: possible effect based on expert opinion of the authors; U: unlikely. Columns are phases of development: planning includes both desk work and field surveys, and impacts are local, on-site; manufacturing is off-site and includes primarily effects of resource extraction on habitat; construction includes transportation to site and on-site road-building and other impacts; operation includes regular operation and maintenance; decommissioning involves breakdown and transportation of waste materials. Carbon emissions and pollution are associated with each phase but are not shown here given the focus on impacts on species and ecosystems.

(phases defined in Table 1). Impacts on species and ecosystems can occur across each of these phases, with some impacts occurring only during a subset of phases[36].

Tools to address the full life cycle impacts of wind facilities are not fully developed. The available life cycle assessments (that is, formalized studies of impacts over the life of the wind turbine) have focused primarily on greenhouse gas emissions rather than consequences for biodiversity[37–39]. Currently, the effects of wind power on biodiversity are most thoroughly explored for the construction and, especially, the operation stages, whereas limited information exists about effects on biodiversity during the planning, manufacturing and decommissioning stages[40]. Despite the research gaps, it is reasonable to draw inference about consequences during these phases from other fields of study (Table 1). For example, preconstruction surveys that involve site visits can create a risk of vehicle collision[41], and human presence or use of technology is likely to have similar impacts as they do during other surveys for biodiversity[42,43]. Similarly, the process of manufacturing involves resource extraction and production of waste, and decommissioning involves alteration of habitat, human presence and vehicle use, all of which can affect biodiversity. Among all stages, effects during decommissioning are the least certain because the process is uncommon, costs are poorly understood, and there is uncertainty about when and how decommissioning will take place[37,44,45]. Furthermore, although critical to assessing impacts to biodiversity, cumulative effects of many wind facilities are less well understood than impacts of individual facilities, and, to our knowledge, no study has evaluated the net costs and benefits of wind energy to biodiversity.

In this section, we describe impacts during the construction and operation phases of the life cycle of individual wind facilities. Impacts include effects on weather, habitats, species behaviour and fatality.

Cascading effects of changes to weather

The operation of wind facilities can influence local and regional weather conditions[46,47], with cascading impacts on local biodiversity. For example, when turbines are turning, they reduce wind velocity by extracting kinetic energy from the wind[48]. They also can increase the turbulence, precipitation and temperature in an area[49,50]. Furthermore, landscape changes during construction can alter albedo, humidity, and soil moisture and temperature[51,52].

These changes in temperature and precipitation caused by changes in air flows (in other words, turbined-induced wake effects) can either increase or decrease productivity of downwind plant communities. For example, vegetation greenness decreased after wind facilities were constructed in China[52] and in Turkey[53]. Across 17 wind facilities in the USA where greenness was measured before and after the installation of wind facilities, some sites experienced increases while others saw decreases in greenness due to wake effects[13]. Finally, in the Gobi Desert, vegetation downwind and close to turbines was in better condition and grew more densely than did vegetation farther away[54]. The lack of consistent responses suggests that the carry-over effects of wind installations on weather and then on ecosystems might be somewhat site specific and depend on the background climatological context of the region.

These changes to biodiversity through alteration of weather also presumably propagate to higher trophic levels[55]. For example, it seems reasonable to expect that changes to vegetation will have carry-over effects for invertebrate and vertebrate communities that are strongly influenced by vegetation characteristics[55,56].

Effects on terrestrial and aerial habitats

A central way that wind power affects biodiversity is via its influence on the habitats in which organisms live[57]. A key consideration of these habitat-related impacts is that they are three-dimensional, functioning in both terrestrial and aerial environments[58].

The installation of wind turbines on the landscape results in habitat degradation and land conversion. Construction of turbine pads, connecting roads and associated infrastructure can reform topography and prevent revegetation[59] (referred to as land take; Fig. 2). The amount of preexisting development at the site influences the overall level of new fragmentation or alteration resulting from installation of turbines. To reduce costs, developers preferentially use existing infrastructure, such as roads and powerlines, when possible[60]. However, in areas with minimal existing infrastructure (typically biodiversity-rich regions), wind facilities are recognized as an important driver for loss and degradation of irreplaceable habitats that are important for conservation[61,62]. For example, although new facilities decrease the amount of undeveloped land by only 2%, they can change metrics of landscape pattern by as much as 140% (ref. 60).

These metrics of landscape pattern have been developed for other types of human-driven disturbance such as land conversion for agriculture. However, the height of wind turbines means that they also affect the airspace, resulting in changes to weather and increases in low-frequency noise pollution. In this sense, wind turbines cause the impairment or functional loss of aerial habitat used by many wildlife species[58], including migrating birds[63] and echolocating bats[64]. For example, turbulence on the downwind (lee) side of turbines can displace bats, altering their habitat use as far as 1 km away from the turbines[65]. The extent of aerial habitat disruption has grown over time, as newer, taller turbines can have rotor swept areas (the area that spinning turbine blades cover) greater than 20,000 m^2, more than 110 times larger than an average turbine in the 1980s[66]. When extrapolated to an entire country, this can result in large-scale loss of aerial habitat. In Brazil, for example, the total swept area of the installed turbines can exceed 92.3 million m^2 (ref. 67).

Effects on species' behaviour

Alterations to habitat can have carry-over effects on wildlife behaviour, including both attraction and avoidance, especially among volant species[68,69]. For example, wind turbines can lead to avoidance behaviour, with possible energetic consequences, by tree-roosting bats[70] and transiting eagles[71,72]. These behavioural changes might be attributed to the wind turbines themselves, or to impacts of noise pollution on birds[73,74] and bats[75]. In addition, these species show behavioural effects that can include attraction, avoidance, displacement, and alteration to time budgets in response to the presence of turbines[76,77]. Even among bats, avoidance does not always occur; for example, some species are attracted to the forest gaps created at wind turbines in forested areas[78].

Non-volant terrestrial predators also show a variety of site- and species-specific responses to the presence of turbines. These include attraction by jaguarundi (*Herpailurus yagouaroundi*)[79], no detectable response by red fox (*Vulpes vulpes*)[77] and avoidance by jaguar (*Panthera onca*)[79], jungle cat (*Felis chaus*) and golden jackal (*Canis aureus*)[80]. When the abundance of these top predators is changed, there is the possibility for cascading effects on other trophic levels[81].

Responses by several species of ungulates to the presence of wind turbines also are reasonably well documented. Pronghorn (*Antilocapra americana*)[82,83] and reindeer (*Rangifer tarandus*)[84–87] show behavioural responses suggestive of displacement and avoidance during breeding, non-breeding and migratory seasons. Roe deer (*Capreolus capreolus*) have been shown to avoid turbines[77] and also exhibit a stress response in their vicinity[88]. Blackbuck (*Antilope cervicapra*) and chinkara (*Gazella bennettii*) are less likely to occupy sites as the number of turbines increases[80]. Elk (*Cervus canadensis*) appear not to show a detectable behavioural response to the presence of turbines[89].

Changes in local weather can explain some changes in wildlife behaviour. This is because many animal species depend on meteorological conditions to move[90–92]. For example, the barrier effect of the presence of turbines[93] can be enhanced by the changes in the meteorological conditions they produce, affecting animal movement patterns, modifying the cost of transport and altering collision risk[94]. Similarly, changes in the weather produced by wind power facilities can affect visibility[95], which in turn may alter the activity patterns of flying animals and increase collision rates[96]. Weather can also change

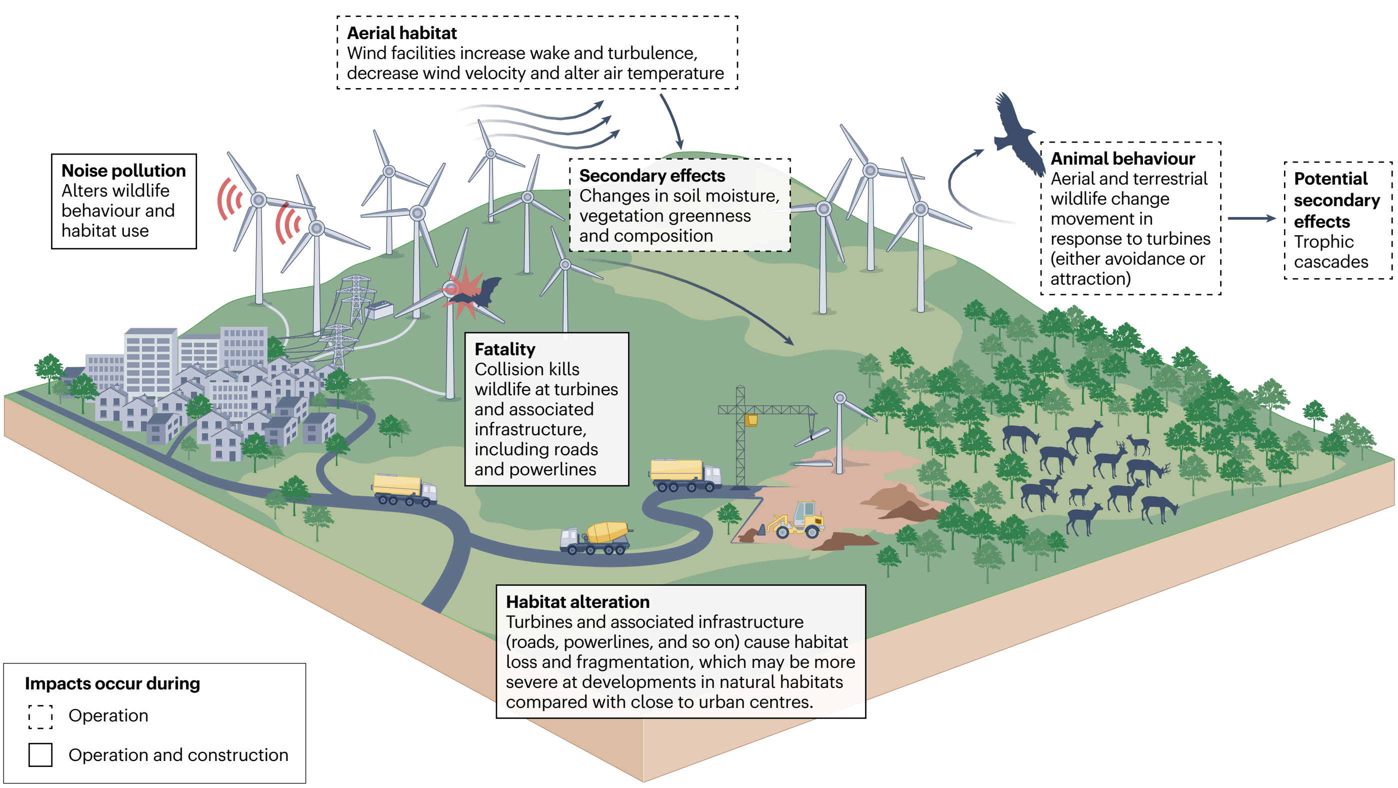

Fig. 2 | Wind energy impacts on biodiversity. Impacts can occur at all stages of wind facility development, but most occur during both construction and operation (solid lines) or during operation only (dashed lines).

the availability of food sources (for example, an increase of insects with temperature or humidity); if food availability increases near wind turbines, it may attract more individuals and potentially raise the risk of collisions[94]. That said, the issue of how turbine-induced changes in weather affect animal use of those habitats, their behaviour and movement patterns, collision risk and energy expenditure remains an important knowledge gap.

Effects on species' fatalities

Fatalities of aerial vertebrates (birds and bats) are regularly observed at wind turbines worldwide. Among the carcasses recorded at wind turbines, bats stand out in terms of numbers[97], and birds of prey in terms of conspicuousness (because of their large body sizes and societal importance). In a global review of collision rates of 9,538 bird species and around 888 bat species, collision rate was predicted to be affected by migratory strategy, dispersal distance, habitat associations and turbine size[98]. Furthermore, a suite of site-specific habitat features and facility- and turbine-specific factors can also influence collision probability[99]. Although less obvious and less frequently detected, fatalities of insects can be great enough to contribute substantially to the build-up of debris on the blades[100]. In addition to causing operational consequences because turbine blades need to be clean to maintain aerodynamic efficiency, the demographic consequences of these insect fatalities are unknown.

Animal fatalities are typically detected either through opportunistic observations of carcasses at turbines or in postconstruction monitoring. Postconstruction monitoring typically occurs within a predefined area that is scaled to the size of the turbine and blades and is centred at the base of the wind turbine. Best practices for postconstruction mortality monitoring recommend systematic searches, accompanied by rigorous methods to estimate the number of carcasses missed by observers and, consequently, the true number of fatalities[101]. For example, searchers can miss a carcass because it was overlooked, because it was removed by a scavenger before the search, because it landed outside of the standardized search area or because the animal was injured but able to move away from the site before death (so-called crippling bias). Many of the biases in estimating mortality rates can be accounted for using experiments in which trial administrators place carcasses in the sampling area and measure the proportion that are removed by scavengers (carcass removal rate) or detected by searchers (searcher efficiency rate)[102]. These parameters are then used together with counts of carcasses found to estimate true mortality rates[103]. In some cases, search efficiency is increased by using dogs instead of humans as searchers[104,105]. Despite the availability of these analytical and field tools, most estimates of fatality rates at North American[106] and global[107] wind power facilities appear to use substandard experimental design and analyses, making it difficult or impossible to draw broad inference or to compare mortality rates from different sites. Further, the degree to which fatalities of wildlife are documented at wind turbines depends in large part on the regulatory and legal environment under which the wind facility is operated (Box 1).

The most likely cause of death for both bats and birds is blunt force trauma – indicated as internal and external injuries – when individuals collide with the rotating blades or, for species such as grouse, with the tower[76]. For bats, but not birds, some fatalities have been attributed to barotrauma, which presents as internal injuries and blood in the thorax or abdomen, caused by exposure to sudden changes in air pressure in the vicinity of rotating blades, but without physical contact with the turbine structure[108]. However, it is unclear how likely barotrauma is as a cause of death[109]. Regardless of the exact conditions that lead to these internal injuries, it is noteworthy that some individuals with mild symptoms might survive the most immediate interaction with the turbine but die later, suggesting that mortality rates derived from numbers of observed carcasses could be underestimates.

Estimates of mortality are often calculated on a per-turbine or per-megawatt basis, but scaling up to estimate cumulative impacts of many wind facilities is challenging. In North America and Europe, annual bat fatalities are in the range of 12–14 individuals per wind turbine, or 6–7 individuals per MW per year[9]. For birds in the contiguous USA, a 2013 estimate suggests annual mortality of 3–7 individuals per turbine, or 2.5–6 birds per MW per year, and 140,000–328,000 individuals per year[110]. Estimated annual losses of bats killed by wind turbines are about 30,000 per year in the UK, about 50,000 per year in Canada, more than 200,000 per year in Germany and more than 500,000 per year in the USA[9,111]. Another uncertainty is whether this mortality is additive (in addition to existing mortality rates and likely to decrease population-level survival rates) or compensatory (meaning mortality that replaces other mortality and therefore does not affect the population-level survival rates). Determining whether wind-related fatalities are additive or compensatory is difficult because demographic parameters, including background mortality rates, are not available for most species, particularly those that are migratory[11,112,113].

Despite limited information on population-level consequences, available evidence suggests that terrestrial wind energy installations may threaten certain species – particularly at-risk species with low reproductive rates – with regional extirpation[114]. Local-scale population models explicitly designed to assess cumulative effects have suggested severe demographic consequences or population collapse from fatalities at multiple wind facilities for cinereous and griffon vultures (*Aegypius monachus* and *Gyps fulvus*) in Europe[115,116] and the Eurasian skylark (*Alauda arvensis*) in Portugal[117]. Broad-scale population models not focused on specific wind facilities[118,119] and field data[120,121] predict that wind-turbine-related deaths could cause population declines for hoary bats (*Lasiurus cinereus*) in North America. Models suggest a similar scenario for lesser kestrel (*Falco naumanni*) in France[122] and black harriers (*Circus maurus*) in South Africa[123]. Population declines have also been reported in central Europe for species with high collision risk, such as the noctule bat (*Nyctalus noctule*)[124–126], and nearly 50% of bird species evaluated in one study in California are vulnerable to population decline caused by fatalities at wind turbines[12]. Mortality of golden eagles (*Aquila chrysaetos*) at Altamont Pass Wind Resource Area in California is so frequent that local populations are sustained by immigrants[127]. Globally endangered Egyptian vultures (*Neophron percnopterus*) in Spain have lower survival rates, population growth rates and population size in the presence of wind facilities[128]. A commonality of all these species-specific modelling efforts is that none of them carries out a full net impact assessment that weighs the costs and balances of renewable energy for a species[21].

Mitigation

Some of the effects of wind power facilities on wildlife can be mitigated through actions such as changing turbine design, changing operation procedures, locating (siting) new turbines in less impactful locations, moving animals away from turbines or improving their habitat elsewhere. These actions, which span the 'mitigation hierarchy' (consisting of avoidance, minimization and compensation[129,130]), are discussed in the following section (Fig. 3). Because most of the work in this field has focused on flying vertebrate wildlife, this section focuses primarily on that literature; we know of little research on mitigation at wind facilities

Box 1 | Legal and regulatory considerations associated with wind energy development

Legal and regulatory considerations, and the extent to which they vary across geopolitical boundaries, can profoundly affect the influence of wind power on biodiversity. These considerations apply to all five phases of a project (as in Table 1) and to each aspect of the mitigation hierarchy.

In the USA, local, state and federal regulations can apply to a particular wind power project; however, before 2025, federal regulations were the primary mechanism for influencing impacts of wind energy on biodiversity. These regulations address issues such as zoning, setbacks from residences, other properties and habitats of conservation concern, as well as whether avoidance, mitigation or compensation measures are mandatory or recommended. As an example, the US Fish and Wildlife Service historically has required wind power projects to obtain an 'incidental take permit' (a permit to authorize unintentional killing or harming of a species) and attempt to minimize fatalities when the facility overlaps with the range of a federally listed bat species[214]. Such actions have not been required when a project is not anticipated to affect a threatened bat species. Similar regulations also apply for birds, which can be covered by state laws, as well as the Federal Migratory Bird Treaty Act (16 U.S.C. §§ 703–712), and the Bald and Golden Eagle Protection Act (16 U.S.C. §§ 668-668d). The US Fish and Wildlife Service 'Land-based Wind Energy Guidelines'[215] are a good example of a non-regulatory, voluntary yet widely adopted model for guiding management to reduce impacts to bats and birds.

In Central and South America, wind power development is growing quickly, but research on biodiversity impacts is scarce[140] and regulations are few. For example, in Argentina, the General Environmental Law No. 25,675 requires an environmental impact assessment for any project that affects the environment and biodiversity. However, in the absence of specific national legislation for wind energy, each province sets its own local regulations. Similarly, in Brazil, the environmental licensing process for wind energy is conducted mainly by state agencies, resulting in a wide variation in requirements and procedures across states[216]. In most cases, associated guidelines are vague and the specific criteria for assessing impacts to wildlife, particularly bats, are limited or non-existent[217]. Continent-wide, the Inter-American Development Bank and the International Finance Corporation have developed a guide based on international standards for assessing and managing risks to birds and bats throughout the life cycle of wind energy projects, but its application is voluntary[218].

In Europe, the EU Environmental Impact Assessment Directive (85/337/EEC of 1985 and its amendments) has been widely used to guide the licensing of new wind energy projects. The European Commission recently introduced legislation under the REPowerEU Plan (launched in March 2022), aimed at accelerating renewable energy projects by streamlining environmental assessments and minimizing public participation steps in the approval process. A crucial element in achieving this acceleration is the development of maps to identify designated 'renewables go-to areas'. However, this shift in approach and simplified licensing procedures in these areas has raised numerous concerns due to the limited baseline data on the distribution and abundance of threatened species, making it difficult to make informed decisions on where to implement renewable energy[219,220].

In Africa, the degree to which environmental impacts assessments are developed or enforced varies by country. Wind developments also often are subject to standards imposed by financing organizations (for example, the International Finance Corporation or World Bank). The largest producers of wind energy in Africa (South Africa and Egypt) also have some of the most well-developed environmental impacts assessment processes[221,222]. In South Africa, wind energy projects require an environmental authorization issued nationally by the Department of Forestry, Fisheries and the Environment[223]. There also are legislated criteria for assessing and reporting impacts to birds[224], but authorizations sometimes predate guidelines, and there are no penalties for fatalities of threatened species. Furthermore, Renewable Energy Development Zones have been identified to promote development in strategic areas, and facilities in these areas are subject to reduced monitoring and reporting requirements[225]. Morocco, also a major producer of wind energy in Africa, has recently developed environmental legislation around environmental impacts assessements; however, they lack enforcement, particularly in the wind energy sector. Some wind energy developments in Morocco have occurred without assessments of their impact on birds[226].

for habitat loss, vegetative communities, invertebrates or terrestrial vertebrate wildlife. The literature is also focused on the construction and operational phases of a wind facility. Finally, although one common goal of deploying wind energy is to offset carbon emissions, existing literature does not evaluate the potential for carbon emissions to be a form of mitigation for biodiversity loss.

Importantly, mitigation is expensive and impacts occur for multiple species; consequently, design of any action must account for economic costs as well as consequences for non-target species or systems[131]. Again, country-specific regulatory and legal environments (Box 1) influence implementation of mitigation actions[23,24].

Avoidance through siting decisions

Avoidance refers to strategies and practices designed to prevent adverse interactions between organisms and wind turbine, mainly by locating wind facilities or individual turbines in locations where they are less likely to cause impacts. It is the first and most crucial step of the mitigation hierarchy[129] and it requires identification of potential impacts in the early stages of development of a wind facility. The effectiveness of avoidance depends on having accurate information about the distribution, abundance and community structure of local biodiversity, as well as effective risk assessment and planning. However, there is typically a poor correspondence between risk assessment based on data collected during preconstruction monitoring and the actual impacts of the facility that is eventually constructed[132,133]. More effective preconstruction risk assessment would, therefore, enhance both the range and effectiveness of avoidance strategies.

At a large spatial scale, avoidance typically involves 'macro-siting' — evaluating broad geographic areas and selecting sites for construction of facilities so that impacts to biodiversity are minimized. This decision-making process requires a multiple-criteria approach, where biodiversity is balanced with technical, economical and societal considerations[134,135], a strategy that seems attainable for large geographic areas[136,137]. At this scale, sites identified as 'biodiversity sensitive' typically include protected areas, habitats with high conservation value, bird and bat migratory routes, and key locations for endangered species or species vulnerable to the impacts of wind power facilities, including breeding, wintering and roosting sites or connectivity corridors[8,130,138].

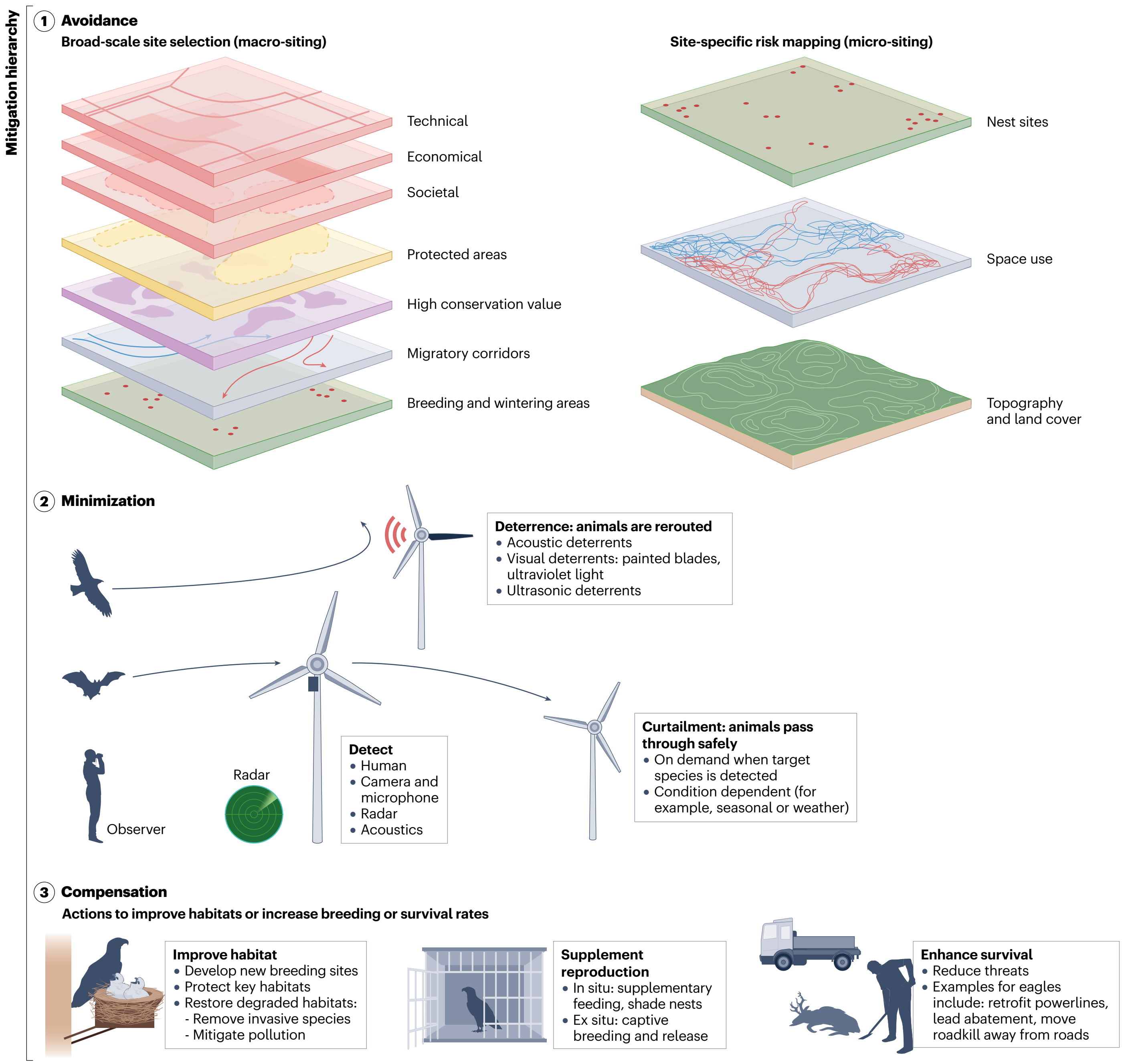

Fig. 3 | The mitigation hierarchy as implemented to address impacts of wind energy on biodiversity. Mitigation begins with avoidance (1), in which sites for new wind facilities (macro-siting) or individual turbines (micro-siting) can be selected strategically to reduce biodiversity impacts. When avoidance is not possible, the next step in the hierarchy is minimizing the risk of fatalities of existing facilities (2). Current examples of minimization include deterring wildlife from approaching turbines and curtailing blade action during certain times; curtailment requires effective detection of wildlife near facilities. When avoidance and minimization are not possible to the desired level, the final option is compensation, also known as replacement or offsetting (3). Typical compensation for fatalities has involved either habitat improvement or attempts to improve the affected species' reproductive success or survival.

Approaches to macro-siting have included using data from atlases on species distributions and spatial prioritization methods to identify priority areas for bird conservation in relation to wind energy in Finland[139] and Brazil[67]. Similar approaches have been proposed in Latin America and the Caribbean Region[140]. Another avenue to avoidance suggests targeting already fragmented landscapes for development[141]. Similarly, species distribution models and spatial prioritization tools have been used to balance wind industry development with minimizing impacts to habitat for wolf reproduction in Croatia[142]. In South Africa, Renewable Energy Development Zones are defined using social, economic and environmental factors[143].

In addition to species distribution maps, identification of areas with higher space use by flying animals is sometimes used at this stage, although, once again, these types of preconstruction survey often do not effectively capture risk[132,144]. Global Positioning System tracking data are commonly used to study birds[145], whereas echolocation call recordings are frequently used to analyse space use of bats[146]. Regarding collision risk, a detailed analysis allowing the evaluation of exposure risk can be achieved by considering flight patterns, particularly by identifying locations where animals fly within the rotor-swept zone. Such an analysis can be done using data collected with biologgers (for example, Global Positioning System tracking) that provide coordinates and altitude of animals[147–149] or with weather surveillance radar[150].

At smaller spatial scales, within an individual wind energy facility, 'micro-siting' decisions are made about where to place each turbine and each associated structure within the project area. Strategic micro-siting typically is designed to reduce the numbers of fatalities[57] or the amount of habitat alteration[59]. This task is site specific, requiring a project-based and a fine-scale analysis. The difficulty of identifying specific sites that would benefit many species probably explains why examples of micro-siting are less common in the literature than are examples of macro-siting. In a small number of cases, localized space use by soaring birds has been modelled and used to identify where the topographical and environmental features selected by birds might put them at higher risk of collision[147,151]. A typical suggestion to reduce fatalities of soaring birds is to plan construction of turbines away from ridgelines that attract soaring birds because they deflect air upwards (meaning they generate orographic updraft)[6]. The execution of such tasks is enabled by the availability of high-resolution remote sensing data, which enables the modelling of orographic and thermal updraft velocities at scales of 100 m (ref. 152).

Minimization

The second part of the mitigation hierarchy is minimization, which attempts to reduce the frequency of wildlife encounters by causing animals to avoid turbines (deterrence) or halting the operation of turbines (curtailment). These have been implemented either proactively – before any species are detected – or reactively, in response to human or automated detections of at-risk wildlife near turbines.

Deterrence. Turbines can be proactively altered to deter animals from approaching. For example, birds in flight could be alerted to the presence of turbines using conspicuous paint schemes that disrupt otherwise more uniform fields of view[153,154], especially during low-speed rotation[155]. Early results show reduction in avian fatalities from altering blades in this manner[156,157], and ongoing research is investigating the generality of this treatment across different habitats and species. The utility of ultraviolet illumination to increase the conspicuousness of turbines has also been tested. However, strobing turbines with ultraviolet light was ineffective at dissuading bats from approaching[158], and bird abundance was only moderately reduced at turbines illuminated with violet and ultraviolet light[159]. Although there is no evidence that birds are attracted to turbines themselves, they can be drawn to lighting on the turbines, such as those required for aviation safety[160]. To counter this attraction, many countries regulate the types and colours of that lighting.

Another approach to deterrence is to startle wildlife with auditory or visual stimuli, reactively, when they are detected near a turbine. Several acoustic deterrents for birds are currently being evaluated, and preliminary results from this work are encouraging[161]. Acoustic deterrents emitting ultrasonic sounds can sometimes reduce bat fatalities[162,163]. However, bat fatalities doubled at one energy facility when deterrents were active, suggesting that the benefits of deterrents are inconsistent[164]. Likewise, the turbine structure can block the sound of a deterrent ('acoustic shadowing'), and, because they are sometimes high ultrasound, they can weaken quickly with distance from the turbine ('range attenuation')[165]. As turbines increase in size, these limitations to acoustic deterrents for bats could increase.

Considerable uncertainty surrounds how individual animals and species will respond to visual or acoustic deterrents. This uncertainty stems from the fact that each flying species uses sight and sound in different ways that vary by behavioural or motivational state and situational awareness[155,166–168].

Curtailment. Curtailment is a mitigation scheme to prevent collisions between aerial vertebrates and wind turbines by suspending turbine operations at times when activity of target species is predicted to be high or when those species are detected on-site. At an operational level, curtailment is most frequently implemented by 'feathering' turbine blades – turning them at their base so that their airfoil properties are attenuated and the blade no longer generates lift that leads to rotation. Its implementation can be condition dependent (proactively setting times and sites for curtailment) or on-demand (reactively implemented when a target species is detected within a fixed range of a turbine). Finally, there is evidence that some flying animals (including grouse[76] and bats[169]) collide with non-moving parts of turbines; those collisions are unlikely to be affected by curtailment.

Most bat fatalities at wind turbines in the USA occur on nights during autumn migration[170] with relatively low wind speeds; curtailment proactively implemented on those nights has been found to reduce fatalities with minimal reduction in quantities of electricity generated[171–173]. In other US settings, however, proactive curtailment strategies can reduce overall wind energy production enough to affect its financial viability[174]. In Germany, curtailment initially involves a standardized blanket action based on parameters such as season, time of day, ambient temperature and wind speed. During the first two years of wind turbine operation, acoustic monitoring of bats on the turbine is then used to fine-tune the curtailment regime. This adaptive approach can result in an improved bat protection at a higher energy yield of the turbine compared with the initial blanket curtailment[175]. Seasonal curtailment strategies also have been implemented for avian wildlife, with mixed results in terms of reductions in fatalities[176].

On-demand curtailment, sometimes referred to as informed or smart, is not specific to a certain time, but instead reactively relies on information about wildlife presence and behaviour in the vicinity of turbines[57]. This approach to curtailment limits the duration and spatial extent of the curtailment response, which reduces production losses.

Detect and minimize. Effective on-demand deterrence or curtailment requires effective detection of flying animals. Traditionally, detection of focal species, almost exclusively large, at-risk birds, relied on visual identification by human observers; curtailment based on human observation has been successful at reducing fatalities of griffon vultures in Spain[177,178]. Increasingly, human observation is being paired with or replaced by automated systems that use visual or thermal cameras[179,180], acoustics, radar or a combination of these methods to detect flying wildlife. Compared with humans, these modern systems are less prone to fatigue, they can resolve smaller animals at greater distances, and they can detect more animals[181]. These technologies have been coupled with machine learning tools to identify flying animals and animal tracking algorithms to determine risk of collision[182–186]. In some settings, these systems are then integrated into existing supervisory control and data acquisition systems[169] that automatically monitor, control and analyse engineering data from wind turbines.

There have been several technologies developed to detect wildlife to support on-demand curtailment. Generally, these are implemented as either networks of many individual sensors or application of a single sensor. For example, computer vision systems are networks of cameras placed throughout a facility. Curtailment in conjunction with two of the most commonly used automated detection systems (IDF and DTBird) is based on computer vision and has been found to be effective for reducing fatalities of birds[180,183–185].

Individual sensors, including cameras and acoustic devices, can also be mounted on the top of the wind turbine (the nacelle), or at its base, to inform curtailment of that device. By contrast, individual radar systems operate over areas large enough to monitor the airspaces around many turbines. Radars classify flying animal targets into coarse size or taxonomic groups, so their role in informed curtailment is best supported by other sensors that reliably identify individuals of a focal species[179]. Generally, radar is targeted at large birds[187], although bats and migratory songbirds are also sometimes considered[188], and weather radar that documents songbird migration has been proposed as a mechanism to inform curtailment[150]. Finally, acoustic call detection systems focus largely on bats. As with the use of ultrasound as a deterrent, ultrasonic bat calls suffer from high attenuation which restricts the range of detection[189]. A range of detection challenges may explain why on-demand curtailment is currently rarely practiced for bats, as the time needed to stop turbines can be too long to effectively reduce collision risk. That said, technologies are being developed that could overcome this problem[169,190–192].

Because it is reactive, detection leading to on-demand curtailment limits the duration and spatial extent of the curtailment response, which reduces losses in energy production. However, other trade-offs influence decisions about use of these systems. For example, such curtailment systems are expensive to deploy and maintain, and their effectiveness is context dependent. Furthermore, the number of false positives and other errors can be high[180,181,186], resulting in reductions in energy generation that exceed the tolerance of facility operators.

Compensation through offsetting or replacement

The third tier of the mitigation hierarchy is compensation, which refers to actions taken to offset the residual adverse effects that remain after implementation of all feasible measures to avoid and minimize impacts[129]. At this stage, the tools considered are those generally used to improve the conservation status of a focal species or system and are not specific to wind facilities. Although mitigation is often conducted near wind facilities, best practices suggest compensation measures should be implemented in areas distant from the project site to avoid creating ecological traps[138,193].

Compensation measures typically aim to improve the population status of the species negatively affected by the wind power facility. One approach to this, habitat improvement, has been achieved through several means[8,193]. Some of these include creating habitats crucial for sustaining the target species, such as providing new breeding sites (for example, boxes or platforms for birds[194] and bats[195] or establishing wetlands for waterfowl[196]); restoring degraded habitats by removing invasive species[197] or implementing measures to remove pollution[198]; and protecting important habitats, for example, by restricting access to key roosting sites for bats to reduce human disturbance that otherwise occurs[199].

Compensation for species adversely affected by wind facilities can also be achieved through measures aimed at improving demographic parameters such as breeding performance or survival rates. For example, breeding performance can be improved by providing supplementary feeding in situ, to nestlings or breeding pairs, or boosting population size through ex situ programmes, or translocating individuals from healthy populations. Alternatively, rates of annual survival can be improved by mitigating other threats that are unrelated to wind power. In the case of eagles, increases in survival rates have been achieved or proposed by retrofitting powerlines to prevent electrocution[200], abatement of exposure to spent lead ammunition[6,201], and moving ungulate roadkill away from vehicles[202]. In these cases, the mitigation is achieved by offsetting fatality at a wind power facility through a reduction in mortality rates from another cause.

Compensation has been criticized in some settings[8,138]. First, it contains an arbitrary component, as it is difficult to know exactly how much compensation is required to offset a given number of fatalities. This is true not only for demographic compensation, but especially for habitat-related compensation; it is not clear how many hectares of land protected, or what degree of habitat improvement, is required to cause a given increase in population size of an affected species[203]. Second, because compensation is the last step in the mitigation hierarchy, it means that other attempts to avoid or minimize were not tried or have been unsuccessful.

Summary and future directions

Wind energy is growing rapidly throughout the world. This Review has shown how species and ecosystems can be affected by onshore wind development. Biodiversity impacts have been documented for only a few well-studied taxa, but the impacts are not negligible and can occur even in locations with strong regulations. Although mitigation measures are sometimes available to reduce impacts to biodiversity, they are often species specific, their effectiveness is variable, they are costly enough that they are only sometimes implemented, and whether they are implemented depends strongly on regulatory and legal considerations.

As a renewable energy, wind power is often deployed to reduce the negative effects of greenhouse gas emissions from fossil fuels. Proponents of wind power often state that wind energy's impacts on biodiversity will be less than the impacts of climate change[21]. Although plausible, this assumption is untested. One way to evaluate this assumption is through scenario-based modelling. Specifically, present conditions can be compared with counterfactuals (conditions different to those presently occurring) describing a range of levels of build-out resulting in different reductions of climate change and different consequences to biodiversity. There are substantial uncertainties in such modelling and questions about its feasibility at the scale of individual wind facilities[204]. However, highly informative efforts with similar levels of uncertainty have been implemented in the fields of climate change attribution[205], energy system modelling[206], cost–benefit analyses of different energy types[207], cost effectiveness for mitigation of avian fatalities[208], emergency conservation decisions[209] and even assessments of impacts to wildlife from renewable energy and from climate change[21]. Such net impact assessments can be used to target mitigation efforts – whether at the species or ecosystem level – and to the necessary degree, thereby enhancing biodiversity conservation[210]. Taking this approach would allow continued growth of wind energy but also provide an additional context for protecting vulnerable ecosystems and species.

Several knowledge gaps impede management of impacts to wildlife from wind energy. First, regulatory and policy considerations will determine how much wind energy is built in coming decades, and how much land is available for that development. Given the immense consequence of land use change and habitat loss for biodiversity[211], factoring in these considerations is essential to assessing future impacts to biodiversity from wind power. A second important knowledge gap lies in the full life cycle effects of wind turbines on biodiversity. Although effects of construction and operation are reasonably well known, the effects of both manufacturing and decommissioning on biodiversity have not been quantified. Third, although the demography of some species is well understood, demographic parameters for many taxa, especially bats, are not well known, and it can be difficult to estimate population-level and cumulative consequences of wind turbines without those data. Finally, mitigation, although moderately well studied, tends to be underutilized, and its implementation and reports on that implementation are highly variable among countries and regions. Identifying effective mitigation tools, and appropriate levels of mitigation[212] that are also financially reasonable for operators, is an important area for future research.

Perhaps the greatest unknown in predicting future effects of wind power on biodiversity lies in the scope of the potential expansion of the technology, and the cumulative consequences of this expansion for species and ecosystems. For example, a 2021 report on potential pathways towards net-zero emissions for the USA identified that the land area required for wind energy ranges from 0.24 to 1.0 million square kilometres, or from about 3% to 13% of the total land area of the contiguous USA[14]. Given that wind turbines are often placed in natural or semi-natural areas, this extent of build-out could have dramatic consequences for biodiversity. Such development generally is not consistent with international frameworks on global biodiversity, specifically the Kunming-Montreal Global Biodiversity Frameworks' target to protect 30% of land area by 2030 (refs. 211,213). Furthermore, these estimates of land area do not consider loss of aerial habitat. Thus, effectively accounting for future impacts to biodiversity from wind power requires a diversity of assessments of cumulative future build-out scenarios and their three-dimensional impacts.

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T.E.K. organized the writing effort, all authors were responsible for writing at least one section of the manuscript, and all authors contributed to revisions of the final document.

Competing interests
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Supplementary information

Impacts of onshore wind energy production on biodiversity

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Supplementary Information

Impacts of onshore wind energy production on biodiversity

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Methods to quantify number of publications per region in Figure 1 in the main text.

To quantify the global distribution of research into the impacts of wind energy on biodiversity we ran a Scopus search using 'rscopus' in R[1,2]. To find papers which focus on these topics we ran a search of scientific materials in the ‘environmental’ subject area, which included a wind energy related term (‘wind energy’ or ‘wind farm’ or ‘wind turbine’ or ‘wind facility’ or ‘wind plant’) AND a biodiversity related term (birds or mammal or biodiversity or habitat or bats or raptor or eagle or insect or vegetation or botany) within either the title, abstract or keywords of the publication. The search was run on 15 May 2025.

This search returned 1317 peer reviewed publications, for which we extracted the country of the author affiliations. We removed duplicate countries (i.e. publications with more than one author from the same country were only counted once) and if authors were from more than one country then the paper was assigned to each country. These publication counts were then grouped by geographical region.

1. rscopus: Scopus Database 'API' Interface v. R package version 0.7.2, (2024).
2. R Core Team. Vol. R Foundation for Statistical Computing (Vienna, 2021).