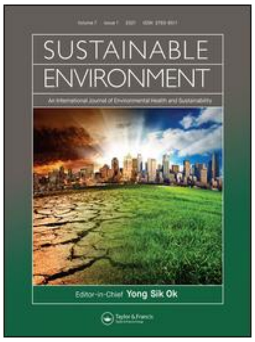


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Sustainable Environment

An international journal of environmental health and sustainability

ISSN: 2765-8511 (Online) Journal homepage: www.tandfonline.com/journals/oaes21

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Elevate Series

SUSTAINABLE ENVIRONMENT
2025, VOL. 11, NO. 1, 2567100
https://doi.org/10.1080/27658511.2025.2567100

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# The emerging need for ecosystem restoration to mitigate the impacts of onshore wind energy

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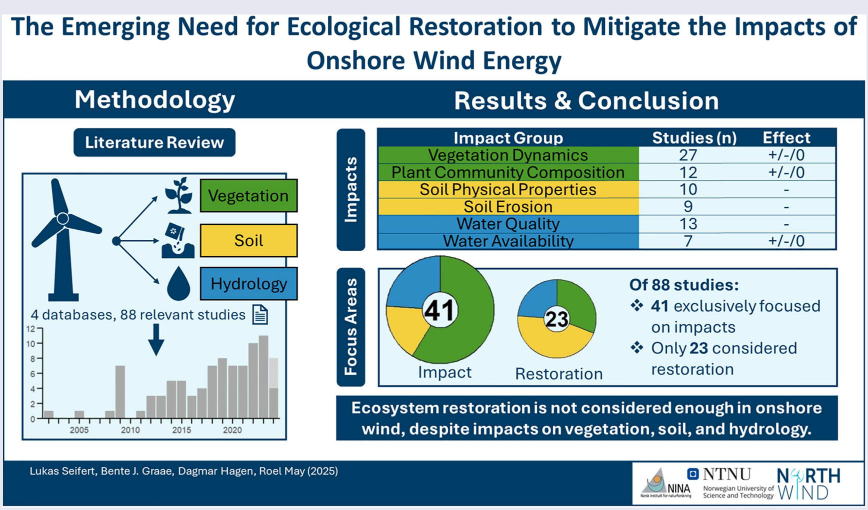
## ABSTRACT

This literature review synthesizes findings from 88 studies on the environmental impacts of onshore wind energy. Most concerned impacts on vegetation, followed by soil and hydrology. The nature and severity of impacts varied across ecosystems and geographic contexts, but despite the growing body of studies documenting impacts that lead to ecosystem degradation, only a few acknowledged the resulting need for mitigation (24) or restoration (23). To bridge this gap, a conceptual framework is presented that links the documented impacts to mitigation potential across all phases of onshore wind energy. This framework illustrates seven key actions to advance the mitigation of environmental impacts by reinforcing existing mitigation strategies or overcoming persistent knowledge gaps. These are: (1) Inform decision-making, (2) Standardize environmental impact assessments, (3) Plan restoration early, (4) Understand feedback-mechanisms, (5) Inform predictive models, (6) Learn from other sectors, and (7) Evaluate restoration outcomes. By synthesizing evidence on impacts, presenting mitigation solutions, outlining actionable steps for improvement, and stressing the emerging need for ecosystem restoration, this review provides a foundation for more effective mitigation of environmental impacts of onshore wind energy. Advancing this shift is essential to ensure that renewable energy expansion aligns with both climate goals and environmental sustainability.

## HIGHLIGHTS

- Onshore wind energy has diverse impacts on vegetation, soil, and hydrology.
- Only 26% of studies considered the need for ecosystem restoration.
- Limited understanding of impacts causes uncertainties in decision-making.
- Implementing targeted key actions can advance mitigation of environmental.
- Impacts Proactive approach to integrating restoration throughout the project lifecycle is imperative.




**ARTICLE HISTORY**
Received 30 April 2025
Accepted 23 September 2025

**KEYWORDS**
Renewable energy development; land use change; environmental impact assessment; environmental conservation; environmental monitoring; ecosystem rehabilitation

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/27658511.2025.2567100.

## 1 Introduction

To halt climate change, international commitments like the Paris Agreement aim to reduce carbon emissions by steering energy production towards renewable solutions. By 2040, more than half of the global energy supply could stem from renewables, with wind energy being the second largest contributor (25%) after solar photovoltaic (32%), and ahead of hydropower (14%) and bioenergy (4%), according to the International Energy Agency (2023). Currently, onshore wind power plants account for over 90% of global wind energy production, and as older plants reach decommissioning, the need for site restoration is growing (Windemer & Cowell, 2021).

Advancements in onshore wind energy production have also raised concerns about potential conflicts regarding land use (Frantá et al., 2023), society (Otto & Leibenath, 2014), and the environment (Katzner et al., 2019). Most studies on environmental conflicts associated with onshore wind energy focus on wildlife disturbance in the form of habitat loss (Diffendorfer et al., 2019; Kati et al., 2021; Kuvlesky Jr et al., 2007), species avoidance and behavior (Barré et al., 2018; Harrison et al., 2017; Thaxter et al., 2017), or bird and bat mortality (Laranjeiro et al., 2018; Thaxter et al., 2017). With wildlife conflicts as a dominant concern, research has largely focused on operational issues (Delgado et al., 2020; Windemer, 2019), while long-term impacts on ecosystems remain understudied. To address this gap, the present study focuses explicitly on ecosystem-level impacts.

Emerging evidence links wind power plants to changes in vegetation, soil, and hydrology. This may contribute to ecosystem degradation, which has been defined as '*[…] a persistent decline in the structure, function, and composition of an ecosystem compared to its former state*' (Society of Ecological Restoration, 2024). To limit ecosystem degradation, the mitigation hierarchy emerges as a valuable framework, linking each project phase with an associated decision gate to reduce negative environmental impacts (Ekstrom et al., 2015). For onshore wind energy, the prioritized steps include avoiding impacts during planning, minimizing them during design, reducing them during construction, compensating for them during operation, and restoring ecosystems at decommissioning (May, 2016). Enhancing our understanding of impacts across all project phases is therefore key to mitigating degradation and supporting the restoration of degraded ecosystems.

In theory, the less land is needed to produce (wind) energy, the less land is degraded. In practice, ecosystem degradation is not restricted to direct land use (i.e. occupation), but can also be caused indirectly, for example through land transformation (Lindeijer, 2000). While for coal and nuclear energy, essentially whole ecosystems must be cleared (McDonald et al., 2009), wind power plants require spacing in between individual wind turbines. This allows for parts of the ecosystem to persist inside the main operation area. Accordingly, the impacts of wind power plants on ecosystems can be separated into direct and indirect impacts. Direct impacts are caused by temporary and permanent infrastructure development and require the clearing of ecosystems. Indirect impacts relate to the total area use of a wind power plant and include, for example, soil compaction through heavy vehicles, hydrological changes due to drainage, or microclimatic effects caused by wind turbine operation (Denholm et al., 2009). The land requirement of onshore wind energy is considered low (1.3 $km^2$/TWh) when only considering direct impacts, but high (126 $km^2$/TWh) when also considering indirect impacts (Trainor et al., 2016). While the land requirement of traditional energy sources like nuclear (0.3 $km^2$/TWh), gas (1.0 $km^2$/TWh), and coal (15 $km^2$/TWh) can be much lower (Gibon et al., 2021), this comes at the cost of substantially higher greenhouse gas emissions and pollutants that result in broader environmental impacts beyond land use alone (Dale et al., 2011).

Although ecosystem restoration has been explored in traditional energy sources (Bandyopadhyay & Maiti, 2022; Haden Chomphosy et al., 2021; Prach & Tolvanen, 2016), it received limited attention in the context of onshore wind, especially during early project phases (Topham & McMillan, 2017; Welstead et al., 2013). This oversight is particularly problematic given the increasing demand for renewable energy production and the resulting pressure on ecosystems from more wind power plant constructions. There is an urgent need to comprehensively understand the environmental impacts of onshore wind energy to implement robust mitigation strategies.

The primary objective of this literature review is to systematically evaluate the current knowledge on the impacts of onshore wind energy on ecosystems, with a focus on vegetation, soil, and hydrology. Given that such impacts necessitate both mitigation and restoration efforts, the review examines whether mitigation and restoration are sufficiently addressed in the scientific literature as a response to documented impacts. By synthesizing these insights, the review aims to provide a framework for understanding current knowledge gaps and guiding the development of effective strategies to mitigate environmental impacts and restore degraded ecosystems accordingly.

## 2 Materials and methods

### 2.1 Literature search

A systematic literature review was conducted, guided by the PRISMA 2020 framework to ensure transparency and reproducibility in the selection of studies (Page et al., 2021). The review process began with a scoping search in Web of Science and the Tethys Knowledge Base to explore available literature and to inform the development of a comprehensive search string. Twenty initial references were consulted to guide the formulation of the final search terms. The final search string was developed to include keywords related to wind energy infrastructure and environmental impacts on vegetation, soil, and hydrology, while excluding offshore and marine contexts and studies focusing on birds, bats, or dunes. The search terms used were:

> ('windfarm' OR 'windpark' OR 'wind energy' OR 'wind farm*' OR 'wind park*' OR 'onshore wind' OR 'wind turbine*' OR 'wind power*') (Topic) AND ('ecosystem degradation' OR 'land degradation' OR 'fragmentation' OR 'microclimate' OR 'water turbidity' OR 'macronutrient*' OR 'suspended sediment*' OR 'local precipitation' OR 'flooding' OR 'runoff' OR 'hydrology' OR 'dissolved organic carbon' OR 'drainage' OR 'DOC' OR 'desiccation' OR 'oil spill*' OR 'soil degradation' OR 'soil erosion' OR 'soil compaction' OR 'soil disturbance' OR 'topsoil' OR 'soil loss' OR 'peat*' OR 'peat slide*' OR 'leaf area' OR 'NDVI' OR 'EVI' OR 'plant growth' OR 'plant diversity' OR 'plant specie*' OR 'plant cover' OR 'vegetation health' OR 'vegetation cover' OR 'vegetation structure' OR 'vegetation disturbance' OR 'vegetation growth' OR 'plant communit*' OR 'invasive plant*' OR 'endemic plant*' OR 'deforestation' OR 'grassland' OR 'flowers' OR 'crop') (Topic) NOT ('offshore' OR 'maritime' OR 'sea' OR 'bird*' OR 'bat*' OR 'dune*') (Topic)

Literature was retrieved on 25 July 2024, from Web of Science, Scopus, and ProQuest (Figure 1). For Tethys, a faceted search strategy was used to retrieve all references listed under land-based wind and linked to habitat change as a stressor and the physical environment as a receptor. The initial search yielded a total of 1477 references. All references were imported into the EndNote reference manager (The EndNote Team, 2013), and duplicates removed automatically.

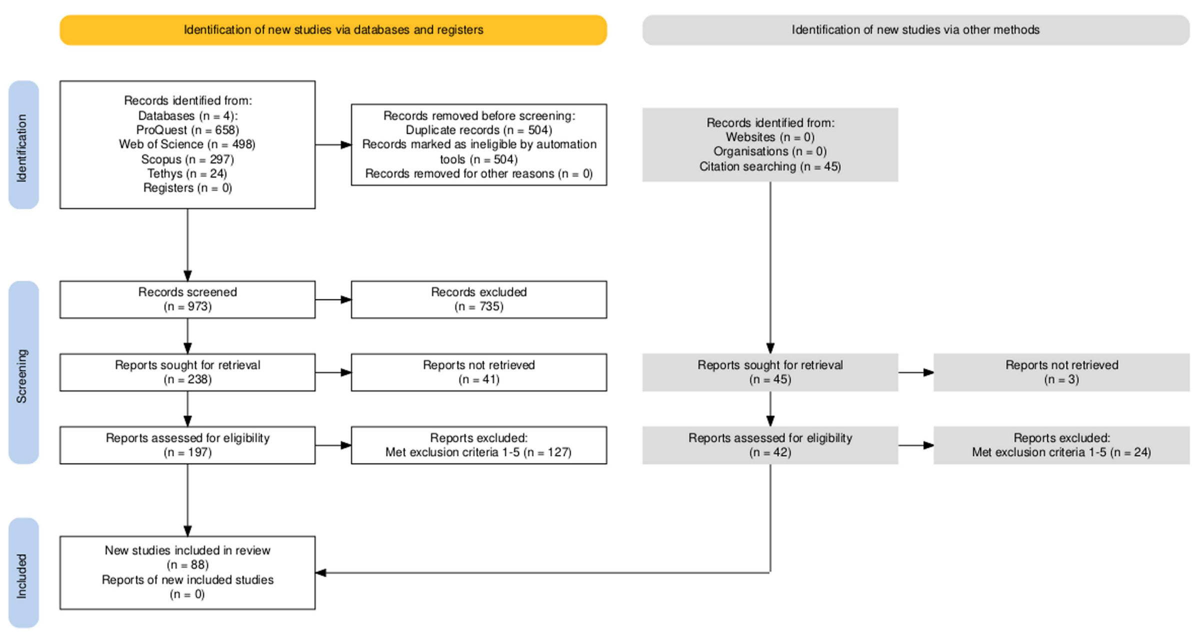


**Figure 1.** PRISMA 2020 flow diagram summarizing the selection process for studies included in the literature review. The diagram was generated using the PRISMA 2020 flow diagram tool (Haddaway et al., 2022).

A three-step screening process was followed to assess eligibility. First, titles and keywords were screened to eliminate obviously irrelevant references. Second, abstracts were reviewed for relevance to the core topics of vegetation, soil, and hydrology in the context of onshore wind energy. Third, full texts were examined for final inclusion. References were assessed by LS, and no automation tools or machine learning classifiers were used in the screening process beyond EndNote's built-in duplicate detection.

Studies were excluded when they: (1) were not in English, (2) did not focus on onshore wind energy, (3) lacked relevance to vegetation, soil, or hydrology, (4) focused on wildlife disturbance, or (5) were not available as full text. This process resulted in 70 references meeting the criteria for inclusion. Following initial selection, a backward and forward reference search was conducted using the Web of Science citation map, identifying 18 additional studies that met the inclusion criteria. In total, 88 studies were included in this review.

### 2.2 Literature categorization

Studies were systematically categorized in three steps: First, they were grouped by their primary environmental focus on vegetation, soil, and/or hydrology. Second, they were classified as empirical or non-empirical. Empirical studies were defined as generating original data through remote-sensing, on-site monitoring, or model simulations. Non-empirical studies consisted of theoretical, conceptual, or review-based analyzes without novel data collection. For empirical studies, further categorization followed a typology adapted from Ze et al. (2024), which distinguished between three main methodological approaches. Remote sensing studies use satellite imagery or aerial data to evaluate spatial patterns and temporal trends in environmental parameters. On-site monitoring studies include field-based data collection, like vegetation surveys, soil sampling, and hydrological measurements. Model simulations involve the use of computational models to estimate or predict impacts. Finally, studies were categorized based on the attention given to mitigation and restoration. Each study was classified as either: (1) Focuses solely on impacts without mention of mitigation or restoration, (2) mentions (the importance of) mitigation, or (3) mentions (the importance of) ecosystem restoration.

No formal meta-analysis was conducted in this review due to the heterogeneity of study designs, metrics, and environmental contexts. Instead, a narrative synthesis approach was used, allowing for the identification of common findings and methodological patterns across diverse empirical and non-empirical contributions. This approach was deemed appropriate given the complex, multi-scalar nature of the environmental impacts under investigation and the diversity of measurement approaches employed across studies.

## 3 Results

### 3.1 General description of the dataset

Out of the 88 studies included in this literature review, the majority focused on impacts on vegetation (59 studies), followed by soil (37 studies) and hydrology (26 studies) (Figure 1). The number of studies published on these topics showed a clear upward trend, particularly after 2010, with a peak of 11 studies in 2023 (Figure 2). Non-empirical studies were less frequent, comprising 26 studies. They typically lacked focus on specific environmental impacts. In contrast, empirical studies were more frequent (62 studies) and focused on specific impacts, such as vegetation dynamics (28 studies), water quality (13 studies), and plant community composition (12 studies) (Figure 3). Remote sensing was the most commonly used methodology, employed in 48% of studies, particularly for studying vegetation dynamics. Of the 28 studies on vegetation dynamics, 23 used remotely sensed data (Figure 3). On-site data monitoring was the second most common methodology, accounting for 40% of the studies. It was often used to study water quality and plant community composition. Model simulations were the least common approach, used in only 11% of the studies.

### 3.2 Environmental impacts

#### 3.2.1 Vegetation dynamics

Vegetation dynamics involve changes in vegetation cover, growth, and physiology. Several studies reported increased vegetation growth following wind power plant construction. For instance, Luo et al. (2021)

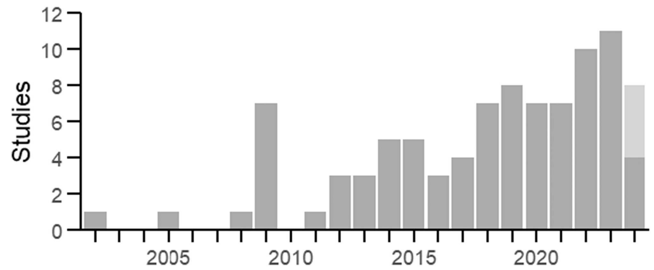


**Figure 2.** Number of published studies on the impacts of onshore wind energy on vegetation, soil, and hydrology from 2002 to 2024 ($N = 88$). The number for 2024 was extrapolated based on publications until July, assuming stable research output.

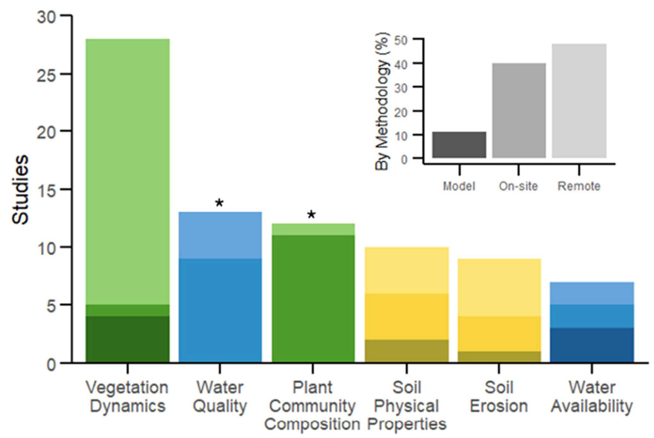


**Figure 3.** The number of empirical studies on the specific impacts of onshore wind energy on ecosystems. Each impact group is represented by a stack of bars, with different shades (dark, medium, and light) indicating the proportions of different methodologies used. The inset displays the overall proportions of methodologies used across all empirical studies ($N = 62$).* No model simulations were used in studies on water quality and plant community composition.

reported increased evapotranspiration rates and vegetation cover after wind power plant construction on a grassland dominated by perennial herbs, suggesting increased vegetation growth following construction. This suggestion was confirmed by studies conducted in the Gobi desert (Xu et al., 2019) and meadow grasslands (Ji et al., 2023), which both reported higher biomass and improved physiological states of vegetation near wind turbines, as well as increased biomass correlating with wind power plant operation.

Negative impacts on vegetation dynamics can result from vegetation clearings prior to construction, vehicle movement in construction areas (Christol et al., 2021), or wake effects caused by wind turbine blade movement (Diffendorfer et al., 2022; Li et al., 2016). For example, the development of wind power plants has been linked to deforestation (Balotari-Chiebáo & Byholm, 2024; Diffendorfer & Compton, 2014; Enevoldsen, 2018) and declines in overall native vegetation cover (Cetin et al., 2022; Guan, 2023; Turkovska et al., 2021). The associated vegetation loss can be substantial, with individual wind turbines contributing to the clearance of up to 3000 $m^2$ of vegetation (Shen et al., 2017). On the project level, the vegetation loss could be as much as 25% of the whole project area (Balik et al., 2017).

Remote sensing studies have confirmed negative impacts on vegetation cover. Qin et al. (2022) found that 59% of 319 wind power plants across the United States exhibited reduced vegetation growth within their main operation area. Other researchers reported decreases in the Normalized Difference Vegetation Index (NDVI), indicating reduced vegetation cover and greenness after wind power plant construction in coastal regions (Aksoy et al., 2023), alpine ecosystems (Ma et al., 2023), and grasslands (Song et al., 2023; Tang et al., 2017). Xia and Zhou (2017) also found a decrease in NDVI after wind power plant construction, although their results were not statistically significant. Lastly, Diffendorfer et al. (2022) observed both increases and decreases in vegetation greenness within the growing season.

### 3.2.2 Plant community composition

Several studies have examined the impacts of onshore wind energy development on plant community composition. While Ji et al. (2023) documented an increase in species diversity around wind turbines in meadow grasslands, Fraga et al. (2009) found that species diversity was decreased inside the main operation area of a wind power plant within a blanket bog. A long-term study by Urziceanu et al. (2021) found that plots disturbed by wind turbines contained less than 40% of the inventoried rare, endemic, and threatened species of the characteristic steppe vegetation. Losses of endemic species as a result of wind power development were also recorded in mixed-grass prairies (Davis et al., 2018), mires with wet heath vegetation (Fagúndez, 2008), and deserts (Keehn & Feldman, 2018).

The takeover of invasive species emerged as a notable concern in several studies. Keehn and Feldman (2018) observed an increased presence of invasive species within the main operation area of wind power plants, particularly in highly disturbed sites. Their findings suggest that disturbances from roads and human activity play an important role in plant community composition following wind energy development in desert-like ecosystems. This trend was corroborated by Villarreal et al. (2019), who noted a similar rise in invasive species abundance following wind energy development in the Mojave and Colorado deserts of southern California.

Conversely, some studies did not report significant effects on plant community composition. Fagúndez (2008) found no changes in plant community composition over a three-year period following wind power plant construction on a mire. Similarly, in a study by Patru-Stupariu et al. (2019), wind turbine presence had no significant effect on the plant community composition of a semi-open pasture landscape, five years after construction.

### 3.2.3 Soil erosion

When vegetation is cleared during the construction phase of a wind power plant, bare soil becomes susceptible to erosion from wind and rainfall (Nazir et al., 2020). Peatlands, when drained for safer wind turbine placement, pose a significant risk of carbon loss through erosion (Smith et al., 2014), which can be intensified by the drying of surface soils, depending on season and wind direction (Wang et al., 2023). Additionally, the construction of access roads for wind power plants can trigger peat slides, contributing to further soil loss (Dykes, 2022). In the Karaburun region of Turkey, researchers recorded a total loss of approximately 18,000 tons of soil organic carbon between 2000 and 2019, likely caused by wind energy development (Pekkan et al., 2021). When planning the siting of wind power plants in Chile, it was suggested that the associated soil erosion could increase soil loss by as much as 50% (Martí et al., 2023). Studies conducted in the Yunnan province of China imply that soil loss may even increase by over 1000% when accounting for factors like vegetation damage and rainfall (Ma et al., 2023).

### 3.2.4 Soil physical properties

Soil physical properties encompass factors such as soil texture, structure, density, temperature, and water-holding capacity (Sanchez, 2019). The construction of onshore wind power plants can alter soil physical properties through activities like excavation, road construction, and the building of related infrastructure (Christol et al., 2021). These disruptions can cause the loss of native soils, topsoil disturbance, and microtopographic changes. They can also lead to soil compaction (Chen et al., 2019), which tended to be highest near wind turbines and decreased with distance (Xie et al., 2014). Furthermore, alterations in ground-level microclimate and soil temperature have been measured (Armstrong et al., 2016), along with changes in nutrient content (Chen et al., 2019; Luo et al., 2021) and soil salinity (Chen et al., 2019). Ji et al. (2023) also studied the influence of wind power plant operation on soil carbon content but found no significant impacts. The effects from decommissioning are expected to be similar to the ones from construction, which is why turbine pads and underground powerlines are often left in situ to minimize further soil disturbance (Welstead et al., 2013).

### 3.2.5 Water availability

Onshore wind energy development can affect an ecosystem's water availability via changes in microtopography and soil physical properties (Christol et al., 2021). Gunn et al. (2002) found that during the construction of an access road for a wind power plant in a peatland, the organic topsoil layer was compacted, causing water to collect on the upslope side. The water availability can also be reduced actively by inserting ditches to regulate water flow and drain the soil for safer wind turbine placement, which is common practice in peatlands (Murray, 2012). Ditches can be inserted temporarily during construction to regulate surface runoff caused by earthwork activities and to prevent wind turbine pads from being uplifted, or permanently to regulate increased runoff caused by road construction (Stunell et al., 2009). It was suggested that the effects of drainage for wind energy development can far exceed conservative land use estimates and need to be backed up by continuous long-term studies on hydrological impacts (Ramchunder et al., 2009; Renou-Wilson & Farrell, 2009).

In addition to drainage, some studies found impacts of wind power plants on local precipitation. Jawaheer et al. (2018) observed a decrease in precipitation one year after the construction of the Roches Noires wind power plant in Mauritius. Similarly, Pryor et al. (2018) found a decrease in summer precipitation caused by wind power plant operation, though the effect was not statistically significant. These findings are contradicted in a study by Fiedler and Bukovsky (2011), who used a regional climate model to demonstrate a significant increase in precipitation resulting from wind power plant operation.

#### *3.2.6 Water quality*

Studies on water quality have predominantly centered around wind power plants in peatlands, where peat degradation can contribute to reduced water quality by mobilizing metals and pollutants stored in the peat (Evans et al., 1999). The establishment of wind power plants was linked to increases in water turbidity and nutrient contents (Stunell et al., 2009), as well as dissolved organic carbon content (Ramchunder et al., 2009) in downstream aquatic habitats. The concentration of dissolved organic carbon and suspended sediments was higher in streams disturbed by wind power plants compared to undisturbed reference streams (Grieve & Gilvear, 2009; Heal et al., 2020; Lindsay & Bragg, 2005; van Niekerk, 2012; Waldron et al., 2009). At the Whitlee wind power plant in Scotland, researchers measured increased macronutrient concentrations (Zheng et al., 2018) and export rates (Murray, 2012) following wind power plant construction on peatland. Another study conducted on peatland reported significant impacts on pH and alkalinity (Millidine et al., 2015). However, studies conducted in a Karst environment found no impacts on groundwater quality (Valente et al., 2022).

### *3.3 Consideration of mitigation and restoration*

The majority of studies (41 studies) focused exclusively on impacts, while fewer considered the subsequent need for mitigation (24 studies) or restoration (23 studies) (Figure 4). This was especially apparent in empirical research, where more than half of the studies (35 out of 62 studies) focused exclusively on impacts, while only few acknowledged the subsequent need for mitigation (16 studies) or restoration (11 studies). In contrast, only 6 of the 26 non-empirical studies focused exclusively on impacts, while the majority addressed the need for mitigation (8 studies) or restoration (11 studies).

Another emerging trend was the low concern for restoration in studies that analyzed vegetation impacts (Figure 4). The share of vegetation studies was 58% in the studies exclusively focusing on impacts, and 55% in those mentioning mitigation. This trend was reversed in the restoration group, where most studies concerned soil-related impacts (45%), but only 30% concerned impacts on vegetation, despite the overall dominance of vegetation studies in the reviewed literature. For hydrological studies, no clear trend was observed regarding their consideration of mitigation and restoration.

## 4 Discussion

### *4.1 Highlights*

This literature review analyzed 88 studies on the impacts of onshore wind energy on vegetation, soil, and hydrology. Empirical studies were more common than non-empirical studies. They primarily focused on vegetation dynamics and highlighted both positive and negative effects, such as increased biomass in grasslands and deserts, but significant vegetation loss in forests. For impacts on soil and hydrology, empirical evidence remained limited. Few studies included direct field-based measurements of soil

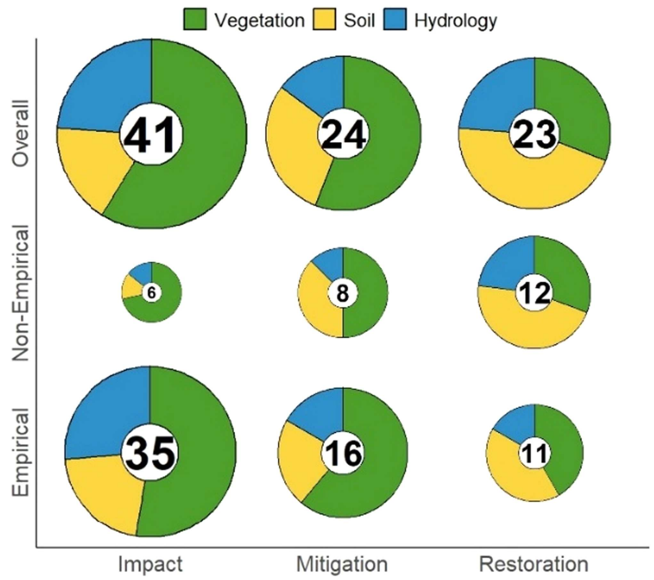


**Figure 4.** The distribution of studies addressing impacts, mitigation, and restoration in the context of onshore wind energy ($N = 88$). The size of each circle corresponds to the number of studies. The colored segments indicate the proportion of different topics studied: Vegetation, soil, and hydrology.

compaction or hydrological alterations, and only a small subset monitored long-term recovery. Moreover, most empirical research lacked standardized methods or site replication, making it difficult to generalize findings across studies. Importantly, nearly half of the studies focused solely on identifying impacts, while few acknowledged the subsequent need for mitigation or restoration. This trend was reversed for non-empirical studies. This imbalance highlights the need to more actively consider how environmental impacts can be mitigated and how degraded ecosystems can be restored in the context of onshore wind energy.

### *4.2 Opportunities for mitigating environmental impacts*

The mitigation hierarchy outlines a systematic framework for addressing environmental impacts at different project phases (Ekstrom et al., 2015; May, 2016). While early-phase measures can help avoid, reduce, minimize, or compensate for some impacts, restoration is often necessary at decommissioning to address residual effects (Bennun et al., 2021). Figure 5 provides a conceptual framework linking knowledge on vegetation, soil, and hydrological impacts to mitigation potential across the wind energy project lifecycle in order to inform mitigation strategies and external factors like regulations or decommissioning bonds.

#### *4.2.1 Planning and design*

During planning and design, impacts can be avoided and minimized by implementing regulations that restrict wind energy development in ecologically sensitive areas (Guan, 2018; Hajto et al., 2017; Sawin, 2001) or by using siting tools that rate a site's suitability for wind power plant installation based on environmental parameters (Hanssen et al., 2018; Höfer et al., 2016; Latinopoulos & Kechagia, 2015; Salkanović, 2023; Tsoutsos et al., 2005). Siting tools can help avoid areas with dense native vegetation or rare plant species, as observed by Urziceanu et al. (2021), thereby preserving local plant communities. They can also be informed by established soil models like RUSLE (Renard, 1997) or PESERA (Kirkby et al., 2008) to avoid negative impacts on hydrology, soil loss, and carbon emissions (Smith et al., 2014).

Environmental impact assessments (EIAs) can increase the knowledge on potential impacts (Figure 5), but were found to be incomplete and insufficient in many wind energy projects (Welstead et al., 2013).

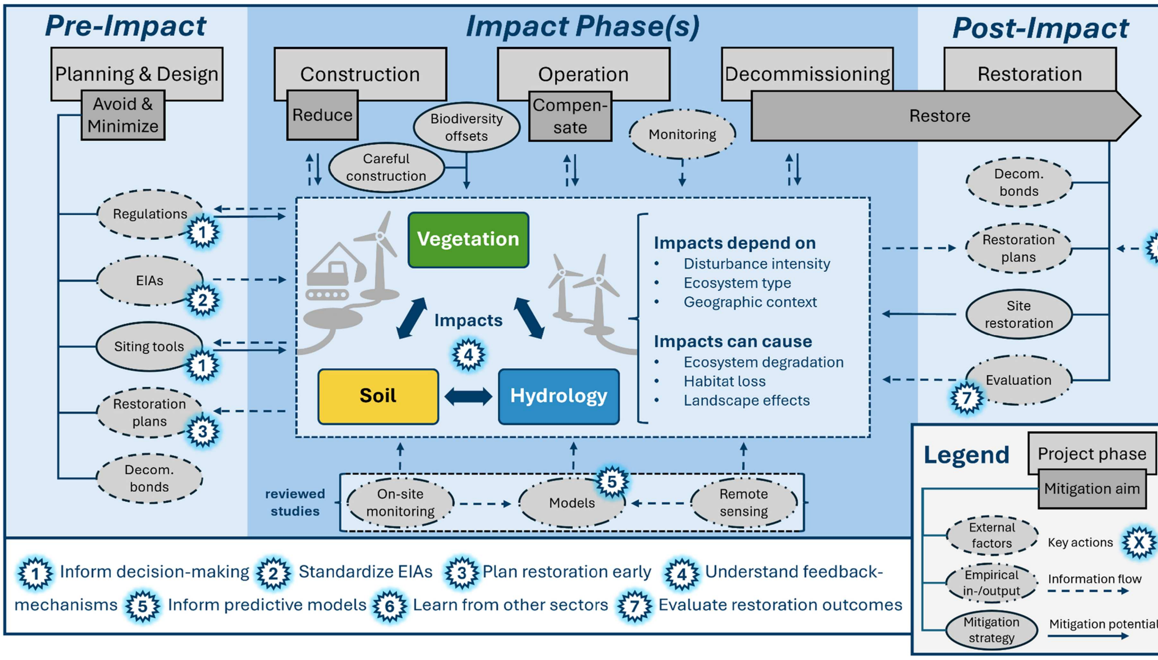


**Figure 5.** Conceptual framework illustrating how knowledge of environmental impacts from onshore wind energy on vegetation, soil, and hydrology can inform mitigation strategies and external governance mechanisms. Solid arrows represent the potential for mitigation at different project phases. Dashed arrows indicate the flow of information between components. Stars (1–7) denote key actions for advancing impact mitigation by reinforcing existing mitigation strategies or initiating measures to overcome knowledge gaps.

However, understanding environmental impacts is imperative in order to balance the socio-economic benefits of onshore wind energy against its potential environmental costs (May, 2023). To do so, it is recommended to set clear restoration goals from the start, allowing developers to design projects with end-of-life in mind (Stecky-Efantis, 2013; Welstead et al., 2013). To ensure sufficient funds for restoration activities, decommissioning bonds can be used (Ferrell & DeVuyst, 2013). Despite these proposed strategies, this literature review shows that ecosystem restoration remains underexplored in scientific research, highlighting a mismatch between policy recommendations and research priorities.

### 4.2.2 Construction

Construction phase measures can reduce ecosystem degradation by using manpower over heavy vehicles (Nazir et al., 2020), deploying specialized vehicles to prevent soil compaction (Scottish Renewables, 2020), limiting vehicle movement to construction areas (Bennun et al., 2021), or training machine operators to prevent impacts (Hagen et al., 2022), thus reducing the need for restoration later on (May et al., 2017). Temporary impacts, such as soil erosion, could be addressed on-site through immediate measures like sediment control systems (Ma et al., 2023). Permanent impacts may require off-site compensation throughout operation, for example via biodiversity offsets, but it remains questionable whether appropriate sites for offsetting can always be identified.

### 4.2.3 Operation

Compensation measures are typically designed to mitigate wildlife conflicts during operation (Arnett & May, 2016; Gartman et al., 2016), while impacts on vegetation, soil, and hydrology remain largely overlooked. To support long-term sustainability, it is essential to expand this focus to include ecosystem processes. This also requires that restoration plans are regularly assessed and updated during operation (Welstead et al., 2013), which could be achieved through ongoing monitoring. Remote sensing can be applied to track vegetation dynamics over time and detect changes in biomass or ground cover (Qin et al., 2022), while on-site monitoring enables early identification of invasive species, thereby supporting conservation planning (Urziceanu et al., 2024). Similarly, hydrological monitoring can help detect flow alterations or erosion risks, allowing for the implementation of targeted measures. In addition, predictive models can be used to estimate future impacts and support mitigation strategies. However, although 11% of the reviewed studies employed model simulations, they generally failed to capture complex environmental interactions and instead focused on individual impacts only.

These limitations reflect a broader challenge in our understanding of ecosystem-level impacts of onshore wind energy. Although this literature review demonstrates a growing body of empirical research, our fundamental understanding remains limited due to three main reasons. First, internal feedback-mechanisms between vegetation, soil, and hydrology complicate the identification of cause-effect relationships (Figure 5). For example, soil erosion may result from drainage associated with turbine placement (Smith et al., 2014) or from shifts in vegetation patterns (Ma et al., 2023). In turn, soil erosion can lead to downstream pollution (Ramchunder et al., 2009) and increased atmospheric carbon emissions (Smith et al., 2014). Such cascading effects highlight the need for ecosystem-based approaches that consider spatial and temporal connections, such as hydrological links in peatlands, rather than isolating impacts (Copping et al., 2020; Wawrzyczek et al., 2018).

Second, the nature and severity of impacts depend on disturbance intensity, ecosystem type, and geographic context. For instance, some studies report increased vegetation growth near wind turbines in grassland and desert ecosystems (Luo et al., 2021; Xu et al., 2019), while others document vegetation loss in forests (Balotari-Chiebá et al., 2024; Diffendorfer & Compton, 2014). These contrasting outcomes underscore the need for site-specific monitoring and solutions.

Third, as demonstrated in this literature review, results also vary considerably between study types. For example, studies using on-site monitoring often focus on fine-scale vegetation responses within individual wind power plants, while remote sensing studies may capture broader spatial patterns but overlook subtle environmental changes. This methodological diversity complicates direct comparison and synthesis of findings across studies. When formulating or updating restoration plans, it is therefore crucial to tailor them to the specific site conditions and ecosystem context. At the same time, developing a generalized framework for mitigation and restoration in onshore wind energy can enhance the systemic effectiveness and consistency of efforts across different locations.

#### 4.2.4 Decommissioning and restoration

At decommissioning, ecosystem restoration can remediate impacts that were not mitigated during earlier project phases (Figure 5). While it is increasingly recognized as a necessary component of sustainable wind energy development, ecosystem restoration is not only an ecological concern but also a socio-political and economic process shaped by land-use planning, regulatory frameworks, and community values (Hagen et al., 2013).

Effective restoration requires cross-disciplinary collaboration across ecology, landscape planning, and the social sciences to ensure that ecological goals align with broader societal priorities. Restoration strategies must comply with political regulations and land lease agreements, and decisions about whether and how to restore a site may be influenced by factors such as opportunity costs, cultural landscape values, and the availability of financial mechanisms like decommissioning bonds (Ferrell & DeVuyst, 2013; Welstead et al., 2013). Restoration feasibility and costs can vary considerably depending on disturbance intensity and ecosystem type. For example, recovery may take decades to centuries in high-latitude or high-altitude regions (Campbell & Bergeron, 2012; Forbes & McKendrick, 2002), though successful restoration has been achieved (Erikstad et al., 2023; Evju et al., 2023).

To evaluate restoration outcomes and predict time to recovery, monitoring is important (Evju et al., 2023), but given the relatively recent and rapid development of onshore wind energy, practical knowledge on restoration in this context remains limited. Drawing on insights from related sectors such as road construction (Wang et al., 2021), solar energy (Tsoutsos et al., 2005), or hydropower (McManamay et al., 2020) can provide valuable perspectives and solutions (Hagen et al., 2013), but ultimately restoration strategies must be tailored to the ecological, social, and economic conditions of each location, and are therefore context-specific.

### 4.3 Key actions for advancing impact mitigation

Building on the opportunities outlined in Section 4.2, the effective mitigation of environmental impacts requires a targeted focus on several key actions that include the reinforcement of existing mitigation strategies and measures to overcome persistent knowledge gaps (Figure 5). These are:

1. Inform decision-making: Avoiding or minimizing impacts prior to construction requires translating existing knowledge of environmental impacts into actionable guidance for policymakers, planners, and developers. Such knowledge can be drawn from EIAs, environmental monitoring programs, and scientific studies, including those synthesized in this review (Figure 5), and should be used to inform regulations and siting tools that can restrict site selection in sensitive areas.
2. Standardize EIAs: EIAs must be standardized in scope, methodology, and reporting to ensure a consistent and comprehensive evaluation of environmental impacts.
3. Plan restoration early: Formulating clear restoration plans from the outset ensures environmental sustainability and regulatory compliance with end-of-life in mind. Early planning allows integration into project design, ensures financial and regulatory preparedness, and provides baseline data for effective ecosystem recovery. Without it, restoration at decommissioning risks being underfunded, technically constrained, or ecologically less effective. For example, constructing deep turbine foundations involves extensive excavation and soil compaction. If the depth, footprint, or reinforcement materials are not considered with restoration in mind, the original soil structure, nutrient profile, and seed bank may be heavily altered, making later re-establishment of native vegetation difficult and costly.
4. Understand feedback-mechanisms: Complex interactions among vegetation, soil, and hydrology must be understood in order to apply tailored mitigation strategies.
5. Inform predictive models: Empirical data collection must continue to better inform models that can estimate or predict impacts and improve mitigation strategies.
6. Learn from other sectors: With limited experience regarding ecosystem restoration in onshore wind energy, insights from other sectors can offer valuable perspectives and solutions.
7. Evaluate restoration outcomes: Ongoing monitoring is essential to predict time to recovery, assess restoration success, and increase empirical knowledge on impacts.

Furthermore, establishing cross-sectoral governance structures involving both energy and environmental authorities can be a critical step towards integrating renewable energy expansion with the need for biodiversity conservation and restoration, as is urgently needed (Gorman et al., 2023). Developing shared monitoring protocols and long-term funding and responsibility mechanisms for restoration, for example via decommissioning bonds or public-private partnerships, will be key to ensuring these measures are sustained beyond project lifespans.

## 5 Conclusion

As the expansion of onshore wind energy continues at an accelerated pace, it becomes increasingly important to assess and mitigate its environmental impacts. This review shows that while impacts on vegetation, soil, and hydrology are receiving growing attention, most research still concentrates on documenting impacts rather than exploring how they can be mitigated or how degraded ecosystems can be restored.

To help bridge this gap, a conceptual framework that links the existing knowledge of environmental impacts to mitigation potential across all project phases of onshore wind energy was proposed. This framework supports a more systematic approach to integrating mitigation and restoration into project planning, implementation, and decommissioning.

Alongside this, a set of key actions to enhance mitigation effectiveness and strengthen governance mechanisms was presented. Crucially, more empirical data are needed to inform mitigation strategies across project phases, and restoration must be considered from the outset to secure effective restoration outcomes in the long term. Advancing this shift is essential to ensure renewable energy expansion aligns with both climate goals and environmental sustainability.

## Acknowledgements

The authors thank all anonymous reviewers for their comments, which helped improve the manuscript.

## Author contributions

CRediT: **Lukas Seifert**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft; **Bente J. Graae:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing; **Dagmar Hagen:** Conceptualization, Supervision, Writing – review & editing; **Roel May:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

## Disclosure statement

The authors report there are no competing interests to declare.

## Funding

This work was funded by the Research Council of Norway as a part of the Center for Environment-friendly Energy Research NorthWind (Norwegian Research Center on Wind Energy) under grant number 321954.

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## Data availability statement

The data that support the findings of this study are available from the corresponding author, [LS], upon reasonable request.

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