Effects of Land-Based Wind Energy on Ecosystems

Wind turbines near Rogaland, Norway. *Photo from Getty Images 955719612*

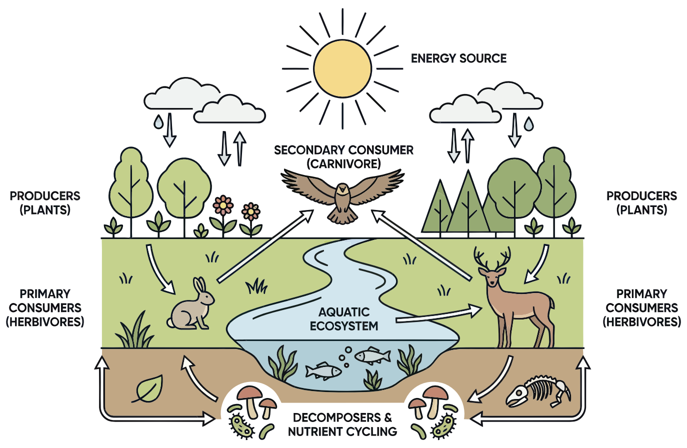
Summary

The construction of wind farms and associated infrastructure can affect local species compositions, trophic interactions and ultimately ecosystem processes. Yet few studies have looked at the effects of wind energy on terrestrial ecosystems. This summary provides an overview of the impacts of land-based wind energy on ecosystem structure and function and highlights an ecosystem-based management approach to sustain a balance between wind energy development and environmental protection.

Introduction

Land-based wind energy has grown rapidly, attracting about one-third of global renewable energy investments from 2013 to 2022, making it the second-largest sector after solar energy. In 2024, global land-based wind energy capacity reached 1,053 GW, accounting for 93% of total wind energy production. While technological advances have increased wind turbine capacity, thereby reducing the footprint of wind energy per kilowatt-hour, rising energy demands still require more land for wind farms.

Most land-based wind farms are located in natural and semi-natural landscapes, so it is essential to better understand the potential impacts of development on surrounding ecosystems. Previous studies generally emphasized wind energy's impacts on individual species or specific habitat components. Systemic impacts of wind energy at the ecosystem scale are lacking despite the direct and indirect effects that wind energy can have on the structure and function of terrestrial ecosystems.



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Ecosystems Defined

An ecosystem is composed of living and non-living components that interact through ecosystem processes to shape its structure and function. Ecosystem structure refers to the spatial patterns of biotic (i.e., producers, consumers and decomposers) communities and abiotic (i.e., soils, hydrology and climate) conditions within a specific area. Ecosystem functions refer to processes such as energy flows, nutrient cycling, and food webs that maintain an ecosystem's resilience.

Effects of Land-Based Wind Farms on Ecosystems

Site preparation and construction activities, such as road construction, material transport, wind turbine installation and powerline construction, affect topography, remove local vegetation, and disturb hydrology and soils—all of which can take a long time to restore. During operation, wind turbines generate aerodynamic and mechanical noise. They also create wake effects that increase downward turbulence, altering local microclimates, including temperature, humidity and wind patterns, and nearby vegetation. The presence of wind farms can indirectly impact species through avoidance and displacement behaviours, which results in functional habitat loss and barriers to movement. Individual animals may be directly impacted by colliding with wind turbines or being electrocuted by powerlines. However, the extent to which these impacts affect the ecosystem varies across species, habitat types and ecosystem processes.

Impacts on Ecosystem Structure

Wind farm construction can negatively impact the physical structure, chemical properties and hydrology of soils, increasing the potential for soil erosion. Changes to the microclimate associated with operating wind turbines are well studied and often show warmer ground surface air temperatures at night, leading to dryer soils. Combined, these changes influence primary productivity, nutrient cycling, soil biota activity and habitat integrity, ultimately affecting ecosystem processes. Most land-based wind farms are typically constructed in remote undeveloped regions, fragmenting the land and resulting in increased human disturbance to such areas. In forested areas, wind energy development can fragment forest ecosystems by increasing open space and forest edges, leading to dramatic changes in local climate and vegetation structure. In the direct vicinity of wind farms, land clearing and vegetation removal can cause increased patchiness and fragmentation of ecosystems. Roads further contribute to habitat fragmentation and disturbance for a variety of species.

Impacts on Ecosystem Function

The noise generated by operational wind turbines has been shown to decrease the abundance of earthworms by 40%. Because earthworms are ecosystem engineers, this may have knock-on effects on soil functioning processes such as water filtration, nutrient cycling and carbon sequestration, and primary production. As the primary producer of ecosystems, vegetation often shows reduced growth, greenness and cover in the vicinity of wind farms. This can lead to changes in diversity and composition of local plant communities and an opportunity for invasive species to establish. Higher road density and increased human activity can also change foraging and predator–prey dynamics. In California, USA, increased roads in wind farms and associated changes in the vegetation can increase grazing opportunities for herbivores, such as big horn sheep. In the Iberian shrub-steppes, nests established near newly constructed roads can lead to higher nest predation through increased abundance of predators and scavengers such as red fox and corvids (e.g., crows). However, a study in southern Poland showed that avoidance of European roe deer and hares reduced the density of the red fox in wind farms. Differential sensitivity to wind turbine disturbance may change the relative abundance of some wildlife species as they are displaced from wind farm areas, potentially causing food web changes. For example, displaced large predatory birds led to increased densities of prey lizards and rodents. Areas with fewer predators may experience ecological release in which prey species' survival and abundance can increase, leading to increased pressure on lower trophic levels. Similarly, such changes may also lead to ecological traps where organisms make poor habitat choices based on cues that formerly were indicative of habitat quality. For instance, wind farms may attract insects, which in turn could lead to increased foraging activity in bats and passerines in the vicinity of wind turbines, augmenting their risk of collision. The extent to which observed changes in interspecific interactions affect the overall function and resilience of ecosystems is yet unstudied.

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Ecosystem Accounting

The United Nations adopted the System of Environmental Economic Accounting (SEEA) Ecosystem Accounting (EA) as its standard statistical framework in 2021. The United Nations describes SEEA EA as a "framework for organizing data about habitats and landscapes, measuring the ecosystem services, tracking changes in ecosystem assets, and linking this information to economic and other human activity" (https://seea.un.org/ecosystem-accounting). This framework helps users assess ecosystem health, monitor changes, and identify key areas for sustainably managing biodiversity.

Monitoring and Mitigation of Ecosystem Impacts

Although some progress has been made, knowledge of the ecosystem effects of land-based wind farms is still limited. There are, however, a few studies on the impacts of land-based wind energy at whole-ecosystem levels, highlighting the need to use "ecosystem accounting" during the planning phase to better quantify the potential impacts of a wind farm project on ecosystem conditions at an early stage. Applicable research approaches to analyse ecosystem impacts of wind energy include high-resolution remote sensing to capture regional spatial and long-term temporal changes in ecosystem structure, integrated field-based multi-sensor monitoring to examine interspecific interactions in multiple species as well as changes to ecosystem function, and simulation models to assess whole-ecosystem impacts. The application of environmental DNA (eDNA) shows promise for tracking changes in biodiversity and monitoring ecosystem health and function before and after the introduction of wind farms. Informed siting decisions may be the most important measure to avoid unnecessary damage to ecosystems and should consider the condition and restorability of ecosystems. A good understanding of how specific ecosystems are likely to be affected by development may help decision makers site wind farms in the least-impacted habitats. Minimizing the footprint of wind turbines and the associated road network reduces soil compaction and hydrological interruptions, consequently limiting impacts on the vegetation. Effects that are expected to occur during wind farm operation should be addressed pre-emptively at the planning phase and mitigated appropriately. This may include adjusting wind turbine designs and wind farm layouts to reduce disturbance and micro-climatic wake effects.

Toward Ecosystem-Based Approaches

One approach to assessing the potential impact pathways and ecosystem responses to land-based wind energy on ecosystems is the Drivers-Pressures-State-Impact-Response (DPSIR) assessment. The DPSIR framework includes:

- Driving force (e.g., land-based wind energy development and related activities throughout a wind farm's life cycle)
- Pressure (e.g., physical presence of wind turbines in the environment and resulting disturbances)
- State (e.g., conditions of physical, biological and chemical phenomena)
- Impact (e.g., changes in the structure and function of ecosystems)
- Response (e.g., actions to restore ecosystem conditions).

Coupling the wealth of ecosystem studies in natural and semi-natural systems to this applied impact framework can result in expectations of salient impacts to focus on. One option to address the impacts of wind energy development is ecosystem-based management, which is a holistic approach to natural resource management that sustains ecological integrity to balance ecological, social, and economic goals. Although it has been applied in the conservation of marine ecosystems and offshore wind energy, its use for land-based wind energy is in early stages. Further guidance on its implementation may support more informed decisions that enable a sustainable balance between wind energy development and environmental protection.

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