



Quantifying land impacts of wind energy: a regional-scale assessment in Finland

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Abstract

Large-scale deployment of wind energy raises ecological concerns about land use changes. Here, we conducted a quantitative assessment of land impacts of 42 wind farms (513 turbines) from Ostrobothnia, Finland. Located on the Baltic Sea coast, Ostrobothnia is a strategic region for national wind energy targets. Our main objectives were (1) to calculate landscape metrics (e.g., habitat composition, loss and fragmentation) within wind farm project areas, (2) compare the amount of building-related deforestation between project areas and simulation-based control areas and (3) compute the overlap between project areas and regional land use plans. According to CORINE Land Cover datasets, the predominant habitats within project areas were forests (371.7 km²; 81%) and transitional forests (52.7 km²; 11%). The remaining 8% were agricultural areas (17.6 km²; 4%), waters (12.5 km²; 3%) and artificial surfaces (2.9 km²; 1%). Wind farm infrastructure corresponded to 1.4–6.0% of project areas and caused similar degrees of habitat fragmentation. Deforestation levels in project areas were higher (~6 times on average) than in control areas, and the micro-siting of turbines did not avoid mature forests by favouring e.g., transitional forests (which are ecologically less valuable). We found some spatial incongruence between project areas and regional land use plans, with 78 turbines falling outside the established boundaries. Our results highlight the need for careful ecological considerations in wind energy spatial planning in Finland (and countries with similar landscapes and land uses) to limit forest loss and its detrimental impacts on forest-dependent species, but also on carbon storage and sequestration.

Keywords Deforestation · Energy sprawl · Landscape change · Spatial planning · Sustainability · Wind energy

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1 Introduction

Large-scale deployment of renewable energy has the potential to increase electricity production while reducing the emissions of air and water pollutants, thereby helping to mitigate climate change and environmental pollution (Hertwich et al., 2015). Wind energy is one of the fastest-growing renewable energy sources in the world, and its growth is predicted to further accelerate in the near future (Global Wind Energy Council, 2022; IEA, 2021). For instance, wind energy is set to play a prominent role in the European Union's energy mix in an effort to reduce greenhouse gas emissions by at least 55% (compared to 1990) by 2030 (European Commission, 2020), a pathway consistent with so-called climate neutrality by 2050 (WindEurope, 2021). There are concerns, however, that the landscape changes that are necessary to achieve current renewable energy targets may negatively impact habitats, ecosystem processes, species distributions and population viability (Sodhi & Ehrlich, 2010). Landscape changes have been, and continue to be, a major driver of biodiversity loss (IPBES, 2019). Without strategic planning, the increasing pressure by renewable energy expansion will pose significant challenges to the often-limited conservation efforts, and perhaps even compromise conservation areas that have already been established (Rehbein et al., 2020; Sonter et al., 2020).

The area directly disturbed by wind turbines and associated infrastructure is usually small (2–5% of the project area) (Wiser et al., 2011), although the effects of habitat degradation can extend over time to areas that are adjacent to infrastructure (Diffendorfer et al., 2019). This means that co-existence with other land uses is possible. However, it is often stressed that development should take place in sites that are already environmentally disturbed (e.g., agricultural fields and industrial areas) (Kiesecker et al., 2011). Moreover, wind energy has extensive land requirements when considering the amount of energy that can be produced in a given area, and this contributes to so-called energy sprawl (i.e., an increase in land area impact due to electricity production) (Davis et al., 2018; Jones & Pejchar, 2013; McDonald et al., 2009; Palmer-Wilson et al., 2019; Trainor et al., 2016). For instance, the land-use intensity of wind energy exceeds that of many other energy sources, including hydropower, petroleum, solar photovoltaic, natural gas, solar thermal and coal (McDonald et al., 2009). Given this land use-related limitation, wind energy expansion will require, among other things, appropriate siting, sustainable practices and mitigation measures to reduce land impacts. Habitat loss from wind energy is a direct result of turbine pads (where turbines are placed), roads, transmission lines, laydown areas, substations and operation buildings (Denholm et al., 2009; Jones et al., 2015). Of these, roads (which intersect and fragment the landscape) can often have the largest share of habitat loss (Denholm et al., 2009). Wind energy can lead to high levels of fragmentation in the landscape with potential impacts on surrounding wildlife (Jones et al., 2015). In particular, development in forested areas, which require additional clearing for roads, turbine pads and setback distances, has the potential to significantly degrade habitat quality (Denholm et al., 2009). Forests contain habitats for a large number of species and act as carbon reservoirs (Hunter et al., 2021). Thus, the felling of trees is not only a serious threat to natural habitats and biodiversity but also exacerbates climate change by increasing the atmospheric concentration of carbon dioxide. Also, the replacement of topsoil by wind farm infrastructure creates impervious surfaces that prevent or impair the natural flow of water into the soil (Jones et al., 2015).

Besides land impacts, wind energy can affect species through collision mortality (direct effect) or displacement due to disturbance (indirect effect). Collision mortality is a main concern for local populations of various bird groups (e.g., raptors, geese, gulls and terns) (Tosh et al., 2014) and bats (Arnett et al., 2008), especially for species with long generation times and low reproductive output (Erickson et al., 2015). For instance, white-tailed eagles were shown to collide in high numbers with, and be displaced by, wind turbines installed in proximity to breeding sites, significantly impairing their breeding success (Dahl et al., 2012). Similarly, species avoidance behaviour due to disturbance or reduced habitat quality is being increasingly recognised as an important indirect effect, as it effectively amounts to functional habitat loss (i.e., animals avoid the habitats that remain available at wind farms). Several studies have reported that areas around wind turbines are used less frequently compared to control sites or pre-construction scenarios, with bird and bat species exhibiting different avoidance distances (Barré et al., 2018; Fernández-Bellon et al., 2019; Gaultier et al., 2023; Larsen & Madsen, 2000; Marques et al., 2020; Millon et al., 2018; Shaffer & Buhl, 2016).

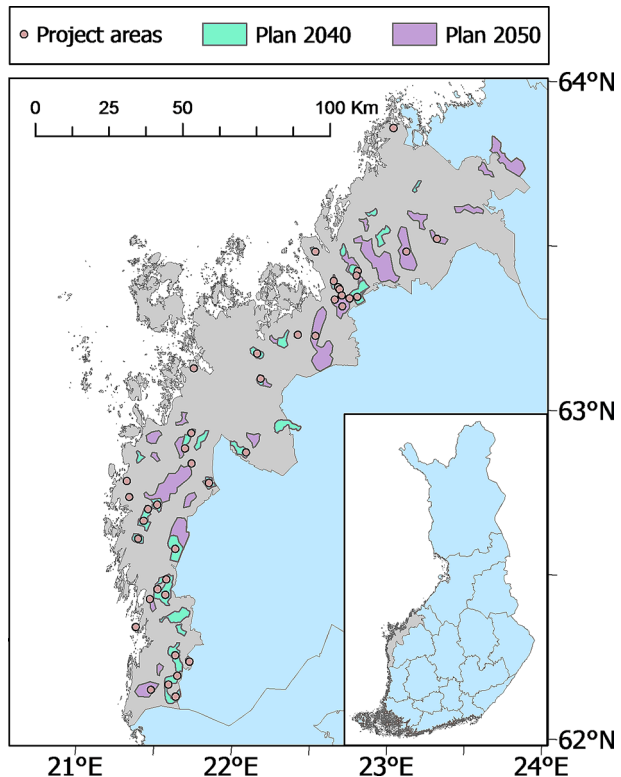
In Finland, wind energy started to gain momentum in 2012–2013 and has expanded considerably in recent years. In 2023, a total of 1601 wind turbines (6946 MW) produced 18.1% of Finland's electricity consumption (FWPA, 2024a). This share is expected to reach 30% by 2030 (FWPA, 2024a), and there are currently a large number of projects that can greatly exceed the installed capacity needed to achieve that target (FWPA, 2024b). Most projects continue to be onshore (~51%), despite a rapid increase in offshore investments (FWPA, 2024b). Thus, there are serious concerns that wind energy may contribute to the loss of natural habitats, particularly the further degradation of forests. Forestry and management activities have already caused widespread ecological damage, with a substantial reduction of old-growth trees and dead wood volume (Mönkkönen et al., 2022). As a consequence, Finland's forest species and habitats continue to be threatened (with a deteriorating conservation status) (Hyvärinen et al., 2019; Kontula & Raunio, 2018). At present, there is thus an urgent need to quantify the degree to which wind energy development overlaps with natural habitats, and to understand the potential consequences of such development for ecological integrity, particularly in forests. Here, we use detailed site-level data (with georeferenced information on project areas, wind turbines and roads) to assess the land impacts of 42 existing and planned wind farms (513 turbines) in Ostrobothnia, Finland. Quantitative assessments based on such detailed data (which allow for the calculation of more detailed metrics) are lacking in the literature, not only for Ostrobothnia but also for the rest of Finland. Located along the Gulf of Bothnia, Ostrobothnia has favourable wind conditions and is thus a strategic region for the achievement of national energy targets. In 2023, Ostrobothnia had 18% of Finland's cumulative wind energy installed capacity (FWPA, 2024c), and held 15% of all investment decisions announced for 2023–2025 (FWPA, 2023). More specifically, our objectives are (1) to compute a set of landscape metrics (e.g., habitat composition, loss and fragmentation) for wind farm project areas (hereafter, project areas), (2) to check whether there is a difference in deforestation between project areas and randomly-selected control areas, (3) to assess the degree of spatial agreement between project areas and regional land use plans (hereafter, regional plans), and (4) to present relevant summary statistics, including land requirements per unit energy (hectare/MW). Our overall aim is to provide information that can enhance ecological considerations in wind energy spatial planning.

2 Materials and methods

2.1 Wind farms and associated data

We analysed 42 wind farms (16 in production, 10 under construction and 16 in the permitting phase) located in Ostrobothnia, totalling 513 turbines (Fig. 1). We focused on three wind farm spatial features: (i) project areas, (ii) turbines and (iii) roads. The project area is a legal boundary that contains the entire wind farm (extending beyond individual turbine sites). The project area is established based on terrain features, turbine size, land use, setback requirements and other restrictions (Denholm et al., 2009). Shapefiles of project areas and turbines were obtained upon request from municipalities. According to Finnish legislation, small wind farms do not need to comply with regional plans (see details below). Thus, project areas for seven single-turbine projects and three other small projects were unavailable. In these cases, we generated a project area by adding a buffer of 533 m around each turbine. This buffer was equivalent to the mean area of a single turbine ($0.89 \text{ km}^2 \pm 0.28 \text{ SD}$) in the project area as a whole. Shapefiles of roads were extracted from a topographic map of the National Land Survey (NLS) of Finland (<https://www.maanmittauslaitos.fi/en>). We used the NLS road classification to exclude line geometries that we deemed irrelevant to the study, such as trails and cycle paths. Based on wind farm land use plans, we used ArcGIS Pro (version 2.8.2) to digitise turbines and roads under construction or in the planning phase that were unavailable from the NLS database.

Fig. 1 Locations of the 42 onshore wind farms (orange circles) in Ostrobothnia (in grey) studied here, overlaid on the two latest regional plans (2040 [in green] and 2050 [in violet]) showing the areas targeted for onshore wind energy production



2.2 Landscape metrics

We estimated habitat loss by assessing the overlap between wind farms and Corine Land Cover datasets from three different years (2006: 25-m resolution; 2012 and 2018: 20-m resolution). The Corine datasets covered three different periods of wind farm construction or planning: 2006–2009, 2010–2015 and 2016–2023. We adjusted Corine 2006's pixel size (to a 20-m resolution) by resampling with the *nearest neighbour* method (Wegmann et al., 2016). We slightly modified Corine's level-1 habitat classification (splitting forests, and merging wetlands and waterbodies) to obtain the following classes: (i) artificial surfaces, (ii) agricultural areas, (iii) forests, (iv) transitional forests and (v) waters. *Forests* referred to broad-leaved, coniferous and mixed forests, while *transitional forests* referred to transitional woodland/shrub (mostly clear-cuts and young plantations) and bare rock. Details of all habitat classes within the project areas are available in Table S1. We estimated direct habitat loss due to infrastructure as follows. We first buffered each turbine with a 39-m radius, representing the turbine pad size of the operational wind farms studied here (39 m \pm 11 SD). Roads were buffered with a 6-m radius, as unpaved forest roads of this dimension are common in Finland (Metsäteho Oy, 2001). We then calculated the amount (number of pixels) of each habitat class within the project areas, and performed a chi-square test to compare the observed frequency of habitat classes with an expected frequency from a homogeneous distribution (Fowler et al., 1998). We also calculated the amount (number of pixels) of each habitat class within the turbine pads. Here, we computed selection ratios (Manly et al., 2002) to check whether turbine placement selected or avoided a particular habitat given its availability in the project area. Observed and available habitat classes were computed separately for each project area (Thomas & Taylor, 1990). To quantify habitat fragmentation, we used the GISFrag metric (see e.g., Jones & Pejchar, 2013). GISFrag describes the mean distance between focal points and the nearest point with habitat loss (represented here by wind farm infrastructure). We first rasterised wind farm infrastructure on a spatial grid (20-m resolution) to identify the pixels containing habitat loss. We then computed the Euclidean distance between all pixels and the nearest pixel with habitat loss. Habitat fragmentation was expressed as the mean distance over all pixels, with lower values indicating higher fragmentation. In addition, we calculated the total area, number of habitat patches, number of turbines, road length and land requirements per unit energy for all wind farms.

2.3 Forest use notifications: a measure of deforestation

Metsäkeskus (Forest Centre) is a state-funded organisation that provides forestry-related services to landowners, also collecting and sharing data on forest use (<https://www.metsakeskus.fi/fi>). We relied on their forest use notifications to quantify deforestation. A forest use notification is made at least 10 days before the felling of trees or intervention in a particular habitat. No notification is required in certain cases, e.g., when felling small trees (< 13 cm in diameter) in habitats of no particular importance (Metsäkeskus, 2023). The data used here are available as shapefiles (updated in May 2023). We used the variable “Cutting realization practice” to identify and calculate the area of forest patches specifically targeted for *building purposes*, a measure of permanent forest loss. Here, we aimed to check whether the amount of deforestation inside project areas differed from control areas. We randomly generated 100 control areas per project area. The control areas were equivalent in shape

and size to the original project areas. For each simulation, we calculated the total amount of deforestation from the randomly-generated control areas. We then employed the Wilcoxon rank sum test for comparing project and control areas for each simulation (Fowler et al., 1998), thus obtaining 100 test statistics. Here, we focused solely on built or under construction wind farms for which land use plans were available ($n=18$). Only forest use notifications that were made after the publication of land use plans were included in the analysis.

2.4 Regional plans

Regional plans are comprehensive plans that target specific areas to fulfil social or environmental functions. Here, we focused on the two latest regional plans for Ostrobothnia (2040 and 2050). These regional plans are available as shapefiles at <https://www.obotnia.fi/omradesplanering/gis-och-kartor>. Ostrobothnia's regional plan for 2040 identifies areas for, among other things, energy supply (Österbottens förbund, 2023a). Ostrobothnia's regional plan for 2050 combines regional and national objectives to address societal areas that have an impact on land use (Österbottens förbund, 2023b). Wind farms with up to 10 or 7 turbines are not required to conform with the 2040 and 2050 regional plans, respectively (pers. comm.; Gustav Nygård; 15 February 2023). We then assessed the extent to which wind farms and regional plans are in agreement to estimate to what degree regional plans are effective in steering wind energy development. We used R (version 4.2.2; R Core Team, 2022) for all analyses, spatial operations and graphic displays (except for Fig. 1, created with ArcGIS Pro [version 2.8.2]).

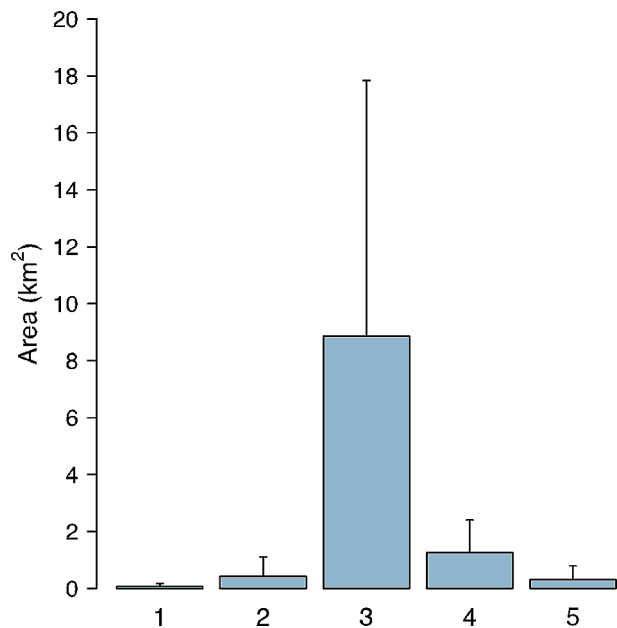
3 Results

The 42 wind farms studied here ranged from small (one turbine, $n=7$) to large projects (44 turbines, $n=2$), thus showing considerable variation in the variables assessed (Table 1). The habitat class that was predominant within project areas was forests (total: 371.7 km²; 81%), followed by transitional forests (total: 52.7 km²; 11%), agricultural areas (total: 17.6 km²; 4%), waters (total: 12.5 km²; 3%) and artificial surfaces (total: 2.9 km²; 1%; Fig. 2). Forests and transitional forests comprised 92% of all habitat classes. Thus, the observed frequency of habitat classes deviated significantly from a homogeneous distribution ($\chi^2=2,720,736$; $df=4$; $p<0.001$). Regarding turbine placement, forests and transitional forests were used in accordance with their availability, while all the other habitat classes (which had smaller proportions) were avoided (log-likelihood $\chi^2=1090$; $df=54$; $p<0.001$; Fig. 3). Building-related deforestation inside project areas was significantly greater (~6 times on average in 100 simulations) than in control areas (Fig. 4). This indicates that wind energy, if primarily deployed in forest areas, lead to deforestation levels that are significantly higher than building-related background levels. Habitat loss due to infrastructure ranged from 1.4 to 6.0% of the project area, with roads varying considerably in extension (1–67 km; Table 1). However, habitat fragmentation was similar across project areas, with an average distance of 202 m between points without infrastructure and the nearest point with infrastructure (Table 1). Here, we should note that our measure of habitat loss is to be regarded as a minimum estimate. A comparison between deforested and infrastructure areas indicates that the reported numbers may be underestimated by 16% (± 73 SD, $n=18$) (Table S2).

Table 1 Summary table of the land variables calculated for wind farms in Ostrobothnia, Finland. Note that the calculations of project areas only include the original shapefiles supplied by Finnish municipalities, building-related deforestation only includes wind farms analysed in the simulation exercise, and land requirements per megawatt only include wind farms with available information on nameplate capacity. Note also that land requirements refer to the project area, which exceeds the area directly affected by turbine deployment. SD stands for standard deviation

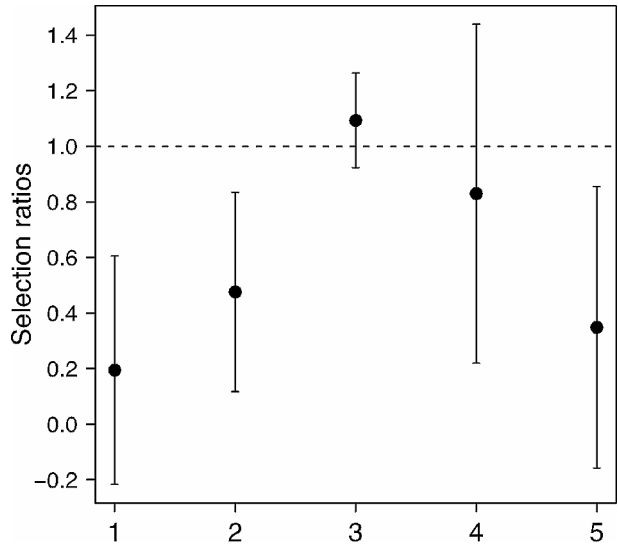
Variables	Min.	Max.	Mean	SD	Total	Sample size
Project area (km ²)	2.5	50	13.9	10.6	445	32
Turbines	1	44	12	11	513	42
Roads (km)	1	67	17	16	700	42
Infrastructure proportion (%)	1.4	6	2.5	0.8		42
Habitat loss due to infrastructure (ha)	1	100	25	23	1057	42
Habitat fragmentation (m)	78	285	202	42		42
Building-related deforestation (ha)	5	108	34	29	620	18
Land requirements (ha/MW)	8	89	23	14		35
Land requirements (ha/turbine)	29	162	87	27		42
Turbines outside regional plans	0	8	2	2	78	42
Proportion outside regional plans (%)	0	100	46	35		42
Area outside regional plans (km ²)	0	13.9	3.4	3.5	143	42

Fig. 2 Habitat composition and relative proportion for 42 wind farms in Ostrobothnia, Finland. Five habitat classes are considered here: (1) artificial surfaces, (2) agricultural areas, (3) forests, (4) transitional forests and (5) waters. The values are shown as means plus standard deviations

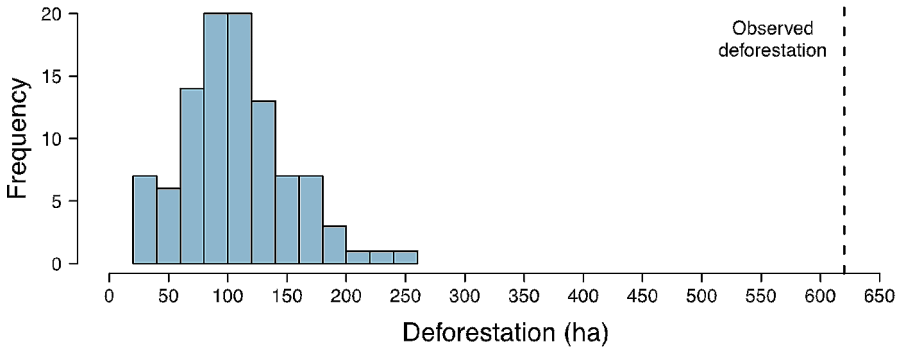


On average, 87 ha of project area were required per turbine (or 23 ha per megawatt [MW]) (Table 1). When considering only the area occupied by infrastructure, these figures drop to 2.1 ha/turbine and 0.6 ha/MW. The overlap between project areas and regional plans varied in proportion and absolute area (Table 1). Seventy-eight of 513 turbines fell outside regional plans, and some areas exceeded 10 km². Eight project areas with 1–8 turbines were entirely outside regional plans. While 37 turbines belonged to small wind farms, and hence with less restrictive spatial planning (see Materials and methods), 41 turbines belonged to larger wind

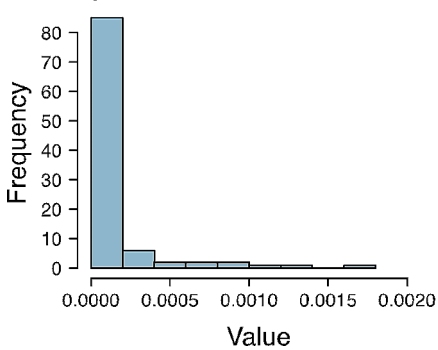
Fig. 3 Selection ratios for comparing used and available habitats for turbine placement in 42 wind farms in Ostrobothnia, Finland. Five habitat classes are considered here: (1) artificial surfaces, (2) agricultural areas, (3) forests, (4) transitional forests and (5) waters. Values above the horizontal line indicate selection, while values below the line indicate avoidance. Point estimates are displayed with 95% confidence intervals



a) Simulated building-related deforestation



b) P values



c) Wilcox's test statistic T

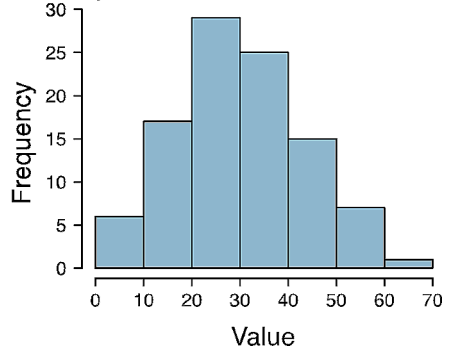


Fig. 4 (a) Comparison of building-related deforestation between project areas and control areas via 100 simulations. The vertical line marks the total observed building-related deforestation from project areas. (b) The distribution of P values and (c) Wilcox's test statistic T from 100 simulations

farms that did not conform with the regional plans studied here. Additional figures displaying all the variables for each wind farm, and a pairplot of variable correlations, are provided as supplementary material (Fig. S1-3).

4 Discussion

Wind energy, despite being a low-carbon technology, can cause ecological damage due to landscape changes. In this study, we assessed the land impacts of wind farms in Ostrobothnia, Finland. We showed that wind farms were primarily built or planned in forest landscapes, and that the deforestation associated with their construction is greater than that from other building activities in the region. This raises concerns about the ecological footprint of wind energy, in particular for forest species, but also for carbon storage and sequestration. Our analytical framework does not allow us to make detailed statements about habitat degradation or biodiversity impacts. We can, however, affirm that the non-use of more disturbed habitats for turbine placement (e.g., artificial surfaces or agricultural areas) increases pressure on forests. Given that Finland's forests are already impacted by forestry and management activities (Mönkkönen et al., 2022), with many species threatened (Hyvärinen et al., 2019), we strongly recommend the use of non-forest disturbed lands as alternative sites. In the same line, turbines are better located in transitional forests (clear-cuts and young plantations) rather than in mature and ecologically more valuable forest habitats. The importance of directing wind energy towards disturbed lands has been emphasised by several authors (see e.g., Diffendorfer et al., 2019; Kati et al., 2021; Kiesecker et al., 2011; Tumelienė et al., 2022).

The land directly impacted by physical structures of wind energy is small relative to the project area, and the values reported here (1.4–6.0%) are comparable with published literature (Harrison-Atlas et al., 2022; McDonald et al., 2009; Wiser et al., 2011). However, the land-use intensity of wind energy is seen as a constraint to large-scale deployment (Kiesecker et al., 2011; McDonald et al., 2009). In the present study, land requirements relative to the project area were 23 ha/MW (corresponding to 87 ha/turbine). This is lower than previously reported for Finland (75 ha/MW; Zakeri et al., 2015), reflecting (at least in part) an increase over time in nameplate capacity (more megawatts can be installed in less space; FWPA, 2023b). While direct habitat loss is relatively small for one wind turbine, the summed habitat loss cannot be considered insignificant as the landscape becomes fragmented due to linear features such as roads. Collectively, wind farms can result in high levels of fragmentation, posing a particular threat to species that rely on large unfragmented areas (Kiesecker et al., 2019). Our estimates of habitat loss and fragmentation are underestimated for a number of reasons. Certain physical structures or areas (e.g., gravel extraction sites), including temporary infrastructure, could not be assessed. In particular, data on transmission lines were limited or unavailable, especially for non-operational wind farms. Transmission lines are needed to carry energy across an electric power system, and can cause significant impacts (due to landscape alterations) on the environment and biodiversity (Biasotto & Kindel, 2018). Similarly, the estimation of deforestation from forest use notifications has its limitations. Despite being a comprehensive and high-quality dataset, forest use notifications offer an incomplete and underestimated picture of deforestation. Given these limitations, and the fact that this dataset was only applicable to a subset of wind farms

(built or under construction; see Materials and methods), we buffered the infrastructure (roads and turbines) to more reliably estimate habitat loss. Nevertheless, we showed that there is an underestimation of habitat loss and, consequently, habitat fragmentation.

Wind energy is an integral part of climate policies that are aimed at reducing greenhouse gas emissions as a means to curb climate change. If inappropriately used, wind energy can paradoxically increase impacts on biodiversity and ecosystem services (Kiesecker et al., 2019; Rehbein et al., 2020). For example, loss of natural habitats can contribute to releases of carbon stocks (Kiesecker et al., 2019). Thus, the land cover on which wind farms are built has implications for the preservation of carbon stocks and achievement of carbon reduction goals (Albanito et al., 2022). Wind farms have been built in various habitats, but usually a single or few habitats make up the largest proportion and are thus under greater pressure. For example, in Austria and Denmark, agricultural lands were shown to have a much larger share (86%) than forests (7%) (Nitsch et al., 2019). In the US, agricultural lands were also very important, with rangeland and cropland supporting 93.4% of deployment since 2000 (Harrison-Atlas et al., 2022). In Scotland, 73% of targeted habitats were coniferous woodland, acid grassland, bog, and heather grassland (Shepherd et al., 2021), while in Brazil 62% were native vegetation and coastal sands (Turkowska et al., 2021). In this study, forests and transitional woodland comprised most of the habitats (92%) encompassed by wind farms in Ostrobothnia, and there is indication that this pattern applies to other Finnish regions (see Fig. S1 in Balotari-Chiebáo et al., 2021). The impact on terrestrial carbon stocks from the loss of the different habitats, especially forests, merits future consideration.

Wind energy impacts on biodiversity and ecosystem services are best addressed following a mitigation hierarchy, a framework that involves the sequential application of four actions: avoid, minimise, restore and offset (IUCN, 2021). The first two steps, avoidance and minimisation of impacts (in the planning and design phase), are of primary importance, as post-construction mitigation strategies have limited efficacy across taxa and biodiversity offsetting can be challenging (Arnett & May, 2016; IUCN, 2021). Reversing impacts of onshore wind energy is complex and it is hampered by, among other things, a mismatch between the often abstract and hypothetical nature of existing guidance and actual end-of-life decisions at facilities (Windemer & Cowell, 2021). Therefore, a common recommendation is to steer wind energy development towards lands already disturbed, e.g., low-quality and highly altered habitats with limited conservation value (Kiesecker et al., 2011). In our case, we would recommend at the least the selection of transitional forests, as opposed to more mature forests. Carefully siting wind farms in areas with low biodiversity and existing infrastructure, e.g., with an already high density of roads and transmission lines, offers an opportunity to further reduce impacts on undeveloped lands (Diffendorfer et al., 2019; Jones & Pejchar, 2013; Kiesecker et al., 2011). The populations of many species are already threatened by the construction of physical structures, as these reduce the availability of suitable habitats and alter the so-called permeability of the landscape via habitat fragmentation, hampering the ability of species to adapt to a warming climate (Hunter et al., 2021). To limit impacts on biodiversity and ecosystem services while pursuing climate and energy goals, wind farms need to be strategically placed in a way that the loss and degradation of natural habitats are minimised. An assessment of land availability or eligibility provides early guidance by identifying and quantifying potentially suitable disturbed lands based on different criteria (see e.g., Kati et al., 2021 for Greece; Martínez-Martínez et al., 2023 for Chile; Nitsch et al., 2019 for Czechia; Tumelienė et al., 2022 for Lithuania). This could be

done in Finland to assess whether wind energy development in disturbed lands with existing infrastructure, rather than forests, would suffice to meet current or future energy targets. In conclusion, we show that wind energy in Ostrobothnia is associated with a level of deforestation that exceeds that from all other building activities combined, and this pattern most likely applies to other regions in Finland. As the project areas were primarily composed by forests (including mature forests), the siting of individual turbines did not favour ecologically less-valuable habitats. The use of forests to accommodate energy infrastructure raises concerns about the ecological footprint of wind energy, as the impacts on local biodiversity and terrestrial carbon stocks are poorly understood. Careful site selection is needed to reduce potential impacts, and we recommend that our findings be considered in spatial planning, from site selection in the early phase of development (macro-siting) to turbine placement in the land use plan (micro-siting).

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10668-024-05048-9>.

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Author contributions Both authors contributed to the study conception, design and material preparation. Data analysis and manuscript writing were performed by FBC, and PB made significant comments and text additions. Both authors reviewed the manuscript.

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Data availability The authors do not have permission to redistribute the shapefiles supplied by Finnish municipalities. All the other spatial datasets are freely available online and their sources are referred to in the Materials and methods.

Declarations

Competing interest The authors have no competing interests to declare.

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