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Research article

Synergies and trade-offs between biodiversity and distance to settlements in the spatial allocation of wind power

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ABSTRACT

The need to phase out fossil energy has promoted a rapid development of wind power, yet this development may negatively affect biodiversity and encounter resistance among local citizens. To study whether optimal locations for wind power differ when considering biodiversity impacts or distance to settlements, we used spatial suitability analysis for allocating wind power in Pirkanmaa region in southern Finland. We clustered high-suitability areas using Anselin Local Moran's I cluster analysis to find spatially contiguous areas for wind power. We compared the results of biodiversity-based and settlement-based allocation in three scenarios for electricity production for the year 2035: the Minimum scenario corresponded to the current production-consumption ratio in the region, the Self-sufficiency scenario to regional electricity self-sufficiency, and the Maximum scenario to the maximum production capacity. The most suitable locations for wind power were forested areas in the sparsely populated parts of the region. Optimal locations for biodiversity-based and settlement-based suitability showed only partial overlap, suggesting trade-offs in wind power allocation. The overlap area increased from 0% in the Minimum scenario to 41% in the Maximum scenario. The total area of the highly suitable locations based on both biodiversity and distance to settlements was not sufficient to cover the production capacity in the Self-sufficiency scenario, indicating that reaching electricity self-sufficiency may not be possible without compromising biodiversity or distance to settlements. The results highlight the importance of considering both biodiversity values and human well-being in wind power development, as potential for conflicts in wind power development is likely to increase with growing electricity demand in the future.

1. Introduction

Mitigation of climate change requires both a rapid decrease in the use of fossil energy and the promotion of renewable energy (Karlilar Pata and Balcilar, 2024). One of the most significant renewable energy forms is wind power, currently supplying over 7% of the global electricity demand and with global production capacity growing by more than 10% every year (Barthelmie and Pryor, 2021; International Energy Agency, 2025). In the European Union (EU), wind power contributes notably to energy production with a share of 19% of total electricity demand (Constanzo et al., 2025).

Although wind power is generally regarded as one of the most environmentally friendly energy sources (Osman et al., 2023; Rahman et al., 2022), it can have negative impacts on nature and human well-being. Concerning nature, wind power development may lead to destruction of habitats (Gasparatos et al., 2017), deforestation and landscape fragmentation (Balotari-Chiebáo and Byholm, 2024), displacement of birds, bats and terrestrial mammals (Tolvanen et al., 2023) and increased nutrient flow to water bodies (Heal et al., 2020). Besides, the considerably larger wind turbines of today are expected to have impacts of different type and scale on, for example, avians compared to the smaller wind turbines previously built (Garvin et al., 2024; Huso et al., 2021). In addition, impacts on many species and ecosystems are still understudied (Sander et al., 2024).

While negative impacts on wildlife are a potential cause of public opposition towards wind power (Diógenes et al., 2020), wind power has also direct human impacts that influence its social acceptance (Ruddat, 2022). For example, wind power impacts landscape aesthetics and can

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cause noise and light pollution (Sander et al., 2024), leading to opposition among nearby inhabitants and other people (Klæboe and Sundfør, 2016). These disturbance effects may be significantly decreased by placing wind turbines further away from settlements, but only up to a certain distance (Peri and Tal, 2021; Salomon et al., 2020). Indeed, a positive association between spatial distance and wind power acceptance by local residents has been observed in many studies (e.g. Ladenburg et al., 2013; Swofford and Slattery, 2010), some recommending placing wind farms at distancesof more than 10 km from population centres (Pouta et al., 2024). The need for longer distances to settlements can drive wind power development to remote areas with high biodiversity values, creating a potential trade-off between nature and human values (Tafarte and Lehmann, 2023). To fulfil the simultaneous needs to safeguard biodiversity and maintain human well-being, methods that optimize wind power locations are needed.

A common approach for identifying optimal locations is a Geographic information system (GIS) based suitability analysis incorporating multi-criteria decision analysis (MCDA) with analytic hierarchy process (AHP) (Bilal et al., 2024; Can et al., 2024; Islam et al., 2026; Villacreses et al., 2023). Spatial optimization of locations for wind power using a suitability analysis has mostly concentrated on technical, economic and legislative aspects, considering impacts on humans through, for example, distance to residential areas (e.g. Can et al., 2024; Doljak et al., 2021; Mokarram et al., 2022; Villacreses et al., 2017; Watson and Hudson, 2015). Biodiversity has often been addressed through legal constraints and by excluding protected areas (e.g. Bilal et al., 2024; Mokarram et al., 2022; Villacreses et al., 2023), with some studies considering distances to sensitive areas or bird migration routes (e.g., Demir et al., 2024; Gigović et al., 2017). In previous research, several methods have been used to model optimal locations considering nature impacts (Eichhorn et al., 2019; Gauglitz et al., 2019; Grimsrud et al., 2024; Kati et al., 2021; Tafarte and Lehmann, 2023). Some studies have compared aiming at minimizing biodiversity impact with minimizing distance to settlements (Eichhorn et al., 2017, 2019; Tafarte and Lehmann, 2023). However, comprehensive biodiversity criteria have rarely been applied in the optimization of locations for energy production.

We investigated how trade-offs and synergies between biodiversity and distance to settlements are reflected in the optimal locations for wind power development. An underlying assumption was that different locations indicate a trade-off between biodiversity and human well-being, whereas overlapping locations indicate synergy. To see how trade-offs and synergies change under increasing land use pressure caused by wind power, we compared three electricity production scenarios. Our study questions were:

1. What are the optimal locations for wind power if either impacts on biodiversity are minimized or distance to settlements maximized?
2. To what extent do the optimal locations between biodiversity- and settlement-based suitability overlap and how do they change in different electricity production scenarios?
3. Does the overlap area provide sufficient capacity to meet the electricity demand in the three scenarios, i.e. how much electricity can

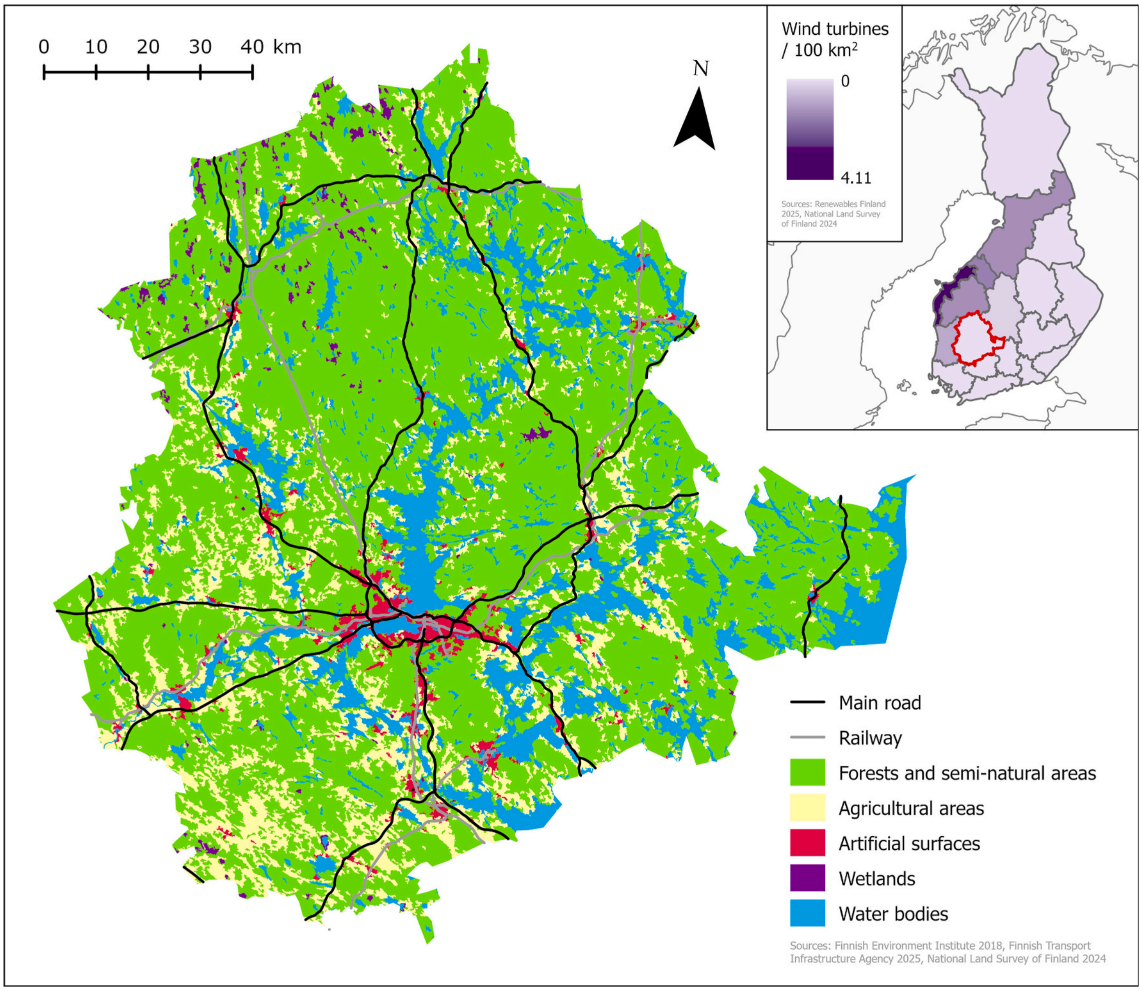

Fig. 1. Region of Pirkanmaa with main roads, railways and land cover. Top right: Number of wind turbines per 100 km^2 across regions in Finland.

be produced while meeting both biodiversity and human well-being needs?

2. Materials and methods

2.1. Study area

The study was conducted in Finland, where wind power accounted for 24% of total electricity production in 2024 (Constanzo et al., 2025), with expected capacity growth by over three times the current capacity by 2035 (Fingrid, 2024). Wind power production is currently heavily concentrated in the western and northern parts of the country (Renewables Finland, 2025a, Renewables Finland, 2025b, Fig. 1).

Our study region, Pirkanmaa in southern Finland, covers 1,554,955 ha and is a newcomer in wind power production. As of 2024, the region hosted only 11 wind turbines with a total generation capacity of 23.9 MW compared to a national total of 1835 turbines with a total capacity of 8358 MW (Renewables Finland, 2025a, 2025b, Fig. 1). In 2023, the electricity production in Pirkanmaa covered only 20% of the regional consumption (Energiateollisuus ry, 2024a, 2024b). The limited capacity of the electricity grid in northern and northwestern Pirkanmaa may restrict the construction of wind power unless new investments are made in the main grid (FCG Finnish Consulting Group, 2020). Land cover in Pirkanmaa consists mainly of forests (68%), followed by water bodies (14%), agricultural areas (11%), built-up areas (5%) and wetlands (2%) (Fig. 1). The population density (41.2 residents/km^2) is over twice as high as the national average (18.5 residents/km^2) (Statistics Finland, 2025).

2.2. Overview of the methodological approach

We used geospatial data from several sources (Table 1) in wind power suitability modelling. For data processing, we used ArcGIS Pro 3.4 (Esri, 2024) and QGIS 3.34.14 (QGIS.org, 2024). The modelling process consisted of two phases: 1) restriction and 2) suitability. In the first phase, we used several restriction criteria to identify areas unsuitable for wind power and thus to be excluded from the suitability analysis. In the second phase, the remaining parts of the study area were ranked based on selected suitability criteria.

2.3. Phase 1: restriction

Before implementation of the suitability analysis, we identified areas completely restricted from wind power using constraints based on legislative and authority guidelines (Appendix S1). These areas included buffers we constructed around features based on authority guidelines (Table 2). All restriction layers were processed in vector format.

To obtain the total restricted area, we merged the restriction layers. Subsequently, we extracted and rasterized the resulting available area to 96 m × 96 m spatial resolution, in order to align it with the resolution of the forest biodiversity value layer.

2.4. Phase 2: suitability

We used GIS-based suitability analysis to find the most suitable locations for a specific wind power capacity determined by electricity production scenarios (Section 2.5). We conducted two separate suitability analyses based on 1) biodiversity values and 2) distance to settlements. We implemented the suitability analyses using the Suitability Modeler in ArcGIS Pro in four steps: 1) selection of criteria and data preparation, 2) transformation of criteria values to a common suitability scale, 3) relative criteria weighting and combining them in a suitability map, and 4) selection of the most suitable locations ("The general suitability modeling workflow," 2024).

First, we selected the biodiversity-based suitability criteria based on existing knowledge of the nature impacts of wind power and availability

Table 1
Data sources for restriction and suitability criteria.

Criterion	Dataset	Reference	Restriction/ Suitability
Railroad network	Railway network (multi-track)	Finnish Transport Infrastructure Agency (2024)	Restriction
Airport areas	National topographic database	National Land Survey of Finland (2024)	Restriction
Airport obstacle limitation surfaces (OLS)	EFHA, EFTP airport obstacle limitation surfaces	Finavia (2024, 2019)	Restriction
Highway airstrips	Assessment of the impact of aviation-related restrictions on the feasibility of wind power projects	Piispanen et al. (2011) Google (2025)	Restriction
Nationally valuable landscapes	Nationally valuable landscapes (VAMA, 2021)	Finnish Environment Institute (2021a)	Restriction
Protected built heritage and ancient monument sites	Protected built heritage (INSPIRE)	Finnish Heritage Agency (2024)	Restriction
Nationally significant built cultural environments (RKY)	Protected built heritage (INSPIRE)	Finnish Heritage Agency (2024)	Restriction
Areas of Finnish defence forces	Regional land use plan of Pirkanmaa	The Council of Tampere Region (2021)	Restriction
Corine residential areas	Corine Land Cover 2018	Finnish Environment Institute and EEAEU/Copernicus (2018)	Restriction
Residential buildings	National topographic database	National Land Survey of Finland (2024)	Restriction/ Suitability
Free time residential buildings	National topographic database	National Land Survey of Finland (2024)	Restriction/ Suitability
Nationally designated protected areas on state owned land	Nature protected areas and wilderness reserves	Metsähallitus (2024)	Restriction/ Suitability
Protected areas on private lands	Nature protected areas and wilderness reserves	Metsähallitus (2024)	Restriction/ Suitability
National Conservation Programme areas	National Conservation Programme areas	Finnish Environment Institute (2021b)	Restriction/ Suitability
Important Bird and Biodiversity Areas (IBA)	IBA area boundaries	Finnish Environment Institute and Birdlife Finland (2020)	Restriction/ Suitability
Finnish Important Bird Areas (FINIBA)	FINIBA area boundaries	Finnish Environment Institute and Birdlife Finland (2012)	Restriction/ Suitability
Natura 2000 sites (SPA and SAC)	Natura 2000 areas	Finnish Environment Institute (2024a)	Restriction/ Suitability
Road network	Digiroad	Finnish Transport Infrastructure Agency (2025)	Restriction/ Suitability
Transmission lines (>110 kV)	National topographic database	National Land Survey of Finland (2024)	Restriction/ Suitability
Freshwater bodies	Ranta10	Finnish Environment Institute and Geological	Restriction/ Suitability

(continued on next page)

Table 1 (*continued*)

Criterion	Dataset	Reference	Restriction/ Suitability
		Survey of Finland (2024)	
Biodiversity value of forests	High biodiversity value forests 2018 (Zonation)	Finnish Environment Institute, 2018 Mikkonen et al. (2023)	Suitability
Biodiversity value of peatlands	Peatland site types of Finland 1.0/ 2023	Geological Survey of Finland (2023)	Suitability
Bird migration routes	Main bird migration routes in Finland	Birdlife Finland (2023); Lehtiniemi and Toivanen (2023)	Suitability
Peat production areas, agricultural areas, landfills	Corine Land Cover 2018	Finnish Environment Institute and EEAEU/Copernicus (2018)	Suitability
Nationally valuable geological formations	Nationally valuable blockfield sites, moraine formations, rocky areas, and aeolian and littoral deposits	Finnish Environment Institute (2024b); Finnish Environment Institute and Geological Survey of Finland (2020); Finnish Environment Institute and Geological Survey of Finland (2018); Finnish Environment Institute and Geological Survey of Finland (2017)	Suitability
Groundwater bodies	Groundwater bodies	Finnish Environment Institute (2025)	Suitability

Table 2
Restriction criteria, buffer zones and source references.

Criterion	Buffer (m)	References
Residential buildings	600	Rescue Department of North Ostrobothnia (2023)
Free time residential buildings	600	Rescue Department of North Ostrobothnia (2023)
Corine residential, commercial and industrial areas	0	Ministry of the Environment (2016)
Road network	Finnish Transport Agency (2012)	Finnish Transport Agency (2012)
Motorways and semi-motorways	350	Finnish Transport Agency (2012)
Main roads of classes I and II	330	Finnish Transport Agency (2012)
Regional and connecting roads	320	Finnish Transport Agency (2012)
Railroad network	330	Finnish Transport Agency (2012)
Airport areas	0	Piispanen et al. (2011)
Airport obstacle limitation surfaces (OLS)	0	Piispanen et al. (2011)
Highway airstrips	12,000 from the centroid	Finnish Transport Agency (2012)
Transmission lines (>110 kV)	471	Fingrid (2020)
Freshwater bodies	0	-
Nationally valuable landscapes	0	Ministry of the Environment (2024)
Nationally designated protected areas on state-owned land	0	Ministry of the Environment (2016)
Protected areas on private lands	0	Ministry of the Environment (2016)
National Conservation Programme areas	0	Klap (2012)
Important Bird and Biodiversity Areas (IBA)	0	Ministry of the Environment (2016)
Finnish Important Bird Areas (FINIBA)	0	Klap (2012)
Natura 2000 sites (SPA and SAC)	0	Klap (2012)
Protected built heritage and ancient monument sites	0	Antiquities Act (1963); Suuronen (2021)
Nationally significant built cultural environments (RKY)	0	Ministry of the Environment (2016)
Areas of Finnish defence forces	0	Ministry of the Environment (2016)

of spatial data (Table 1). We used a pixel size of 96 m × 96 m to align with the forest biodiversity value data (Finnish Environment Institute, 2018) for all layers. We rasterized and resampled all layers to this cell size for the suitability analyses, using the resampling methods *majority* for discrete data and *bilinear* for continuous data. For distance rasters, we first used a smaller cell size of 10 m × 10 m to ensure the recognition of small-scale features, and then resampled the rasters to the final cell size using the bilinear resampling method. In addition, we assigned suitability values for discrete rasters to align with a common suitability scale of 1 (least suitable) to 10 (most suitable) to be used later in the suitability analysis (Table 3).

For the forest biodiversity value layer, we determined 0 as the most suitable and 1 the least suitable for wind power location. We used the national-scale high-biodiversity value forests data from version 6 analysis, which considers tree stock, forest management and drainage, internal forest connectivity, observations of red-listed forest species, short-distance connectivity to key forest habitats and long-distance connectivity to permanently protected areas (Finnish Environment Institute, 2018; Mikkonen et al., 2023).

To determine the biodiversity value of peatlands, we used peatland site types (Geological Survey of Finland, 2023). We classified the peatland site types into six suitability classes (1 = most suitable, 6 = least suitable; Table S1) based on their drainage state (Geological Survey of Finland, 2023), conservation status in the Red List of Habitats (Threatened Habitat Types in Finland 2018, 2019) and trophic status.

For nature conservation areas (Table 1), we considered distances to large (>20 km^2) and small (<20 km^2) areas separately (Kangas et al., 2016). In the classification, we treated separate protected areas with a shared border as single, larger units. We assigned increasing suitability values with increasing distance from protected areas up to 5 km, a threshold beyond which impacts on biodiversity are expected to be minor (Tolvanen et al., 2023).

The bird migration routes included 21 taxa (Table S2), mostly at the species level. For some taxa, both spring and autumn migration routes were included, resulting in a total of 37 routes. We merged the bird migration routes to produce polygons indicating the number of overlapping routes, resulting in a maximum of 22 overlapping migration routes across whole Finland and 4 across Pirkanmaa. We ranked areas with the most overlapping bird migration routes as least suitable for wind power construction.

Degraded environments, such as peat production areas, agricultural areas and landfills can be especially suitable for wind power (Doljak et al., 2021; Villacreses et al., 2017). We assigned the highest suitability to peat production areas, while agricultural areas and landfills had the second highest scores and other land use classes the lowest scores.

Proximity to transmission lines and roads is important to avoid biodiversity loss through new infrastructure construction, and hence wind power facilities should be as close as possible to existing transmission lines and road networks (Diffendorfer et al., 2019). Hence, we assigned decreasing suitability scores to increasing distances from transmission lines and roads.

Wind power construction may have impacts on freshwaters, such as changes in river water quality (Heal et al., 2020; Sander et al., 2024). Therefore, we assumed that suitability for wind power increases with distance from freshwaters, up to 1 km. We applied the same principle and distance to groundwater areas.

We compiled nationally valuable geological formations from blockfield sites, moraine formations, aeolian and littoral deposits and rocky

Table 3
Biodiversity-based suitability criteria and their relative weights based on analytic hierarchy process (AHP) for wind power.

Criterion	Original scale	Suitability function or scale	Weight
Biodiversity value of forests	0–1	Negative linear	20.3
Biodiversity value of peatlands	0–6	0 → 10 1 → 6 2 → 5 3 → 4 4 → 3 5 → 2 6 → 1	20.3
Distance to large conservation areas ($\geq$20 km^2)	0–5000	Logistic growth	20.3
Distance to small conservation areas ($<$20 km^2)	0–5000	Logistic growth	10.7
Bird migration routes	0–4	0 → 10 1 → 4 2 → 3 3 → 2 4 → 1	7
Peat production areas, agricultural areas, landfills	categorical	Peat production areas = 10, agricultural areas and landfills = 7, others = 1	6.6
Distance to transmission lines	0–∞	Negative exponential	4
Distance to road network	0–∞	Negative exponential	3.3
Distance to freshwater bodies	0–1000	Logistic growth	3.9
Distance to groundwater bodies	0–1000	Logistic growth	1.7
Nationally valuable geological formations	0–4	0 → 10 1 → 4 2 → 3 3 → 2 4 → 1	1.9

areas, which were originally classified on a scale of 1–4 from most to least valuable. We assigned the lowest suitability to the most valuable geological formations.

After selecting the criteria, we determined their relative importance. For biodiversity-based suitability, we determined relative weights using AHP, a common expert-based criteria-weighting method (Saaty, 2008). We constructed a pairwise comparison matrix (Table S3) which we then used to calculate relative weight vectors for the criteria. According to the results of the AHP, the biodiversity value of forests and peatlands and the distance to large conservation areas were the most important criteria (Table 3). The consistency ratio of the AHP was 5.9%, which is generally considered acceptable (Saaty, 1990). For suitability based on distance to settlements, we used two criteria with equal weights: distance to residential buildings and to second homes. To identify the most suitable areas for wind power development in the study region, we applied a weighted overlay analysis using the Suitability Modeler in ArcGIS Pro with the relative weights. We used a suitability scale of 1 to 10 and percentage weights for each input layer, as determined by the AHP. To prioritize optimal values, we standardized data with continuous raster values based on their distribution and relevance for biodiversity values (ESRI, n.d., Table 3). For settlement-based suitability, we applied a linear standardization function to both input raster datasets (distance to residential homes and distance to second homes).

As a result, we yielded suitability rasters with continuous suitability values for wind power. To assess the link between biodiversity- and settlement-based suitability rasters, we performed a correlation analysis using Spearman's correlation analysis in R 4.5.1 (R Core Team, 2025).

To determine the most suitable locations for wind power, we applied Anselin Local Moran's I cluster analysis to both suitability layers (biodiversity, distance to settlements). We used a fixed distance band of 850 m based on the average minimum distance between wind turbines. This distance was derived from an earlier study, in which up to nine turbines per grid cell (2570 m × 2570 m) could be evenly placed to maximize energy production while maintaining appropriate spacing to reduce wake effects and operational constraints (Tolvanen et al., 2025). The even distribution of turbines was a simplification, since turbine siting arrangements are known to influence the land area requirements and energy production of wind power (Meier et al., 2024). We used a false discovery rate (FDR) correction, 499 permutations and no standardization to identify contiguous clusters of high suitability values (high-high clusters).

For biodiversity-based suitability, we conducted a sensitivity analysis by modifying the weight of the three most important variables identified by AHP by ±20%. We then calculated Spearman correlations between the original biodiversity-based suitability map and the perturbed maps, as well as the overlap and Jaccard similarity index (Jaccard, 1912) between the original and perturbed clusters.

2.5. *Land use requirements for wind power and electricity production scenarios*

Estimates of complete ecosystem alteration per GW of electricity production capacity due to direct wind power land use vary substantially (Turkovska et al., 2024). We used the estimates used by Tolvanen et al. (2025) to calculate area requirements and feasible electricity production capacities for wind power. They estimated area requirements for wind farms by turbine capacity and associated infrastructure to optimize energy production costs with minimum deforestation impact at the municipal level. For practical reasons, we used their estimates showing that each 6.6 MW wind turbine requires a space of 72.25 ha (850 m × 850 m) of which 0.4 ha is covered by built-up land below the turbine, on average 0.8 ha of roads, and on average 1.6 ha of grid connections. The area required for roads and grid connections varies depending on the distance to high-voltage transmission lines, but we did not account for this variation in this study. As the minimum number of wind turbines in a wind farm depends on economic and site-specific constraints, we determined five turbines as the minimum wind farm size (361.25 ha) to ensure that the selected locations represent economically feasible wind farm sites, and included only high-suitability clusters larger than this in further analyses.

We examined wind power development in three electricity production scenarios for the year 2035: 1) Minimum, 2) Self-sufficiency and 3) Maximum. The first two scenarios were based on the national electricity production forecast for 2035 (Fingrid, 2024). For the Self-sufficiency scenario, we estimated the wind power capacity in Pirkanmaa by scaling the predicted national capacity of Finland for 2035 based on the region's predicted share of the national population. Although mere population-based estimates may not accurately predict future electricity consumption as they do not consider regional disparities such as the siting of industrial and data centre facilities, this assumption was made due to limited data availability on predicted large electricity consumers. For the Minimum scenario, we used the estimate from the Self-sufficiency scenario applied with the current electricity production-consumption ratio in Pirkanmaa (20%; Energiateollisuus ry, 2024a, 2024b) to calculate the wind production capacity. For the Maximum scenario, we calculated the maximum wind power capacity and corresponding area based on all suitable polygons obtained from the cluster analysis. For the Minimum and Self-sufficiency scenarios, we obtained the most suitable clusters by selecting polygons larger than 361.25 ha in descending order of mean suitability until the total area of the selected polygons reached the required area for each scenario (Minimum: 7519 ha; Self-sufficiency: 37,597 ha).

For all three scenarios, we calculated the total wind power area in hectares and the corresponding capacities in MW. With the biodiversity-based suitability cluster layer as a reference, we calculated the spatial overlap between biodiversity-based and settlement-based suitability clusters in all scenarios. We also calculated the maximum wind power capacity for highly suitable locations based on both biodiversity and distance to settlements using the overlap result from the Maximum scenario. We compared this maximum overlap area to the area requirements of different scenarios by dividing the overlap area by the area requirement of each scenario.

3. Results

Based on the restriction criteria, 16% (245,767 ha) of the study area was included in the suitability analysis (Table S4). The largest areas available for wind power were in forested areas in northern Pirkanmaa, where population density is relatively low. For biodiversity-based suitability, the highest suitability scores were relatively dispersed and primarily found in the western, northwestern and northern parts of the region, while the lowest scores appeared in the eastern, southeastern and central areas (Fig. 2). For settlement-based suitability, areas of high suitability were more uniform and predominantly concentrated in the northern and northwestern parts of the region. The biodiversity- and settlement-based suitability rasters showed a weak correlation ($R_{\text{Spearman}} = 0.036$, $p < 0.001$).

In Minimum and Self-sufficiency scenarios, the wind power production areas were <10,000 ha and <40,000 ha, respectively. The maximum suitable production area (Maximum) was ca. 60,000 ha, providing >5000 MW of electricity production capacity.

The suitability clusters (Fig. 3) were concentrated in locations with the highest suitability values in the original suitability maps (Fig. 2). Biodiversity- and settlement-based suitability clusters showed only partial spatial overlap. There was no overlap in the Minimum scenario, while in Self-sufficiency and Maximum scenarios, the overlap percentages were 11.3% and 41.4%, respectively (Table 4).

The sensitivity analysis showed a high correlation between the original suitability map and all perturbed suitability maps ($R_{\text{Spearman}} >$ 99%, $p < 2.2\text{e-}16$). In addition, high-suitability clusters from the cluster analysis showed a high degree of overlap (>90%) between the perturbed and the original results, and the Jaccard similarity index exceeded 0.92 for all perturbed clusters, indicating a high level of stability.

The maximum wind power capacity in areas with high suitability based on both biodiversity values and distance to settlements was 2153 MW (23,564 ha). This would be sufficient to cover more than three times the area requirement of the Minimum scenario, but only 62.7% and 41.4% of the area requirements of the Self-sufficiency and Maximum scenarios, respectively.

4. Discussion

We investigated trade-offs and synergies between biodiversity and distance to settlements in the spatial allocation of wind power. First, we discovered that areas of highest suitability for wind power were mostly located in forested areas of the region. Second, the most suitable locations based on biodiversity values overlapped only partly with those based on distances to settlements, while the overlapping area increased with increasing electricity production capacity and thus total area required for production. Third, the total overlapping area between biodiversity-based and settlement-based high-suitability clusters exceeded the area demand for the Minimum scenario but was insufficient for that of the Self-sufficiency and Maximum scenarios.

Forests predominated in the areas suitable for wind power in both biodiversity- and settlement-based layers, which was expected as forests cover most (68%) of the region. Due to the high forest cover, it may not be possible to build wind power only in heavily degraded or built environments to reduce habitat fragmentation and other nature impacts, as proposed by Kiesecker et al. (2011). However, the dispersed spatial pattern of the most optimal biodiversity-based suitability values indicates that there may be small-scale spatial variation in biodiversity values. This may be partly because the suitability map was based on many different biodiversity value layers that may not always overlap. As direct impacts on biodiversity occur in only a fraction of the whole wind farm area (Balotari-Chiebáo and Byholm, 2024; Tolvanen et al., 2025), it is important to consider this small-scale spatial variation in biodiversity values when placing wind turbines. Micro-siting of turbines to avoid locations of high biodiversity value and to create flight corridors for birds is important to mitigate the effects (Arnett and May, 2016). In addition, directing wind power development to commercial forests that have recently been disturbed rather than to mature ones with higher

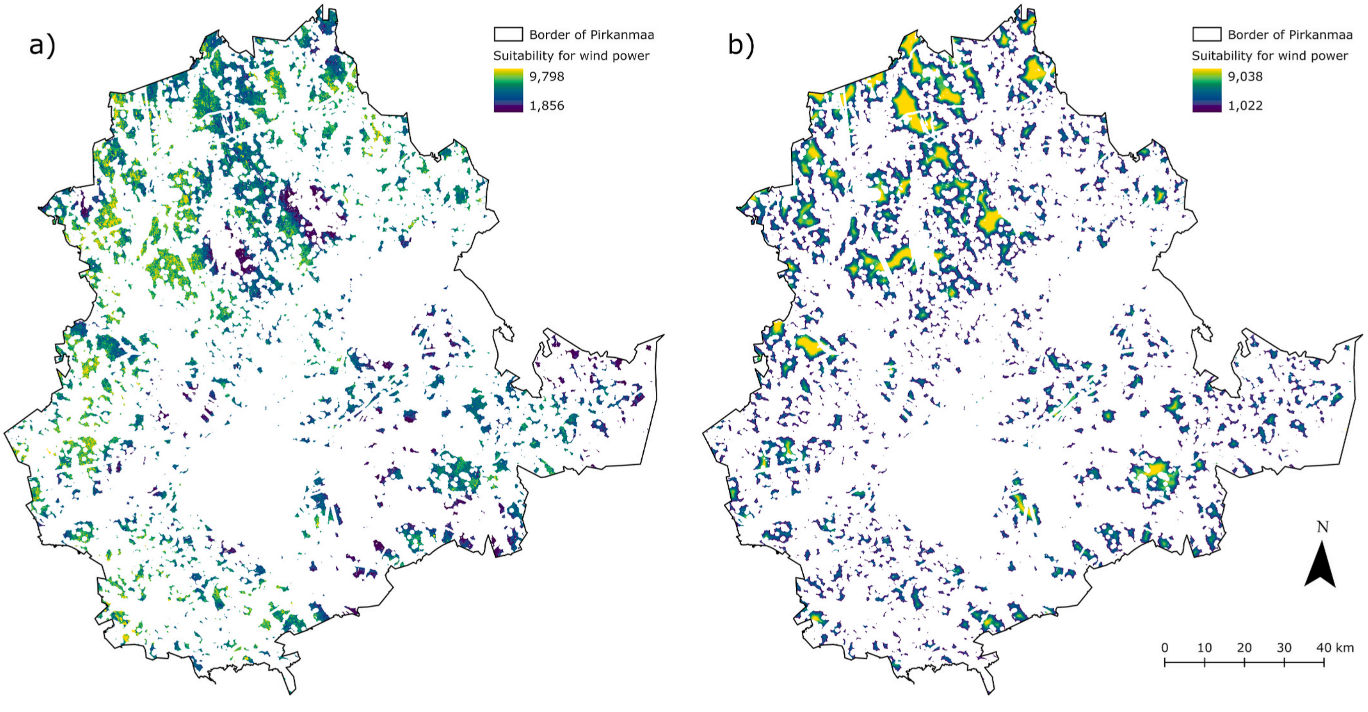

Fig. 2. Suitability for wind power in the region of Pirkanmaa based on a) biodiversity values, b) distance to settlements.

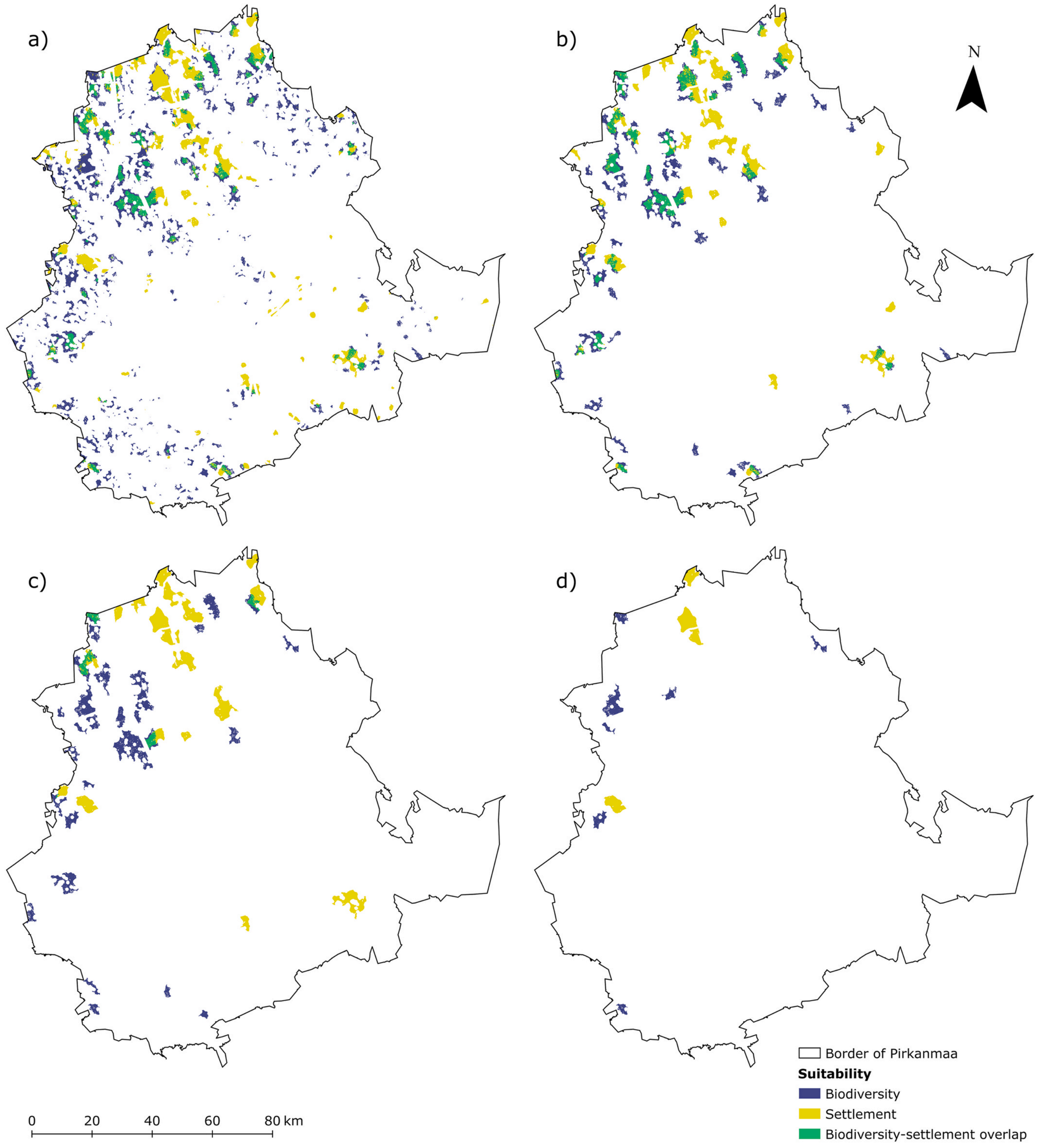

Fig. 3. High-high suitability clusters based on Anselin Moran's I for biodiversity- and settlement-based suitability for wind power. a) All clusters, b) clusters larger than 361.25 ha (Maximum scenario), c) clusters >361.25 ha with total area of about 37,597 ha (Self-sufficiency scenario), d) clusters >361.25 ha with total area of about 7519 ha (Minimum scenario).

biodiversity values may reduce impacts on valuable habitats and species (Balotari-Chiebáo and Byholm, 2024). For settlement-based suitability, the map was based on only two distance layers, which explains the more clustered pattern of high values. The low correlation between biodiversity- and settlement-based suitability maps suggests that these two maps are spatially independent and exhibit an inconsistent relationship. This reflects largely different underlying processes rather than consistent trade-offs between the two objectives. Although the settlement-based suitability map shows the highest values where population density is relatively low, high values of the biodiversity-based suitability map are also partly located in similar areas. This may be partly connected with the fact that most of the areas with the highest population density around Tampere are also completely restricted from wind power. Moreover, the settlement-based suitability map includes

Table 4
Area (ha) and potential wind power capacity (MW) for biodiversity- and settlement-based suitability for whole suitability layers, all High-high clusters, and different scenarios: clusters >361.25 ha with total area of about 7519 ha (Minimum), clusters >361.25 ha with total area of about 37,597 ha (Self-sufficiency) and all clusters larger than 361.25 ha (Maximum).

Suitability layer	Area (ha)			Wind power capacity (MW)			Overlap (% of biodiversity)
	Biodiversity	Settlement	Overlap	Biodiversity	Settlement	Overlap	
Suitability layer total	245,373	245,373	245,373	22,415	22,415	22,415	100
Anselin Local Moran's I High-high clusters	94,968	77,140	31,666	8675	7047	2893	33,3
Minimum	7941	8782	0	725	802	0	0
Self-sufficiency	37,791	38,461	4273	3452	3513	390	11,3
Maximum	56,938	60,746	23,564	5201	5549	2153	41,4

second homes which are often located in natural environments that potentially have high biodiversity values.

According to the cluster analyses, the most suitable locations for wind power in terms of biodiversity values and distance to settlements overlapped only partly. Similar patterns have been reported in previous studies comparing spatial allocation of wind power based on biodiversity values and distance to settlements. For example, Eichhorn et al. (2019, 2017) found significant differences in the spatial allocation of wind power depending on whether the distance to settlements or to conservation areas was prioritized. Tafarte and Lehmann (2023) likewise discovered that placing wind power based on bird abundances differed substantially from placing based on disamenities for residents. However, unlike these studies, our analysis incorporates a more comprehensive set of biodiversity criteria, capturing multiple dimensions of conservation values. While this has been rare in studies on the spatial allocation of wind power, Gauglitz et al. (2019) also considered several biodiversity aspects in their assessment of the conflict risk between wind power and nature conservation. However, they did not account for distance to settlements in their analysis.

While there was no overlap between the two suitability layers in the Minimum scenario, the overlap increased with increasing production capacity and thus total wind power area. This indicates that the most optimal locations differ substantially, but including locations that are less suitable leads to increased synergy between distance to settlements and biodiversity. That is, if both human well-being and biodiversity values are considered, compromises must be made regarding the most optimal locations.

Considering only locations highly suitable based on both biodiversity values and distance to settlements, the overlapping clusters could host more than three times the electricity production capacity of the Minimum scenario, in which the ratio between electricity consumption and production corresponds to the current situation in the study region. For Self-sufficiency and Maximum scenarios, the area requirements cannot be met solely in these high-suitability locations. This suggests that the higher the wind power production capacity, the more likely there will be conflicts between human well-being and biodiversity conservation in wind power development. As observed by Grimsrud et al. (2024), placing wind turbines further away from settlements may increase negative impacts on biodiversity. Besides, this may also cause public opposition if wind power is developed in scenic areas (McKenna et al., 2021) or close to vacation homes (Pouta et al., 2024). On the other hand, living closer to wind farms (Swofford and Slattery, 2010), visibility of turbines from the residences (Ladenburg et al., 2013) and daily encounters with them (Ladenburg and Dahlgaard, 2012) are often associated with more negative attitudes towards wind power. The maximum overlap area could host wind power generation capacity about 90 times higher than the current level in Pirkanmaa, indicating that this capacity level may be feasible while maintaining synergy between biodiversity and human well-being. However, reaching electricity self-sufficiency in Pirkanmaa may not be possible without compromising biodiversity or causing adverse effects on people. This may be also the case across whole Finland as presumed by Kiesecker et al. (2024), despite that the country is more sparsely populated than most countries in Europe. While the construction of a wind farm completely alters only a fraction of ecosystems within the farm area, the whole wind farm is impacted to a varying degree. For example, many species avoid the immediate surroundings of wind turbines (Tolvanen et al., 2023), and wind farms may decrease landscape connectivity and hamper species migration (Guo et al., 2020). Therefore, it is reasonable to claim that substantial impacts on biodiversity occur across the whole wind farm area.

Since electricity production targets may be difficult to reach due to competing interests, compromises that consider all relevant aspects, including ecologically most valuable areas and distances to settlements, are needed. Indeed, Eichhorn et al. (2019) showed that considering multiple interests, including impacts on both nature and humans, can lead to more sustainable results compared to focusing on a single interest. Regarding biodiversity, the ultimate goal of wind power development should be no net loss of nature values through the steps of mitigation hierarchy: avoidance, minimization and compensation (e.g. Arnett and May, 2016; Kiesecker et al., 2010). Finding and avoiding areas of highest biodiversity value, along with micro-siting of turbines during the planning phase, should be considered the most important measures to mitigate the impacts of wind power on biodiversity. Nevertheless, when impacts cannot be completely avoided, minimization measures, such as monitoring systems that allow pausing wind power generation during bird migration (Liechti et al., 2013), become relevant. If the goal is to reach electricity self-sufficiency while avoiding conflicts between biodiversity and the interests of local inhabitants, compensating for biodiversity impacts may be necessary to avoid net biodiversity loss. Biodiversity offsetting can be implemented by, for example, creating or restoring habitats that correspond to those degraded by the wind power development (Arnett and May, 2016; Gasparatos et al., 2017). For impacts on residents, minimum distance requirements have been proposed (Salomon et al., 2020); however, a constant setback distance may be inferior to a set of spatially differentiated ones in reducing social costs (Reutter et al., 2024). A more effective solution to increase acceptance may be collaborative planning with incentives and involvement of stakeholders and communities in the planning process (Sander et al., 2024).

4.1. Limitations

In planning of power lines, biodiversity impacts are often overlooked (Biasotto et al., 2022), although the construction of power lines sometimes greatly affects habitats and plant, bird and mammal communities (Richardson et al., 2017). The limited capacity of the electricity grid in Pirkanmaa suggests that new investments are required in both the main grid and smaller transmission lines, the construction of which causes habitat destruction. We incorporated the impacts of power line construction into the suitability analysis by including distance to existing power lines as a layer, where longer distance implied lower suitability due to increased disturbance from the construction of new power lines. Yet, the development of power grids may even cause more deforestation than that of wind turbines (Tolvanen et al., 2025), calling for a more in-depth consideration of the impacts of new power lines. Some selected clusters, for example in the western and northern parts of the region, have no existing or planned power grids in their vicinity (Fingrid, 2025), which may not only increase the overall biodiversity impacts of wind power development but also limit their technical feasibility. Thus, incorporating a maximum distance to power grids into the restriction criteria could improve the accuracy of the analysis. These aspects should be examined in future studies.

Although we used the best available data spanning multiple ecosystem types for the biodiversity-based suitability analysis, they do not fully capture the regional biodiversity. This is not exceptional, as most large-scale forest and other ecosystem biodiversity assessments are limited to the use of biodiversity surrogates, such as the cover of old-growth forests, stand ages or sometimes volumes of deadwood, and not on directly measured data. While wind turbines could negatively impact functional connectivity for many species (e.g. Guo et al., 2020; Skarin et al., 2015), we could consider this only for forest ecosystems, with the forest biodiversity layer considering internal forest connectivity as well as short-distance connectivity to key forest habitats and long-distance connectivity to permanently protected areas (Mikkonen et al., 2023). For birds, we considered migration routes, but data for important nesting and foraging areas were not available. Moreover, we could not consider large mammals due to the lack of data of adequate quality. Data quality posed other challenges as well; for example, the peatland site type classification has an accuracy of only 29.5−49.2% depending on the vegetation zone (Middleton et al., 2023). This is a potential source of systematic bias in the results, however, considering the relatively fragmented values of the peatland biodiversity value layer, the effect on the clustering results is probably minor. Furthermore, the peatland site type classification data has the reported accuracy at the highest thematic resolution (i.e., number of classes). When aggregating the peatland site type classes into fewer and broader ones, as we do, the classification accuracy is higher. Finally, in addition to the selected criteria, the criteria weights gained from AHP may affect the results. However, the consistency ratio below 10% and our sensitivity analysis showed that the results change little when adjusting the weights for the most important variables.

5. Conclusions

Our study shows that the most suitable locations for wind power development may differ substantially depending on whether the assessment prioritizes biodiversity values or distance to settlements. The most suitable areas for wind power were located in forested areas with lower population density. Locations of high suitability based on biodiversity values and distance to settlements overlapped only partly. Moreover, our results suggest that reaching electricity self-sufficiency in the study region may not be possible without compromising either biodiversity conservation or human well-being. As these objectives may be conflicting, it is important to consider both in the spatial allocation of wind power. In future research, all stages of the mitigation hierarchy should be considered to identify ways to alleviate the negative impacts of wind power.

CRediT authorship contribution statement

Saara Luukkonen: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Aleksi Räsänen:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Matti Koivula:** Conceptualization, Supervision, Writing – review & editing. **Anne Tolvanen:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.130132.

Data availability

Data will be made available on request.

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