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Land Cover analysis of European wind park development

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Abstract

This study examines the multifaceted land use changes associated with the development of wind energy infrastructure across Europe during the period from 2015 to 2023. Utilizing high-resolution multispectral data from the Copernicus Sentinel-2 satellite in combination with a sophisticated Multivariate Alteration Detection (MAD) algorithm, our research quantifies both the direct physical impacts and the indirect ecological and socio-economic consequences of wind farm construction. The comprehensive analysis encompasses over 15,000 turbines spread across 1829 wind parks in 18 European countries, capturing diverse regional patterns of land transformation. Key indicators include the conversion of agricultural and forest lands for turbine foundations, access roads, and associated electrical infrastructure, as well as secondary effects such as habitat fragmentation, biodiversity loss, and shifts in land ownership. The results reveal that while the direct spatial footprint of wind energy installations is modest compared to fossil fuel infrastructure, the cumulative indirect impacts on land use can be substantial, particularly in regions with intensive renewable energy development. Notably, the Mediterranean and Boreal regions experienced higher rates of land use change relative to the continental and Atlantic areas, highlighting significant regional disparities in environmental pressures. These findings underscore the importance of integrating advanced geospatial techniques in environmental impact assessments and call for balanced, strategic planning that reconciles renewable energy expansion with sustainable land management practices. Overall, this study contributes critical insights into the environmental trade-offs inherent in the global transition towards renewable energy sources.

1. Introduction

By 2023 Europe has 272 GW of installed wind capacity, 232 GW onshore (EU: 201 GW) and 34 GW offshore (EU: 19 GW), while it is expected that two thirds of the new wind installations up to 2030 will continue to be onshore. For 2024 for all of Europe more than 16.000 installations of onshore and 5000 offshore wind turbines are to be expected (WindEurope, 2024), with even increasing installation numbers until the end of the decade. These figures make it clear that it is of paramount interest to assess the implications of these installations, including the expected changes on-land, but also offshore. It is widely recognised that the satisfaction of energy demands whilst concurrently reducing the adverse effects of climate change is a matter of significant concern. However, an additional challenge that warrants consideration is the impact of expanding energy demands on land use and land cover (De Boer et al., 2015). The expansion of land use, colloquially termed *energy sprawl* is predicted to exert a substantial negative influence on biodiversity and ecosystem services through the loss and fragmentation of habitats (Trainor, McDonald, & Fargione, 2016). In general, wind power plants induce two major types of land use changes: direct impacts and indirectly affected area. The first type identifies the disturbed land due to the development of the plant (foundation) itself, while the latter depicts further changes involved in the deployment of wind turbines, for example (permanent) service roads, temporary roads, or storage areas (Denholm, Hand, Jackson, & Ong, 2009). A wind power plant's development causes a range of disturbances, both short-term and long-term (Arnett et al., 2007). Wind turbine pads, access roads, substations, service buildings, and other equipment that physically occupy land or produce impermeable surfaces are examples of these disruptions. Development in forested areas, where more land must be removed around each turbine, is linked to extra direct impacts. Although the land cleared around a turbine pad does not produce impermeable surfaces, the quality of the ecosystem may be significantly degraded as a result of this alteration (Kuvlesky et al., 2007). Construction of the plant has transitory effects in addition to permanent ones that last the facility's lifetime. These effects are related to lay-down, storage, and temporary construction access roads (Schöll & Nopp-Mayr, 2021). Following the completion of plant building, these locations will ultimately revert to their pre-construction form. Moreover, the indirect effects of wind energy infrastructure extend beyond the immediate physical footprint. Consequently, it becomes imperative to adopt a multiscale analysis approach that not only quantifies the immediate land disturbance but also maps the broader spatial repercussions of energy sprawl.

This study adopts such an integrative perspective by employing high-resolution spatial analysis techniques to distinguish onshore development patterns (Enevoldsen & Jacobson, 2021). By analysing actual location data from present wind parks across Eu-

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rope, this research investigates whether and to what extent these installations drive changes in land use / land cover. Key factors—such as topography, altitude, and infrastructure (i.e. road networks) are incorporated into the analysis, allowing for a more detailed understanding of how varying landscape characteristics mediate the impact of wind power developments. We not only aim to provide a quantitative assessment of land use changes associated with wind energy but also seeks to bridge the gap between energy infrastructure planning and environmental conservation. By mapping both direct disturbances (e.g., turbine pads and access roads) and show potential indirect impacts (e.g., habitat fragmentation and ecosystem degradation (Dilts, Blum, Shoemaker, Weisberg, & Stewart, 2023)), the study offers insights for future renewable energy projects for minimizing ecological disruptions. Furthermore, the synthesized data serves as a valuable resource for subsequent case studies, mapping assignments, and further analysis of disturbances affecting both terrestrial fauna and aquatic life.
This article contributes to the growing body of research on renewable energy landscape ecology by critically examining the trade-offs between energy production and environmental sustainability. By integrating multi-scale spatial analysis with an evaluation of ecological impacts, the research underscores the importance of adopting holistic planning strategies that account for the full spectrum of land use changes induced by wind power development.

2. Material and Methods

2.1. Input data

Satellite data: Earth observation data, including satellite imagery, provides vital information on land cover and atmospheric conditions. While commercial satellites like *SkySat* offer very high resolution (down to 0.5 m × 0.5 m), their recent data availability led to the selection of *Copernicus Sentinel-2* (Drusch et al., 2012). This project, offering a 10 m × 10 m resolution and data back to 2015, is freely available and sufficiently detailed to distinguish wind turbines from other land cover types like agricultural fields and forests.

Wind Turbine data: OpenStreetMap (OSM) serves as a collaborative platform for aggregating and displaying wind turbine data (OpenStreetMap contributors, 2023). This includes locations, and often, hub height, capacity, and approximate construction dates. Its up-to-date naturWe have determined that the use of OSM data is the simplest and best solution for our use case, especially under the conditions of Europe-wide and free availability. e and comprehensive data make it a valuable resource for visualizing and analysing wind energy infrastructure. Additional non-centrally organized data sources are available by country (i.e. official cadastral data) or commercial datasets ((EI, 2025) have been screened. We have determined that the use of OSM data is the simplest and best solution for our use case, especially under the conditions of Europe-wide and free availability.

Land Use and Land Cover data: The EEA's *CORINE* Land Cover database (European Environment Agency, 2019) provides detailed land-use and land-cover information for the EU, Norway, Switzerland, and Turkey. This dataset is crucial for analysing land utilization changes around wind turbine locations, covering categories like agricultural land and forests.

Terrain data: Digital Elevation Models (DEMs) from Copernicus GLO-30 and GLO-90 (European Space Agency & Airbus, 2022) are used to analyse terrain features. Slope and ruggedness, derived from these DEMs, are essential for statistical analysis, providing insights into various landscape types.

Ecological, Environmental, and Geographical data: EEA bioregions (Metzger, 2018), classified by ecological characteristics, and environmental zones, based on climatic, topographic, and human activity variables, are used to categorize and analyse land-use changes within ecologically and environmentally similar areas.

Territorial units: Eurostat's Nomenclature of Territorial Units for Statistics (NUTS) (EuroStat, 2020) provides a hierarchical framework for standardizing the statistical aggregation of results across European regions, facilitating consistent analysis.

2.2. Sentinel-2 Processing

Data preparation, download and preprocessing It is necessary to identify the Sentinel-2 coverage and tile names for the region / country of interest, in order to have the necessary information for later processing. After selecting one wind turbine location for each tile, the location is then recorded as a point shapefile. The tile name is obtained by intersecting the point shapes with the Sentinel-2 tiling grid. The tile name is one of the parameters that is used to query and download scenes from the Google Sentintel-2 Cloud (Google Earth Engine, 2023). Included in the list of additional criteria for the Sentinel-2 tiles is a predetermined value for the maximum cloud coverage (in this case we chase 5 percent, as well as a specified time period for the years 2015 and 2023. The time frame is modified in accordance with the climatic and vegetation zones of the region / country which are analysed, with the intention of avoiding snow covering as well as periods of dense vegetation, as the change detection between two different years is likely to produce invalid values or is simply very hard to interpret. After the files have been downloaded, a check is performed to determine whether the pixel data for the wind turbine is legitimate and relevant. This includes a point where the raster outline and the wind turbine location intersect, applying a buffer of one hundred meters. In order to process the raster outline, a byte conversion is performed on one band of the dataset. If the wind turbine is located outside the raster outline the raster file is discarded and a fresh scene is fetched from the Google Cloud and the process is repeated. In case the wind turbine is situated within the raster outline, the analysis proceeds with the intersection with the provided cloud mask from the Sentinel-2 dataset. The cloud mask is usually provided as either a JP2 (jpeg2000) image standard, or GML (geography markup language) file format. In the event that the wind turbine is under cloud cover, a fresh scene is downloaded. Following the discovery of valid scenes for the years 2015 and 2023, a procedure known as *Sen2Cor* (Main-Knorn et al., 2017) is performed. Sen2Cor is a collection of tools developed by the ESA for the purpose of correcting atmospheric and terrain conditions. In this work, the atmospheric adjustment correction is applied to the downloaded datasets.

Change detection Once the necessary steps of download and preprocessing are finished, a change detection raster map is constructed using true colour images that have been acquired from the

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Sen2Cor output. This raster map is created using the open source toolbox *Orfeo* (Grizonnet et al., 2017) utilizing the *Change detection algorithm*. In order to obtain information on the amount of land that wind power facilities use, this map is utilised. First, raster values will be recovered for the OSM wind power plant point data, which also include the four consecutive pixels, north and south, east and west. In order to compute the horizontal and vertical sums, which give extra information on whether the pixel value has changed, these 4 neighbouring pixels are included in the calculation. In most cases, negative pixel values imply a change, and this information is used to filter out wind turbines that were constructed between the years 2015 and 2023. For actual wind turbine points, square meter and hectare values of change are extracted by employing a change detection map filtering the negative change values. By applying the filter on positive change values, the algorithm is also capable of detecting the removal of wind turbines, for example to detect changes of repowering measures, where generally many smaller wind turbines are replaced with fewer but larger designs.

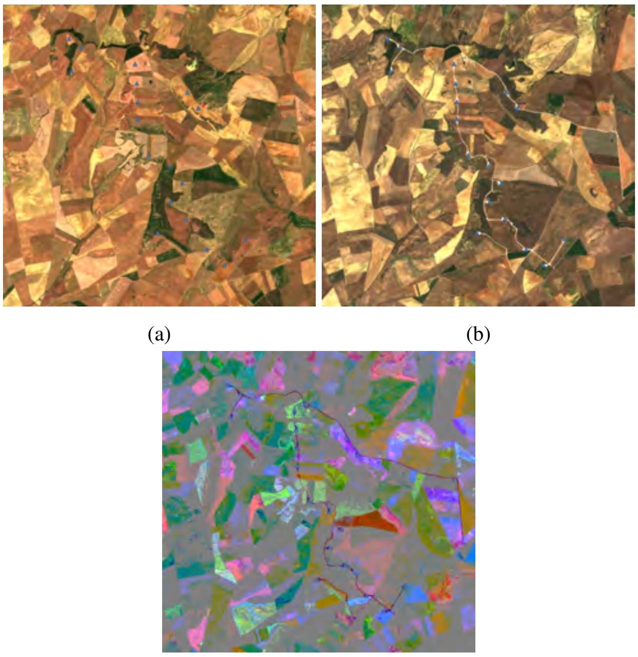
2.3. Statistical analysis

The methodology employs statistical analysis to quantify and validate the observed changes. For the purpose of descriptive statistics, time series analysis is utilised to evaluate the statistical significance and geographical arrangement of identified changes. The values calculated include: absolute change (i.e. in ha) and the change percentage (%). The following tasks are performed to assess the change values: First, a cluster analysis using the DBSCAN algorithm (Schubert, Sander, Ester, Kriegel, & Xu, 2017) is performed. The algorithm is run with a minimum cluster size of 2 (meaning one wind park consists of at least two turbines) and a maximum distance between clustered points of 1500 meters. Within a cluster, a nearest neighbour analysis is performed to get the average distance between wind turbines, which is applied on created concave and convex hulls to represent wind parks. A convex hull is the minimal convex polygon that encompasses a set of points in a two-dimensional plane. The term refers to the common area shared by all convex sets that include the specified points. On the other hand, a concave hull is a shape that encloses a set of points but can have indentations or concavities. It is designed to better represent the non-convex geometry of certain point sets. Within these areas the above change values are calculated.

3. Results and Discussion

Our analysis of wind parks in Europe reveals that between 2015 and 2023, circa 1900 wind parks were constructed, while there are some notable concentrations in specific regions including northern Spain, particularly the vicinity of north-eastern Spain, north-eastern France, Belgium, the Netherlands, and north-eastern Sweden. The number of turbines per wind park in these areas ranges from approximately 80 turbines to 250 turbines, indicating a substantial investment and development in wind energy infrastructure.

The actual change detection analysis involves the application of a MAD algorithm (Multivariate Alteration Detection) (Nielsen & Conradsen, 1997) yielding - when using True Colour Images as an input - a 3-band change detection image. The output values may either be negative, indicating the construction of access roads or lay off sites, positive, indicating mainly a difference in vegetation, or zero, meaning no change. Figure 1 shows the RGB satellite images before (1a) and after (1b) development, while on the 1c is the result of the output values: negative (blue), positive (green) and zero change (gray). The output image is the raw output of the *change detection* algorithm provided by the *Orfeo toolbox*.



(a) (b)

(c)

Figure 1: True Colour images for two different time stamps (a) and (b) with the resulting change detection image (c)

The features of interest such as access roads, lay off areas and turbine foundations be extracted by performing additional filtering on different bands which eventually results in a binary image (figure 2 - 2a). This binary change data is the basis for the calculation of the amount of land-use change within the vicinity of each wind turbine location.

The consecutive geostatistical analysis integrates CORINE land cover data (European Environment Agency, 2019), digital terrain models (European Space Agency & Airbus, 2022), and biogeographical regions (European Environment Agency, 2017) in order to elucidate spatial patterns and environmental relationships, where the regions and the turbine locations are visualized in figure 3.

Figure 4 shows an overview of the area of change per windturbine for the predominant biogeographical regions in Europe. The analysis reveals a mean area of change of 0.56 hectare per windturbine. Values tend to be higher in the Mediterranean and Boreal regions of Europe indicating a higher amount of land used for infrastructure, particularly for construction of road networks. In contrast, land cover change is lowest in the continental and Atlantic regions, because of the usage of already existing roads, i.e within agricultural areas.

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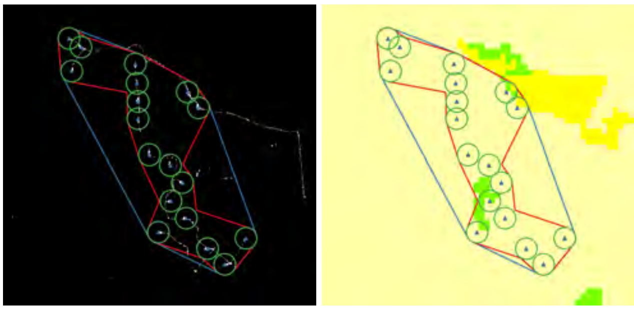

(a) (b)

Figure 2: Binary result showing a wind park in Spain (a) and the concave hull of the same park (b).

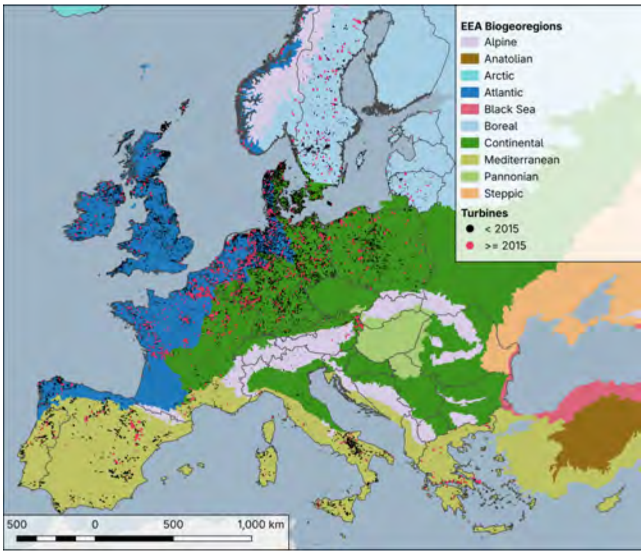

Figure 3

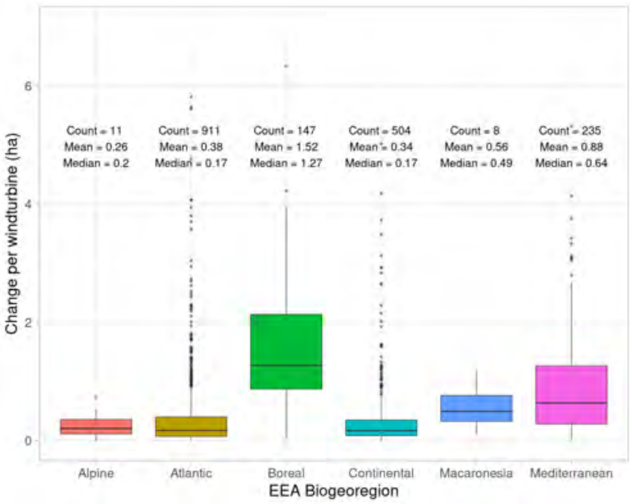

Figure 4

4. Difficulties and Obstacles

OSM Accuracy The accuracy of OSM can be inconsistent due to human error, outdated information, and varying contributor expertise, impacting applications like navigation, disaster response, and urban planning (Haklay, 2010). In our study, we encountered inaccuracies with turbine locations and omissions: roughly 10 percent of turbines were misplaced by over 10 m, with some deviating by more than 50 m. This level of error hindered a completely automated Sentinel-2 analysis, necessitating manual verification of turbine positions. As mentioned above, there are also national and/or commercial turbine location databases available, but we opted to use the readily available OSM data.

Sentinel-2 Resolution Sentinel-2, with its 10x10 m resolution, barely meets the requirements of a land-use change analysis for wind turbine construction. For turbines exactly positioned in the center of a pixel, the foundation and layoff areas are captured fully during the analysis, while for turbines at the edge of a pixel the changes might not be fully covered by a pixel-by-pixel analysis. Therefore, we always consider an entire area around the turbines (buffer polygons) or wind farms (concave and convex hulls). While the resolution does not necessarily affect the direct change caused by the wind turbine and the setback area, it can lead to inaccuracies, especially for newly constructed roads and also combined with the effects described in the next paragraph.

Sentinel-2 Shift Sentinel-2, part of the European Space Agency's Copernicus programme, provides high-resolution multispectral imagery essential for applications such as agriculture, forestry, and environmental monitoring. However, factors like orbital variations, sensor misalignment, and atmospheric conditions can lead to misalignments between images, complicating change detection and multi-temporal analysis (Li & Roy, 2017). Even minor shifts can result in significant errors in applications demanding high positional accuracy. Mitigation techniques—such as geometric correction, co-registration, and the use of ground control points—are crucial to enhance data reliability (Gascon et al., 2017). Consequently, our change-detection process required manual adjustments, with visual comparisons ensuring a precise image overlap.

5. Conclusions and Outlook

The findings of this study demonstrate the necessity for precise and adaptive approaches in the monitoring and management of the implications of wind energy projects. The documented challenges, such as data accuracy from OpenStreetMap and spatial inconsistencies in Sentinel-2 imagery, emphasise the need for meticulous manual verification and the continuous development of robust analytical tools. Addressing these issues is vital for maintaining the integrity of assessments and ensuring the reliability of the data provided to project partners and stakeholders.

Although this analysis provides a first comprehensive insight into this issue, there are many improvements to be made. For example, a time series analysis instead of a pure before and after analysis. This would capture any major impacts during construction, as well as areas that have been restored after construction. Also the

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usage of higher resolution satellite imagery may improve results, although no comparison was done yet.

This study is intended to better understand the effects of wind power development on the landscape, biodiversity (flora and fauna) and also on the acceptance of the local population, and also to be able to use the data generated in further modelling in these fields of research.

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