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Shifts in wind energy potential following land-use driven vegetation dynamics in complex terrain

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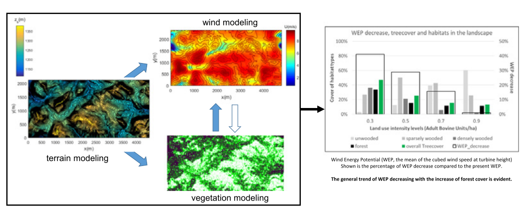
HIGHLIGHTS

- Modeling framework coupling large-eddy simulation of boundary layer, vegetation dynamics and digital elevation model.
- Wind energy potential in complex mountain terrain strongly depends on land cover changes driven by land-use change.
- Trade-off between renewable energy production and biodiversity under agro- and forest policies in landscape development.
- The framework could support the long-term planning of wind energy projects under land-use and climate change scenarios.

GRAPHICAL ABSTRACT



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ABSTRACT

Many mountainous regions with high wind energy potential are characterized by multi-scale variabilities of vegetation in both spatial and time dimensions, which strongly affect the spatial distribution of wind resource and its time evolution. To this end, we developed a coupled interdisciplinary modeling framework capable of assessing the shifts in wind energy potential following land-use driven vegetation dynamics in complex mountain terrain. It was applied to a case study area in the Romanian Carpathians. The results show that the overall shifts in wind energy potential following the changes of vegetation pattern due to different land-use policies can be dramatic. This suggests that the planning of wind energy project should be

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integrated with the land-use planning at a specific site to ensure that the expected energy production of the planned wind farm can be reached over its entire lifetime. Moreover, the changes in the spatial distribution of wind and turbulence under different scenarios of land-use are complex, and they must be taken into account in the micro-siting of wind turbines to maximize wind energy production and minimize fatigue loads (and associated maintenance costs). The proposed new modeling framework offers, for the first time, a powerful tool for assessing long-term variability in local wind energy potential that emerges from land-use change driven vegetation dynamics over complex terrain. Following a previously unexplored pathway of cause-effect relationships, it demonstrates a new linkage of agro- and forest policies in landscape development with an ultimate trade-off between renewable energy production and biodiversity targets. Moreover, it can be extended to study the potential effects of micro-climatic changes associated with wind farms on vegetation development (growth and patterning), which could in turn have a long-term feedback effect on wind resource distribution in mountainous regions.

1. Introduction

As a safe and renewable non-polluting resource, wind energy has been undergoing a large-scale development worldwide in the past decade. With the continuous advance of wind power technology and decrease of its effective costs, it is foreseen that wind power penetration levels will continue to increase in many countries. Accurate wind energy potential assessments are crucial to the successful development of wind power plants. Knowing the spatial distribution of wind and turbulence at a specific site guides the wind power planners to select the wind farm site, evaluate the production and cost, and optimize the micro-siting of wind turbines to maximize wind energy production and minimize fatigue loads.

There are two main methods for assessing wind energy potential: one is based on observational data and the other relies on numerical wind field simulations. In practice, the two methods are often combined to produce wind resource maps which, in some countries/regions such as Canada, USA, and Europe, are collected together as national wind atlases. Various wind flow modeling systems targeted at different scales have been developed and applied to wind resource assessment. Examples of mesoscale systems include the widely used Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) developed for both research and operational purposes and the operational Consortium for Small-scale Modeling (COSMO) model (Nolan et al., 2014). Mesoscale modeling typically covers a domain size of 10^7 m to 10^5 m with a grid resolution of 10^5 m to 10^3 m. Generally, several levels of physical downscaling by domain nesting are required within these ranges to overcome the computational complexity. Initial and boundary conditions are obtained from large scale weather models like the Global Forecast System (GFS) produced by the National Centers for Environmental Prediction (NCEP). Many studies have validated mesoscale models such as WRF and apply them for wind resource assessment and wind power forecast. So far satisfactory results have been reported mainly for cases where the terrain features are simple. For example, Hahmann et al. (2015) show that WRF is able to predict the annual mean wind speed within the measurement uncertainty in the North and Baltic Seas. It is worth mentioning that global wind data, based on WRF is now available (https://www.globalwindatlas.info/). However, in complex terrain, mesoscale models tend to yield considerable errors for both wind speed and wind direction predictions (Jiménez and Dudhia, 2012, 2013). This is mainly due to the fact that effects of local topography and land cover are insufficiently captured at relatively coarse grid resolutions in mesoscale models. To tackle this problem, further downscaling to microscale is required. Recently, the coupling of mesoscale and microscale models has become a strong area of research for the next generation of wind resource assessment. This is because it can better handle the multi-scale nature of the problem by simulating the various physical processes directly and capture both large scale weather and microscale topography effects on local wind conditions (Moeng et al., 2007; Carvalho et al., 2013; Gopalan et al., 2014; Castro et al., 2015; Bilal et al., 2016; Sanz Rodrigo et al., 2017).

A microscale model typically adopts a domain size ranging from 1 to 20 km and a grid resolution ranging from 1 to 100 m. The majority of microscale models apply Computational Fluid Dynamics (CFD) techniques to solve the Navier-Stokes (N-S) equations governing turbulent flows in the atmospheric boundary layer (ABL) with stationary forcing (i.e. mesoscale tendencies are neglected). Among the various CFD methods, Large-Eddy Simulation (LES) based on the spatially-filtered N-S equations has become an important tool for simulating turbulent flows. LES has been successfully validated and applied for the study of ABL flows over homogeneous terrain. The development and application of LES-based numerical models for wind field simulations over complex terrain is on the rise (Wan et al., 2007; Silva Lopes et al., 2007; Wood, 2000; Wan and Porté-Agel, 2011; Diebold et al., 2013; Bechmann and Sørensen, 2011; Cheng and Porté-Agel, 2013; Mirocha et al., 2014; Liu et al., 2016; Fang and Porté-Agel, 2016; Shamsoddin and Porté-Agel, 2017). To apply LES to complex heterogeneous terrain, however, there is a need for coupling it with high-resolution data of the relevant surface properties, namely surface elevation (topography) and land cover. Conventionally, Monin Obukhov Similarity Theory (MOST) is used as surface-layer scheme to relate vegetation with the turbulent fluxes in the near-wall gird cells by assigning corresponding aerodynamic surface roughnesses, while obstacles and tall canopies are explicitly modeled in CFD when they are directly influencing the sites of interest. So far, in numerical wind field simulations, vegetation was treated as a static surface property like topography and little research has been done to study the long-term impacts of vegetation dynamics on local wind conditions and their implications on wind energy project planning.

The need to address landscape structural dynamics can be derived from the 2009 European Environment Agency Report concerning Europe's onshore and offshore wind potential. Among the steps to be addressed in the future, the report explicitly mentions the necessity of a more detailed analysis of areas where model prediction and observed wind velocities differed most, notably mountainous and forested areas. Furthermore, the analysis of specific vulnerabilities of biodiversity related to specific bird and other species and of landscapes was requested, as well as the explicit consideration of such vulnerabilities in mapping wind energy potential in Europe.

In mountainous regions, a high potential for wind turbines exists, especially at higher altitudes and on the crests of these middle-range mountains. For example, the Juvent wind farm in the Jura mountains of Switzerland has 16 wind turbines installed on two hills, Mont Soleil (alt. 1291 m) and Mont Crosin (alt. 1268 m), where the land cover varies from grasslands to forests. Unfortunately, these regions are also often very sensitive to turbine installations, because of their high value in terms of biodiversity and landscape scenery (Bergmeier et al., 2010; Etienne, 1996). During the past decades, at higher altitudes there was a drastic land-use and landcover change,