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News & Views

Observed impacts of large wind farms on grassland carbon cycling

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Deployment of wind energy is an essential renewable energy source that mitigates climate change and reduces air pollution [1]. Over the last several decades, wind energy development has increased worldwide, expanding from ~20 to ~900 GW (gigawatt) during 2001–2022 [1]. Nonetheless, researchers have identified unintended consequences of wind energy on microclimate via turbine-altered surface-atmosphere exchanges of energy, momentum, mass, and trace gases [2,3]. Based on multi-source observations and models, researchers also have drawn some conclusions that wind farms could warm the land surface, especially at night, at regional and continental scales [4,5]. Consequently, altered microclimates at wind farms may affect vegetation productivity and carbon sequestration, two critically important ecosystem services related to carbon dynamics; however, such potential impacts and driving mechanisms remain poorly understood [6]. Wind energy deployment is increasing globally to meet carbon neutrality goals, with upscaling of onshore wind power capacity projected to grow from 542 GW in 2018 to 1787 and 5044 GW by 2030 and 2050, respectively [7]. Increased demand for wind energy deployment may lead to much larger wind farms in open, expansive landscapes [7]. In turn, a large array of geographically clustered wind turbines could collectively modify local microclimate and amplify turbine-atmosphere interactions, which, if large enough, may produce detectable impacts on ecosystem dynamics. Thus, identifying and quantifying the potential impacts of wind farms on carbon-related ecosystem services may facilitate sustainable wind energy development globally.

Currently, China is the world leader in wind energy deployment, accounting for one-third of global installed capacity [8]. Total installed capacity has been rapidly growing in China over the last two decades, increasing from less than 1 GW in 2001 to nearly 200 GW in 2018 (Fig. S1 online), and ~334 GW in 2022 [1]. China's northern grasslands are considered prime environments for wind energy deployment because they provide abundant and accessible onshore wind resources [9]. Compared to the United States (https://eerscmap.usgs.gov/uswtdb), where most wind farms are co-located with croplands, wind farms in northern China's grasslands experience less human disturbance (e.g., no agricultural irrigation and fertilizer use), providing a unique opportunity to assess wind energy impacts on carbon-related ecosystem services (Fig. S2 online).

(i) Impacts of wind farms on vegetation growth. We evaluated the effects of wind farms (i.e., array of geographically clustered wind turbines; Methods) on grassland growth during peak growing season (June–August; Fig. S3 online), using time series of the normalized difference vegetation index (NDVI) from moderate-resolution imaging spectroradiometer (MODIS) during 2001–2018. We calculated NDVI anomaly as the difference in NDVI between wind farms and nearby control regions with similar local environmental conditions but no turbines (Figs. S4 and S5; Tables S1–S5 online). We quantified the effects of wind farms on vegetation growth by calculating the changes in NDVI anomaly during 2001–2018 (denoted as ΔNDVI; Methods; Fig. S6 online). We found that eleven out of the sixteen (~70%) wind farms exhibited reduced grassland growth over time, as indicated by negative ΔNDVI (Fig. S7 online). Reductions in grassland growth were exacerbated by the size of wind farms (Fig. 1a), with stronger negative ΔNDVI at large wind farms (>1000 turbines). The spatial variation of ΔNDVI was not correlated with spatial heterogeneity in climate (i.e., temperature, precipitation, and vapor pressure deficit), elevation, vegetation cover, and density of clustered wind turbines (Fig. S8 online), which suggests that the size of wind farms (i.e., number of the clustered wind turbines) primarily drove reductions in grassland growth. These findings are further corroborated by additional

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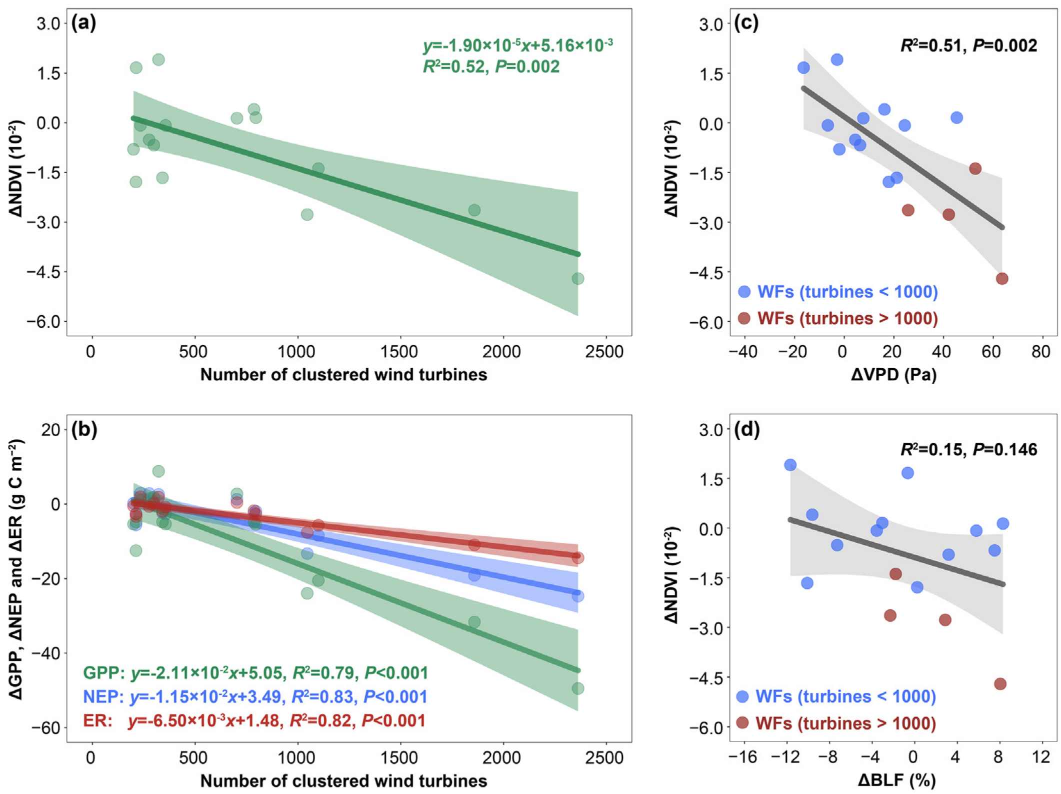

Fig. 1. Impacts of wind farms on vegetation growth and carbon cycling in peak growing season. (a) Relationship between the number of turbines and the MODIS ΔNDVI (the normalized difference vegetation index) across the sixteen wind farms. (b) Relationship between the number of turbines and ΔNEP (net ecosystem productivity), ΔGPP (gross primary productivity), and ΔER (ecosystem respiration) across the sixteen wind farms. (c) Relationship between MODIS ΔNDVI and ΔVPD (vapor pressure deficit) across the sixteen wind farms. (d) Relationship between MODIS ΔNDVI and ΔBLF (bare land fraction) across the sixteen wind farms. The grey shaded area represents 95% confidence interval of the linear regression.

vegetation metrics sourced from multiple satellite platforms (Figs. S9 and S10 online).

(ii) Impacts of wind farms on carbon sequestration. To explore the implications of reduced grassland growth at wind farms for regional ecosystem carbon sequestration, we evaluated the net ecosystem productivity (NEP), estimated as the difference between gross primary productivity (GPP) and ecosystem respiration (ER) [10]. Following the same time-series analysis (see Methods), we defined ΔGPP, ΔNEP, and ΔER as the changes of GPP, NEP, and ER anomaly during 2001–2018, respectively. Our results show a strong, negative relationship between the size of wind farms and ΔNEP (Fig. 1b; R^2 = 0.83), indicating that losses of ecosystem carbon sequestration enlarge most at the largest wind farms. In comparison to multi-year mean carbon sequestration, relative carbon sequestration loss can reach 50% at the largest wind farms (Fig. S11 online). Negative ΔNEP is primarily driven by decreases in GPP rather than ER (Fig. 1b). Further assessment of effects on carbon sequestration outside of the peak growing season corroborated that reductions in carbon sequestration primarily occurred during the growing season (Fig. S12 online) rather than in the non-growing season (Fig. S13 online).

(iii) Mechanisms of the impacts on vegetation growth. In arid and semi-arid grasslands, natural vegetation dynamics are constrained by both soil and atmospheric water availability [11], and local hydrometeorological factors affected by the presence of wind farms may influence grassland growth. Thus, using the same time-series analysis for vegetation growth (see Methods), we investigated the effects of wind farms on the local hydrometeorological factors that can affect grassland growth, including precipitation, soil moisture, and vapor pressure deficit (VPD)—an atmospheric dryness metric calculated as the difference between saturated vapor pressure and actual vapor pressure (see Methods). Wind farms showed no effects on peak growing season precipitation and soil moisture but significant impacts on VPD (Figs. S14 and S15 online). Specifically, ΔVPD (i.e., changes of VPD anomaly during 2001–2018) at large wind farms (>1000 turbines, ~46 Pa) showed a greater increase than small and medium wind farms (<1000 turbines, ~10 Pa). Further, we found that increased saturated vapor pressure and decreased actual vapor pressure contributed equally to local atmospheric drying at large wind farms (Fig. S16 online). The increased saturated vapor pressure may be a result of local warming due to turbine-enhanced turbulence, which can alter vertical heat distribution in the atmospheric boundary layer and ultimately raise near-surface temperature [4]. This local warming may also be linked to less land surface cooling by reduced evapotranspiration (Figs. S14 and S15 online). The decrease in actual vapor pressure is likely caused by turbine-enhanced turbulence as well, which brings drier air in the upper atmospheric boundary layer to the near-surface [2] and thereby decreases air humidity (Fig. S16 online).

We determined that turbine-induced atmospheric drying can largely explain reduced grassland growth across all wind farms (Fig. 1c; R^2 = 0.51). Specifically, stronger reductions in grassland growth at larger wind farms are associated with greater increases in VPD. In water-limited grasslands, vegetation growth is highly constrained by atmospheric moisture conditions [12]. Leaf stomata close in response to atmospheric drying, which can limit photosynthesis and growth [13]. We verified the negative impact of atmospheric drying on grassland growth in subsequent analyses of other vegetation metrics from various satellite platforms (Fig. S17 online).

Aside from the climatic impacts of wind farms, we also quantified effects of land-use change (i.e., increased bare land fraction, BLF) on vegetation growth at the wind farms. We found a weak relationship between ΔBLF (i.e., changes of BLF anomaly during 2001–2018) and ΔNDVI (Fig. 1d), and the ΔBLF explains ~10% of changes in grassland growth as inferred from a range of vegetation indices (Fig. S18 online). The lack of a strong signal of land-use change on grassland growth is likely due to the relatively small footprint of individual turbines compared to the large, inter-turbine spacing extending hundreds of meters to optimize wind farm efficiency [14]. Thus, we conclude that atmospheric drying could be the main driver of reduced grassland growth, as confirmed by a multiple regression model considering both ΔVPD and ΔBLF as independent variables (Fig. S19 online).

(iv) Issues and perspectives. Our work mainly detected the impacts of wind farms on vegetation growth and carbon cycling using multi-source remote sensing datasets. In addition to vegetation productivity, since wind farms are widely observed to increase near-surface temperature in their host ecosystems [4,5], wind farms may affect the microbial decomposition of soil organic carbon. Thus, long-term field experiments and flux observations are highly recommended to detect the possible impacts and background mechanisms [6]. In addition, given that the current mesoscale weather research and forecasting (WRF) model has integrated the effects of wind farms on the local climate [6], coupling the climate model and ecosystem model should be developed on a high priority to provide simulations and predictions of the wind farm impacts on ecosystem carbon cycling at large spatial scales [3,5].

To dive into detailed mechanisms of the wind farm impacts on local environments, we require more public datasets in terms of the wind turbine information (e.g., construction time, nominal power, and operation periods) and wind farm microclimate (e.g., wind direction and wind speed). The information can also help to optimize the methods in our study and reduce the potential uncertainties. Currently, the United States Wind Turbine Database (USWTDB) has provided the geolocations and construction time of all wind turbines in the United States (https://eerscmap.usgs.gov/uswtdb/), while there are still no available datasets of wind turbines in China. Given that our view paper highlights the importance of identifying and quantifying wind farms' potential impacts on carbon-related ecosystem services, our work can help call for public wind turbine datasets from energy departments.

In summary, we show here that large wind farms decrease vegetation productivity and cause losses in carbon sequestration, indicating a previously unknown trade-off between wind energy production and carbon-related ecosystem services. The need to meet net-zero emission targets by mid-century leads to much larger arrays of geographically clustered wind turbines in open, expansive landscapes [7]. This trend towards larger wind farms may amplify turbine-induced atmospheric drying (Fig. S20 online), increasing water stress on local vegetation productivity. Understanding and assessing these unintended consequences of large-scale wind energy development for ecosystems and their services can facilitate efficient adaptation and management strategies for a sustainable energy future [15].

Conflict of interest

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Appendix A. Supplementary materials

Supplementary materials to this news & views can be found online at https://doi.org/10.1016/j.scib.2023.10.016.

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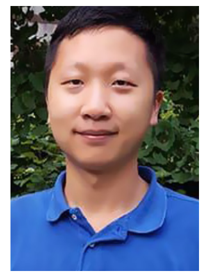

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