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Development of mountain wind power in China significantly reduces ecosystem resistance to soil water erosion

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Dear Editor,

Wind power generation has emerged as a critical strategic option for many countries worldwide in addressing climate change and advancing energy transitions and has undergone rapid development in recent years, with substantial future prospects. Owing to the advantages of abundant wind resources, stable wind speeds, and minimal land occupation,[1,2] mountainous wind farms have experienced accelerated expansion and are now widely distributed. Compared with wind farms in plain regions, mountainous wind farms exhibit distinct characteristics and are associated with considerably greater risks of soil erosion. First, during the construction phase, site levelling for turbine installation and booster stations, along with road construction, causes substantial disturbance to surface vegetation, thereby readily inducing soil erosion.[3] Second, mountainous wind farms are typically characterized by complex terrains and steep slopes, where surface runoff accelerates under natural conditions such as rainfall, resulting in a strong scouring effect on soils. In China, the wind power industry has exhibited a downwards trend in its spatial deployment,[4] and the prevalence of mountainous terrains and abundant precipitation in southern China further exacerbate the risk of soil erosion. The environmental impacts of mountainous wind farms, particularly issues pertaining to soil water erosion, have attracted increasing research attention;[3,5,6] nevertheless, systematic understanding of their national-scale spatial patterns remains lacking.

To address this scientific gap, we propose an improved quantitative method for assessing the effects of mountainous wind farms on soil water erosion, which builds upon traditional approaches (see attached files). This method overcomes the limitations of buffer-zone comparison approaches, which fail to eliminate the confounding effects of climatic factors,[3] and enhances analytical accuracy by incorporating elevation control at the grid cell scale. Subsequently, based on the self developed spatiotemporal dataset of wind turbines across China's terrestrial and marine territories, we identified 474 mountainous wind farms (see attached files). In conjunction with the recently released "The 30 m annual soil water erosion dataset in Chinese mainland from 1990 to 2022",[7] we systematically quantified, for the first time, the impacts of the construction and operation of mountainous wind farms on soil water erosion across China. Furthermore, drawing on existing studies,[8,9] we propose an attribution framework for disentangling the pathways through which mountainous wind farms affect soil water erosion (see see attached files) from the perspectives of environmental pressure, ecosystem sensitivity, and ecosystem resilience. Finally, we explore management strategies for soil erosion control at mountainous wind farms, aiming to provide scientific references for relevant research while contributing to the sustainable development of the wind energy industry and the achievement of China's "dual carbon" goals (carbon peaking and carbon neutrality).

SPATIAL PATTERNS OF THE IMPACTS OF MOUNTAINOUS WIND FARMS ON SOIL WATER EROSION

Nationwide, mountainous wind farms have significantly intensified soil water erosion by 0.16 ± 0.83 t ha^{-1} yr^{-1} (mean ± 1 standard deviation) ($p< 0.001$, t test). Among these, 267 mountainous wind farms experienced increased soil water erosion, whereas 207 experienced decreased erosion, revealing pronounced spatial differentiation (Figure 1A). For those wind farms with increased erosion, the maximum increase in the three-year average preconstruction soil water erosion rate reached 148.56%. The 51 wind farms where erosion increases exceeded 1.0 t ha^{-1} yr^{-1} were concentrated predominantly in the northern, southern, and southwestern regions and were composed primarily of cropland-based (n= 11) and forestland-based (n= 39) wind farms. With respect to the soil water erosion intensity at mountainous wind farms, neither the regional slope nor the wind farm scale had a significant effect; however, land use type had a significant effect (Figure 1B). Specifically, no significant difference in soil water erosion was detected between cropland and forestland wind farms or between cropland and grassland wind farms, whereas forestland and grassland wind farms differed significantly from each other (each type being defined as those where the corresponding land use—e.g., grassland for grassland wind farms—is the most widespread). The mean soil water erosion rates across the three land use types ranked as follows: cropland (0.41 t ha^{-1} yr^{-1}) > forestland (0.17 t ha^{-1} yr^{-1}) > grassland (−0.04 t ha^{-1} yr^{-1}).

ATTRIBUTION ANALYSIS OF THE INTENSIFICATION OF SOIL WATER EROSION BY MOUNTAINOUS WIND FARMS

Based on the attribution results, the construction and operation of mountainous wind farms nationwide significantly increased both the ecosystem resistance factor *CP* (in this study, *CP* was defined as an index of ecosystem resistance to soil water erosion, quantified as the product of the cover management factor (*C*) and the soil and water conservation measure factor (*P*) within the revised universal soil loss equation (RUSLE) model, with an increase of 0.0009 ($p<0.05$, Wilcoxon signed-rank test), and its contribution rate, which increased by 1.60% ($p<0.05$, t-test) (Figure 1C). An elevated *CP* factor indicates diminished vegetation cover and soil-and-water conservation functionality, suggesting that the construction and operation of mountainous wind farms may exacerbate soil erosion by weakening the resistance of the ecosystem to soil water erosion. Concurrently, the *R* factor in the control areas (in this study, *R* is defined as the environmental stress of regional soil water erosion, quantified as the rainfall erosivity factor (*R*) within the RUSLE model) significantly decreased by −280.28 ($p<0.001$, t-test), whereas its contribution rate increased markedly by 1.82% (Figure 1D). These findings indicate that the overall rainfall erosivity in the study region weakened and that the regional climatic context was, to a certain extent, favourable for reducing the risk of soil water erosion. Nevertheless, despite this regional decline in rainfall erosivity conducive to erosion control, soil water erosion within the wind farm areas still intensified. This suggests that the vegetation destruction and surface disturbances caused by wind farm construction and operation may have offset the erosion-reducing effect of diminished rainfall erosivity. Consequently, it is imperative to strengthen vegetation restoration and soil-and-water conservation measures during both the construction and operational phases of mountainous wind farms. Furthermore, compared with the three years prior to construction, *CP* increased notably during the three years after construction, with this change occurring predominantly in the first year after construction, which coincided with the construction period of the wind farms (Figure 1E), indicating that vegetation damage from the wind farms is concentrated mainly during the construction stage. In the subsequent years, CP continued to decline, which may reflect a gradual and slow ecological recovery process, although it may not have fully returned to pre-construction levels. For instance, for originally grassland-based wind farms, this recovery process may be particularly slow

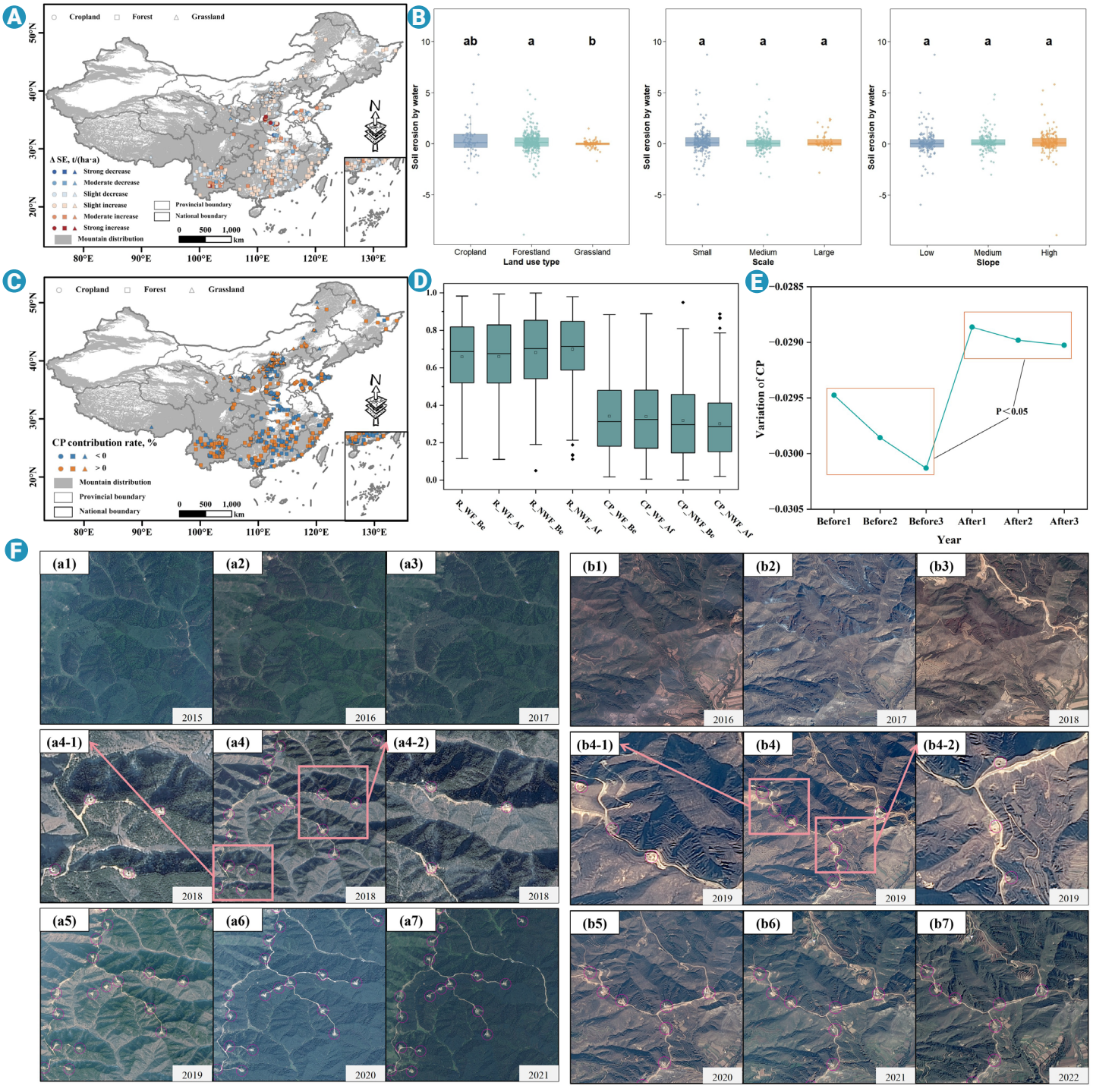


Figure 1. (A) Impacts of mountainous wind farms on soil water erosion (Δ SE, t ha^{-1} yr^{-1}), classified using the natural breaks method into strong decrease (−8.95 to −5.96), moderate decrease (−3.26 to −1.20), slight decrease (−1.11 to <0), slight increase (>0 to 1.11), moderate increase (1.16 to 3.08), and strong increase (3.84 to 8.72), and the different symbols represent the land cover types of the wind farms; (B) comparative analysis of soil water erosion among different categories of mountainous wind farms; (C) changes in the relative contribution rate of the ecosystem resistance factor *CP* attributable to the construction and operation of mountainous wind farms (the different symbols indicate the land cover types of the corresponding wind farms); (D) changes in the contribution rates of the environmental stress factor *R* and the ecosystem resistance factor *CP* between wind farm areas and control areas; (E) changes in the difference in the ecosystem resistance factor *CP* between wind farm areas and control areas over three years before and after construction; (F) high-resolution GF-2 true-color imagery showing two wind farms with severe soil erosion before and after construction (the local inset panels provide magnified views to clearly mark the wind power construction areas, while the main panels preserve the overall landscape context). The test in (B) is the Kruskal-Wallis test. The test in (D) is the Wilcoxon signed-rank test. The lines indicate the median (50th percentile), with boxes showing the first (Q1, 25th percentile) and third (Q3, 75th percentile) quartiles. Whiskers extend to Q1 − 1.5 × IQR and Q3 + 1.5 × IQR. The test in (E) is the Wilcoxon signed-rank test. All statistical tests were performed using IBM SPSS Statistics 26 software.

because the vegetation regrowth is severely hindered by construction-induced soil compaction, altered microtopography, and harsh climatic conditions can severely hinder vegetation regrowth. High-resolution satellite imagery further visually demonstrates the substantial impact of mountainous wind farm construction and operation on surface vegetation, with the inset panels clearly showing the exposed bare surfaces in the construction areas (Figure 1F).

MANAGEMENT RECOMMENDATIONS FOR MOUNTAINOUS WIND FARMS IN CHINA

China's wind power industry is developing rapidly, with mountainous wind farms constituting a critical component. Based on the analysis of our self-interpreted spatiotemporal dataset of wind turbines, as of 2023, a total of 67,047 wind turbines had been deployed in mountainous areas, accounting for approximately 47.01% of all onshore turbines. During 2015–2023, although the proportion of newly installed turbines located in mountainous regions declined, approximately 40 out of every 100 newly constructed turbines were still situated in such areas. Our findings demonstrate that the construction and operation of mountainous wind farms nationwide significantly intensified soil water erosion by 0.16 ± 0.83 t ha^{-1} yr^{-1} (mean ± 1 standard deviation) ($p < 0.001$, t-test) (Figure 1A). According to projections from major reports and existing studies, driven by the green energy transition and national "dual carbon" goals (carbon peaking and carbon neutrality), the scale of wind power development in China is expected to grow exponentially in the future, accompanied by a substantial expansion of mountainous wind farm deployments. Without effective ecological restoration measures, the soil erosion hazards associated with mountainous wind farms are likely to be significant. Therefore, strengthening ecological restoration efforts for wind farms in mountainous regions is imperative.

We recommend establishing an ecologically sustainable development model for mountainous wind farms that integrates the entire process of site selection, construction, monitoring, and restoration, specifically as follows: (1) The construction and operation of mountainous wind farms exacerbate soil erosion primarily through increasing the ecosystem resistance factor *CP*, and land use type significantly influences soil water erosion intensity. Site selection should therefore consider regional land use types, avoiding large-scale forestland clearing for wind power development, and special attention should be given to soil erosion control when constructing wind farms in areas with extensive cropland distribution. (2) Vegetation damage from wind farms is concentrated mainly during the construction phase. During construction, we recommend implementing soil erosion control measures that follow the overarching principle of "zonal management and systematic prevention," which is integrated with regional characteristics, and combining engineering and biological approaches to mitigate erosion. (3) Given the extensive distribution, complex processes, and prolonged duration of soil erosion at mountainous wind farms, we advocate the establishment of a comprehensive monitoring system that integrates multiple levels and technologies. This system should leverage conventional ground-based monitoring to provide high-precision "point" data; employ multi-source remote sensing to obtain long-term, large-scale "area" information; and utilize artificial intelligence techniques to enhance quantitative analysis and predictive capabilities, thereby achieving comprehensive and accurate soil erosion monitoring. (4) Nature-based solutions (NbS) have demonstrated promising potential for reducing soil erosion[10] and can offer a sustainable alternative to traditional erosion control techniques that over-rely on concrete structures and embankments. We recommend adopting NbS as a core philosophy for the ecological restoration of mountainous wind farms. Based on the baseline conditions of the regional environment, site-specific native species screening and vegetation configuration studies should be conducted to improve the self-restoration capacity of the ecosystem, thereby promoting natural succession and positive ecological cycles.

REFERENCES

1. Wang Q., Luo K., Yuan R. et al. (2020). A multiscale numerical framework coupled with control strategies for simulating a wind farm in complex terrain. *Energy* **203**:117913. DOI:10.1016/j.energy.2020.117913
2. Gao X.,Wang T., Li B. et al. (2019). Investigation of wind turbine performance coupling wake and topography effects based on LiDAR measurements and SCADA data. *Appl. Energ.* **255**: 113816. DOI: 10.1016/j.apenergy.2019.113816
3. Ma B., Yang J., Chen X. et al. (2023). Revealing the ecological impact of low-speed mountain wind power on vegetation and soil erosion in South China: A case study of a typical wind farm in Yunnan. *J. Clean. Prod.* **419**:138020. DOI:10.1016/j.jclepro.2023.138020
4. Wu Y., Liao M., Hu M. et al. (2020). A decision framework of low-speed wind farm projects in hilly areas based on DEMATEL-entropy-TODIM method from the sustainability perspective: A case in China. *Energy* **213**:119014. DOI:10.1016/j.energy.2020.119014
5. Zhang C., Li X., Lyu X. et al. (2025). Impact of mountain wind farms on different vegetation types: A case study in Yunnan Province. *Environ. Sustain. Ind.* **28**: 100873 (2025). DOI: 10.1016/j.indic.2025.100873
6. Xia Z., Li Y., Guo S. et al. (2025). Assessment of forest disturbance and soil erosion in wind farm project using satellite observations. *Resour. Conserv. Recy.* **212**:107934. DOI:10.1016/j.resconrec.2024.107934
7. Yan J., Wang S., Feng J. et al. (2025). New 30-m resolution dataset reveals declining soil erosion with regional increases across Chinese mainland (1990–2022). *Remote Sens. Environ.* **323**:114681. DOI:10.1016/j.rse.2025.114681
8. Liu Y., Fu B., Liu Y. et al. (2019). Vulnerability assessment of the global water erosion tendency: Vegetation greening can partly offset increasing rainfall stress. *Land Degrad. Dev.* **30**:1061–1069. DOI:10.1002/ldr.3293
9. Wang H., Zhao W., Li C. et al. (2021). Vegetation greening partly offsets the water erosion risk in China from 1999 to 2018. *Geoderma* **401**:115319. DOI:10.1016/j.geoderma.2021.115319
10. Tarolli P. Liu G., Castelli G. et al. (2026). Nature-based solutions for soil and water conservation in an era of climate extremes: Limitations and future scenarios. *Int. Soil Water Conse.* **14**:100604. DOI:10.1016/j.iswcr.2025.12.004

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AUTHOR CONTRIBUTIONS

X. Lyu was responsible for the conceptualization, study design, and drafting of the initial manuscript. X. Lyu and D. Dang conducted data collection and interpreted the results. X. Lyu, Y. Dong, and H. Ren performed data analysis. X. Lyu and X. Lyu engaged in discussions, and revised the manuscript. All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The 30 m annual soil water erosion dataset for the Chinese mainland from 1990 to 2022 was obtained from the Science Data Bank (https://doi.org/10.57760/sciencedb.12876). We developed a spatiotemporal distribution dataset of onshore and offshore wind turbines across China by integrating OpenStreetMap data and Sentinel satellite imagery. The dataset encompasses the spatial locations of more than 150,000 wind turbines as of 2023, with construction year information available for turbines installed after 2014. The validation results indicate a spatial accuracy of 90% and a temporal accuracy of 88%, confirming its adequacy for research applications. This dataset has already supported the publication of multiple peer-reviewed studies.