

1 Supplementary Information for

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3 Regional priorities in implementing forestation and wind energy as climate solutions in facing their trade-offs

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21 **Supplementary Information includes:**

22 Supplementary Methods,

23 Supplementary Figures 1–30,

24 Supplementary Tables 1–9.

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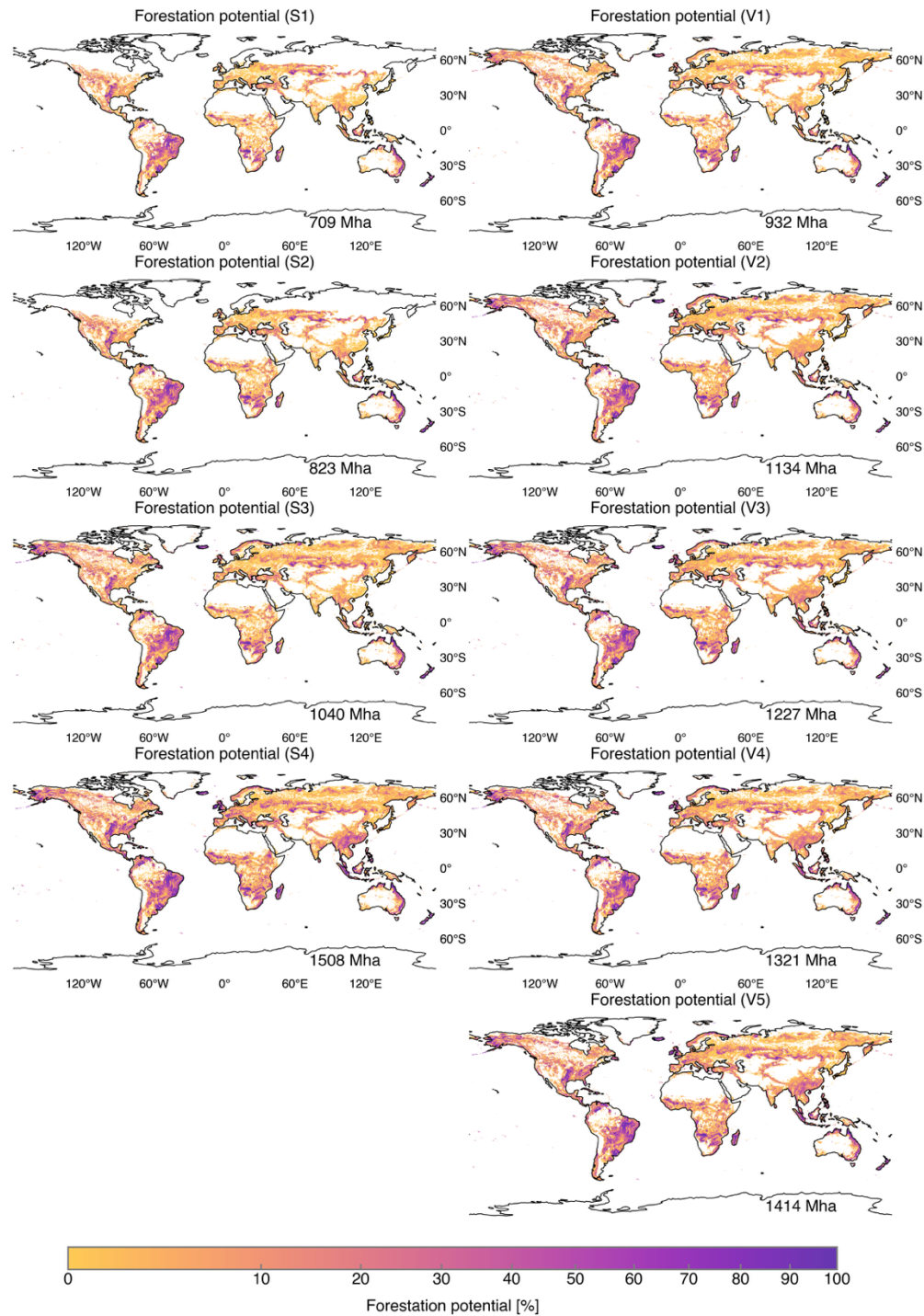
Supplementary Methods

Comparison of CO₂ sequestered by forestation versus the reduction in avoided CO₂ emission caused by forestation-induced wind energy generation reduction

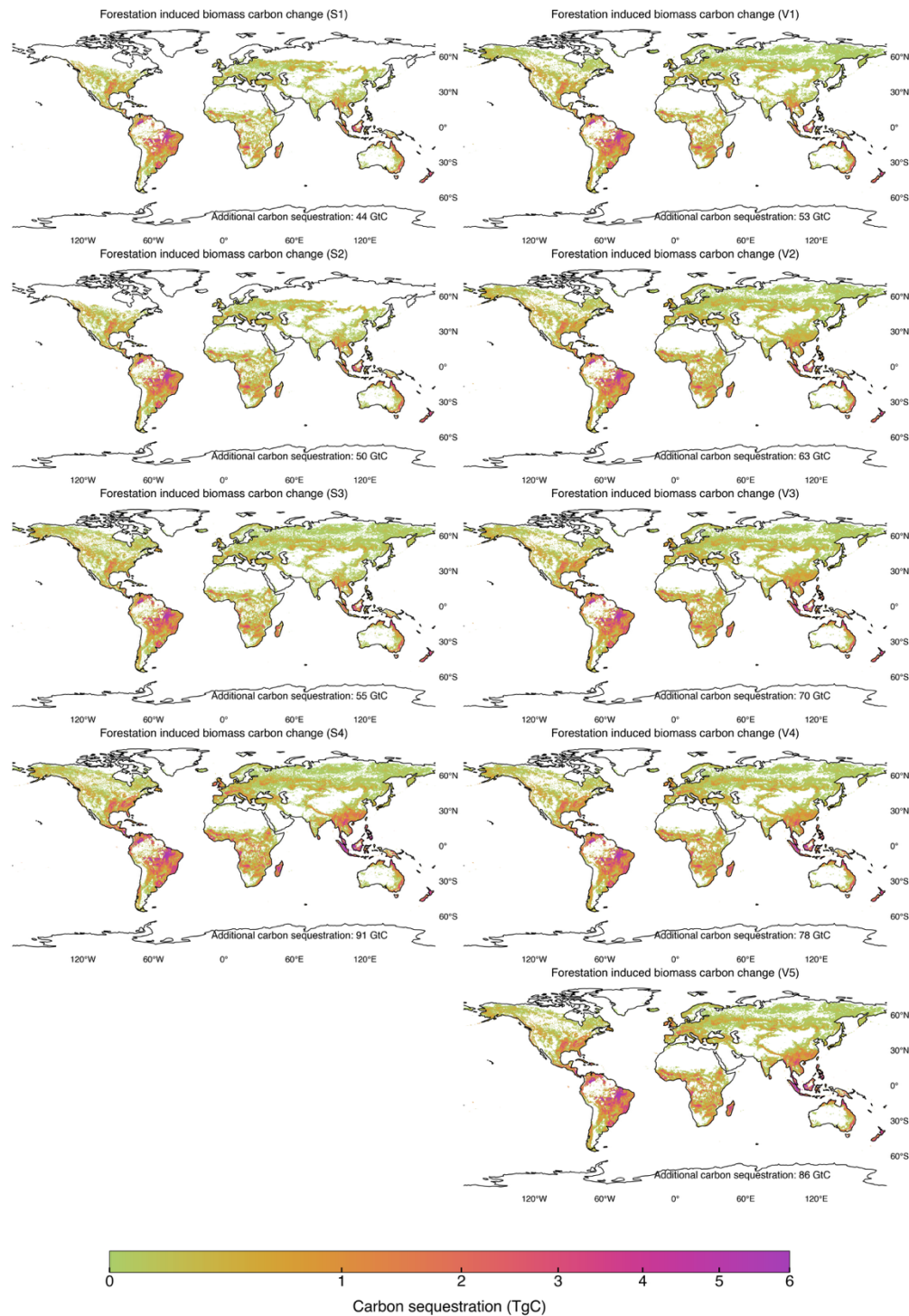
Carbon emission avoidance from wind energy refers to the CO₂ emissions avoided by assuming that the same amount of electricity was generated by fossil fuel rather than by wind^{1,2}. For its calculation, we assumed that wind-generated electricity displaces a fossil-fuel-based electricity-generation source with an average emission intensity of 600 g CO₂-equivalent per kWh, according to the estimations by Pryor et al. (2020)¹ and the Global Wind Energy Outlook report³. Subsequently, the carbon emission avoidance from wind energy can be calculated by multiplying the annual electricity generated by wind energy installation (wind turbine installation capacity (i.e., the total rated power of all wind turbines) × CF × 8760 hours), the avoided CO₂ emission factor (600 gCO₂/kWh), and the typical operational life cycle of a wind turbine^{1,4}. To evaluate the potential gain in carbon removal by forestation versus the loss in avoided carbon emissions due to wind energy potential loss, their comparison should be based on a common, meaningful time frame. The typical operational lifetime of a wind turbine is 30 years, whereas the time required for newly established forests to reach maturity can take several decades to even a century. Given that we are aiming for a rough comparison, we assume on average, the newly established forests can reach their mature carbon stocks in about 60 years globally, corresponding to two life cycles of global wind turbines.

Considering that forestation is to occur in the future, which is accompanied by inevitable expansion of global wind installation, we made the comparisons described above not only for the current global wind installation capacity, but also for several future scenarios of wind energy expansion (See Supplementary Table 4). For this purpose, we established four wind turbine installation capacity scenarios reflecting current and progressively ambitious policy pathways: a baseline scenario corresponding to the current wind turbine installation capacity, under which wind energy generation contributes approximately 6.2% of global electricity generation⁵; a moderate expansion scenario with twice the current turbine installation capacity, a scenario achieving the COP28 renewable energy tripling target⁶ and a high-ambition scenario consistent with the International Energy Agency (IEA) Net Zero 2050 roadmap, representing an elevenfold increase over current capacity, under which wind energy generation will contribute approximately 30.0% of global electricity generation⁷.

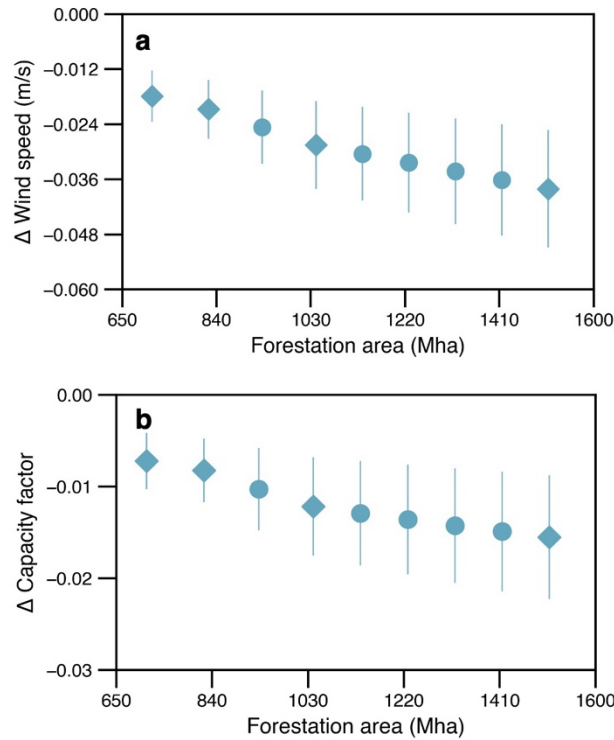
Several uncertainties, however, exist for the comparisons made above. First, a single and constant factor of avoided CO₂ emissions per kWh of wind-generated electricity was used, which can not account for technology development or changes in the regional distribution of wind installation capacity in the future. Second, we assumed that it takes on average 60 years for the newly established forests to reach mature, which has great uncertainty. Hence, the results in Supplementary Table 4 should be considered highly preliminary and interpreted with caution.



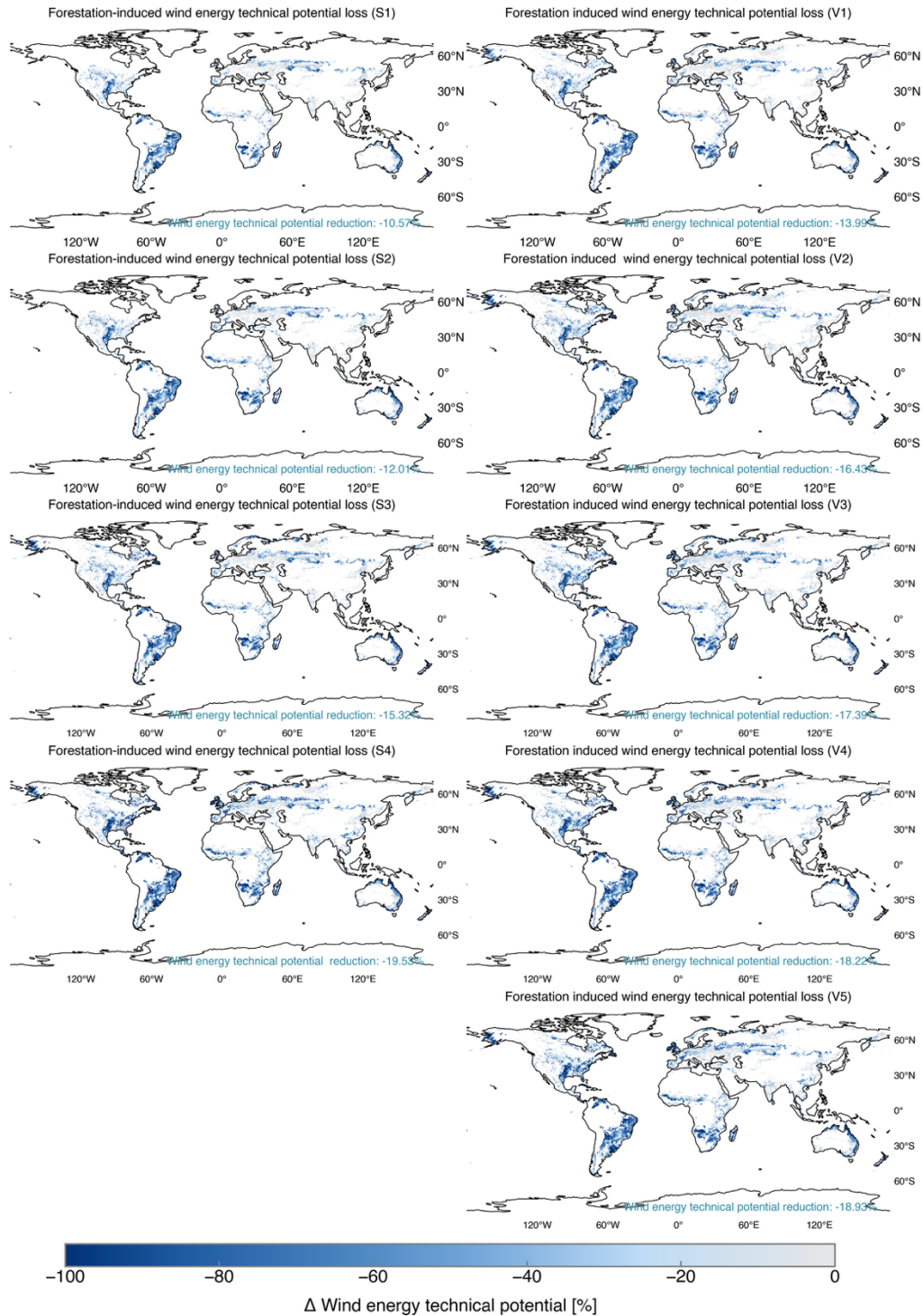
Supplementary Figure 1 Global forestation potential distribution under different scenarios. Forestation scenarios are subject to constraints regarding the source land cover type, with various considerations of food security, net biophysical warming, and biodiversity conservation. Four different forestation scenarios were designed, ranging from potential forestation with the maximum constraint (the S1 scenario, corresponding to the smallest forestation area) to that with the minimum constraint (the S4 scenario, corresponding to the largest forestation area). To better visualize the relationship between forestation-induced wind-energy change and carbon sequestration potential, five additional auxiliary forestation scenarios (V1 to V5) were interpolated using S2 and S3, and S3 and S4, respectively. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



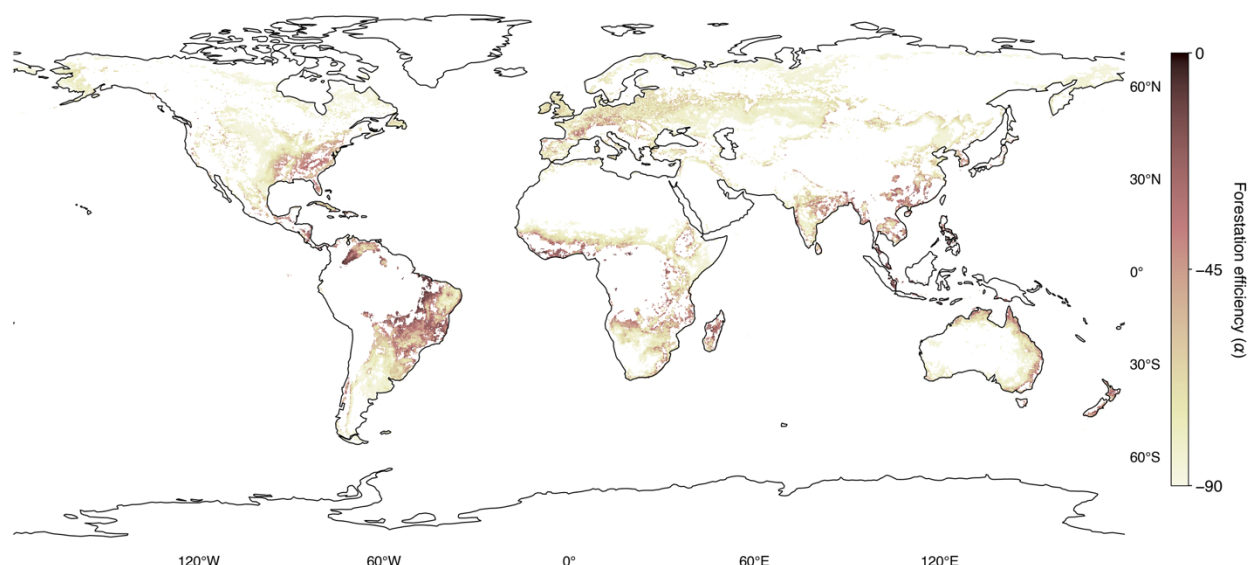
Supplementary Figure 2 Spatial distribution of forestation-induced biomass carbon sequestration capacity under different scenarios. Biomass carbon sequestration capacity following forestation was estimated by multiplying equilibrium biomass carbon density and the forestation area under the different forestation scenarios. The equilibrium biomass carbon density for different grid cells was obtained using global potential living tree biomass under the natural potential. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



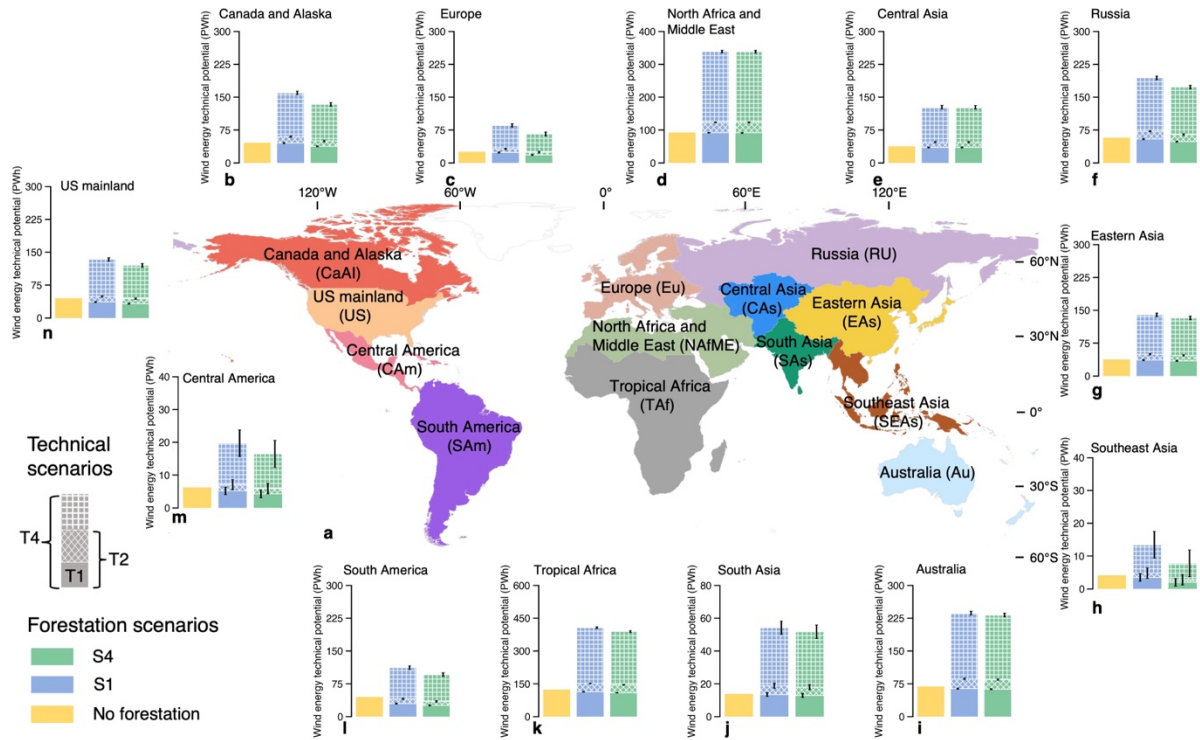
Supplementary Figure 3 Changes in global mean annual surface wind speed (10 m height) (a) and wind-energy capacity factor (b) following different forestation scenarios. The wind-energy capacity factor was calculated under the assumption that each pixel contains a wind turbine with current technological features (T1 scenario). The diamonds represent the four different forestation scenarios of S1–S4; the circles represent additional forestation scenarios derived by interpolating S2 and S3, and S3 and S4. The vertical lines in (a) and (b) represent the standard deviations derived using the eight individual ESMs in LUMIP (n=8). The center of the error bars (a, b) indicates the multimodel mean value.



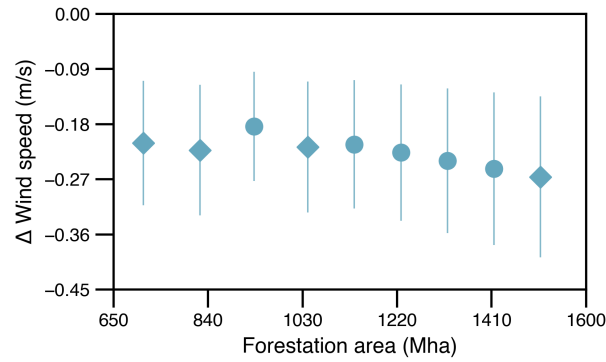
Supplementary Figure 4 Reduction in wind-energy technical potential under different forestation scenarios (S1 to S4). The wind-energy technical potential reduction was calculated by employing current wind turbine technical feature (T1 scenario), using the present-day monthly wind speed and the modified monthly wind speed following forestation. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



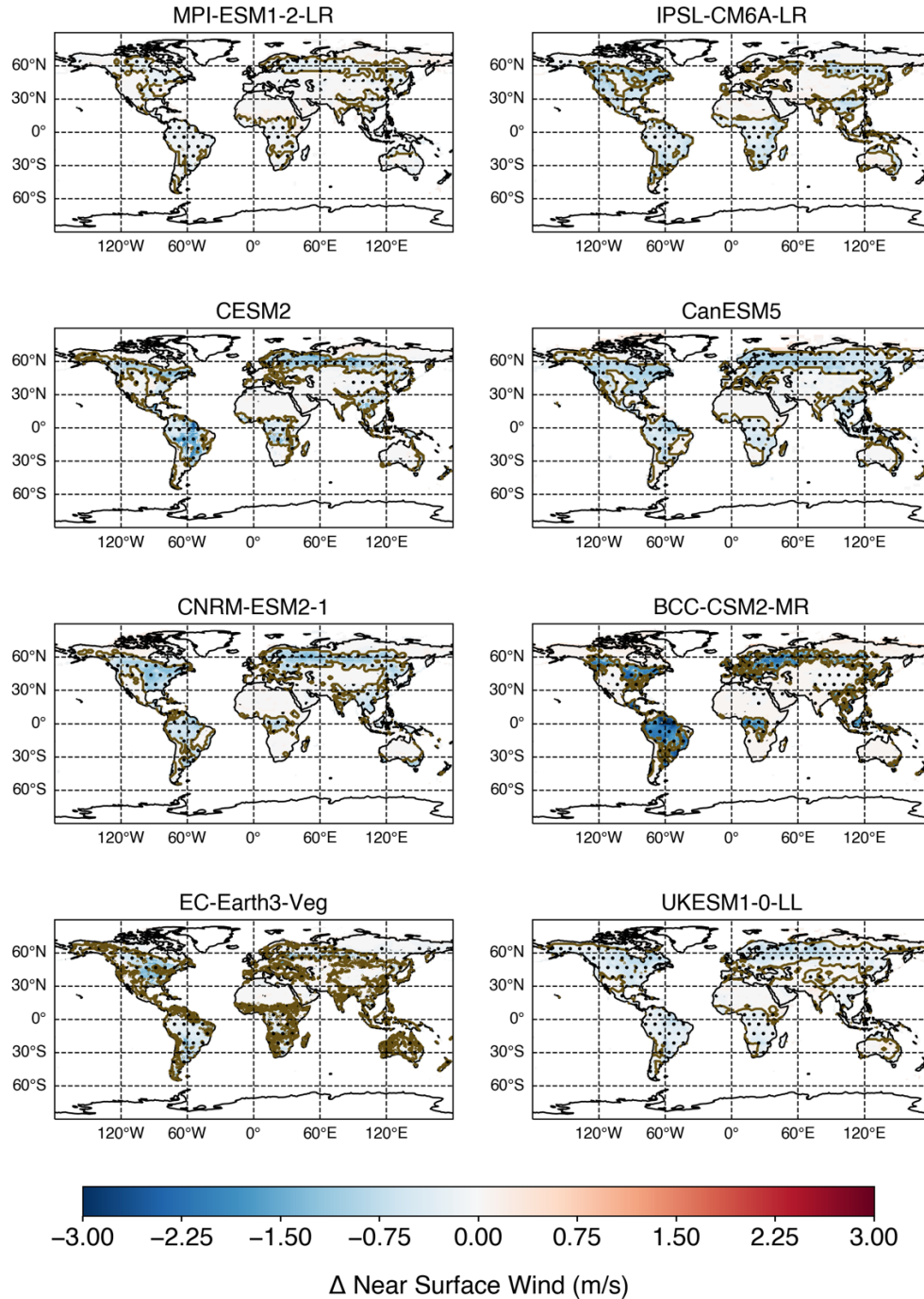
Supplementary Figure 5 The spatial pattern of forestation efficiency in terms of the arctangent of the ratio between wind-energy technical potential loss (in the unit of TWh) and biomass carbon sequestration potential (in the unit of TgC) (refer to Equation 7 and Figure 2e in the main text). The map has a spatial resolution of 0.25°. Forestation efficiency represents the the loss of wind energy technical potential per unit gain in carbon sequestration potential following the forestation scenario S4 (a negative number). A less negative number (darker color) indicates greater carbon sequestration with a corresponding less reduction in wind energy following forestation and hence greater forestation efficiency. This figure was produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



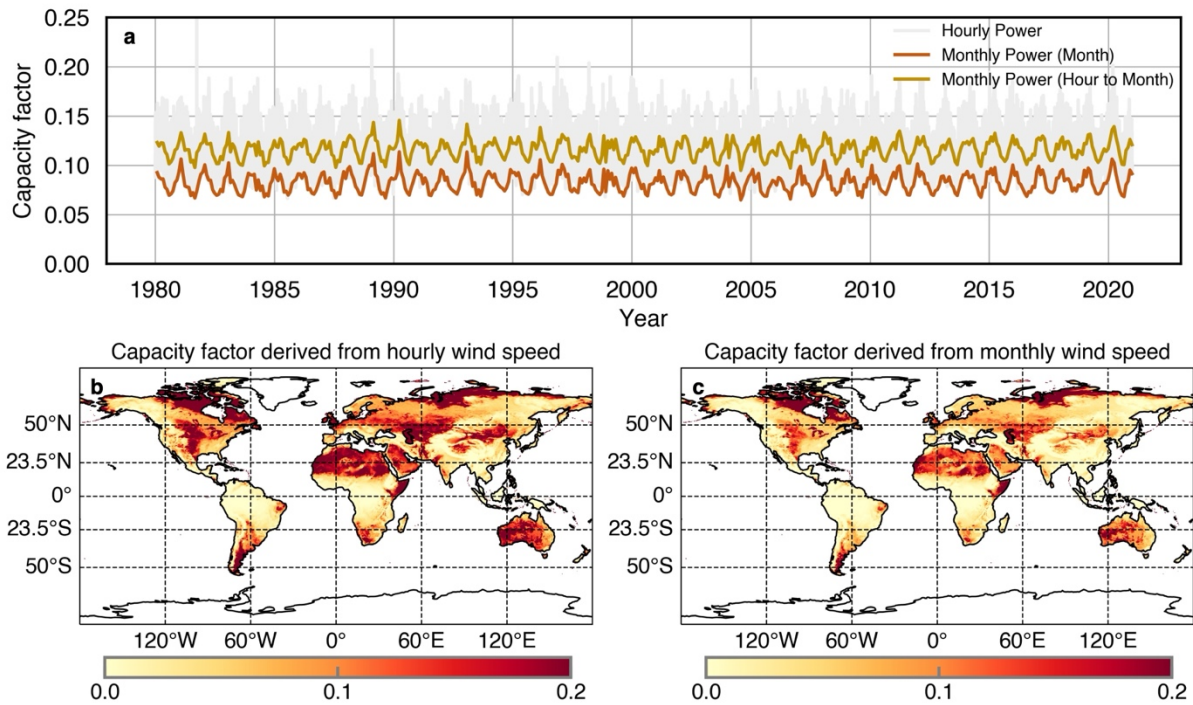
Supplementary Figure 6 Forestation-induced changes in the total wind-energy technical potential across different regions. (a) The division of the globe into thirteen regions. Panels (b) to (n) show the total wind energy technical potential for different regions, for the case of no forestation (i.e., present day using the climate of 2000–2020) (yellow) and under the minimum (S1) (blue) and maximum (S4) (green) forestation scenarios. In addition, Panels (b) to (n) show total wind energy technical potential in different regions, for the case of T1 technical scenario (i.e., current technical scenario) (no texture), and under the T2 technical scenario (cross-hatched pattern) and T3 technical scenario (plus-hatched pattern). For the no-forestation scenario, the bar plots are calculated using the ERA5 dataset, and consequently, each bar corresponds to a single value. The results in S1 and S4 forestation scenarios, based on the multi-model mean output, are shown as bar plots. The uncertainties (error bars) of each bar plots in S1 and S4 forestation scenarios were derived by using the standard deviation of eight individual model outputs ($n=8$). The world map used in (a) was obtained from the World Bank (<https://datacatalog.worldbank.org/search/dataset/0038272/world-bank-official-boundaries>), which is publicly available under the Creative Commons Attribution 4.0 International License (CC BY 4.0, <https://creativecommons.org/licenses/by/4.0/>). Maps have been modified.



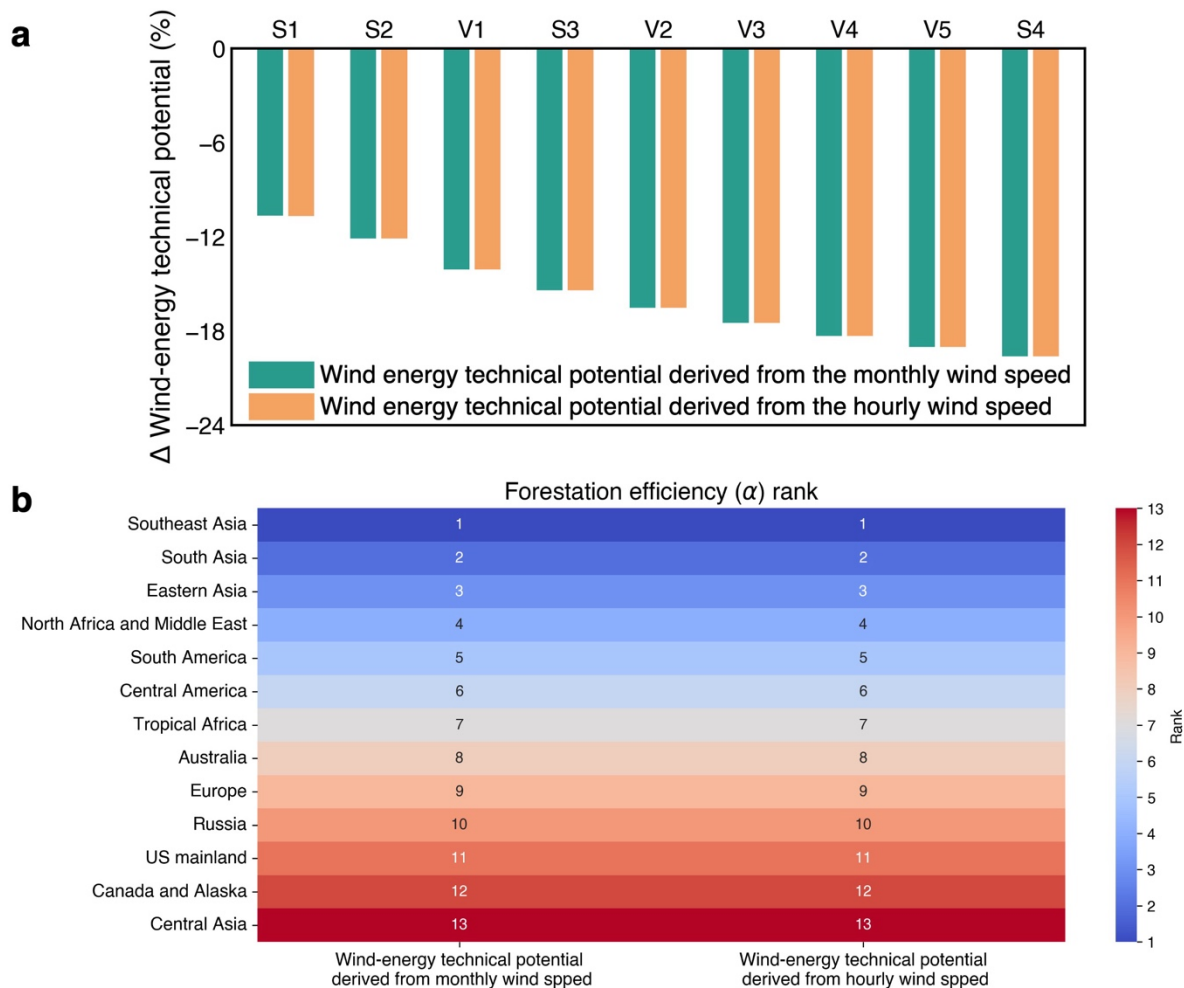
Supplementary Figure 7 Changes in annual mean surface wind speed (10 m height) in forestation areas. The diamonds represent the four different forestation scenarios S1–S4; the circles represent additional forestation scenarios derived by interpolating S2 and S3, and S3 and S4. The vertical lines in this figure represent the standard deviations calculated from the eight individual ESMs in LUMIP ($n = 8$), while the center of the error bars indicates the multimodel mean value.



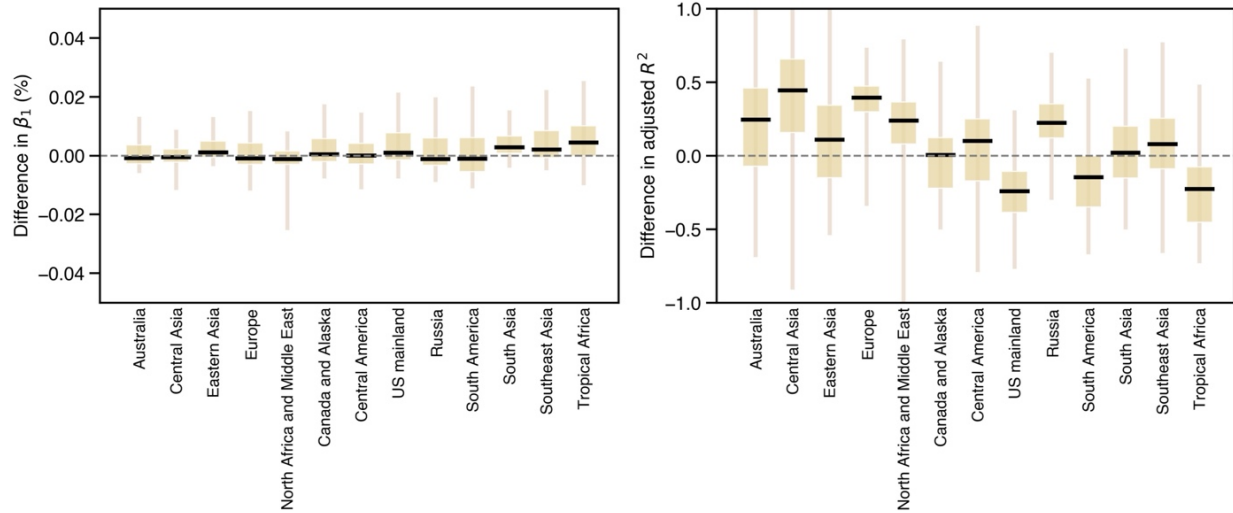
Supplementary Figure 8 Forestation induced wind speed change between piControl and deforest-glob experiments (piControl minus deforest-glob). The piControl simulation of CMIP6 was used as a forestation scenario and the idealized global deforestation simulation ('deforest-glob') of the LUMIP was used as a reference scenario to diagnose the sensitivity of surface wind speed to forest coverage change. Stippling in panels indicates statistically significant changes in the wind speed at the 5% significance level ($p < 0.05$), based on a two-sided paired t-test. Contours depict the areas of forestation. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



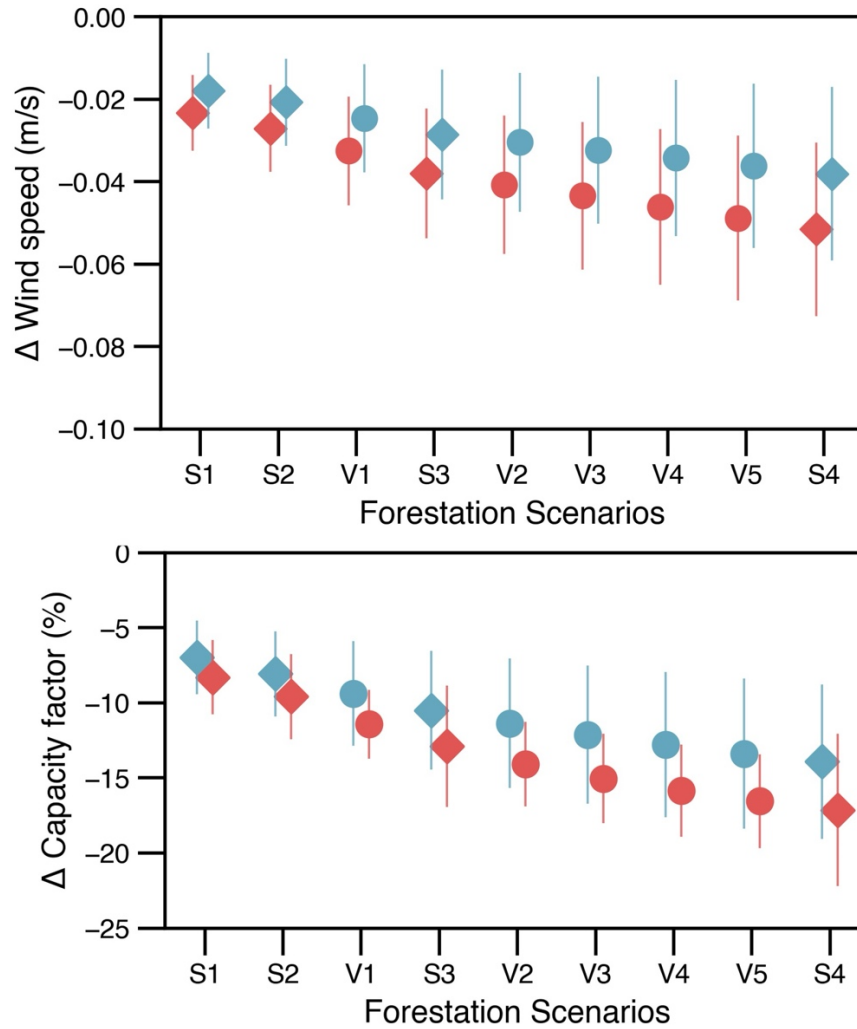
Supplementary Figure 9 Time series and spatial patterns of global wind energy capacity factor driven using hourly and monthly-aggregated wind speeds. (a) Time series of global monthly mean capacity factor based on hourly wind speed and on the same hourly wind speed but aggregated to monthly scale before the computation of capacity factor, using ERA reanalysis climate data for 1980–2020. Following several previous studies which calculated wind-energy potential using surface wind speed^{10–13}, we used the power curve of a typical 1 MW wind turbine. This procedure minimizes the need for turbine-specific information while also ensuring consistency with previous studies. Wind energy capacity factor computed from hourly winds is shown in gray (hourly power) and brown (monthly average of hourly power); wind energy capacity factor computed directly from monthly winds is shown in red. (b) The spatial pattern of monthly mean wind energy capacity factor based on hourly wind speed during 1980–2020. (c) The spatial pattern of monthly mean wind energy capacity factor based on the same hourly wind speed but aggregated to the monthly scale before the computation of wind energy capacity factor. Panels b and c were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



Supplementary Figure 10 Comparison of wind-energy reductions and carbon-energy trade-offs derived using monthly versus hourly wind speeds for different forestation scenarios. (a) Comparison of wind-energy reductions following different forestation scenarios between those derived from monthly wind speed (dark brown) and hourly wind speed (light brown) but applying the monthly-scale wind-speed model (M2). The bar plots in panel (a) are based on the multi-model mean outputs, and consequently, each bar corresponds to a single value. (b) Comparing the strengths of the carbon-energy trade-off for 13 regions following the forestation scenario S4 between that derived from monthly wind speed and hourly wind speed but applying the monthly-scale wind-speed model (M2).

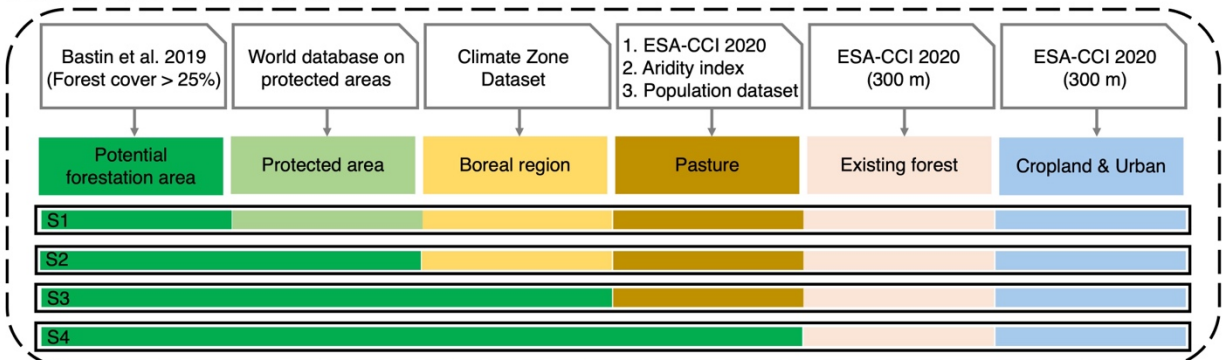


Supplementary Figure 11 The differences in the sensitivity of wind speed to forest cover (β_1) and evaluation performance (adjusted R^2) in two M2 models. One M2 model (idealized deforestation experiment) was constructed using data from the pi-control experiment and the idealized deforestation experiment, while the other M2 model (realistic future climate scenarios) was constructed using data from the ScenarioMIP ssp126 experiment and the LUMIP ssp126-ssp370Lu experiment. Five ESMs carried out all idealized deforestation experiment, ScenarioMIP ssp126 experiment and the LUMIP ssp126-ssp370Lu experiment: MPI-ESM1-2-LR, IPSL-CM6A-LR, CESM2, CNRM-ESM2-1, UKESM1-0-LL. Hence these five ESMs were used to quantify the sensitivity of local surface wind speed to forest coverage under different climate scenarios ($n=5$). The center lines in the boxplots represent the mean value. The lower whisker in the boxplots is at the lowest datum above $Q1 - 1.5 \cdot (Q3 - Q1)$, while the upper whisker is at the highest datum below $Q3 + 1.5 \cdot (Q3 - Q1)$, where $Q1$ and $Q3$ are the first and third quartiles.

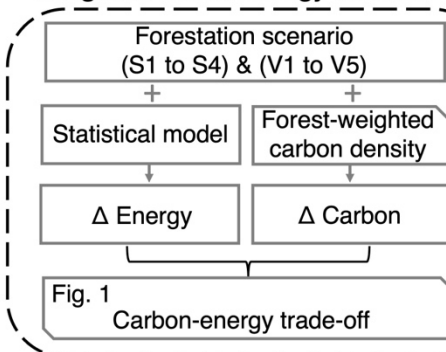


Supplementary Figure 12 Changes in global surface wind speed (10m height) and wind-energy capacity factor following different forestation scenarios derived from M2 models constructed from two M2 models (idealized deforestation experiment and realistic future climate scenarios). The red represents forestation-induced wind speed and capacity factor changes derived from the sensitivity of wind speed to forest cover under realistic future climate scenarios by using the ScenarioMIP ssp126 experiment and the LUMIP ssp126-ssp370Lu experiment. The blue represents forestation-induced wind speed and capacity factor changes under different forestation scenarios derived from the sensitivity of wind speed to forest cover in this study by using idealized deforestation experiment. Five ESMs carried out all idealized deforestation experiment, ScenarioMIP ssp126 experiment and the LUMIP ssp126-ssp370Lu experiment: MPI-ESM1-2-LR, IPSL-CM6A-LR, CESM2, CNRM-ESM2-1, UKESM1-0-LL. Hence, these five ESMs were used to quantify the changes in global surface wind speed (10m height) and wind-energy capacity factor. The vertical lines indicate the standard deviation of changes in wind speed and capacity factor, derived from the five ESMs in LUMIP (n=5). The center of the error bars indicates the multimodel mean value.

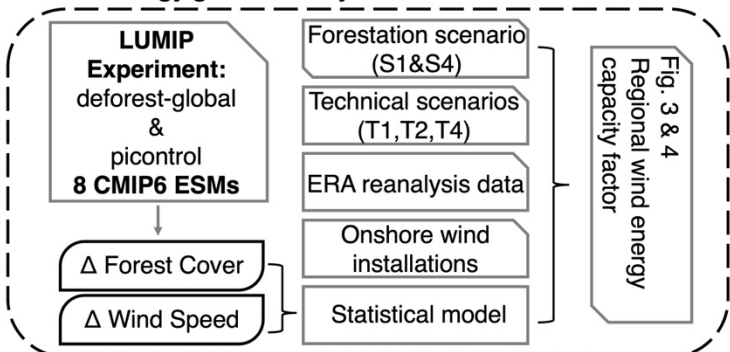
Potential forestation scenarios



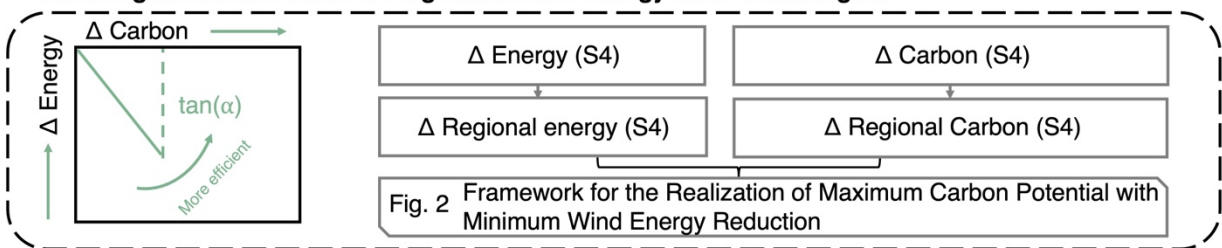
The global carbon-energy trade-off



Loss in energy generation by future forestation

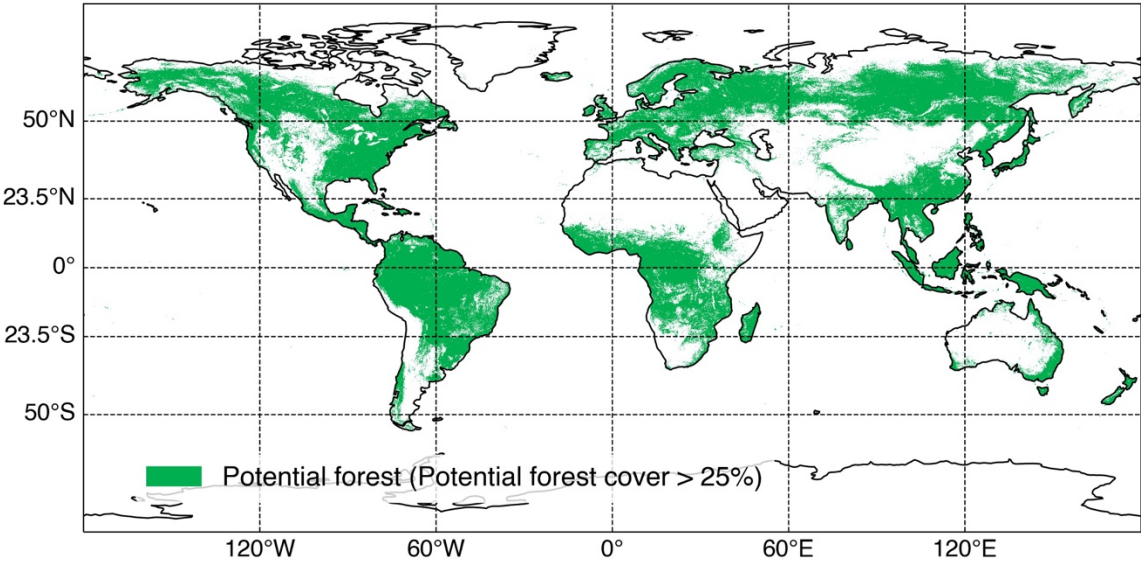


Prioritizing forestation based on regional carbon-energy trade-off strengths

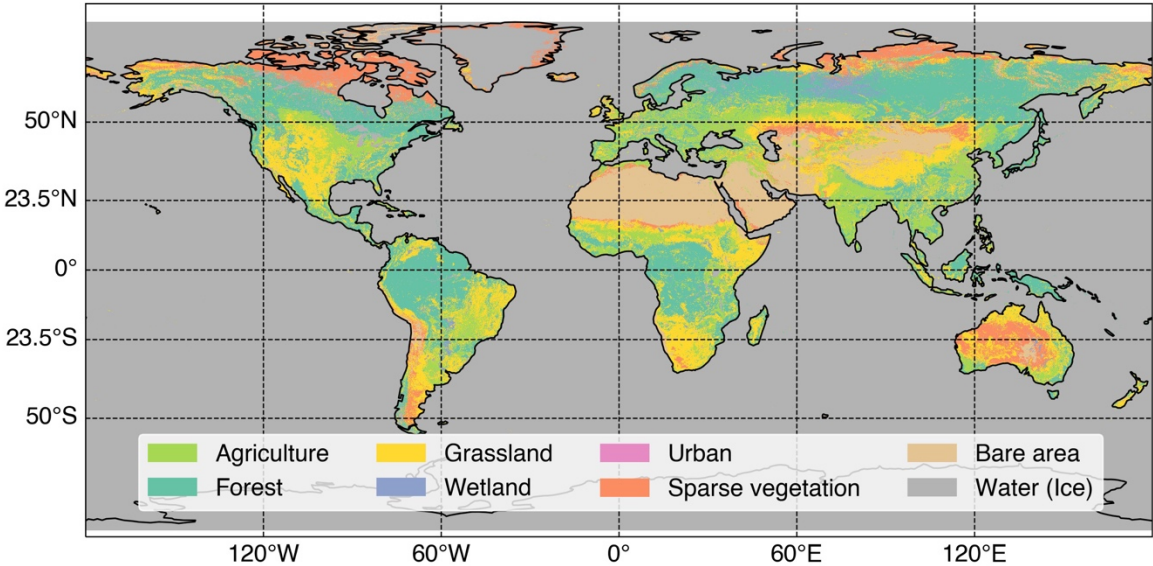


Legend: Input Intermediate variable Predictor/selection var. Output

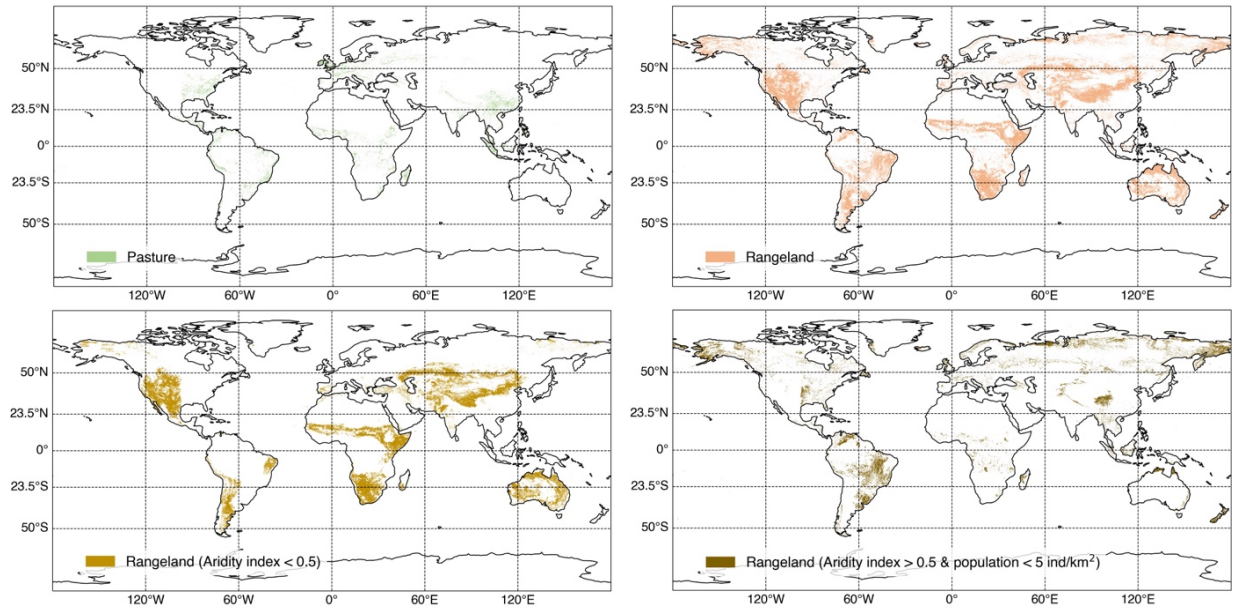
Supplementary Figure 13 The methodological work flow of this study. This figure illustrates the complete workflow used in this study, showing how different datasets—including potential forestation areas, protected areas, land cover types, climate zones, and population data—were integrated to assess forestation-induced carbon sequestration and associated energy trade-offs.



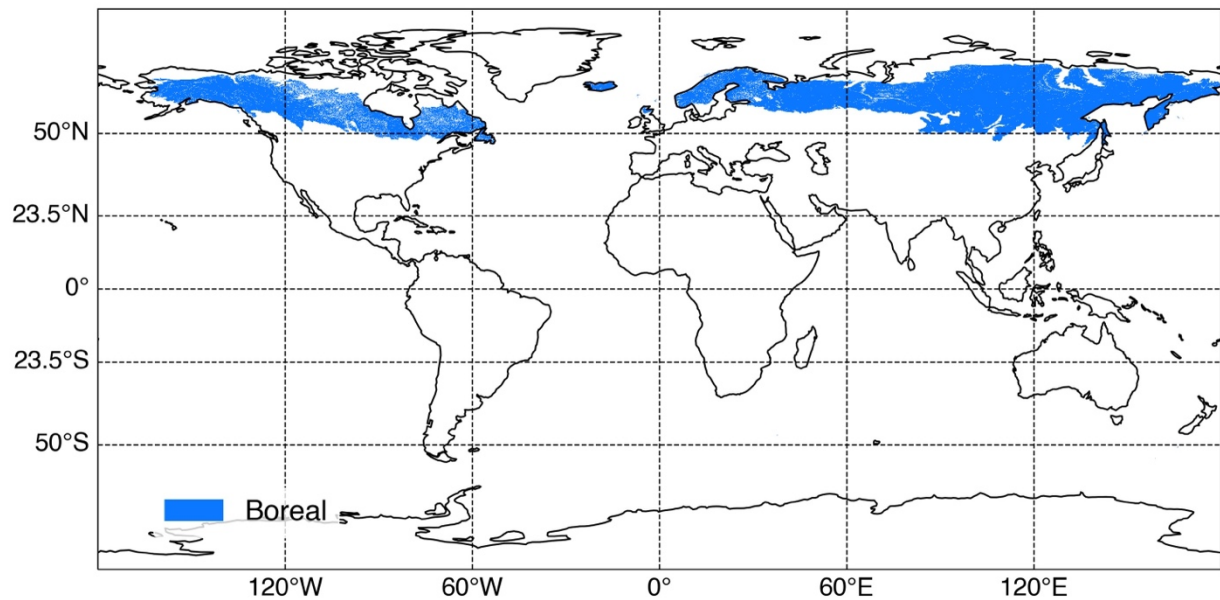
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195 Supplementary Figure 14 Global spatial distribution of potential forest under current climate and environmental
196 conditions¹⁴. Forests are defined as pixels with a forest cover of $\geq 25\%$. This figure was produced using Cartopy⁸, a
197 Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset;
198 <https://www.naturalearthdata.com/>)⁹.
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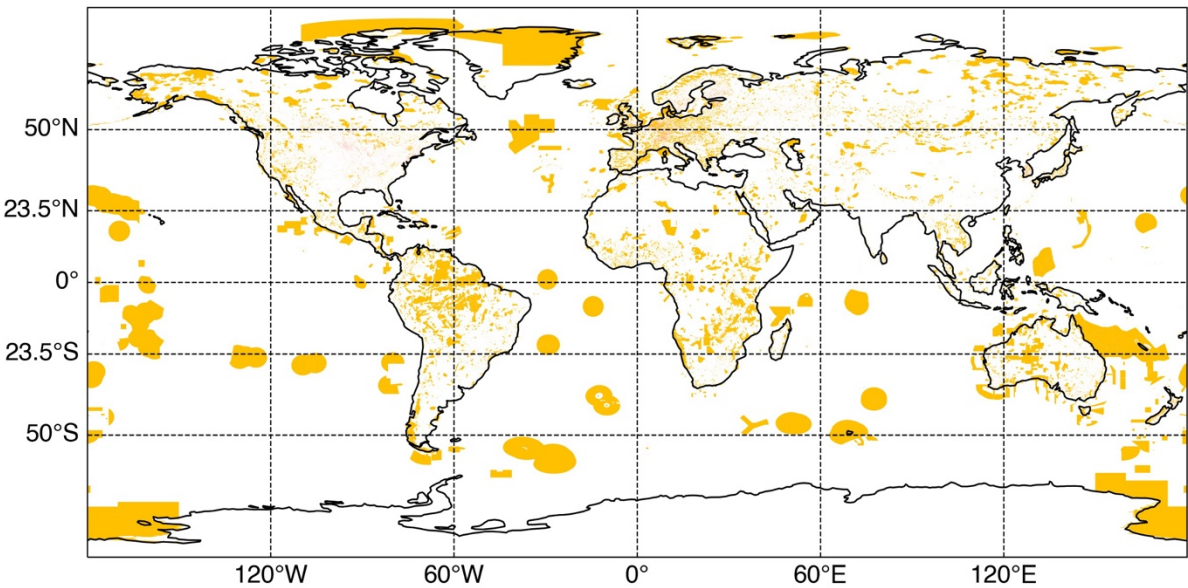
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201 Supplementary Figure 15 Spatial distribution of forest, agricultural, grassland, and urban land according to the
202 ESACCI dataset. The ESA CCI product was re-gridded from 300-m resolution to 1-km according to the dominant land
203 cover type (i.e., the most frequent land cover type) of all 300-m pixels within the 1-km grid cell. Refer to
204 Supplementary Table 5 for the corresponding relationship between the land cover type shown here and original ESA
205 CCI land cover types. This figure was produced using Cartopy⁸, a Python library for geospatial data visualization,
206 with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.
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Supplementary Figure 16 Spatial distributions of pasture and rangeland derived from grassland distribution according to the ESA-CCI dataset. Grassland is defined as rangeland if one of two criteria are met: 1) the aridity index (calculated as annual precipitation divided by annual potential evapotranspiration) is below 0.5; 2) the aridity index exceeds 0.5 but the population density is less than 5 inhabitants per km². Otherwise, grassland is defined as pasture. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.

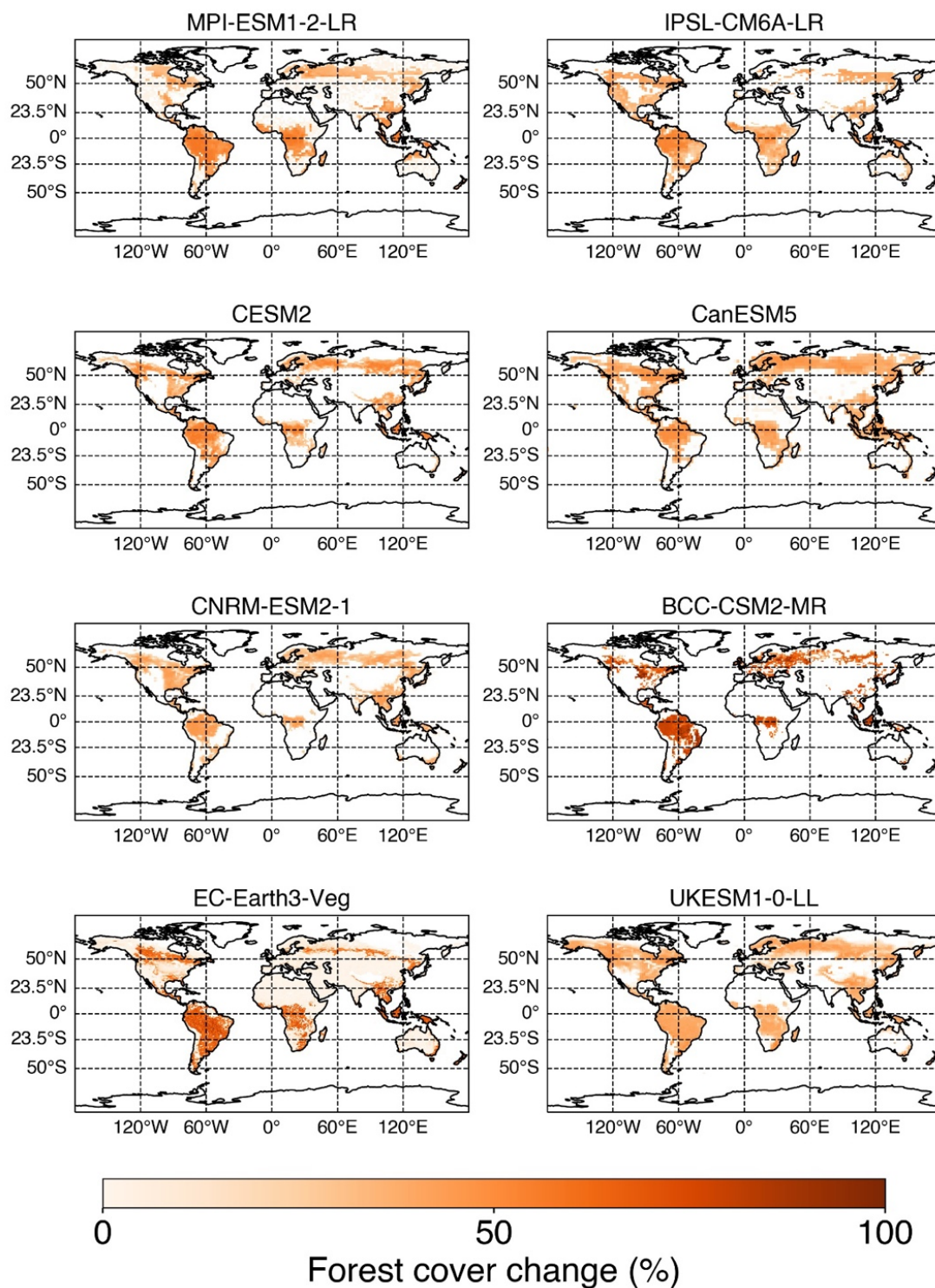


Supplementary Figure 17 The geographical scope of the Boreal regions used in this study. The Spatial distribution of boreal regions is derived from the bioclimate zone map used by Walker et al.¹⁵. the bioclimate zone map was obtained from the the Harvard Dataverse (<https://doi.org/10.7910/DVN/DSDDQK>)¹⁶, which is publicly available under the Creative Commons Attribution 4.0 International License (CC BY 4.0, <https://creativecommons.org/licenses/by/4.0/>). No modifications were made to the original data. This figure was produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.

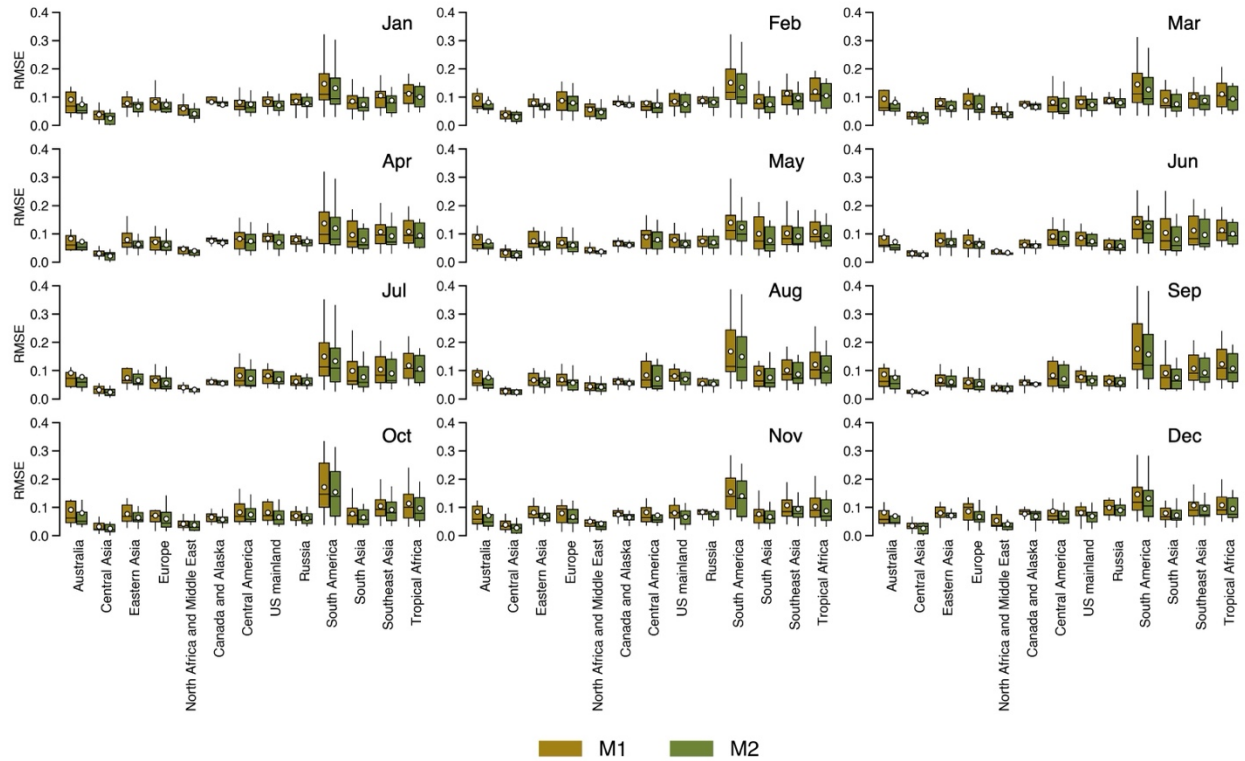


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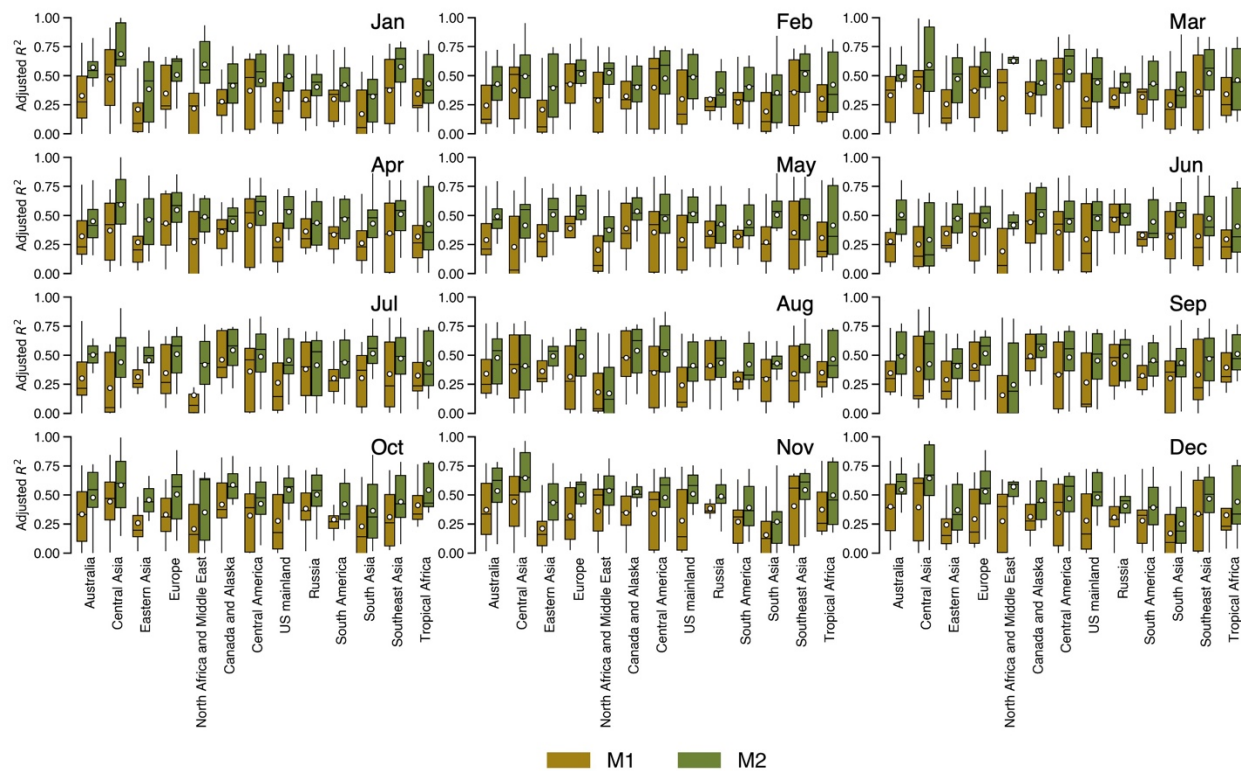
Supplementary Figure 18 The geographical distribution of the Protected areas used in this study. Spatial distribution of protected areas is derived from the World Database on Protected Areas (WDPA), the most comprehensive global database of marine and terrestrial protected areas. This figure was produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



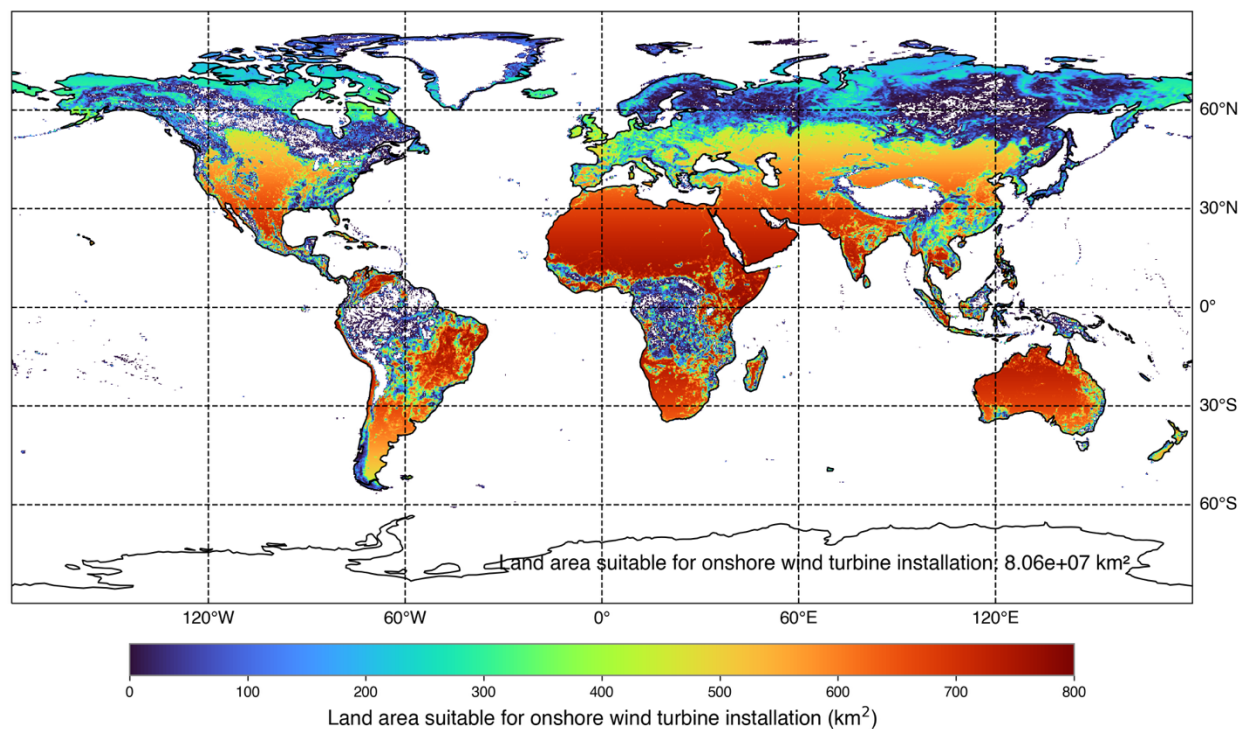
Supplementary Figure 19 Forest cover change between piControl and deforest-glob experiments (piControl minus deforest-glob). The piControl simulation of CMIP6 was used as a forestation scenario¹⁷ and the idealized global deforestation simulation ('deforest-glob') of the LUMIP was used as a reference scenario to diagnose the sensitivity of surface wind speed to forest coverage change. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



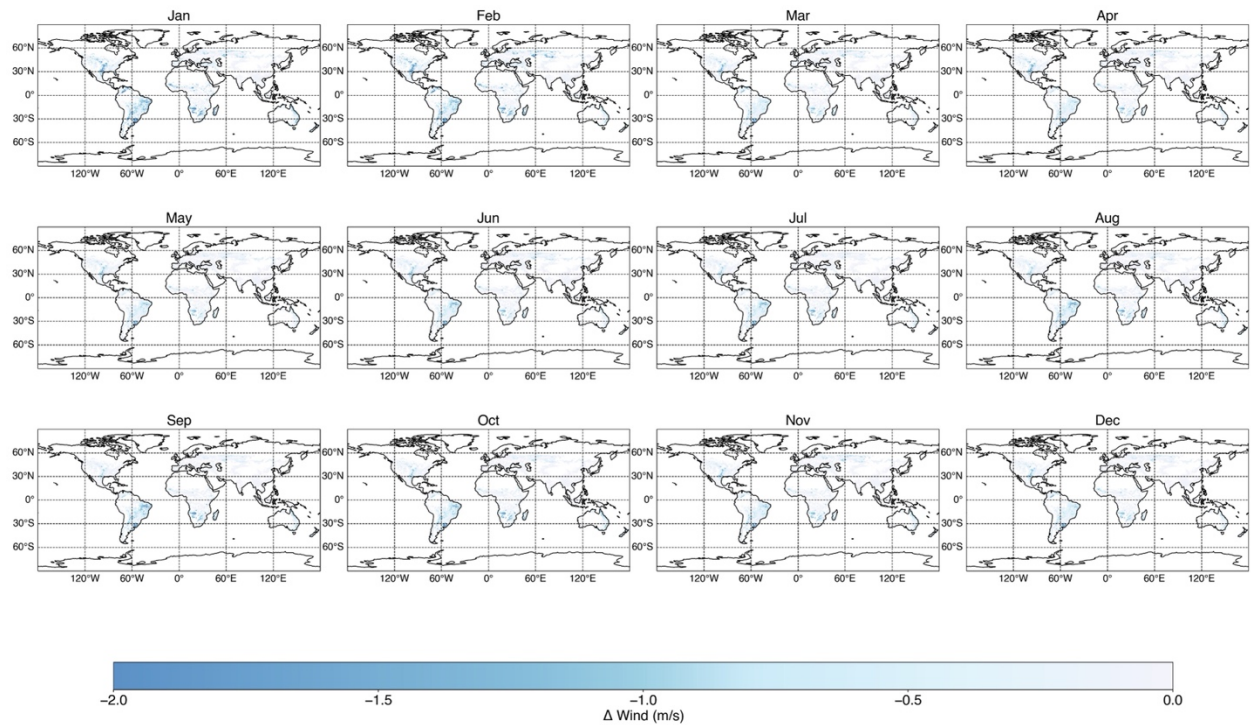
Supplementary Figure 20 Comparing root mean square error (RMSE) between M1 and M2 models across all months. The RMSE of models M1 and M2 was calculated for all 12 months in all 13 regions of the globe. The center lines in the boxplots represent the median value, while the white circles represent the mean (n=8). The lower whisker in the boxplots is at the lowest datum above $Q1 - 1.5 \cdot (Q3 - Q1)$, while the upper whisker is at the highest datum below $Q3 + 1.5 \cdot (Q3 - Q1)$, where Q1 and Q3 are the first and third quartiles.



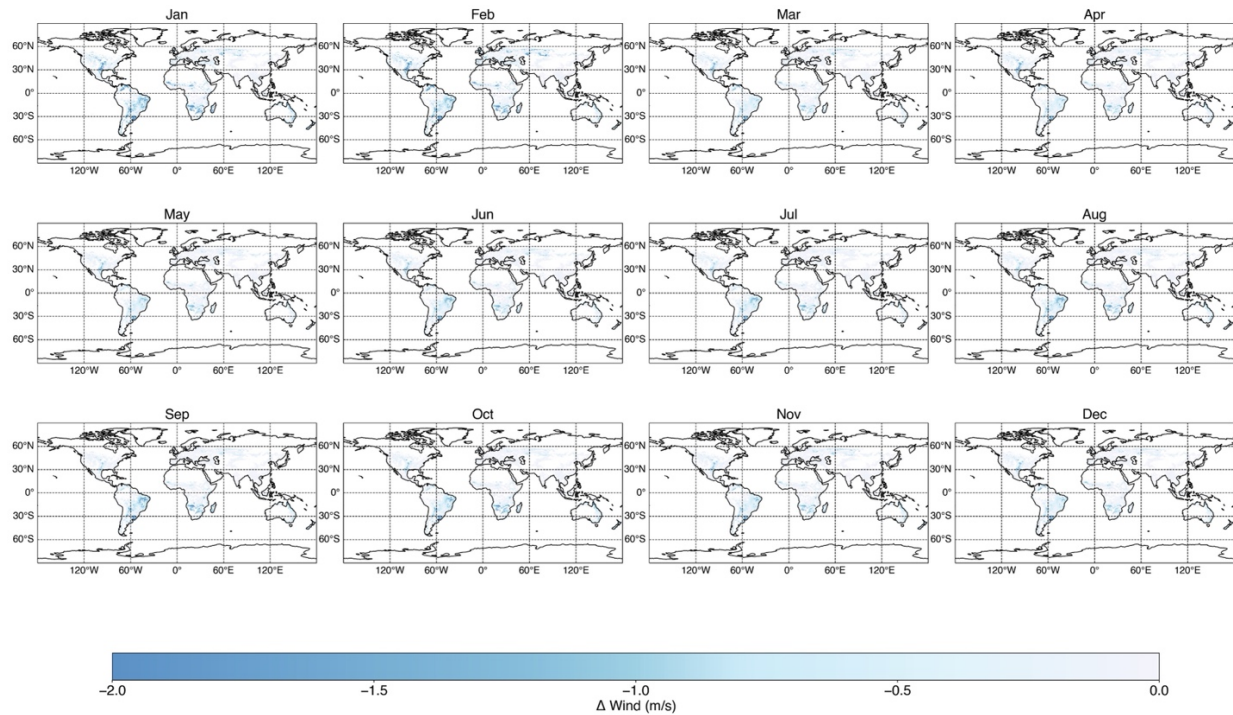
Supplementary Figure 21 Comparing adjusted coefficient of determination (R^2) between M1 and M2 models across all months. The adjusted R^2 values of models M1 and M2 were calculated for all 12 months and all 13 regions of the globe. The center lines in the boxplots represent the median values, while the white circles represent the mean ($n=8$). The lower whisker in the boxplots is at the lowest datum above $Q1 - 1.5 \cdot (Q3 - Q1)$, while the upper whisker is at the highest datum below $Q3 + 1.5 \cdot (Q3 - Q1)$, where $Q1$ and $Q3$ are the first and third quartiles.



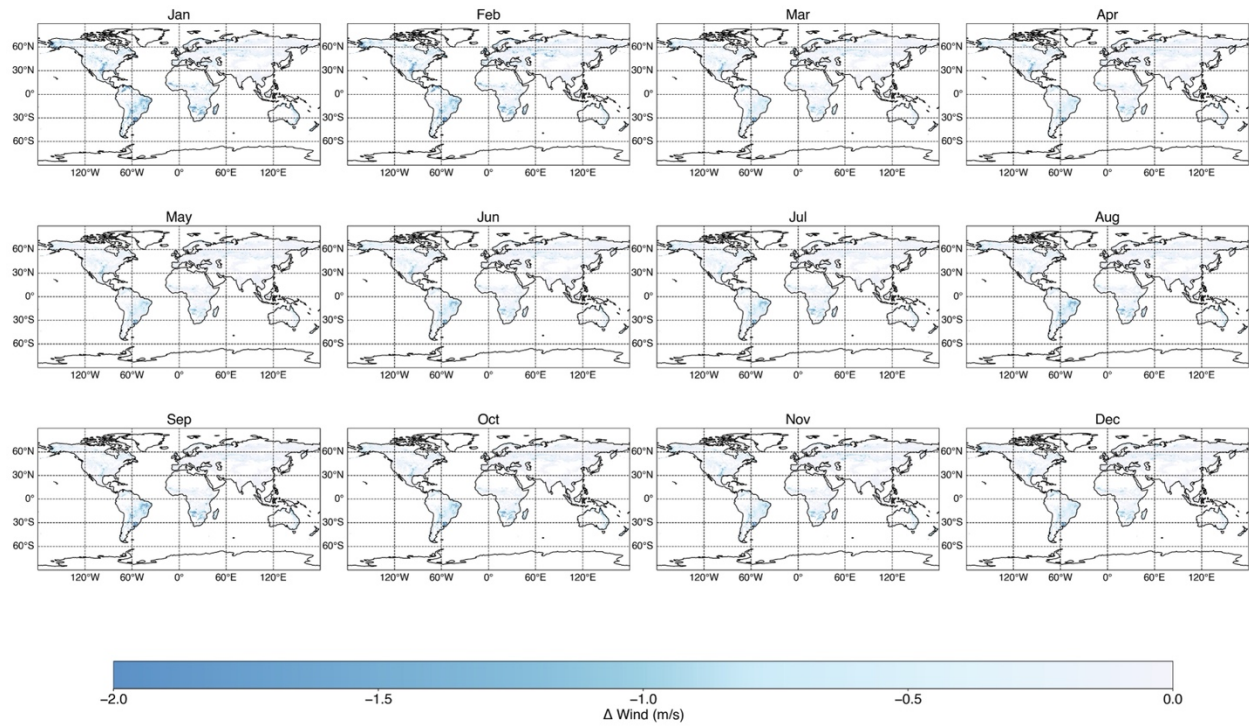
Supplementary Figure 22 The Land area suitable for onshore wind turbine installation without accounting for forestation scenarios examined in this study. For each forestation scenario, the corresponding potential forestation areas were further excluded from the land area suitable for onshore wind turbine installation. This figure was produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



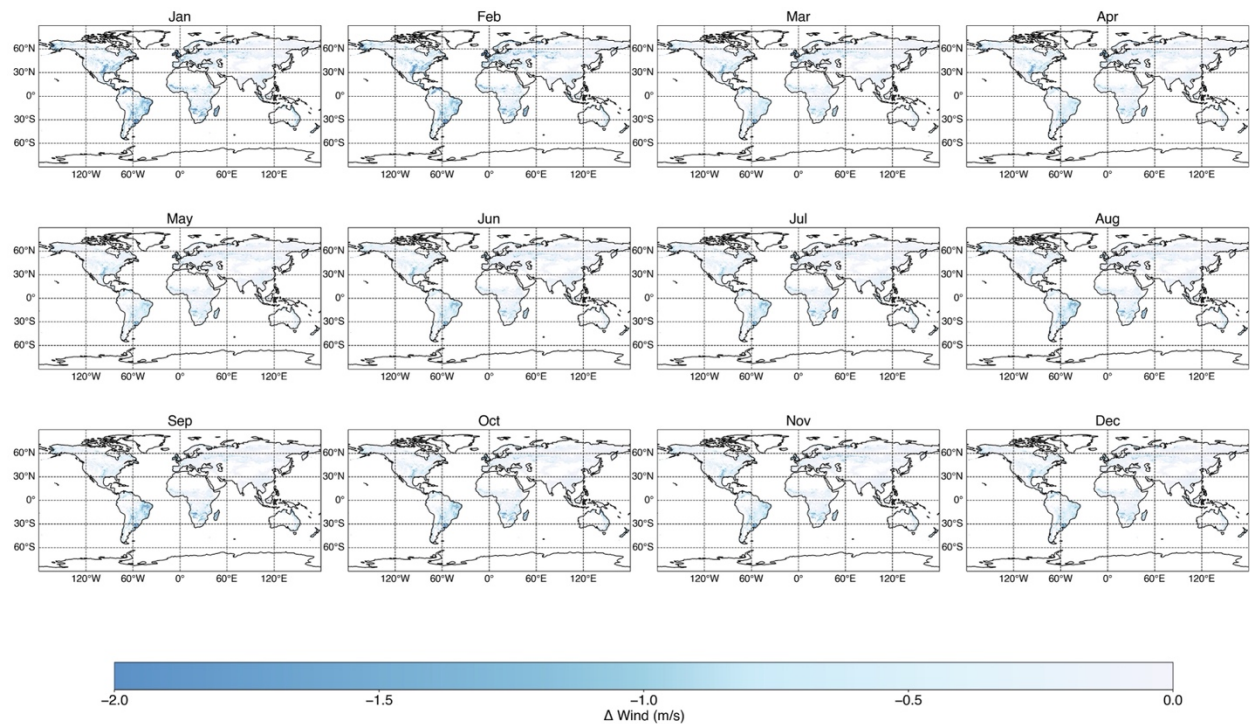
Supplementary Figure 23 Surface wind speed change over 12 months under the forestation scenario S1. The change in surface wind speed over 12 months under the forestation scenario S1 was calculated by multiplying the relative change in monthly surface wind speed (%) by the current monthly wind speed. The relative change in surface wind speed (%) was obtained by multiplying the regression coefficient of β_1 derived in the M2 models by the forestation fraction (converted to percentage) under forestation scenario S1. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



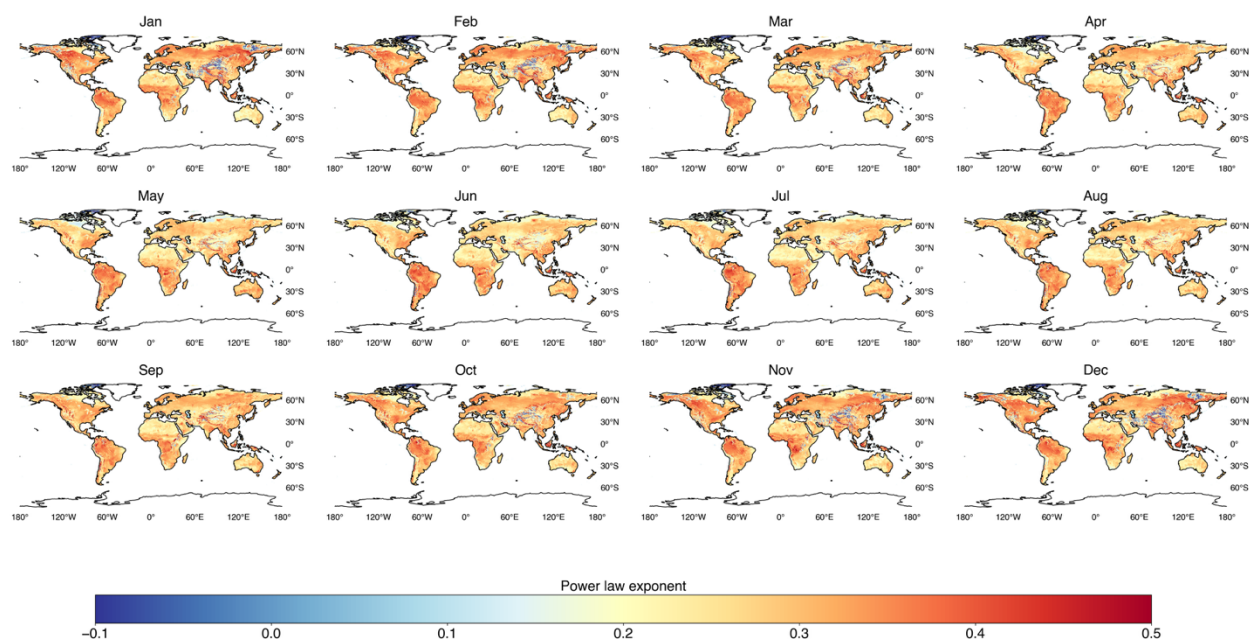
Supplementary Figure 24 Surface wind speed change over 12 months under the forestation scenario S2. The change in surface wind speed over 12 months under the forestation scenario S2 was calculated by multiplying the relative change in monthly surface wind speed (%) by the current monthly wind speed. The relative change in surface wind speed (%) was obtained by multiplying the regression coefficient of β_1 derived in the M2 models by the forestation fraction (converted to percentage) under forestation scenario S2. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



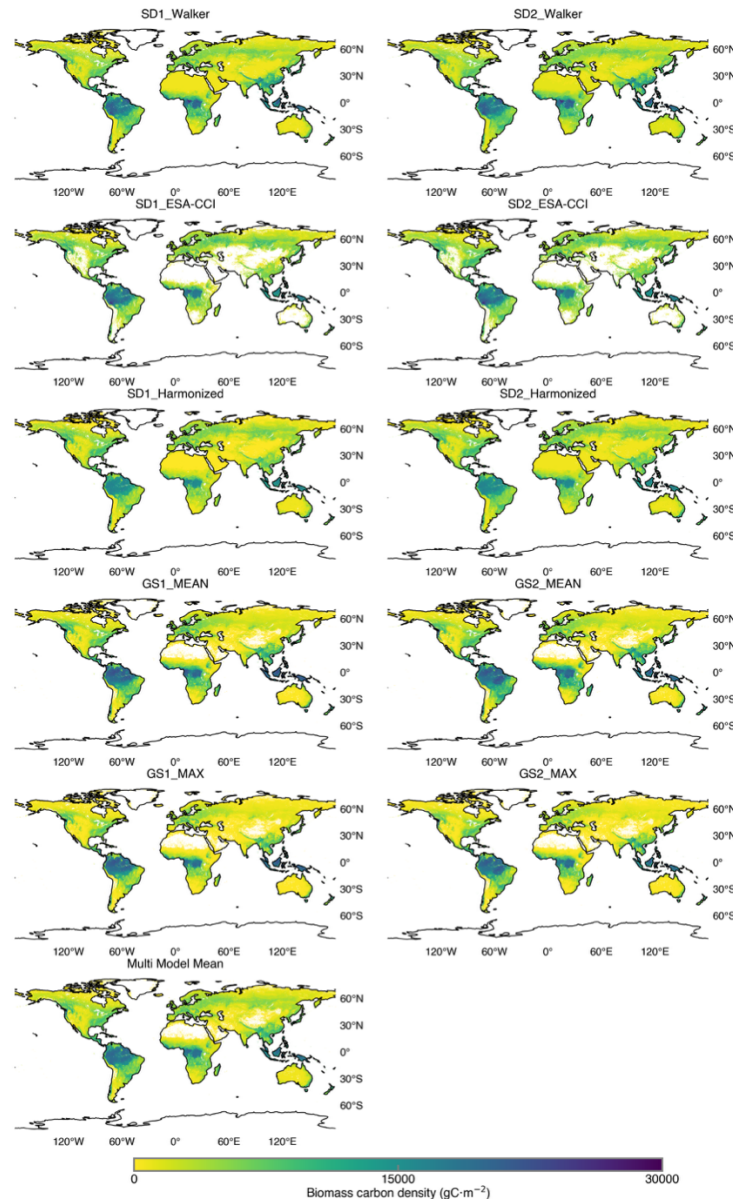
Supplementary Figure 25 Surface wind speed change over 12 months under the forestation scenario S3. The change in surface wind speed over 12 months under the forestation scenario S3 was calculated by multiplying the relative change in monthly surface wind speed (%) by the current monthly wind speed. The relative change in surface wind speed (%) was obtained by multiplying the regression coefficient of β_1 derived in the M2 models by the forestation fraction (converted to percentage) under forestation scenario S3. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



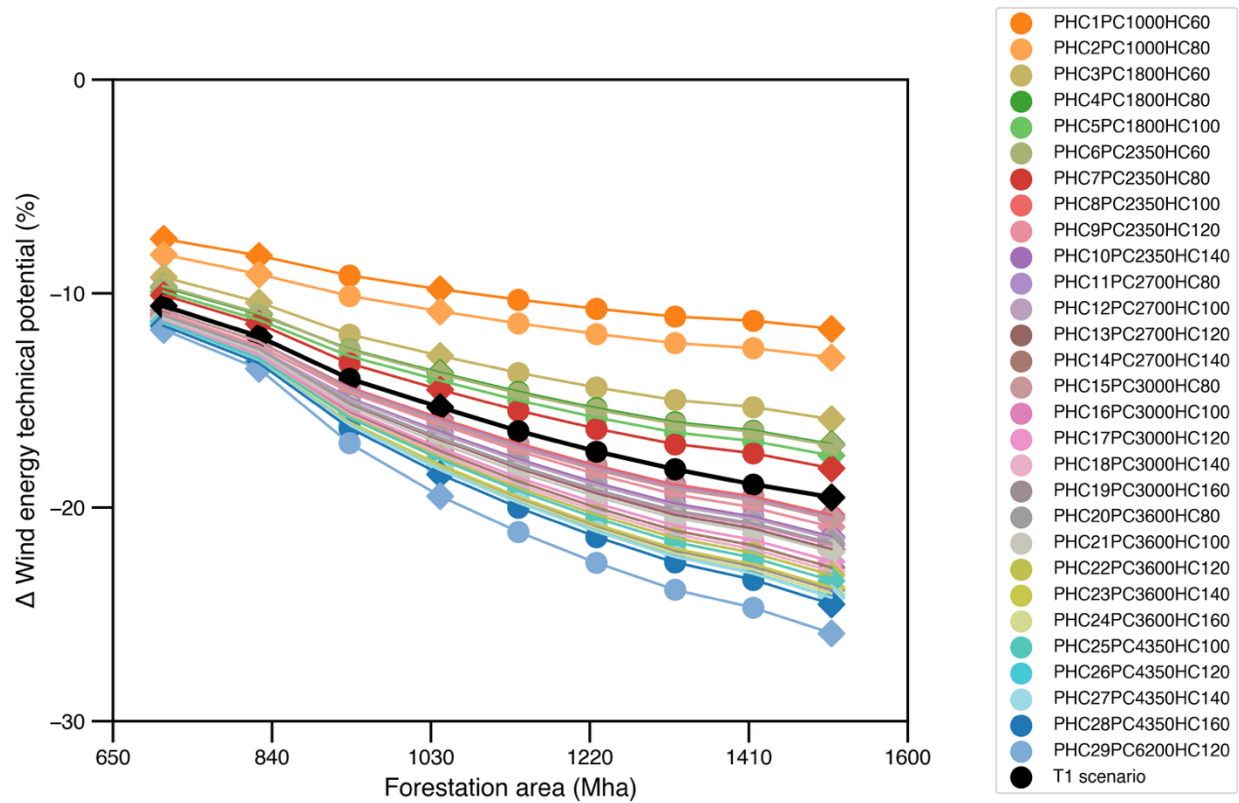
Supplementary Figure 26 Surface wind speed change over 12 months under the forestation scenario S4. The change in surface wind speed over 12 months under the forestation scenario S4 was calculated by multiplying the relative change in monthly surface wind speed (%) by the current monthly wind speed. The relative change in surface wind speed (%) was obtained by multiplying the regression coefficient of β_1 derived in the M2 models by the forestation fraction (converted to percentage) under forestation scenario S4. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



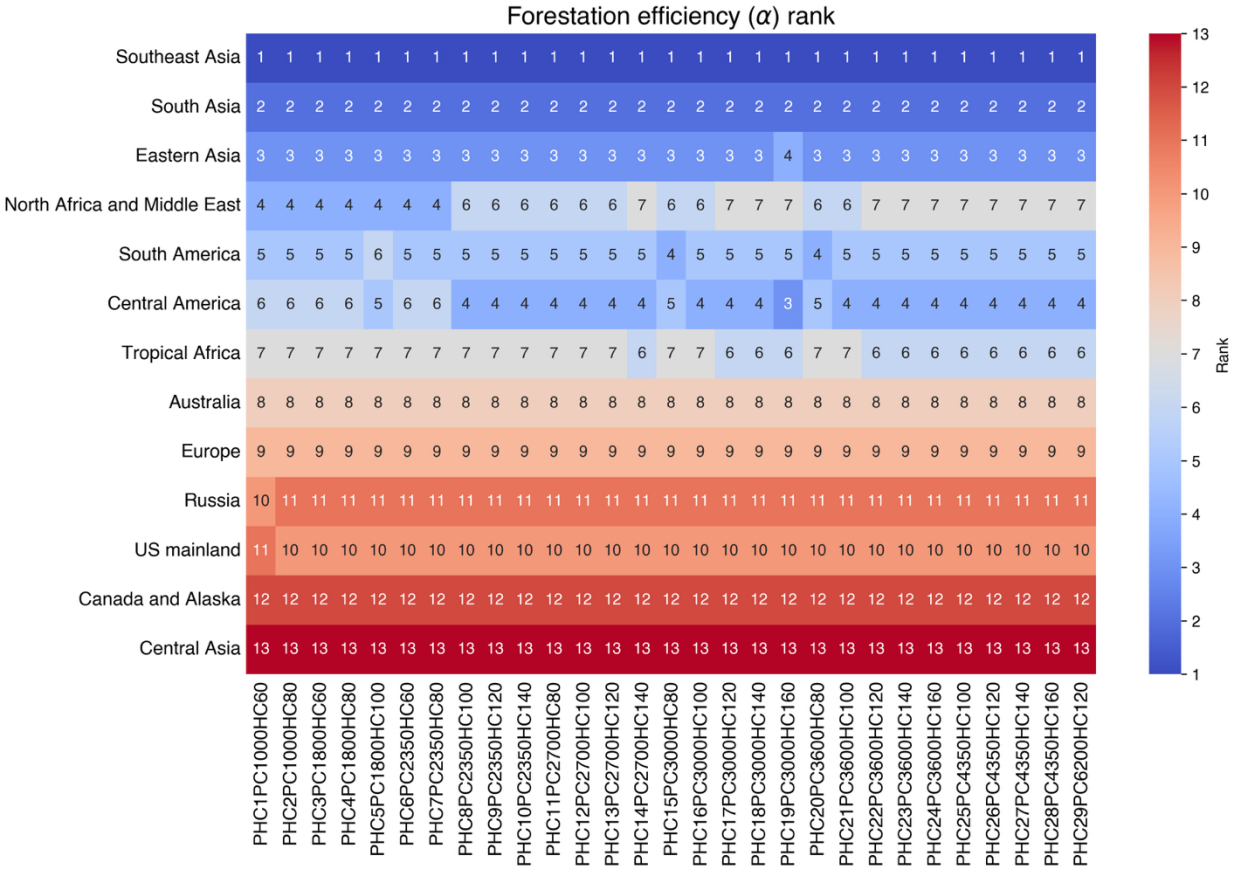
Supplementary Figure 27 Global maps of the power law exponent (α). The spatial variations of the power law exponent (α) are influenced by topography and vegetation composition. The power law exponent (α) was calculated by using the gridded wind speed at 10 m and 100 m heights, averaged over the period 2000–2020 for each month, of the ERA5 climate reanalysis dataset with a spatial resolution of 0.25° . Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



Supplementary Figure 28 The global forest carbon potential under hypothetical natural conditions was predicted by combining two sets of models developed from ground-sourced data and two satellite-derived data. The first set of models (GS1 and SD1) estimated the global potential living tree biomass under the natural potential by statistically accounting for the impact of human disturbance, setting all variables directly reflecting human disturbance to zero. The second set of models (GS2 and SD2) differs from the first set of models (GS1 and SD1) in a reduced number of observations (only pixels with minimal human disturbance) and a reduced number of predictors (no human-disturbance variables). To account for uncertainties in canopy-cover estimates from ground-sourced data, this study incorporated upper and lower boundaries of canopy cover in each pixel, resulting in a total of four GS models: GS1_MAX, GS1_MEAN, GS2_MAX and GS2_MEAN. To assess the uncertainty in biomass potential across various satellite-derived biomass products, this study included three satellite-derived biomass products (ESA-CCI, Walker et al. and harmonized), resulting in a total of six SD models: SD1_ESA-CCI, SD1_Walker, SD1_Harmonized, SD2_ESA-CCI, SD2_Walker and SD2_Harmonized. Panels in this figure were produced using Cartopy⁸, a Python library for geospatial data visualization, with base map data from Natural Earth (public domain dataset; <https://www.naturalearthdata.com/>)⁹.



Supplementary Figure 29 Changes in global wind-energy technical potential following different forestation scenarios across the wind turbine types with different hub height. PHC in the legend refers to 29 power–height wind turbine combinations. PC denotes the rated power, and HC represents the rotor hub height.



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Supplementary Figure 30 The forestation efficiency ranks under the maximum forestation scenario of S4 across the wind turbine types with different hub height. PHC in the legend refers to 29 power–height wind turbine combinations. PC denotes the rated power, and HC represents the rotor hub height.

350 Supplementary Table 1. The definition of afforestation, reforestation, forest restoration and forestation crosses
351 different literature.

	Definition
Afforestation	Establishment of forest through planting and/or deliberate seeding on land that, until then, was under a different land use, implies a transformation of land use from non-forest to forest ¹⁸ .
	Direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land ¹⁹ .
	Afforestation involves planting trees on land that has not recently been covered with forest ²⁰ .
	Afforestation is defined as the establishment of forest on rangeland, secondary forest and secondary non-forest in non-forest biomes ²¹ .
	Afforestation is planting or seeding of trees on land that was not previously forested ²² .
	Afforestation is establishing forests where not previously forests ²³ .
	Afforestation is the process of introducing trees to an area that was previously not forested ²⁴ .
	Afforestation is the process of forest cover gain ²⁵ .
	Afforestation is the process of forest cover gain ²⁶ .
Reforestation	Re-establishment of forest through planting and/or deliberate seeding on land classified as forest ¹⁸ .
	Establishment of forests on land that was previously forested, but currently is not (e.g. due to historical land clearing) ¹⁹ .
	Reforestation includes planting trees or allowing trees to regrow on land that had recently been covered with forest ²⁰ .
	Reforestation is either through deliberate replanting after forest land is disturbed (e.g., burned), or where previously nonforested lands (e.g., cultivated) are converting to forestland ²⁷ .
	Reforestation is defined as the establishment of forest on rangeland, secondary forest, and secondary non-forest land within forest biomes ²¹ .
	Reforestation (re-establishment of forest through planting trees or deliberate seeding on land already classified as forest) does not increase forest area, as it occurs on lands already defined as forest ²² .
	Reforestation is the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was forested but that has been converted to non-forested land ²⁸ .
	reforestation is reestablishing forests where they previously colonized ²³ .
Forest Restoration	Forest restoration involves helping degraded forest land recover its forest structure, ecological processes, and biodiversity ²⁰ .
	Restoration narrowly to describe recovering an ecosystem that has been lost. Restoration do not include replacing native with non-native ecosystems (for example, the afforestation of natural grasslands) ²⁹ .
	Forest restoration is often considered as part of a landscape approach aiming to contribute to a range of sustainability goals; this has become known as forest landscape restoration (FLR). FLR is defined as “a planned process that aims to regain ecological functionality and enhance human well-being in deforested or degraded landscapes”, and can include forest restoration with biodiversity-related objectives, planting woodlots of fast-growing species for fuelwood, and agroforestry activities ³⁰ .
	Natural regeneration of secondary forests is one of the lowestcost forest restoration options. Another restoration method being promoted, one that endeavors to blend the benefits of secondary forests and tree plantations, is enrichment planting, whereby commercially valuable timber trees are interplanted in either young secondary forests or in underperforming tree plantations ³¹ .
	Forest restoration is defined as the process of assisting the recovery of forest that has been degraded, damaged, or destroyed ³² .
	Forest restoration emphasizes historical fidelity and recovery of native species composition (ecological integrity) ²² .
	Forest restoration includes through afforestation of currently unforested land and reforestation of depleted forests ³³ .

	Forest restoration refers to actions helping a natural, but formerly removed, forest to re-establish ²⁴ .
	Forest restoration refers to bringing back forest where it has disappeared or restoring the conditions of forests to how they were before degradation had occurred ³⁴ .
	Forest restoration is a mechanism to achieve multiple goals, including climate mitigation, biodiversity conservation, socioeconomic benefits, food security, and ecosystem services ³⁵ .
	Forest restoration is defined as increasing tree cover in any region, independent of the land-use history ³⁶ .
	Forest restoration is seen as symmetric with degradation: An undisturbed forest in a natural or historical condition can be degraded, and a degraded forest can be restored to that natural or historical condition ³⁷ .
	Forest Landscape Restoration (FLR) is a process to regain ecological integrity and enhance human well-being in deforested or degraded forest landscapes ³⁸ .
Forestation	Large-scale Reforestation (of rangeland, secondary forest, and secondary non-forest in forest biomes), forest enhancement (forests where tree cover density is less than its potential), and afforestation (of rangeland, secondary forest and secondary non-forest in non-forest biomes where tree cover is greater than 10%) are referred to as forestation ²¹ .
	Forestation defined here to include both reforestation and afforestation ³⁹ .
	Forestation, including forest restoration, reforestation, and afforestation, is the process of restoring damaged forests or growing forests on currently unforested land ²⁰ .
	The establishment of forest, naturally or artificially, on an area, whether previously carrying forest or not ⁴⁰ .
	Forestation (including both afforestation and reforestation) is generally advocated as an effective method to increasing ecosystem carbon sequestration ⁴¹ .
	Forestation is forest cover increase ⁴² .
	Forestation includes reforestation and afforestation ⁴³ .
	Forestation here used as an umbrella term for reforestation and afforestation ⁴⁴ .

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Supplementary Table 2. Total wind-energy installation capacity for the 13 regions according to the Global Wind Report⁴⁵ and Kudelin and Kutcherov⁴⁶.

Region	Installation capacity (MW)	Country	Installation capacity (MW)
Russia	106	Russia	106
Central Asia	755	Kazakhstan	755
Southeast Asia	3545	Philippines	443
		Vietnam	3102
North Africa and Middle East	3912	Egypt	1702
		Saudi Arabia	422
		Morocco	1788
Tropical Africa	5796	Kenya	435
		South Africa	3442
		Other Africa	1919
Central America	7317	Mexico	7317
Australia	10537	Australia	10537
Canada and Alaska	15261	Canada	15261
South America	37374	Brazil	25632
		Argentina	3309
		Chile	4268
		Other Americas	4165
South Asia	43747	India	41930
		Pakistan	1817
US mainland	144184	USA	144184
Europe	225204	Europe	225204
Eastern Asia	340324	China	333998
		Japan	4668
		South Korea	1658
Total	838052		

Supplementary Table 3. Reductions in regional wind-energy generation under the minimum (S1) and maximum (S4) forestation scenarios with current wind turbine technical feature (T1 scenario). Potential changes in annual wind energy generation for current onshore wind installations were estimated by multiplying regional wind-energy installation capacity by the change in CF, and the number of hours within a year (8760 hours).

Region	Wind energy generation (no forestation) (TWh)	Wind energy generation (S1) (TWh)	Wind energy generation (S4) (TWh)	Wind energy reduction (S1) (TWh)	Wind energy reduction (S4) (TWh)
Russia	0.28	0.27	0.25	-0.01	-0.03
Central Asia	0.72	0.64	0.63	-0.08	-0.09
Southeast Asia	4.35	4.27	3.38	-0.08	-0.97
North Africa and Middle East	8.29	7.93	7.62	-0.36	-0.67
Tropical Africa	11.27	9.91	9.72	-1.36	-1.55
Central America	19.25	18.35	17.09	-0.90	-2.16
Australia	26.13	20.39	19.96	-5.74	-6.17
Canada and Alaska	45.53	44.69	44.29	-0.84	-1.24
South America	104.31	79.71	70.16	-24.60	-34.15
South Asia	75.83	74.88	74.21	-0.95	-1.62
US mainland	395.05	372.22	367.03	-22.83	-28.02
Europe	603.93	592.07	522.79	-11.86	-81.14
Eastern Asia	784.34	776.27	770.42	-8.07	-13.92
Total	2079.3	2001.6	1907.6	-77.7	-171.7

Supplementary Table 4. The comparison between biomass carbon sequestration potential and the reduction in CO₂ emission avoidance caused by the forestation-induced wind energy generation loss in different regions. The reduction in avoided CO₂ emission was calculated based on current installation capacity, as well as for scenarios in which the capacity doubles, triples, doubles, triples, and increases elevenfold relative to current levels. The elevenfold increase in wind energy installation capacity relative to current levels could contribute approximately 30.0% of global electricity generation.

	S1 Forestation Scenario	S4 Forestation Scenario
Forest carbon sequestration (GtCO ₂)	160.7	332.5
Reduction in avoided CO ₂ emissions (GtCO ₂) with 1 × Current wind turbine deployment	-2.8	-6.2
Reduction in avoided CO ₂ emissions (GtCO ₂) with 2 × Current wind turbine deployment	-5.6	-12.4
Reduction in avoided CO ₂ emissions (GtCO ₂) with 3 × Current wind turbine deployment	-8.4	-18.6
Reduction in avoided CO ₂ emissions (GtCO ₂) with 11 × Current wind turbine deployment	-30.8	-68.2

Supplementary Table 5. Land cover classes in ESA CCI were grouped into the six IPCC land categories, i.e., cropland, forest, grassland, wetland, settlement, and other land. The last type ('other land') is further split into shrubland, sparse vegetation, bare area, and water.

Values in ESACCI	Land Cover Classification System in ESACCI	IPCC land categories
10, 11, 12	Cropland, rainfed	Agriculture
20	Cropland, irrigated or post-flooding	Agriculture
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	Agriculture
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (50%)	Agriculture
50	Tree cover, broadleaved, evergreen, closed to open (>15%)	Forest
60, 61, 62	Tree cover, broadleaved, deciduous, closed to open (>15%)	Forest
70, 71, 72	Tree cover, needleleaved, evergreen, closed to open (>15%)	Forest
80, 81, 82	Tree cover, needleleaved, deciduous, closed to open (>15%)	Forest
90	Tree cover, mixed leaf type (broadleaved and needleleaved)	Forest
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	Forest
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	Grassland
120, 121, 122	Shrubland	Shrubland
130	Grassland	Grassland
140	Lichens and mosses	Sparse vegetation
150, 151, 152, 153	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	Sparse vegetation
160	Tree cover, flooded, fresh or brackish water	Forest
170	Tree cover, flooded, saline water	Forest
180	Shrub or herbaceous cover, flooded, fresh/saline/brackish water	Wetland
190	Urban areas	Settlement
200, 201, 202	Bare areas	Bare area
210	Water bodies	Water
220	Permanent snow and ice	Water

Supplementary Table 6. List of CMIP6 models used in this study. Detailed information on CMIP6 experiments and these models can be obtained from Boysen et al.⁴⁷ and the official CMIP6 website (<https://esgf-node.llnl.gov/projects/cmip6/>).

Model name	Land model	Spatial resolution	Number of years simulated	Dynamic vegetation module	Branching year
MPI-ESM1.2.0	JSBACH 3.2	192×96 ~ 1.9°×1.9°	150	Only in piControl	piControl year 1899
IPSL-CM6A-LR	ORCHIDEE	144×143 ~ 2.5°×1.27°	80	no	piControl year 1870
CESM2	CLM5	288×192 ~ 1.25°×0.94°	80	Only in piControl	piControl year 501
CNRM-ESM2-1	ISBA-CTRIP	256×128 ~ 1.4°×1.4°	80	no	piControl year 1850
BCC-CSM2-MR	BCC_AVIM	320×160 ~ 1.125°×1.1°	80	no	piControl year 2289
CanESM5	CLASS3.6/CTE M1.2	128×64 ~ 2.8°×2.8°	90	no	piControl year 5700
UKESM1-0-LL	JULESES-1.0	192 × 144 ~ 1.87°×1.25°	80	Both on but off in deforested grid cell fraction.	piControl year 1960
EC-Earth3Veg	Matsiro/VISIT	512×256 ~ 0.7°×0.7°	80	both	piControl year 1930

Supplementary Table 7. The mean values of R^2 and RMSE averaged over 12 months for two regional models (M1 and M2) constructed using multi-model mean values for the thirteen regions of the globe. For each region, the M2 model yields a higher R^2 and lower RMSE, than M1, when averaged over the 12 months.

Region	M1 Adjusted R^2	M2 Adjusted R^2	Adjusted R^2 (M2-M1)	M1 RMSE	M2 RMSE	RMSE (M2-M1)
Australia	0.32	0.50	0.18	0.089	0.076	-0.013
Central Asia	0.36	0.52	0.16	0.033	0.026	-0.008
Eastern Asia	0.27	0.44	0.17	0.076	0.065	-0.012
Europe	0.36	0.51	0.15	0.074	0.064	-0.011
North Africa and Middle East	0.24	0.44	0.20	0.048	0.039	-0.008
Canada and Alaska	0.39	0.50	0.11	0.069	0.062	-0.007
Central America	0.36	0.48	0.12	0.084	0.075	-0.010
US mainland	0.28	0.48	0.20	0.082	0.069	-0.013
Russia	0.37	0.44	0.07	0.075	0.070	-0.005
South America	0.30	0.43	0.13	0.153	0.136	-0.017
South Asia	0.24	0.40	0.16	0.090	0.074	-0.015
Southeast Asia	0.35	0.50	0.15	0.106	0.092	-0.014
Tropical Africa	0.34	0.46	0.12	0.113	0.099	-0.014
Total	0.32	0.46	0.14	0.084	0.073	-0.011

Supplementary Table 8. The shares of different wind turbine types (PHC class) under three technical scenarios.

Turbine types	Turbine share in T1 scenario	Turbine share in T2 scenario	Turbine share in T4 scenario
PHC1PC1000HC60	0.01678236	0	0
PHC2PC1000HC80	0.01678236	0	0
PHC3PC1800HC60	0.17060127	0.07226667	0
PHC4PC1800HC80	0.17060127	0.07226667	0
PHC5PC1800HC100	0.17060127	0.07226667	0
PHC6PC2350HC60	0.04464011	0.05434	0.005205
PHC7PC2350HC80	0.04464011	0.05434	0.005205
PHC8PC2350HC100	0.04464011	0.05434	0.005205
PHC9PC2350HC120	0.04464011	0.05434	0.005205
PHC10PC2350HC140	0.04464011	0.05434	0.005205
PHC11PC2700HC80	0.00913073	0.027225	0.002502
PHC12PC2700HC100	0.00913073	0.027225	0.002502
PHC13PC2700HC120	0.00913073	0.027225	0.002502
PHC14PC2700HC140	0.00913073	0.027225	0.002502
PHC15PC3000HC80	0.03281115	0.06124	0.005803
PHC16PC3000HC100	0.03281115	0.06124	0.005803
PHC17PC3000HC120	0.03281115	0.06124	0.005803
PHC18PC3000HC140	0.03281115	0.06124	0.005803
PHC19PC3000HC160	0.03281115	0.06124	0.005803
PHC20PC3600HC80	0.00356778	0.01104	0.013613
PHC21PC3600HC100	0.00356778	0.01104	0.013613
PHC22PC3600HC120	0.00356778	0.01104	0.013613
PHC23PC3600HC140	0.00356778	0.01104	0.013613
PHC24PC3600HC160	0.00356778	0.01104	0.013613
PHC25PC4350HC100	0.00325335	0.0103	0.018265
PHC26PC4350HC120	0.00325335	0.0103	0.018265
PHC27PC4350HC140	0.00325335	0.0103	0.018265
PHC28PC4350HC160	0.00325335	0.0103	0.018265
PHC29PC6200HC120	0	0	0.7932

Turbine types	Cut-in Speed (m/s)	Rated Speed (m/s)	Cut-out Speed (m/s)	Rated Power	Pr_fit	v0_fit	k_fit
PHC1PC1000HC60	2	14.1	25	1000	1046.24596	8.7691	0.67511
PHC2PC1000HC80	2	14.1	25	1000	1046.24596	8.7691	0.67511
PHC3PC1800HC60	2	14.2	25	1800	1876.04116	8.8645	0.64742
PHC4PC1800HC80	2	14.3	25	1800	1886.70824	8.89	0.64411
PHC5PC1800HC100	2	14.2	25	1800	1899.37477	9.1044	0.62858
PHC6PC2350HC60	2	15.9	25	2350	2405.94094	9.0607	0.63594
PHC7PC2350HC80	2	16.3	25	2350	2402.31997	9.0414	0.64017
PHC8PC2350HC100	2	15.7	25	2350	2363.98597	8.1903	0.69017
PHC9PC2350HC120	2	15.5	25	2350	2348.92458	8.2767	0.65763
PHC10PC2350HC140	2	14.4	25	2350	2379.03088	8.1613	0.70967
PHC11PC2700HC80	2	13.5	25	2700	2811.2791	8.238	0.69064
PHC12PC2700HC100	2	13.5	25	2700	2790.5403	7.9476	0.73042
PHC13PC2700HC120	2	13.7	25	2700	2771.84284	7.9763	0.71566
PHC14PC2700HC140	2	12.5	25	2700	2841.12693	7.7402	0.74852
PHC15PC3000HC80	2	16.5	25	3000	3034.48872	8.3453	0.70334
PHC16PC3000HC100	2	13.7	25	3000	3129.47357	8.042	0.7364
PHC17PC3000HC120	2	12.5	25	3000	3198.33198	7.9816	0.7348
PHC18PC3000HC140	2	12.5	25	3000	3198.02927	7.9788	0.73255
PHC19PC3000HC160	2	12.3	25	3000	3148.25326	7.4895	0.78729
PHC20PC3600HC80	2	15.3	25	3600	3664.15431	8.1168	0.7412
PHC21PC3600HC100	2	15.2	25	3600	3698.75346	8.338	0.72186
PHC22PC3600HC120	2	12.8	25	3600	3848.75314	8.1528	0.71179
PHC23PC3600HC140	2	12.4	25	3600	3853.84776	7.9808	0.73537
PHC24PC3600HC160	2	12.3	25	3600	3882.178	8.0721	0.71237
PHC25PC4350HC100	2	14.1	25	4350	4513.96535	8.2682	0.66266
PHC26PC4350HC120	2	13.4	25	4350	4532.55533	8.0178	0.67754
PHC27PC4350HC140	2	14.1	25	4350	4513.96535	8.2682	0.66266
PHC28PC4350HC160	2	14.1	25	4350	4513.96535	8.2682	0.66266
PHC29PC6200HC120	2.1	11.2	25	6200	6891.75176	7.6811	0.76013

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