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Low impact siting for wind power facilities in the Southeast United States

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Abstract

Although installed wind power generation capacity in the United States reached 132 GW in 2021, more than quadruple the capacity in 2008, a noticeable void exists in the Southeast. Scant wind power development in this region is due to relatively poorer wind resources, other competitive energy sources, and political opposition. However, the dramatic increases in wind turbine hub height, which allow harvesting the faster wind speeds that occur farther from the ground, combined with a growing sense of urgency to develop renewable energy, point to a near future with significant wind development everywhere, including the Southeast. Nevertheless, the enthusiasm for replacing fossil fuels with renewable sources is tempered by fears that the vast land requirements of utility-scale wind farms may disrupt valuable ecosystems. In this paper, we identify the areas where installed wind power capacity is least likely to disrupt wildlife and sensitive natural areas in the southeastern United States. The generated maps exclude geographic areas unsuitable for wind power development due to environmental concerns or technical considerations corresponding to five categories. The resulting geospatial product suggests that even after removing sizable areas from consideration, there is significant land for wind development to meet the Southeast's energy needs and clean energy goals.

KEYWORDS
conservation, GIS, Southeast region, wind energy

1 | INTRODUCTION

In 2019 and 2020, wind power capacity in the United States grew more than any other electricity-generating technology, to a total of 132 GW by 2021.[1] In 2019, wind energy supplied 7.2% of the United States' electricity, making it the country's largest source of renewable energy.[2] Annual net wind capacity (both offshore and onshore) is expected to continue increasing through the foreseeable future, but there will likely be some

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Abbreviations: ABC, American Bird Conservancy; ATB, Annual Technology Baseline; EPA, Environmental Protection Agency; FEMA, Federal Emergency Management Agency; GW, gigawatts; HIFLD, Homeland Infrastructure Foundation-Level Data; MW, megawatts; NGOs, nongovernmental organizations; NREL, National Renewable Energy Laboratory; PAD, Protected Areas Database; PoP, Power of Place; SWR, Site Wind Right; TNC, The Nature Conservancy; TWh, terawatt-hours; USACE, US Army Corps of Engineers; USDOE, US Department of Energy; USFWS, US Fish & Wildlife Service; USGS, US Geological Survey.

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added political and social resistance when siting new onshore facilities.[3] Most of the installed capacity is concentrated in Texas, the eastern plains, and the West.[1]

In contrast, wind development in the Southeast has been limited by low-cost coal and nuclear electricity, abundant solar resources, and opposing regulations, such as a moratorium motivated by potential threats to military bases in North Carolina.[4] But perhaps the most constraining factor has been the relatively low quality of wind resources prevalent in this area.[5] Turbines are sited in areas with annual average wind speeds of 7.0 m/s or greater if they are going to be profitable electricity-generating resources. But, although the wind speeds at 80 m high in the US wind belt range between 4 and 10 m/s, in the Southeast they are between 4 and 6 m/s.[6] Consequently, the total wind power capacity installed in Alabama, Florida, Georgia, Kentucky, Maryland, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia by the end of 2020 was just 3320 MW[7] or 2% of the installed wind power capacity in the country. The bulk of capacity (2640 MW) corresponds to the Coastal Virginia Offshore Wind facility.

Global wind power deployment is expected to significantly increase and account for more than 25% of the total emissions reductions that the Paris Climate Targets[8] calls for by 2050.[9] This goal can only be reached by significantly scaling up wind capacity and moving into untapped areas such as the Southeast United States. Despite not having a rich wind resource, the Southeast's wind generating capacity in 2050 is expected to increase tenfold to 34 GW.[10] This projected growth will be made possible through the deployment of taller wind turbines able to harvest higher wind speeds[11] and facilitated by the availability of land in places with abundant wind resources and low development, such as coastal areas and rural counties in Louisiana and the Carolinas.[10]

While wind turbines do not create air pollution during operations and instead can offset the energy used in their manufacturing, transportation, and installation within a few months of electricity generation,[12] their development can impact wildlife. Habitat loss, degradation, and fragmentation can occur if wind farms are sited at unsuitable locations, particularly with intact, natural vegetation,[13] but avian collisions with turbines remain a primary concern.[14,15] Bird turbine collision mortality rate averages 3.1 birds/MW/year with a broad range of 0.9 to 11.7 birds/MW/year, as lighting conditions, weather, tower design, and height of flight can all impact avian mortality rates.[16] Similarly, bat mortality is estimated to average 4.6 bats/MW/year with a range of 0.9 to 43.2 bats/MW/year.[16]

When sited too close to residential buildings, turbine noise and shadow flicker can also affect human well-being.[16,17] Most impacts to people include annoyance, with little evidence of negative physical or mental health outcomes, although sleep disruption has been documented.[18] Most harmful impacts to wildlife and humans can be mitigated by either altering the design and engineering of wind turbines,[19] which has been successful in reducing bat fatalities via curtailment.[20] Another strategy is siting wind turbines in suitable locations identified by following science-based spatial guidelines.[21] Incorporating environmental and social considerations early in the siting process has been shown to reduce regulatory and stakeholder conflict, leading to faster permitting and a decrease in project cancellations.[22,23]

The US government, nongovernmental organizations (NGOs), and academic groups have developed guidelines for least-impact wind siting. The US Fish & Wildlife Service's (USFWS's) land-based Wind Energy Guidelines[24] provide instructions for reducing the environmental impacts of all stages of a wind farm project, from siting to decommissioning. In addition, several examples of multi-criteria decision analysis in the academic literature identify suitable wind siting areas; the criteria considered include wind resources, the proximity to electric power transmission lines and roads, and population density.[25–28] An analysis of social constraints found that state regulations and county ordinances can significantly impact wind siting options.[29] Few wind siting studies in the United States consider environmental factors; they tend to be at the state level or smaller, and they incorporate two or fewer land-exclusion criteria at a time, including birds and bird habitat (New York State[30]), areas of summer bird activity (Ohio[31]), critical wildlife habitat for birds and bats (West Virginia[32]), important bird areas (Ohio[33]), "landscape features" (forests and streams) and bird and bat habitat (Indiana[34]), and wetlands and presence of endangered plants (California[28]).

Prior efforts by The Nature Conservancy (TNC) have explored environmentally responsible siting and development of renewable energy projects in the United States in two regions—the western United States and the wind belt area. TNC's Power of Place (PoP) study covers the western region of the United States, including Washington, Oregon, and California,[35] plus additional analyses include Nevada, Arizona, New Mexico, Colorado, Utah, Wyoming, Idaho, and Montana.[36] The study identifies four categories of land that should be excluded for wind development: legally protected, administratively protected, high conservation value, and landscape intactness.[36]

Similarly, TNC's Site Wind Right (SWR) project covers 17 states in the US wind belt and identifies lands where wind development is unlikely to encounter significant wildlife-related conflicts.[26,37] The geospatial analysis maps species-specific data layers such as migratory birds, bats, eagles, prairie/sage grouse, whooping crane stopover sites, big-game habitats, eagle and other raptor nesting areas, and other threatened and endangered species. Both studies provide clear spatial guidelines for wind development and estimate the total installed wind capacity potential, and together cover almost the entire continental United States with only the Northeast and Southeast missing. This paper aims at filling this gap by conducting a similar study for the Southeast, using the Wu et al.[36] methodology. Here, we develop a geospatial database specifying the regions where wind farms can be developed responsibly, based on the most recent data on ecological, regulatory, technical, and socioeconomic considerations in the states of Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia. To our knowledge, this is the first effort to provide spatial guidelines in the form of a geospatial database for wind power siting in the Southeast.

2 | MATERIALS AND METHODS

2.1 | Determination of land-exclusion categories

Like in the TNC's PoP analysis, we identify areas suitable for wind development after excluding those based on five considerations, which we call "exclusion categories."[35] The first four categories are related to environmental protection and conservation (Table 1) while Category 5 accounts for non-environmental limitations to wind development.

Under land-exclusion criteria in Category 1, all legally protected areas are excluded. These areas are those listed in the PAD-US[38] and those affected by North Carolina's Mountain Ridge Protection Act.[41] The PAD-US is the US official inventory of land protected from disturbance and conversion from its natural state and managed by federal, state, regional, local, NGO, and private institutions. The database includes areas that cannot be dedicated to any potential uses (energy included) affecting the preservation of biological diversity, outdoor recreation, or cultural enjoyment. It includes public and privately owned lands. In the Southeast, notable legally protected areas are the Everglades National Park, Big Cypress National Preserve, Francis S. Taylor Wildlife Management Area, Eglin Air Force Base in Florida, Great Smoky Mountains National Park in Tennessee, and Okefenokee National Wildlife Refuge in Georgia.

The North Carolina Mountain Ridge Protection Act of 1983 forbids the construction of tall buildings or structures on "mountain ridges whose elevation is 3,000 feet and whose elevation is 500 or more feet above the elevation of an adjacent valley floor."[41] Accordingly, under this category, we looked at a neighborhood window of 1000 ft to determine the minimum elevation that would correspond to the adjacent valley floor.

Category 2 excludes administratively protected areas where land use reviews and other procedures would be required before determining the suitability for wind power development. Therefore, it excludes areas managed by the US Army Corps of Engineers, tribal lands, wetlands, and flood zones. Developing a wind project in the lands managed by the US Army Corps of Engineers would require a permitting process following the federal rights-of-way and National Environmental Policy Act reviews (Stoel Rives,[23] p. 39). Developing a wind project in tribal lands may require review and permitting processes with uncertain outcomes.[44,45]

Wetlands are excluded because wind farms can cause erosion and impact aquatic environments.[46] Flood zones are excluded because all utility infrastructure should be designed and constructed to avoid or resist the effects of the hazards or combinations of dangers that exist in floodplains (Federal Emergency Management Agency[47]). Since areas with a 1% annual chance of flooding are high-risk areas,[42] and all development proposals in the Special Flood Hazard Area need a permit,[48] these areas are all excluded under Category 2.

Category 3 excludes areas with high conservation value, and Category 4 excludes those where the landscape is intact, as indicated by TNC's Connected and Resilient Landscape dataset.[43] The lands excluded under Category 3 are in resilient areas and climate flow zones; those in Category 4 are climate corridors. TNC's Connected and Resilient Landscape dataset resulted from an effort involving 60 scientists and 70 source datasets. It maps areas of above-average resilient scores; areas of concentrated, diffuse, or riparian climate flow; and areas of either confirmed rare species or high taxa diversity. This dataset is different from traditional datasets in that it represents current areas of high biodiversity and characterizes areas that are highly sensitive to the threats that a changing climate can cause to wildlife and plant biodiversity. Species-specific datasets such as American Bird Conservancy's (ABC's) Wind Risk Assessment Map[49] that characterize areas of high importance to birds were not included. There is overlap between TNC's Resilient and Connected dataset and the ABC bird area, with 32% of the land in TNC's Resilient and Connected dataset overlapping with 67% of the land in the ABC dataset (see Appendix B).

TABLE 1 Summary of four spatial exclusion categories to identify areas unsuitable for wind power development.[35]

Category	Areas excluded	Data source	Data type
1	All protected areas listed in the Protected Areas Database (PAD-US)	US Geological Survey (USGS) Gap Analysis Project[38]	Polygon
1	Areas in North Carolina with an elevation of 3000 ft and where the elevation is 500 or more feet above the elevation of an adjacent (1000 ft) valley floor	USGS EROS Center[39,40] Generated according to the North Carolina Mountain Ridge Protection Act of 1983[41]	Raster—30 m resolution
2	US Army Corps of Engineers (USACE) land	USACE Geospatial	Polygon
2	Tribal land	US Census Bureau	Polygon
2	Wetlands	USACE Geospatial	Polygon
2	Flood zones with 1% flood hazard	Federal Emergency Management Agency[42]	Raster—30 m resolution
3	Climate-resilient areas and climate flow zones identified by the TNC's Resilient and Connected Landscapes	TNC's Resilient and Connected Landscape dataset[43]	Raster—30 m resolution
4	Climate corridors (i.e., species movement areas) identified by the TNC's Resilient and Connected Landscapes	TNC's Resilient and Connected Landscape dataset[43]	Raster—30 m resolution

Categories 3 and 4 take TNC's Connected and Resilient Landscapes for Terrestrial Conservation dataset[43] as a main source of information on connected microclimates, areas of high biodiversity, and corridors where significant plant and animal movement is expected to occur in response to climate change and hence are unsuitable for wind power development. Further detail on data and the geospatial analysis to map the lands excluded by each category can be found in Appendix A.

Category 5 excludes land where economic and technical considerations make wind power development difficult (Table 2). To identify this land, we combined the US Department of Energy's (USDOE's) National Renewable Energy Laboratory (NREL) data on annual average wind speeds at 120 m above surface level (link to map, see Appendix B[51]) with a relative elevation model and a slope model. Most utility-scale wind farms have turbines with hub heights between 80 and 100 m, such as North Carolina's Amazon Wind Farm (92 m); thus, it is reasonable to determine wind power potential based on 100 m or higher. NREL[50] uses heights of 110 m in the Annual Technology Baseline (ATB) which provides the assumptions for our energy generation estimates, and thus, we applied the 120-m wind speed dataset to our analysis. Reduced costs of tall turbines, compounded with the much higher wind energy available at higher altitudes, have made the development of turbines with hub heights of 120 m and greater economically attractive.[61–63] Developers may be willing to incur the extra costs of high turbine hubs if this allows the profitable development of local resources.[64]

The USDOE's wind dataset used in this analysis provides the output of computer models based on meteorological data from 2007 to 2013 with a lower spatial resolution than the one required for this analysis. Hence, instead of excluding areas based solely on their estimated wind speeds, we identified and excluded lands whose relative elevation is below the mean of the surrounding areas. The relative elevation model uses the raster calculator to determine if the cell is higher than its surroundings, which implies access to higher quality wind resources due to less mixing and friction. Following White et al.,[52] the equation we used to calculate the relative elevation is as follows:

$$f(x) = x - ((a + b + c + d)/4),$$

where x is the input cell and a, b, c, and d are the mean elevation values of cells in the annulus of the internal radius of 3, 6, 12, and 24 km, respectively. The outer radius is the internal radius + 0.06 km for all. The mean value of the relative elevation model was 20.88 m, and all values below the mean were removed. A map showing the relative elevation is presented in Appendix B.

TABLE 2 Wind development technical criteria (Category 5).

Criteria	Reasoning	Exclusion criteria	Data type	Source
Wind speed	NREL[50] uses heights of 110 m in the Annual Technology Baseline (ATB).	<6.5 m/s at 120 m height	Raster at 2000 m resolution	National Renewable Energy Laboratory[51]
Slope	Range of acceptable slopes is between 10% and 84%.[6,25,28]	>84%	Raster at 30 m resolution	USGS
Relative elevation	"Areas that are higher in elevation relative to their immediate surroundings, and thus have greater wind exposure."[52]	<Mean relative elevation value	Raster at 30 m resolution	US Geological Survey (USGS) EROS Center[39,40]
Distance to urban area	Urban wind energy has not been widely adopted.[53] For information about noise and health impacts that require a setback from homes of at least 2 km.[54–56]	<2 km	Polygon	US Census Bureau
Distance to railway	In no case less than 500 ft.[57]	<500 ft	Polyline	Homeland Infrastructure Foundation-Level Data (HIFLD)
Distance to airport	Wind turbine wakes pose a significant roll hazard to general aviation aircraft at downwind distances as far as 4.57 km (2.84 miles).[58]	<5 km	Point	Federal Aviation Administration
Distance to radar stations	Turbines sited at least 18 km from the radar generally only impact the lowest radar scan at 0.5° elevation, and clutter is confined to the wind farm area.[59]	<18 km	Point	HIFLD
Distance to existing wind farms	Rule of thumb is to install a wind turbine 150 m (492.1 ft) away from any nearby obstruction.[60] Areas within 1.6 km of existing wind turbines are considered unsuitable for new wind development.[37]	<150 m	Points/polygon	USGS

Beyond excluding areas with wind speeds below the cutoff value or relative elevations under 20.88 m, we also excluded areas with pronounced slopes, as these are difficult or prohibitively expensive to develop into wind farms. Similarly, land with existing urban infrastructure or too close to railway, airports, radar stations, and wind farms were also excluded (Table 2).

2.2 | Geospatial data and analysis

All the geospatial data on land and technical constraints used in this analysis are publicly available in federal, state, or NGO websites as listed in Appendix A. The datasets were pre-processed with Arcpy, a Python-based geospatial scripting package, and analyzed with Model Builder, a visual programming interface of ArcGIS Pro. The Python script and the Model Builder file can be accessed on the ArcOnline TNC Wind Siting group page. For details on the steps followed for the analysis, see Appendix A. To account for artifacts that may have resulted from this geospatial analysis, any area less than 20 km^2 (4942 acres) was eliminated from the final output (i.e., "minimum area criteria") after applying the criteria in Category 5. We mapped existing and planned wind farms[7] to determine if they are in areas deemed by our analysis as suitable for wind development.

2.3 | Wind farm power generation capacity and annual electricity generation potential

To obtain a high-level estimate of the wind power that could be generated in the areas deemed as suitable for development, we make several assumptions about the wind resource and turbine performance. A detailed estimation of the wind power production that could be obtained in the

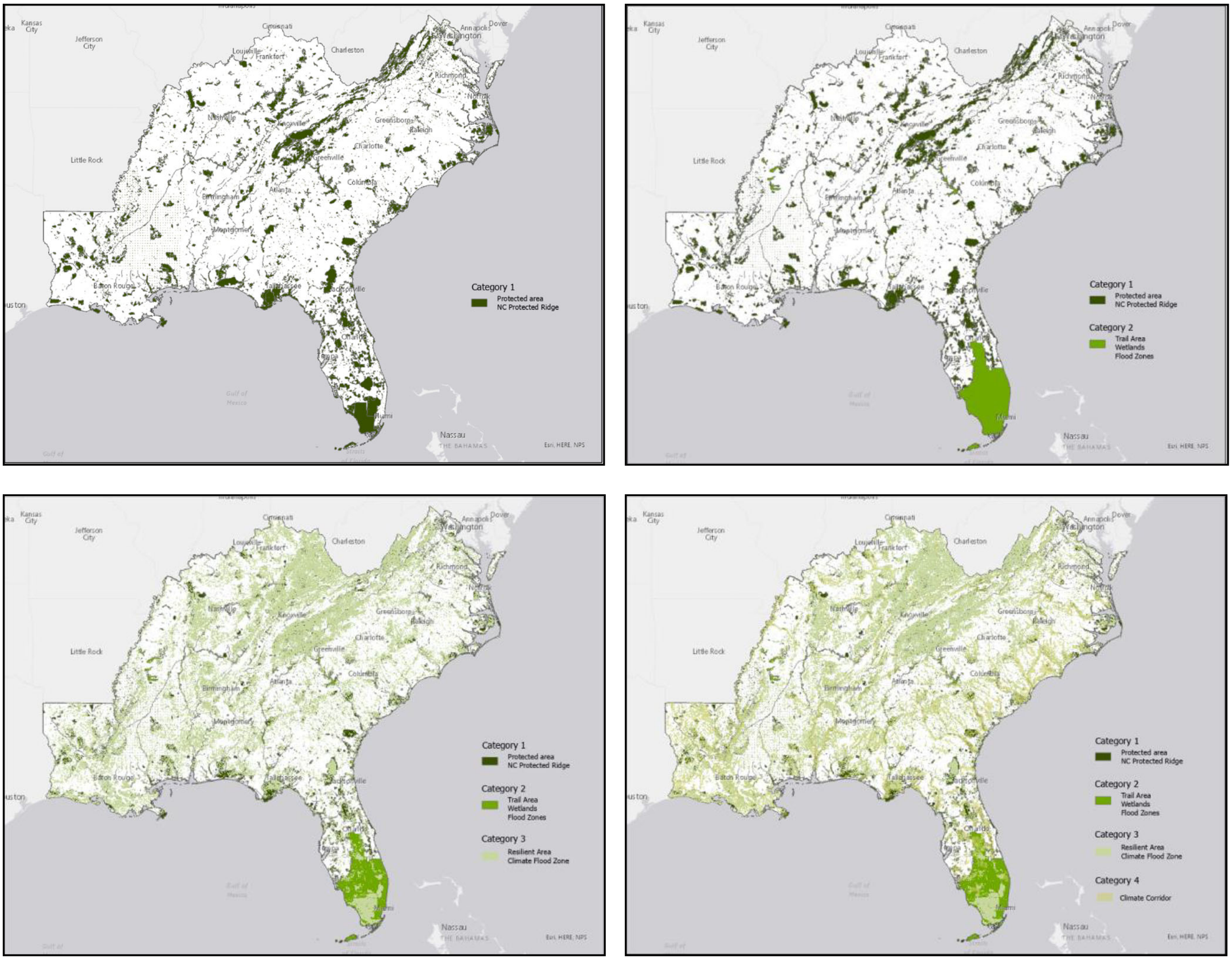

FIGURE 1 Shaded areas are unsuitable for wind power development after considering Categories 1–4 spatial exclusion criteria.

suitable areas would require considering wind speeds at a fine temporal and spatial resolution to then select the most suitable turbine design and layout in the site. Instead of following this approach, we make assumptions about the wind resource and wind farm characteristics. To characterize wind resources, we used NREL's[50] land-based wind classification which defines 10 classes according to speeds at 110 m high. In this classification, sites with wind speeds at 110 m high in the 6.5 to 7.1 m/s range are Class 8, and those with wind speeds in the 5.9 to 6.53 m/s range are

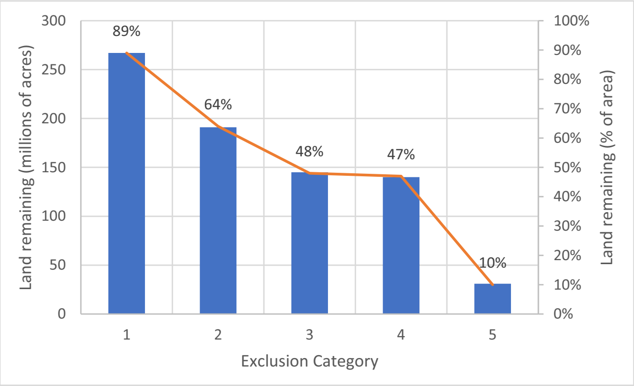

FIGURE 2 Available land suitable for environmentally responsible and economically feasible development of wind power potential after applying four categories of spatial exclusion criteria plus the technical criteria (Category 5).

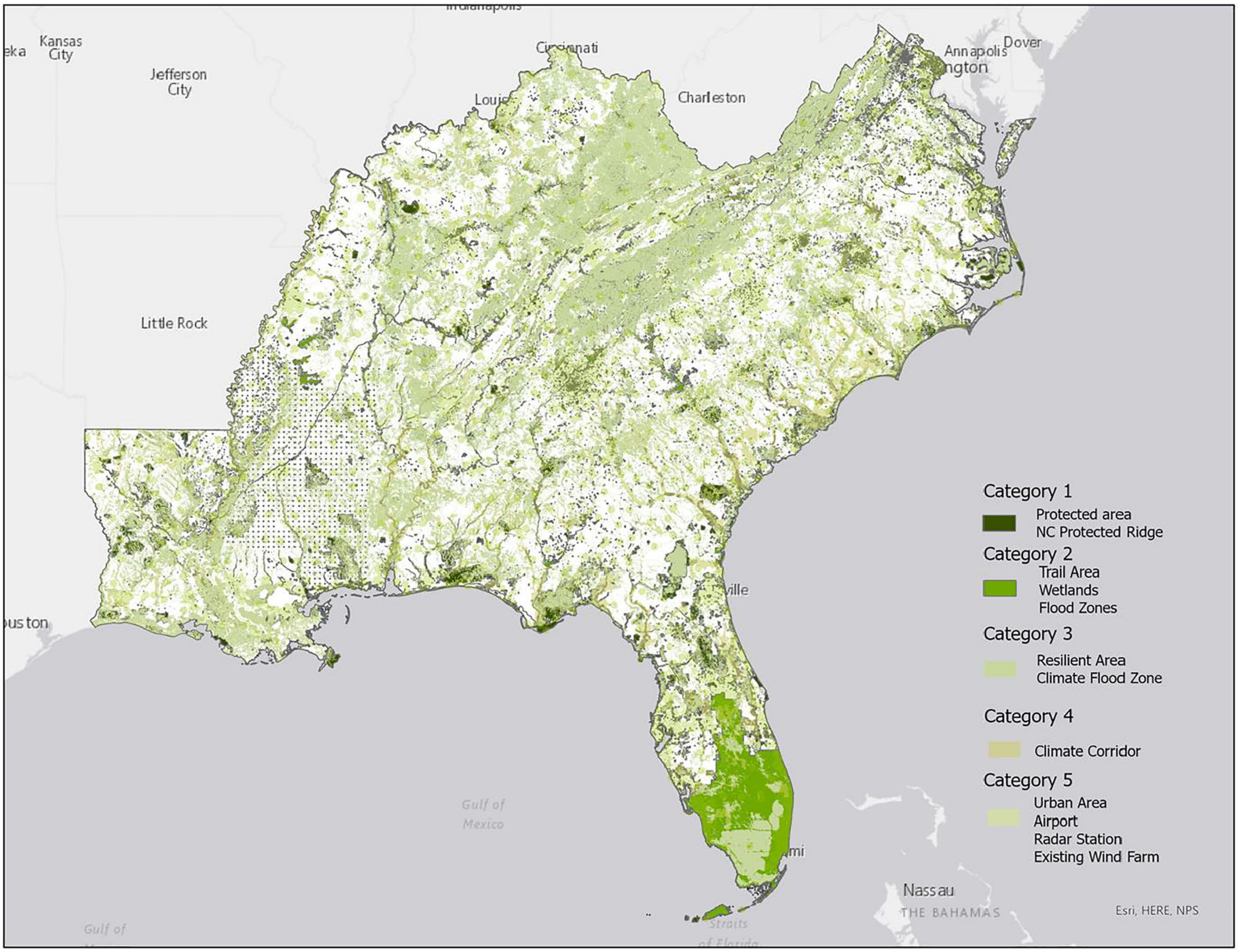

FIGURE 3 Shaded areas are unsuitable for wind power development identified by considering all five categories of spatial exclusion criteria.

Class 9. Since this study identifies sites as suitable for development if their wind speeds exceed 6.5 m/s at 120 m, it is safe to assume that all of them are Class 9 or better. This is because wind speeds improve by 0.5 to 1 m/s when moving from 80 to 110 m high and by 1 to 1.5 m when moving from 80 to 160 m.[65] Hence, wind speeds at 110 m will be 0.33 m/s lower than those measured at 120 m, implying a worse-case wind speed value of 6.27 m/s at 110 m height, translating into a Wind Speed Class 9.

The estimated performance of the wind farms that could be developed in regions with Class 9 wind resources depends on assumptions about technological advancement. We assume that the state of wind turbine technology innovation can be represented with one of three scenarios as described by NREL in the ATB: conservative, moderate, and advanced, with annual net capacity factors in 2030 of 28%, 30%, and 32%, respectively.[66] The annual net capacity factor of a wind farm is equal to its net yearly power generation, in megawatt-hours, divided by the production that would have been observed if the farm had generated electricity at its full installed capacity during the 8760 h of the year.

Note that the ATB's assumption of a 28% capacity factor from Class 9 wind resources is indeed conservative for the Southeast. According to the Environmental Protection Agency (EPA)[7] eGRID database, only two southeastern states, North Carolina and Tennessee, had operational land-based wind farms in 2021. The facility in North Carolina has a nameplate capacity of 208 MW and, in 2021, operated at a capacity factor of 27.7%. The facility in Tennessee is small (<30 MW), almost 20 years old, and its low capacity factor (12%) is probably not representative of the performance of any future wind power development in the region. Similarly, the ATB's assumption of a 32% capacity factor for the advanced technology case of Class 9 resources seems reasonable given that the average wind capacity factor (weighted by nameplate capacity) for the entire United States during 2021, according to the same eGRID database, was 32%.

FIGURE 4 Area suitable for wind power development (in brown) after eliminating areas that did not meet the minimum area criteria. Existing or announced wind farms include BMEC, Buffalo Mountain Energy Center (27 MW); BM, Buffalo Mountain (1.8 MW); DWF, Desert Wind Farm, LLC (208 MW); PCWF, Poplar Camp Wind Farm (72 MW expected to be commissioned in 2025).

NREL's ATB wind turbine technologies[50] include conservative, moderate, and advanced scenarios with turbine ratings of 4, 5.5, and 7 MW, with rotor diameters of 150, 175, and 200 m, and specific power values of 226, 229, and 223 W/m^2, respectively. The ATB does not provide the information on the assumed spacing between turbines to achieve the reported capacity factors. However, NREL's researchers assumed an installed power density of 3 MW/km^2 (equivalent to 82.37 acres/MW) for wind farms with three turbine designs considered in a recent estimate of US power potential.[29] The spacing between turbines implied by a power density of 3 MW/km^2 is larger than observed in actual wind systems, where the average land requirement for wind turbines of 1–10 MW is 44.7 acres/MW with a standard deviation of 25 acres/MW.[67] Given the three ATB representative technologies for 2030, a power density of 3 MW/km^2 is equivalent to a spacing of ~7.6 times the turbine's rotor diameter (i.e., a spacing of 7.6D). Recent research investigating optimum turbine spacing suggest values of 9D,[68] 12D,[69] and even 15D.[70–73] We use these three turbine separation values to estimate the maximum installed power capacity in the suitable lands. Although wider separation between turbines reduces the wind power development potential, it may slightly increase the wind farm capacity factor and facilitate the co-location of solar photovoltaic panels and the continuation of agriculture and/or ranching.

3 | RESULTS AND DISCUSSION

3.1 | Spatial siting analysis

After considering the environmental exclusion criteria in Categories 1–4, 140 million acres, representing 47% of the Southeast, appear as potentially suitable for environmentally responsible wind development (Figures 1 and 2). Consideration of Category 5 results in the exclusion of 109 million additional acres (Figures 2 and 3). After these lands are excluded, 31 million acres remain suitable for economic and environmentally responsible wind power development (Figure 2).

After eliminating areas below the minimum area criteria, total land suitable for wind power development is 24 million acres and 8% of the total considered in the Southeast (Figure 4). Known existing or planned onshore wind plants are shown as point locations; none of these falls within the suitable area identified in this analysis.

3.2 | Wind farm power generation capacity and annual electricity generation potential

The 24 million acres identified as suitable for environmentally responsible and economically viable wind power development in the Southeast (Figure 4) were translated into power generation capacity and a projection of annual power generation. The estimates of the power generation

TABLE 3 Estimated area suitable for wind power development after considering the five exclusion categories (i) and corresponding capacity (in GW) assuming different wind farm layouts expressed in three equivalent metrics (a) separation between wind turbines (number of rotor diameters), (b) installed power capacity density (MW/km^2), and (c) land requirement estimates (acres/MW); (ii) lower bound estimate of land requirement used by Lopez et al.[29]; and (iii)–(v) other estimates from the literature on optimal separation to maximize turbines' electric power production.[68–73]

State	Area suitable for wind power development (millions of acres) (i)	Potential wind power installed generation capacity (GW) assuming a turbine separation/installed power capacity density/land requirement of:			
		7.65D, 3 MW/km^2, 82 acres/MW (ii)	9D, 2.2 MW/km^2, 112 acres/MW (iii)	12D, 1.36 MW/km^2, 182 acres/MW (iv)	15D, 0.79 MW/km^2, 313 acres/MW (v)
N. Carolina	4.48	54.39	39.89	24.66	14.32
Kentucky	3.72	45.16	33.12	20.47	11.89
Tennessee	3.14	38.12	27.96	17.28	10.04
Louisiana	2.93	35.57	26.09	16.13	9.37
Mississippi	2.76	33.51	24.57	15.19	8.82
Virginia	2.72	33.02	24.22	14.97	8.70
Georgia	2.23	27.07	19.85	12.27	7.13
S. Carolina	1.46	17.73	13.00	8.04	4.67
Alabama	1.08	13.11	9.62	5.94	3.45
Florida	0.02	0.24	0.18	0.11	0.06
Total	24.54	297.93	218.48	135.06	78.45

TABLE 4 Wind farms' installed power generation capacity and estimates of annual electricity generation for the southeastern United States under four turbine spacing assumptions and three turbine technologies for Class 9 wind resources.

Installed power density/land requirements			Installed power generation capacity given the assumed installed power density/land requirement (GW) (iii)	Estimated annual electricity generation (TWh) assuming a capacity factor of:		
Separation between turbines (number of turbine rotor diameters)	Installed power density (MW/km^2) (i)	Land requirement (acres/MW) (ii)		28% (iv)	30% (v)	32% (vi)
7.65	3	82	297.93[a]	731	783	835[a]
9	2.2	112	218.48	536	574	612
12	1.36	182	135.06	331	355	379
15	0.79	313	78.45[a]	192[a]	206	220

Note: Category (i) corresponds to the turbine separation stated on column 1; (ii) corresponds to the installed power density on column 2; (iii) assumes 24.5 million acres of suitable land and the land requirement of column 3; (iv)–(vi) are the capacity factors of the conservative, moderate, and advanced wind power technologies for 2030 described by NREL's ATB.[66]

[a] Lower and upper bound estimates.

capacity that could be installed in each state are summarized in Table 3. Florida ranks at the bottom of the southeastern states by potential wind power generation capacity due to low wind speeds even at a 120 m hub height.

The 24.5 million acres suitable for wind development in the Southeast could accommodate between 78.4 and 297 GW of wind power generation capacity (Table 3) depending on assumptions about the spacing between turbines. Table 4 shows a range of annual net generation in terawatt-hours (TWh) using three levels of possible capacity factors for each of the four levels of installed wind power capacity presented in Table 3. The capacity factors considered correspond to expected performance for three scenarios of technological advance and the corresponding annual capacity factors (see methods).

Under different assumptions of land requirements for wind power development and capacity factors, annual generation production in 2030 would range between 192 and 835 TWh.

4 | CONCLUSIONS

This analysis combines five categories of environmental and technical considerations that constrain the placement of land-based wind power generation equipment in the Southeast. Assuming all the suitable lands for wind development have Class 9 resources and considering wind power land requirements of 82–313 acres/MW (Table 3), a rough estimate of the onshore wind power capacity that could be installed in the Southeast ranges between 78 and 297 GW, which is between 24% and 90% the power electricity generation installed in 2021.[7] Assuming a capacity factor of between 28% and 32% for wind farms in the region,[66] annual power generation would be between 192 and 835 TWh (median is 458 TWh). The lower bound of this estimate is equivalent to 17% of the electricity obtained in 2021 from all sources in the 10 southeastern states, while the upper bound is equivalent to 73% and the median is 40% (total generation was 1149 TWh[7]). It is worth highlighting that even the upper bound estimate is somewhat conservative in that it assumes that all sites have Class 9 wind resources when these may in fact be of better quality. Also, the lower bound of this estimate is extremely conservative because it assumes a large spacing between wind turbines of 15 rotor's diameters (15D), which is two times the spacing considered by Lopez et al.[29] and implies a land requirement of seven times the average observed for turbines of between 1 and 10 MW.[67] Nevertheless, it is worth looking at these scenarios as such wide spacing may allow co-location of solar or other land uses, which may facilitate acceptance and deployment of this technology. In any case, this analysis shows that the Southeast can significantly contribute to national goals of generating 35% of energy supply from wind power by 2050.[10] Of course, the amount of wind capacity that may be economically developed may be further reduced after considering constraints on power transmission capacity, interconnection availability, land leasing opportunities, local ordinances, and public opposition, but this analysis shows that imposing stringent environmental constraints does not preclude deep decarbonization.

The analysis can be improved, and the lands suitable for development can be narrowed down by considering other factors omitted from this analysis such as local zoning ordinances and the presence of structures that would obstruct the placing of wind turbines in rural areas like mines, landfills, and industrial facilities. In this analysis, urban areas are mapped according to census data and deemed not suitable for wind development, but no rural lands were excluded due to any considerations of human proximity. Future work could consider higher resolution analyses to exclude rural areas based on proximity to humans and their infrastructure. Similarly, the identification of economically promising areas for wind development can be refined by assessing the distance to access roads, which would lower construction costs. A remote sensing-based land cover dataset such as USGS's National Land Cover Database (USGS EROS Center, National Land Cover Database, 2018)[40]—which identifies land cover types and changes in categories such as urban environments, impervious surfaces, forest canopy, and agricultural land—could be used to obtain better estimates of annual wind electricity generation considering impacts of different surfaces with varying friction coefficients on wind speeds and turbulence. To more precisely map parcels where wind power can be placed after taking into account economic and logistical considerations, it would be necessary to examine in detail local ordinances stating access standards and easements, aesthetics of turbines, electrical and equipment standards, and permitting processes.[57]

Our results demonstrate the feasibility of powering the Southeast with wind while abiding stringent sitting constraints to uphold conservation values. The resulting geospatial product suggests that even after removing sizable areas from consideration, there is available land for wind development to meet the energy demands of the Southeast and to achieve and exceed US climate goals of supplying 35% of the Southeast energy needs with wind power by 2050.

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PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/we.2868.

DATA AVAILABILITY STATEMENT

The Python script and the Model Builder file can be accessed on the ArcOnline TNC Wind Siting group page.

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APPENDIX A: GEOSPATIAL ANALYSIS

1. Software and code

Arcpy, a Python-based geospatial scripting package, was used to preprocess the various input datasets. Model Builder, a visual programming interface as part of ArcGIS Pro, was also used to analyze viable wind development areas. Both processes provide ease of adjustment in certain variables such as buffer distances and provide an easy way to document and reproduce the workflow. The model, Python code, and ArcGIS Pro geodatabase can be accessed here.

2. Process followed

A high-level overview of the five steps followed in this geospatial analysis is provided in Figure 2. The first step consisted of downloading the databases. Since most of the data relevant to this study are available at a national level, data were first processed to keep only values in the study area. The data layer was then processed to remove areas that did not meet the inclusion criteria. For example, we assumed that wind farms must be located 5 km away from airports, so we used the buffer tool to identify a circle from the point location of the airport. Other than the buffer tool, the select-by-attribute tool was also used to cutoff values less than or greater than the selection criteria.

The raster-to-polygon tool was used to prepare for Step 5 (elimination) to allow for the use of the erase tool since input features can only be feature classes. The individual criteria were combined using the merge tool and then the dissolve tool was used to aggregate the separate polygons. To account for artifacts that may have resulted from this geospatial analysis, any area less than 20 km^2 or 4942 acres was eliminated from the final output after applying the criteria in Category 5. This minimum area value was chosen based on SWR's methodology. It a value larger than the minimum area required for one wind turbine which is estimated to be 1.5 acres based on the minimum distance required between turbines.

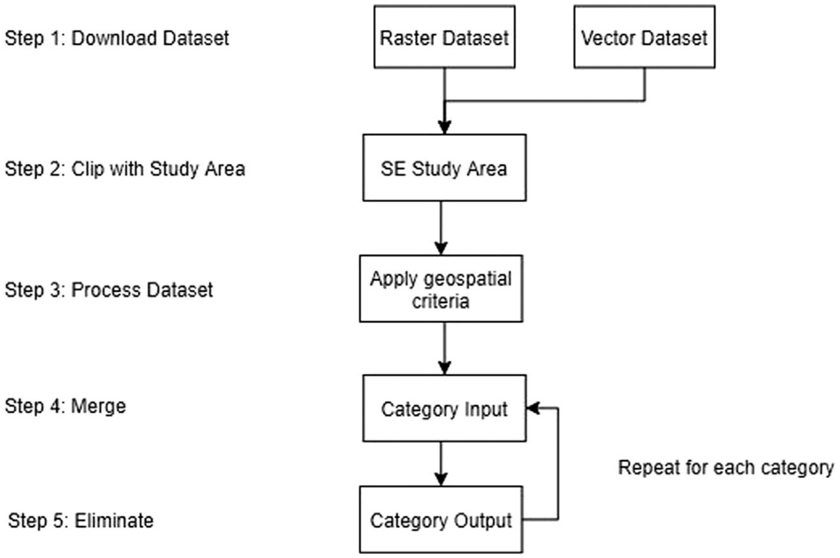

FIGURE A1. Five steps followed for geospatial analysis.

3. Cell-size resolution

The two main types of geospatial data that ArcGIS can read and manipulate are vectors and raster. To represent areas, vectors use a combination of lines and nodes to form shapes, while raster data uses cells of equal area to represent features. Common uses of vector data are point sources and roads, while raster data is used to represent land cover and elevation. The granularity of our geospatial analysis was limited by the resolution of available datasets. The final map output is provided in raster format at 30 m resolution (i.e., each cell in the raster represents a 30 × 30 m area on the ground). To account for the fact that NREL wind speed data were provided at 2 km resolution (i.e., a coarser scale as more area is represented in a single cell, leaving room for added error form a lack of finer detail), the relative elevation model at 30 m was used as the input while the wind speed layer was used as a mask so that the output was a raster dataset of wind speed but at 30 m resolution. An example of resolution mismatch is shown in Figure A2 as the blue represents a higher resolution, finer scale dataset while the gray represents a lower resolution dataset.

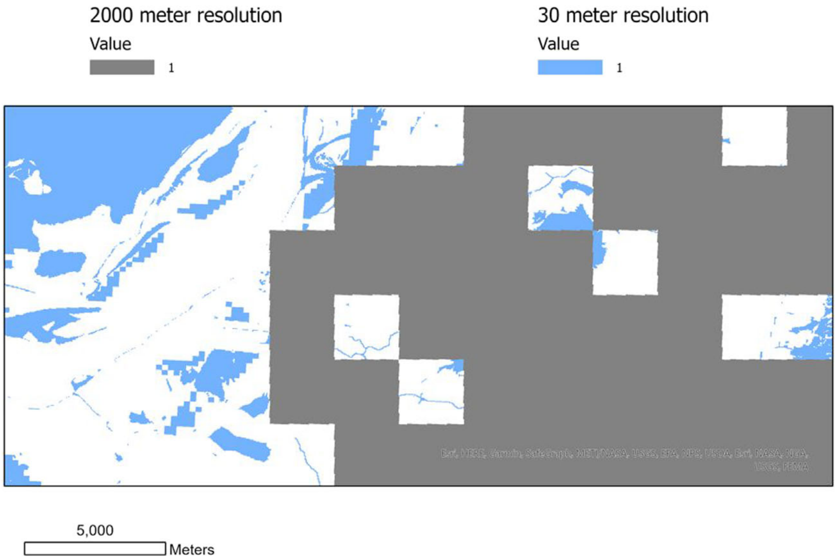

FIGURE A2. Illustration of the mismatch in the resolution of the wind speed dataset (gray) and the TNC's Resilient and Connected Network dataset (blue).

APPENDIX B: ADDITIONAL MAP OUTPUTS

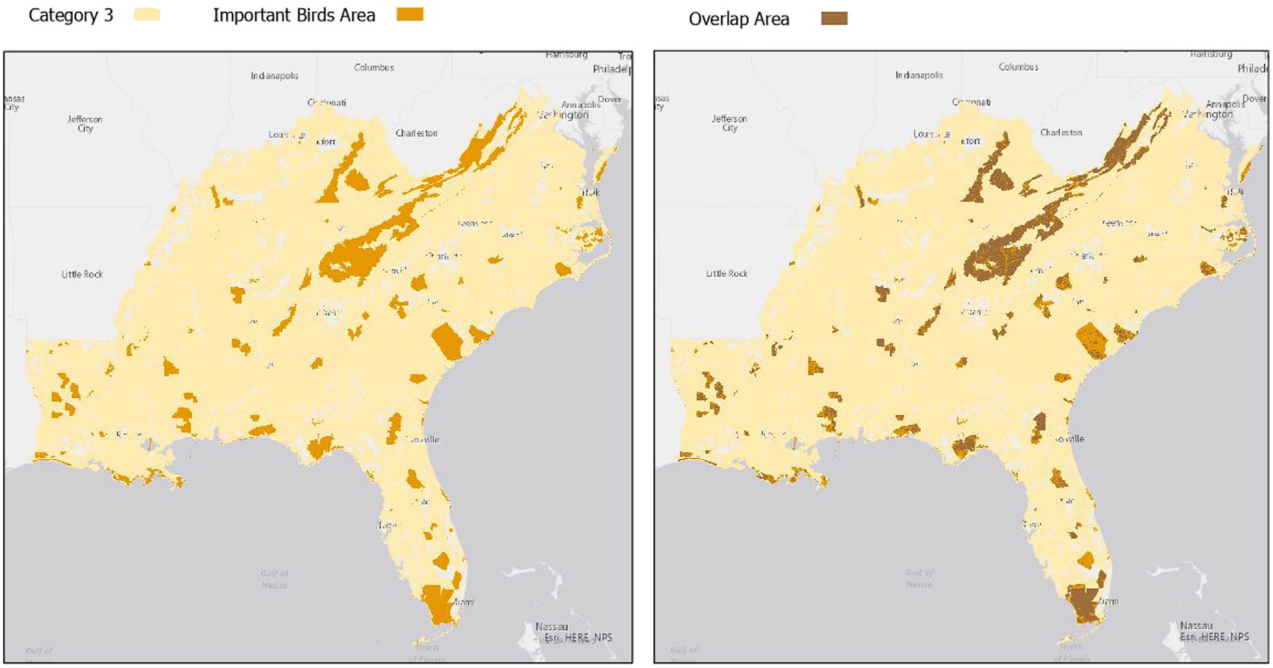

FIGURE B1. Comparison of TNC's Resilient and Connected Network dataset versus ABC's Wind Risk Assessment Map.

FIGURE B2. Relative elevation map, with areas in red that are higher than their surroundings. Riverbeds and valleys can be seen as non-red areas.

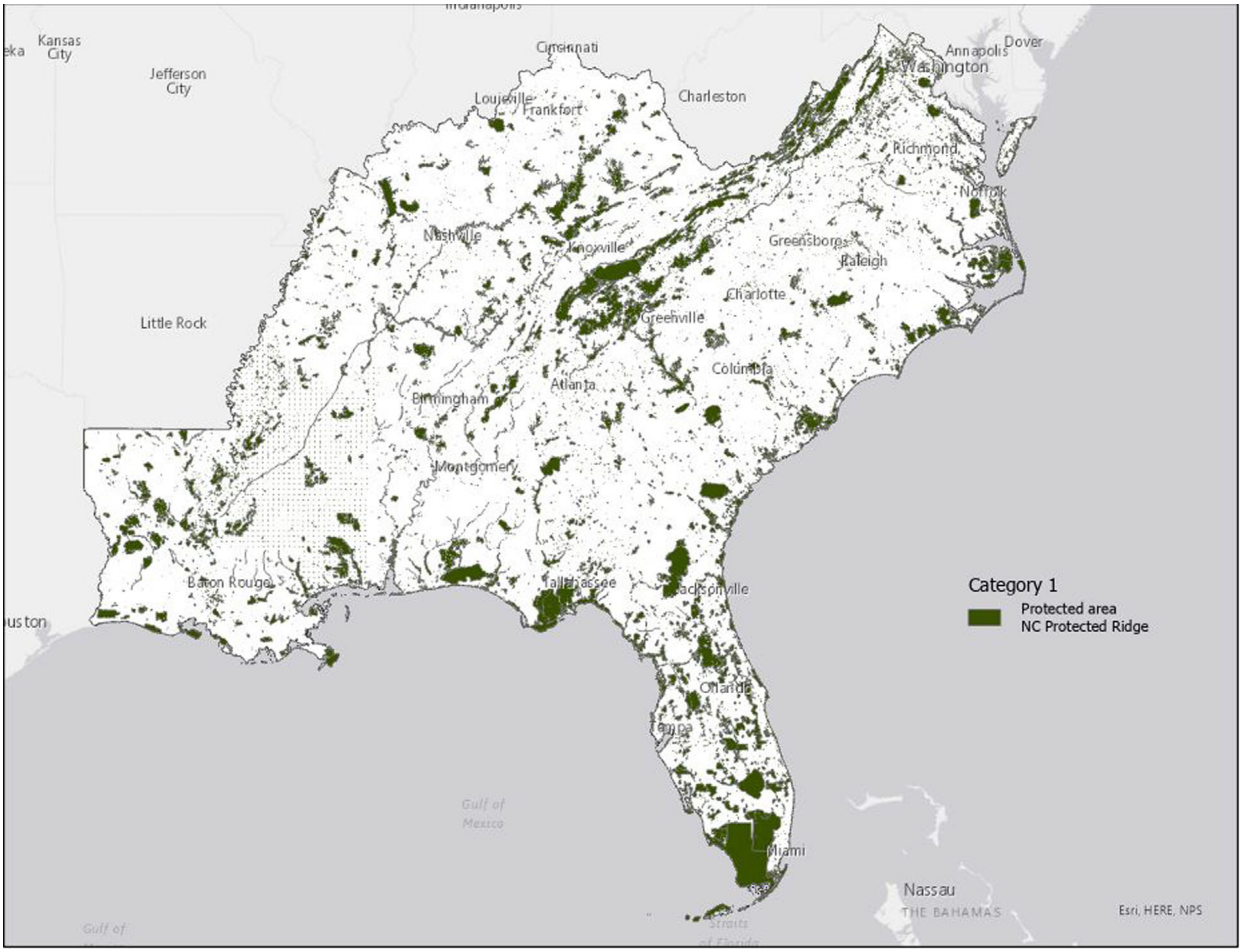

FIGURE B3. Unsuitable areas for wind power development identified by considering Category 1.

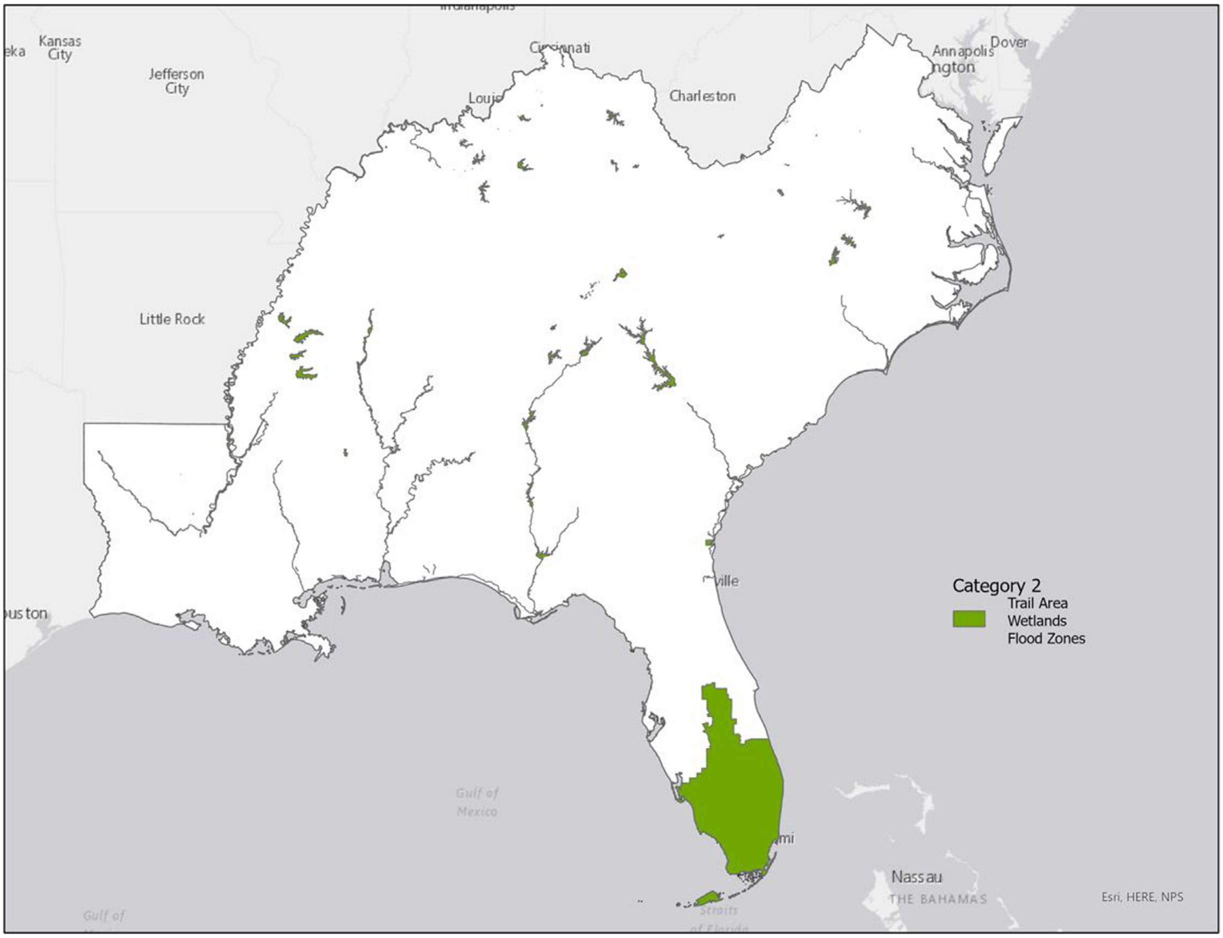

FIGURE B4. Unsuitable areas for wind power development identified by considering Category 2.

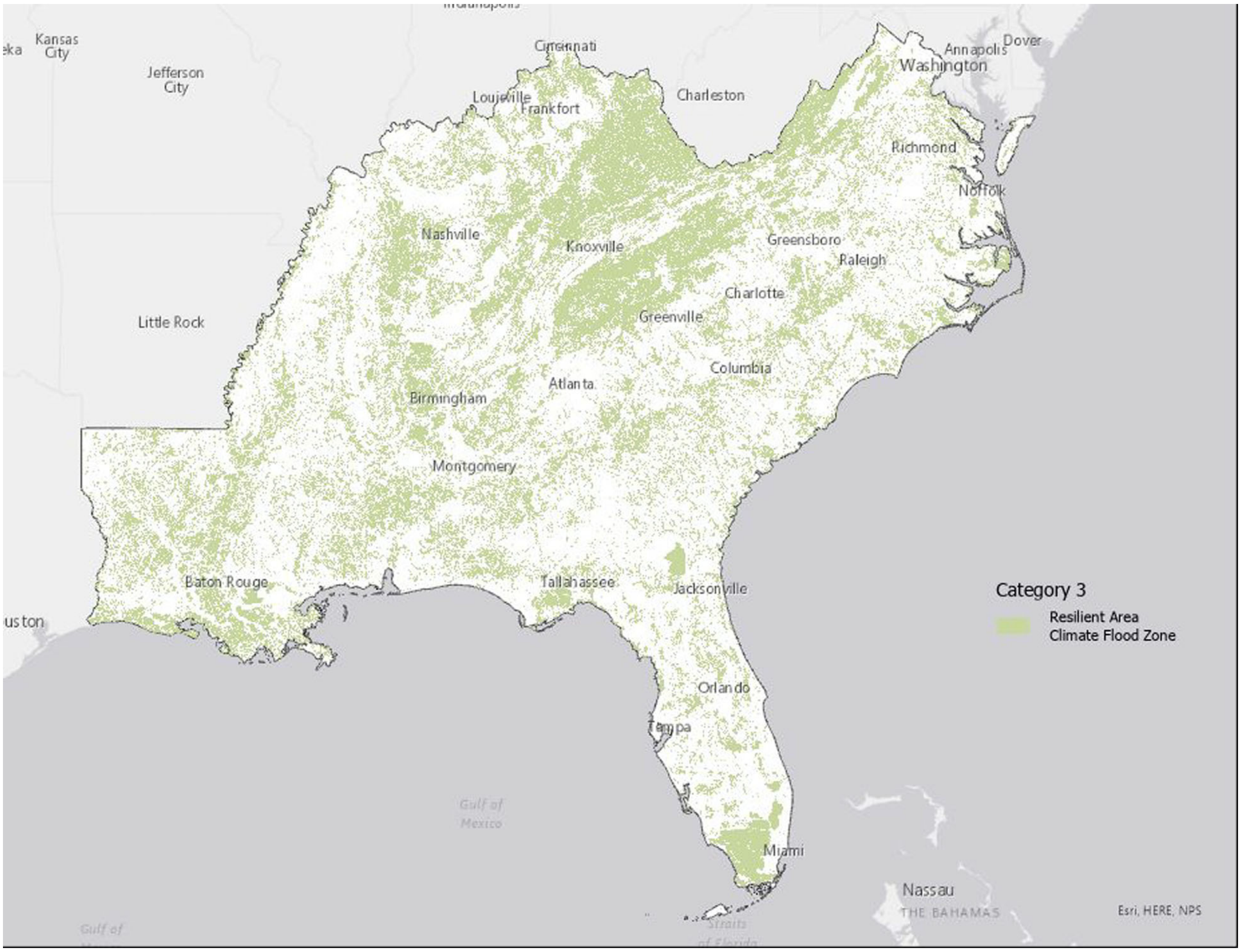

FIGURE B5. Unsuitable areas for wind power development identified by considering Category 3.

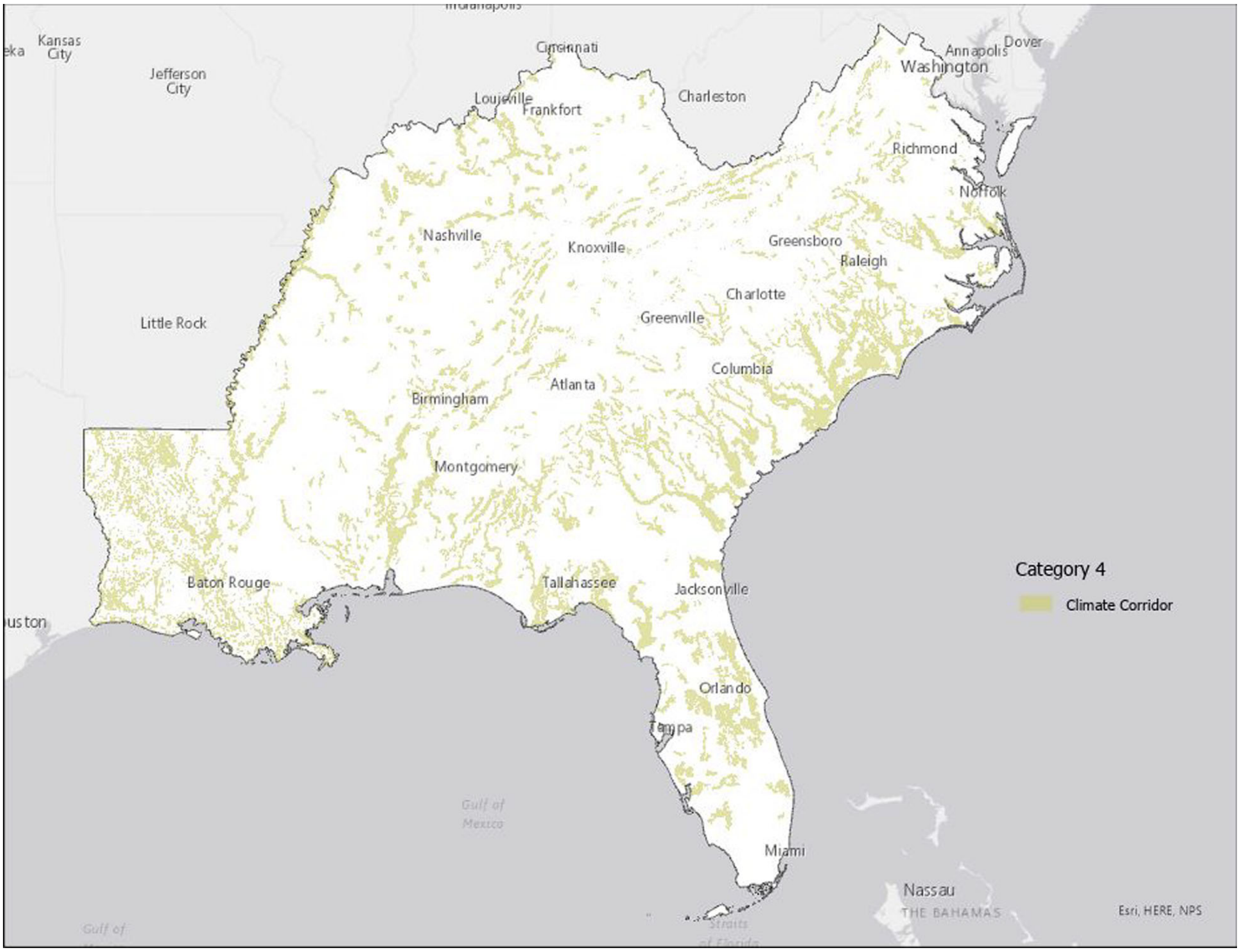

FIGURE B6. Unsuitable areas for wind power development identified by considering Category 4.

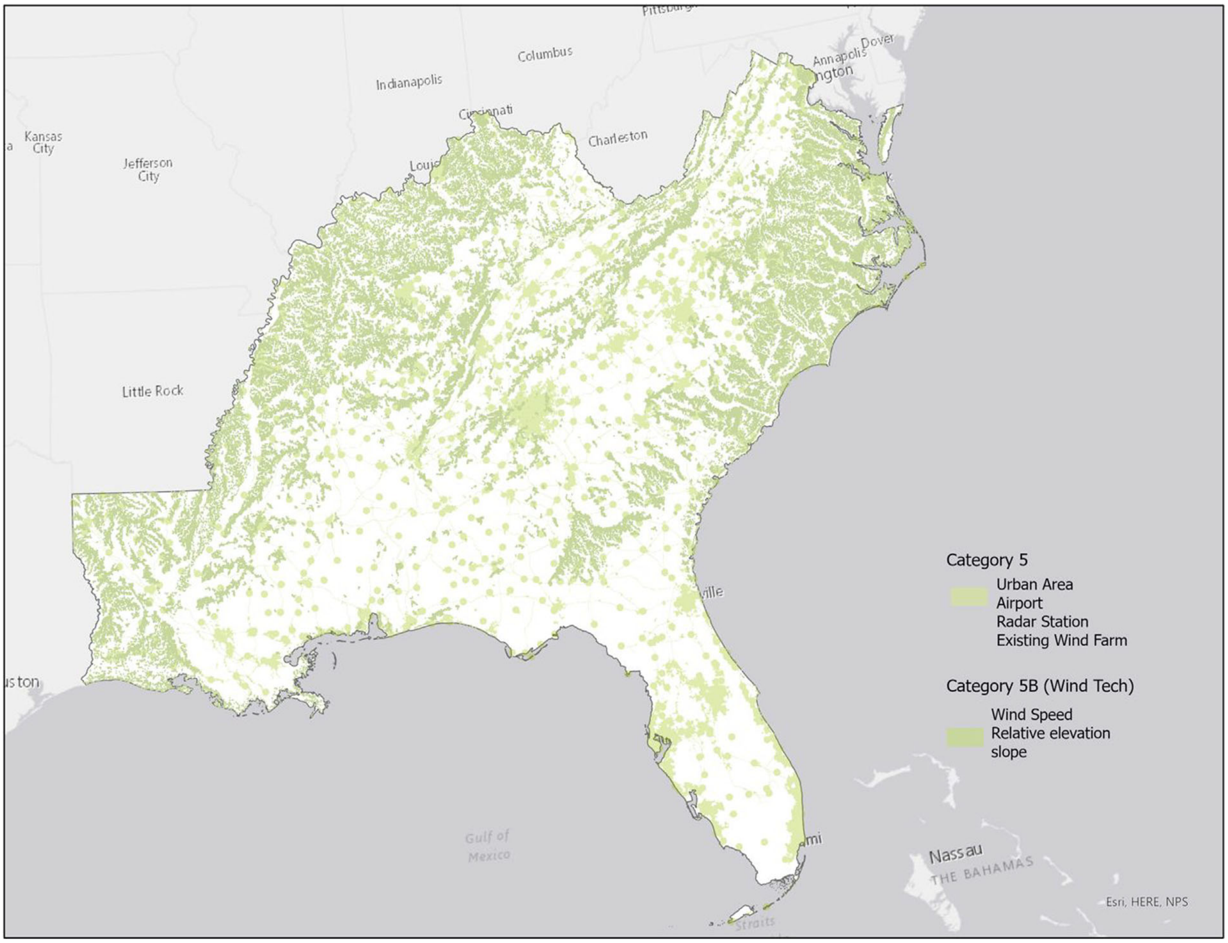

FIGURE B7. Unsuitable areas for wind power development identified by considering Category 5.

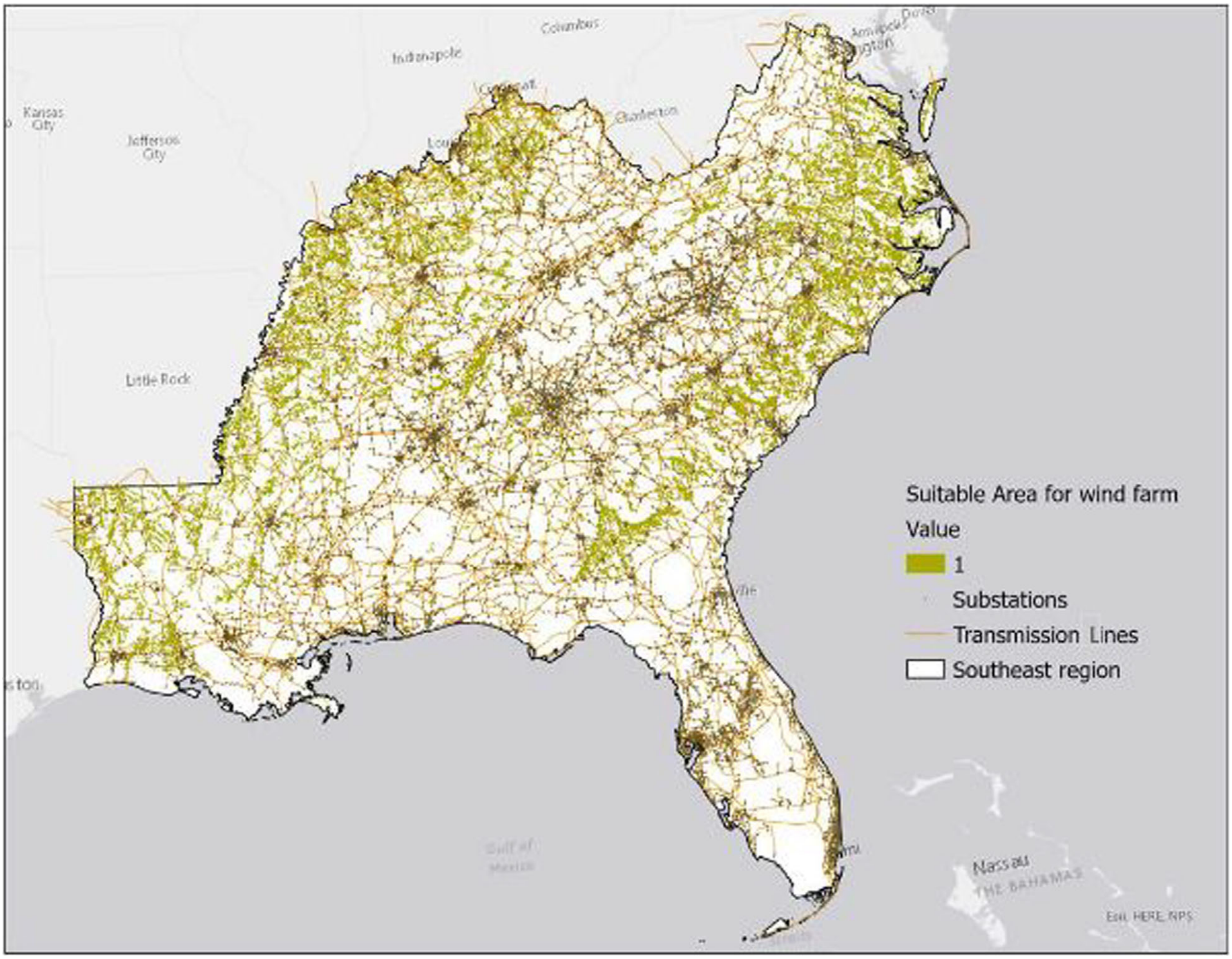

FIGURE B8. Electric power transmission lines and substations in the southeastern United States overlaid on the areas where wind energy development would have minimum environmental impact (green).

FIGURE B9. Areas where wind speed at 120 m height exceeds 6.5 m/s.[51]