

Original article

Integrating avian habitat suitability and modelled potential migration corridors into an ecological suitability zoning framework for sustainable wind energy deployment on the Qinghai–Tibet plateau

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ABSTRACT

Wind energy expansion is intensifying conflicts with biodiversity conservation in ecologically sensitive regions. Existing siting studies mainly assess individual wind projects, with limited attention to regional planning, and often emphasize construction and operational conditions but rarely incorporate wind-resource carrying capacity and broader ecological constraints. Reliance on official protected-area boundaries may overlook avian habitats and potential migration corridors. This study develops a regional ecological suitability zoning framework for wind-energy planning on the Qinghai–Tibet Plateau (QTP). Its innovation is to extend project siting to regional-scale zoning and incorporate identified priority avian conservation areas and potential migration corridors as explicit exclusion indicators. Using GIS-based multicriteria decision analysis, the framework includes eight exclusion indicators and nineteen graded indicators covering wind-resource endowment, construction and operational suitability, socioeconomic feasibility, importance of ecosystem functions, and eco-environmental sensitivity. Habitat suitability for 66 protected bird species was modelled using MaxEnt, priority conservation areas were identified using Marxan, and potential migration corridors were delineated using a least-cost approach. The analysis identified three high-suitability habitat clusters, 21 priority conservation areas, and 40 potential migration corridors. The QTP was classified into six suitability zones; policy-prohibited zones covered more than half of the region, whereas priority and suitable zones together accounted for only 11.3 %. Three existing wind farms in Qinghai overlapped policy-prohibited zones associated with avian conservation, revealing potential development–conservation conflicts. The framework provides spatial decision support for regional wind-energy planning and helps reconcile wind-energy development with avian biodiversity conservation.

Introduction

Fossil fuels still supply more than 80 % of global energy. Their combustion releases substantial greenhouse gases and air pollutants, intensifying climate change and ecosystem degradation, which highlights the pressing need to transition to clean energy [1]. Wind power has therefore become a central component of the low-carbon transition because of its technological maturity, low generation costs, and substantial resource potential. Renewables are projected to provide 61 % of

global electricity by 2030 and up to 85 % by 2050, led by solar photovoltaics and onshore wind power [2]. As the world's largest wind-power market, China generated 991.6 billion kWh of wind electricity in 2024 [3]. However, rapid capacity expansion has intensified concern about ecological impacts, particularly in biodiversity-sensitive landscapes [4,5]. Consequently, sustainable wind-energy development increasingly depends on siting strategies that reconcile energy production with ecological protection.

Current wind-farm siting studies primarily emphasize wind-resource

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availability and the feasibility of wind-farm construction and operation. They commonly consider wind speed or power density, terrain, road and grid accessibility, land use, settlements, protected areas, and planning restrictions [6,7]. These factors are commonly integrated using GIS-based multicriteria decision analysis (MCDA) to identify suitable areas for wind-energy development [8]. More recent integrated assessments combine technical, socioeconomic, and environmental criteria to delineate spatially suitable development areas [9]. These studies reflect growing recognition that wind-farm siting is a spatial coordination problem between wind-energy development and ecological conservation.

However, important limitations remain. First, most existing studies address wind-farm siting at the project or local scale and primarily evaluate wind-resource availability and the feasibility of construction, operation, and maintenance. Consequently, regional-scale ecological suitability zoning for the strategic planning of wind-energy development remains insufficiently explored, and ecosystem-function importance and continuous spatial variation in eco-environmental sensitivity are not consistently represented. Second, most existing studies have overlooked the effects of wind-energy development and construction on migratory birds. Some exclude avian protected areas but do not account for the potential barrier effects of wind-turbine development on migratory movements or its ecological impacts on migratory stopover and wintering sites [10–13]. Finally, the direct weighted aggregation of ecological and development criteria may obscure critical ecological constraints within a composite suitability score. These limitations may result in candidate development areas overlapping ecologically important habitats and potential migration corridors, increasing the risks of habitat loss and fragmentation, displacement, collision mortality, and disruption of migratory connectivity [14–17]. Incorporating ecological avoidance into early-stage regional planning is therefore essential for minimizing these risks throughout the life cycle of wind-energy facilities [18,19].

The Qinghai–Tibet Plateau (QTP) was selected as the case study because it combines substantial wind-energy potential with ecological importance and important avian habitats. Covering approximately 25 % of China's land area, the plateau contains about 26 % of the country's technical wind-energy potential [20]. In recent years, China's "dual carbon" commitments have positioned the QTP as a strategic frontier for large-scale renewable energy expansion. It also serves as a vital ecological barrier in Asia and a critical hub in the global network of migratory flyways, supporting more than 700 bird species, approximately half of China's avian diversity [21]. Of these, 18 are National Class I and 48 are National Class II protected species. The plateau is also characterized by pronounced eco-environmental sensitivity, including susceptibility to permafrost degradation, soil erosion, and desertification [22].

To address these limitations, this study develops an integrated ecological suitability zoning framework to support the coordination of regional wind-energy development with ecosystem and avian conservation. The framework integrates several complementary dimensions that represent different requirements of wind-energy planning. Wind-resource endowment indicates energy-production capacity, whereas construction, operational, and socioeconomic conditions determine whether development is practically feasible. Ecosystem-function importance and ecological environmental sensitivity are needed to identify areas where wind-energy development may conflict with critical ecological functions or where landscapes are particularly vulnerable to disturbance. To address the inadequate representation of migratory-bird conservation, modelled habitat suitability, avian priority conservation areas, and modelled potential migration corridors are incorporated into the zoning process. They represent important avian habitats and migration spaces beyond formal protected-area boundaries.

The main contributions of this paper are summarized as follows:

- (1) A regional-scale ecological suitability zoning methodology is developed for the strategic planning of wind-energy systems. It establishes an indicator system comprising eight exclusion indicators and nineteen graded evaluation indicators. The graded evaluation covers five foundational dimensions: wind-resource endowment, construction and operational suitability, socioeconomic feasibility, ecosystem-function importance, and eco-environmental sensitivity. This shifts wind-energy assessment from individual projects site selection toward macro-scale ecological suitability zoning.
- (2) The framework extends avian ecological screening beyond formal protected-area boundaries by jointly incorporating modelled habitat suitability, avian priority conservation areas, and modelled potential migration corridors. These spatial outputs serve as important ecological criteria for wind-energy zoning, enabling critical habitats and migration spaces outside existing protected areas to be identified and avoided during early-stage planning.
- (3) The framework translates multidimensional assessment into spatially differentiated planning decisions. Explicit exclusion rules are first applied to designate areas subject to ecological or governance constraints as policy-prohibited construction zones. This process reduces the risk that ecological constraints are obscured by favourable wind-resource or infrastructure conditions within an aggregated suitability score. The remaining areas are classified as priority, suitable, controlled, or restricted construction zones using multidimensional graded evaluation indicators. It thereby provides a basis for directing wind-energy development towards comparatively suitable areas.

Study area and data sources

Study area

The Qinghai–Tibet Plateau spans the Tibet Autonomous Region and Qinghai Province and extends into Xinjiang, Gansu, Sichuan, and Yunnan (Fig. 1). Covering approximately 2.6×10^6 km² and averaging over 4,000 m in elevation. It spans latitudes 26°00'12"N–39°46'50"N and longitudes 73°18'52"E–104°46'59"E. The QTP is the world's highest, largest, and most geomorphologically complex plateau [23]. Its distinctive geological history, topographic features, and diverse climate have collectively fostered the evolution of endemic mountain species, establishing the plateau as a global biodiversity hotspot and a critical habitat for many rare bird species [24,25]. More than 15 % of the plateau avifauna are classified as China's nationally protected (Class I or II priority-protected species). The plateau harbours three-quarters of China's avian diversity, underscoring its exceptional conservation value [26]. Moreover, it is the largest high-elevation ecosystem in the world and has abundant wind energy resources in China, and it is primarily distributed in the Tibet Autonomous Region and Qinghai Province. At a 100 m hub height, wind resources with an annual mean wind power density of ≥ 400 W/m² have a technically developable potential of 102 GW, representing 26 % of the national total in 2022.

Data sources and processing

Basic data

The net primary productivity (NPP), land use type, elevation, population distribution, and agricultural carrying capacity data used in this study were obtained from the Resource and Environment Science Data Platform, Chinese Academy of Sciences (<https://www.resdc.cn/>). The vegetation cover data, temperature, precipitation, and relative humidity data (spatial resolution: 0.1-degree grid) were sourced from the National Qinghai–Tibet Plateau Science Data Center (<https://data.tpdac.ac.cn/>). Soil physicochemical property data were obtained from the Harmonized World Soil Database (HWSD). The wind speed data were derived from

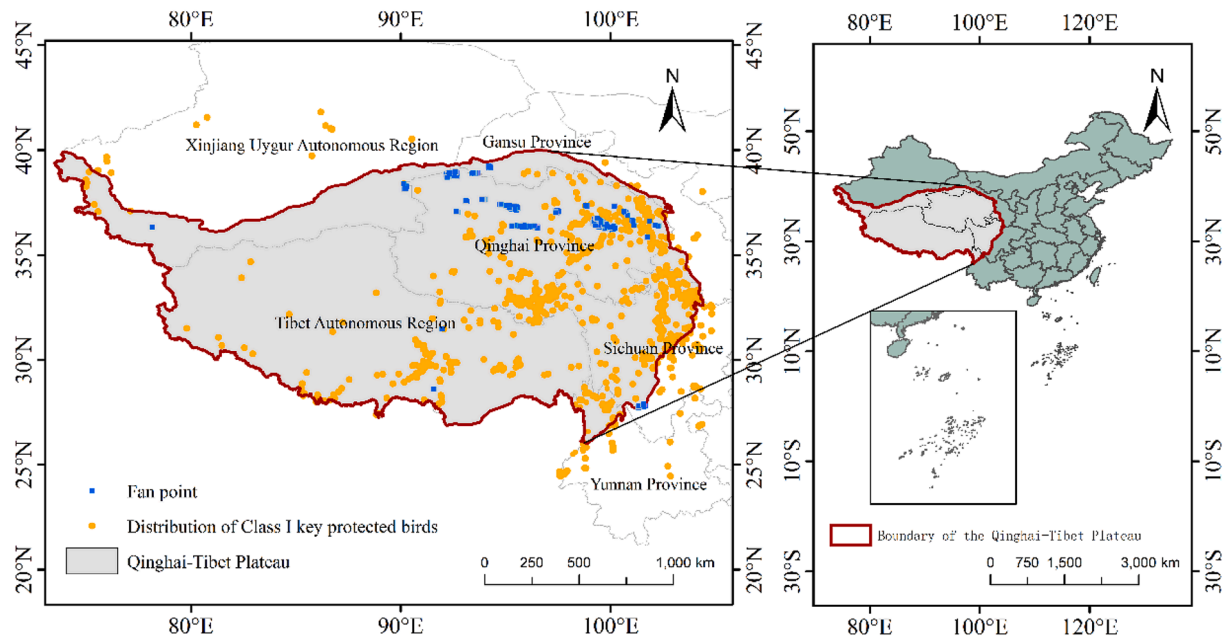


Fig. 1. Location map of the Qinghai-Tibet Plateau.

the National Earth System Science Data Center (<https://www.geodata.cn>) and have a spatial resolution of 1 km and monthly temporal resolution. Additional data sources and information are detailed in Table 1. Species occurrence records were obtained from the Global Biodiversity Information Facility (GBIF), as described in Section “Key protected bird species”.

Key protected bird species

The maximum entropy model (MaxEnt) requires species distribution point data and environmental variables as input data. Following the representativeness principle of systematic conservation planning theory, conservation targets should be those key species that represent local biodiversity. In this study, 66 key protected bird species on the QTP were selected on the basis of *Birds of the Qinghai–Tibet Plateau of China* and the *List of key protected wild animals in China*, combined with bird distribution coordinate points from the GBIF database. China classifies protected wildlife into two levels: Class I and Class II. Among them, the species classified as Class I include the Eastern Imperial Eagle (*Aquila heliaca*), White-tailed Sea-eagle (*Haliaeetus albicilla*), Sclater’s Monal (*Lophophorus sclateri*), Steppe Eagle (*Aquila nipalensis*), Black-necked Crane (*Grus nigricollis*), Chestnut-throated Partridge (*Tetraophasis obscurus*), Satyr Tragopan (*Tragopan satyra*), Bearded Vulture (*Gypaetus barbatus*), Grey

Peacock-Pheasant (*Polyplectron bicalcaratum*), Golden Eagle (*Aquila chrysaetos*), Saker Falcon (*Falco cherrug*), Chinese Monal (*Lophophorus lhuysii*), Sichuan Partridge (*Arborophila rufipectus*), Cinereous Vulture (*Aegypius monachus*), Greater Spotted Eagle (*Aquila clanga*), Pallas’s Fish Eagle (*Haliaeetus leucoryphus*), Himalayan Monal (*Lophophorus impejanus*), and Scaly-sided Merganser (*Mergus squamatus*). The Class II protected species are listed in Appendix A. S1.1. Detailed information on the 66 focal species and their occurrence distributions is provided in Appendix A, Section S1.1 (Table A-1 and Figs. A-1–A-2).

Prior to modelling, the georeferenced bird occurrence records obtained from GBIF were checked for coordinate validity and restricted to the QTP study area. To reduce spatial clustering and duplicate records, the occurrence data were spatially filtered by retaining only one record of each species within each 1 km × 1 km grid cell. Species with fewer than 10 occurrence records after filtering and spatial deduplication were excluded from subsequent modelling. The retained records were then standardized by species name, longitude, and latitude and spatially matched with the selected environmental raster layers in ArcGIS.

Methodology

The methodological framework of this study is illustrated in Fig. 2 and primarily comprises two major components. The first component involves modelling bird priority conservation areas and potential migration corridors (Sections “Avian suitability distribution simulation”–“Avian migration corridors”). The second component focuses on ecological suitability zoning (Section “Ecological suitability zoning”), encompassing the construction of an indicator system, hierarchical evaluation, and spatial overlay zoning.

Avian suitability distribution simulation

The distribution of suitable distributions for birds was estimated using the maximum entropy (MaxEnt) model, which is widely used for species distribution modelling [27–29]. Phillips et al. first proposed the use of maximum entropy theory to model the geographic distributions of species [30,31]. MaxEnt integrates multisource environmental variables and species data to predict the optimal distribution pattern under specific ecological constraints [32]. Its functional form is expressed as follows:

Table 1
Sources and descriptions of key datasets.

Type	Content	Resolution	Data source
Road network	National road network data (May 2024)	1:250000	OpenStreetMap
Power grid	Qinghai Province grid connection map (≥330 kV, 2022); Tibet Autonomous Region grid connection map (≥110 kV, 2021)	1:250000	Northwest Engineering Corporation Limited of POWERCHINA
Settlements	National spatial distribution dataset of settlements	1:250000	Geo-ecological Remote Sensing Network
Nature reserves	Nature reserve dataset	1:250000	National Specimen Information Infrastructure for Nature Reserves of China

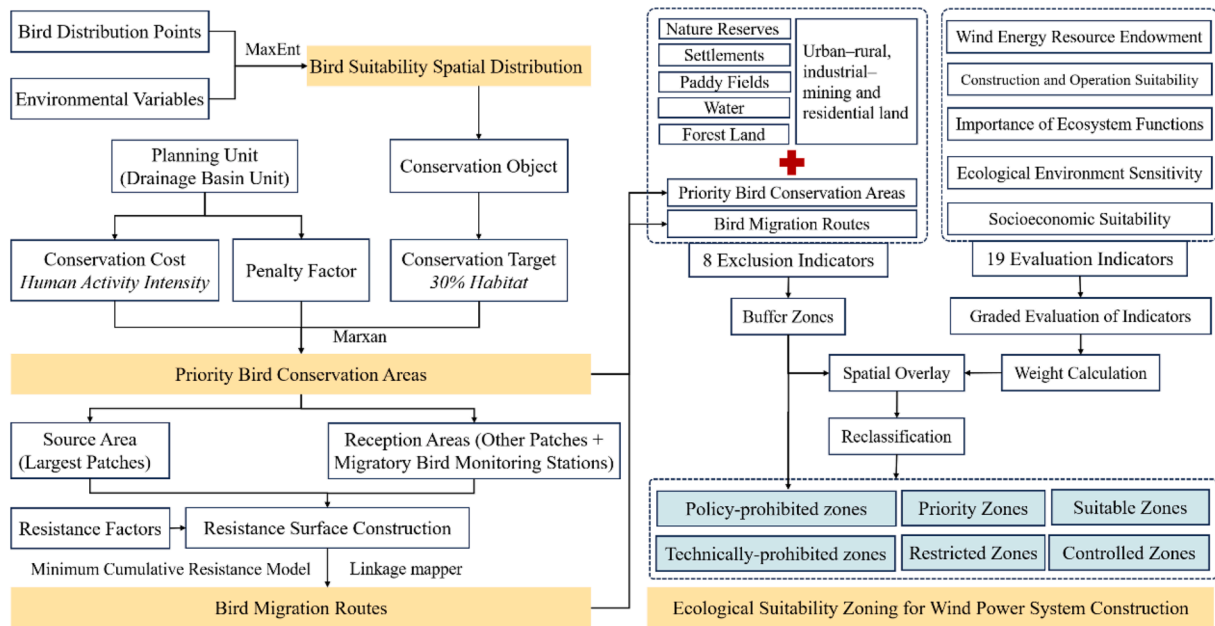


Fig. 2. Technical workflow.

$$S(p|p_0) = - \sum_i p_i \ln \frac{p_i}{p_{0i}} \quad (1)$$

where S represents entropy and p_0 denotes the prior distribution under known conditions. The objective of the model is to calculate the probability distribution of a species within a specific spatial area while satisfying the constraints and maximizing the entropy.

In this study, the distribution points of 66 key protected bird species on the QTP, along with environmental variables, were input into the MaxEnt version 3.4.1. model for simulation. The initial environmental variables set comprised three topographic variables (elevation, slope, and aspect) and 19 climatic variables (Table A-3 in Appendix A). Topographic conditions further shape migratory pathways by creating geographic barriers or modifying airflow patterns, while microclimatic differences generated by complex terrain influence the spatial distribution of species. On the other hand, seasonal variations in temperature and food availability are the primary drivers of bird migration. To reduce multicollinearity, Pearson correlation analysis was conducted among the climatic variables, after which eight climatic variables were retained together with the three topographic variables for modelling (Table A-4 in Appendix A).

MaxEnt was run using automatic feature selection and cloglog output, while the remaining parameters were retained at their default settings. Model performance was assessed using the area under the receiver operating characteristic curve. For each species, 80 % of the occurrence records were randomly used for model training, while the remaining 20 % were withheld for validation. Each model was run ten times, and the mean prediction was adopted as the final result. According to the adopted evaluation criteria, AUC values of 0.9–1.0, 0.8–0.9, and 0.7–0.8 indicate excellent, good, and useful discriminatory performance, respectively [33].

The predicted suitability values ranged from 0 to 1. Following relevant studies and expert-based grading systems, suitability was classified into five categories: unsuitable (0–0.2), low suitability (0.2–0.4), moderate suitability (0.4–0.6), high suitability (0.6–0.8), and optimum suitability (0.8–1.0) [34]. The resulting habitat-suitability surfaces were subsequently visualized and processed in ArcGIS. The species habitat suitability distributions were used to quantify suitable-habitat area within individual watershed planning units, providing the basis for setting conservation targets in Marxan and identifying priority conservation areas. The resulting priority areas were subsequently used

to define ecological source areas for potential migration-corridor modelling. Both the priority conservation areas and the modelled corridors were then incorporated into the ecological suitability zoning for wind-energy development.

Priority avian conservation areas

This study identified priority bird conservation zones on the basis of systematic conservation planning (SCP) theory. Priority avian conservation areas were identified using Marxan, a SCP model that selects planning units to meet biodiversity targets while minimizing conservation costs and spatial fragmentation [35,36]. The objective function is expressed as follows:

$$\sum_{PUs} Cost + BLM \sum_{PUs} Boundary + \sum_{ConValue} SFP \times Penalty + CostThresholdPenalty(t) \quad (2)$$

where $Cost$ represents the total cost of all planning units; BLM (boundary length modifier) is a coefficient that balances boundary length and cost consumption within the evaluation function; SFP denotes the species penalty factor; $Penalty$ is the corresponding penalty value; and $CostThresholdPenalty$ is applied when the predefined cost threshold is exceeded, which was not considered in this study.

In terms of the parameter settings, watershed units were adopted as the planning units because they provide ecologically meaningful boundaries for representing spatial heterogeneity and landscape processes. Watershed units were delineated from the digital elevation model using the hydrological-analysis tools in ArcGIS. Considering China's "30–30 target" to protect 30 % of the terrestrial area, the conservation target was set at 30 %, indicating that the results must cover at least 30 % of the habitat area for each bird species. The human activity intensity for each watershed unit was used as the conservation cost. Human activity intensity was represented using the Human Footprint Index derived from the global annual terrestrial Human Footprint dataset [37]. The BLM was calibrated using the *Estimate BLM* and *Graph BLM* functions in ArcMarxan 2.0.2. Candidate values ranging from 0 to 100 at intervals of 10 were evaluated. Based on the trade-off between total boundary length and relative conservation cost (Fig. A-5 in Appendix A), $BLM = 20$ was selected to balance the spatial compactness and cost-effectiveness of the priority-area network. Marxan outputs

included irreplaceability scores and the resulting priority conservation areas. Higher values represented stronger human disturbance and, consequently, greater potential conservation costs and conflicts.

Avian migration corridors

In this study, potential bird migration corridors were modelled using the minimum cumulative resistance model combined with linkage mapper. First, the bird priority conservation patches and the surrounding 98 migratory bird monitoring stations representing breeding, wintering, or stopover sites, were designated as ecological source areas [38,39]. Secondly, to characterize migration resistance, we selected four natural geographic variables (elevation, slope, vegetation cover, and water body density) and seven ecological stressor variables (cropland density, construction land density, railway density, expressway density, and the densities of primary, secondary, and tertiary roads). All the factors were assigned equal weights to construct a composite resistance surface.

Migration corridors were simulated using least-cost path analysis based on resistance surfaces derived from habitat suitability modelling. Using ArcGIS Cost Distance and Linkage Mapper tools, the minimum cumulative resistance values and path directions between sources and sinks were calculated. Linkage Mapper then generated the potential ecological corridors with the lowest cumulative resistance, which were identified as the most likely migration corridors of birds across the QTP.

Ecological suitability zoning

Development of the indicator system

Ecological suitability zoning for wind power system development should adhere to the principle of achieving coordinated economic, social, and ecological benefits. To ensure scientific rigor and practical applicability, this study systematically reviewed 25 high-quality articles on wind farm siting and ecological suitability zoning published in Science Direct since 2001.

Eight exclusion indicators and nineteen evaluation indicators were identified on the basis of a comprehensive consideration of (1) wind resource endowment; (2) China's land space management factors encompass ecological function zoning, ecological redlines, environmental quality baselines, and resource utilization ceilings. (3) Ecological impacts of large-scale wind power systems; (4) natural geographical factors (topography, land cover types, etc.); (5) socioeconomic factors (transport accessibility, grid construction density, etc.); (6) potential bird conservation areas and migration corridors. This formed the ecological suitability zoning indicator system for plateau-based wind power development (Table 2).

Evaluation indicators are used to classify suitability levels and cover five dimensions: wind energy resource endowment, construction and operation suitability, ecosystem functional importance, ecological environmental sensitivity, and socioeconomic suitability.

Indicator weights were determined using the entropy weight method, an objective weighting approach based on information entropy principles. The calculation steps are as follows [40]:

$$P_{ij} = R_{ij} / \sum_{i=1}^m R_{ij}, (0 < P_{ij} < 1) \quad (3)$$

$$e_i = -k \sum_{i=1}^n P_{ij} \ln(P_{ij}) \quad (4)$$

$$W_i = \frac{1 - e_i}{\sum_{i=1}^n 1 - e_i} \quad (5)$$

where $k = 1/\ln n$.

Considering the potential disturbance to birds from hub height and rotor blades during turbine operation, "distance from bird migration corridors" was introduced as an evaluation indicator within the construction and operation suitability dimension. Surveys indicate that

Table 2

Evaluation indicator system for ecological suitability zoning of wind power development.

Guideline Level	Number	Indicator Level
Wind energy resource endowment	1	Wind energy carrying capacity
Construction and operation suitability	2	Stability of wind energy supply
	3	Land use
	4	Elevation
	5	Road network density
	6	Power grid density
	7	Distance from settlements
	8	Slope
	9	Distance from bird migration corridors
Importance of ecosystem functions	10	Importance of water source conservation function
	11	Importance of soil and water conservation function
	12	Importance of windbreak and sand fixation function
	13	Importance of biodiversity maintenance function
Ecological environmental sensitivity	14	Land desertification sensitivity
	15	Soil erosion sensitivity
	16	Landslide disasters sensitivity
	17	Freeze-thaw erosion sensitivity
Socioeconomic suitability	18	Population density
	19	Agricultural capacity

most key protected terrestrial species on the QTP, such as ungulates, are already confined within designated nature reserves and have been excluded from construction zones.

Exclusion indicators are used to delineate and exclude areas where wind power development is prohibited (see Appendix A. S2, Table A-6), including bird priority conservation areas and buffer zones generated from migration corridors.

Hierarchical evaluation of the evaluation indicators

Given the numerous indicators involved in assessing ecosystem function importance, ecological environmental sensitivity, and socioeconomic suitability, their formulas, definitions, classification standards, and detailed explanations are provided in Appendix A. S2. The main text presents only the evaluation logic and the mapping of classification levels.

Wind energy resource endowment. Considering the average hub height of wind turbines at present, we used 100 m wind speed data from the QTP for 2022 to calculate the wind energy resource carrying capacity (WRCC). The WRCC for each grid cell is defined as the maximum available wind energy, which is derived from the wind power density between the cut-in and cut-out wind speeds, the maximum conversion efficiency of the wind power system, and the annual operating hours. The unit is kWh/m² per year. Its calculation formula is as follows, with detailed computational steps and definitions of symbols and units provided in Appendix A. S2.1:

$$WRCC = \frac{1}{2} \rho A C_p \times \int_{v_{in}}^{v_{out}} \tilde{v}^3 f(\tilde{v}) d\tilde{v} \quad (6)$$

Wind energy resource variability was assessed using the coefficient of variation (CV) derived from 100 m wind speed data over the QTP for the year 2022, which reflects supply stability. Lower variability indicates higher reliability and more stable power output from wind power systems.

$$V_{wind} = \frac{1}{\bar{v}} \sqrt{\frac{1}{T} \sum_{i=1}^T (v_i - \bar{v})^2} \quad (7)$$

where V_{wind} represents the coefficient of variation of wind energy resources over one year; the parameters T , v_i and $\bar{v}$ represent the coefficient

cient of variation, total number of days in a year, daily mean wind speed, and annual mean wind speed, respectively.

Both the WRCC and the wind energy supply stability were visualized in ArcGIS. The indicators were classified into five suitability levels using the natural breaks method, corresponding to the ecological suitability for wind power system construction: optimum suitability, high suitability, moderate suitability, low suitability and unsuitable.

Construction and operation suitability. In this study, hierarchical evaluation criteria for construction and operation suitability were established (Table 3), while evaluation standards for land use indicators are detailed in Appendix A. S2.2 with Table A-5 [41]. These criteria were developed with reference to current Chinese industry standards for wind farm construction [42], relevant policies, previous zoning studies [7,43–47], expert consultations, and the natural conditions of the QTP. All the indicators were classified into six levels, namely, optimum suitability, high suitability, moderate suitability, low suitability, and unsuitable and technically inhibited zones, which were assigned scores ranging from 5 to 0.

To account for potential disturbance to migratory birds caused by turbines, a 1000 m buffer was applied, and the data were further divided into equal-interval distance classes [44]. Greater distance from modelled migration corridors indicates a lower likelihood of disturbance and thus higher construction suitability. Details of the migration corridor modelling are provided in Section “Hierarchical evaluation of indicators”.

Importance of ecosystem functions. Following the Guidelines for Delineating Ecological Protection Redlines, we quantified ecosystem functional importance using the NPP quantitative assessment method. Four key indices were selected—the Water Retention Service Capacity Index, the Soil and Water Conservation Service Capacity Index, the Windbreak and Sand Fixation Service Capacity Index, and the Biodiversity Maintenance Service Capacity Index—to evaluate the importance of each function. Each indicator was classified into five importance levels using natural breaks: extreme importance, high importance, moderate importance, low importance and no importance. Areas with higher functional importance were assigned lower suitability for wind power development, thus corresponding to ecological suitability levels of unsuitable, low suitability, moderate suitability, high suitability and optimum suitability.

Ecological environmental sensitivity. Sensitivity indicators, including soil erosion sensitivity, land desertification sensitivity, landslide disaster sensitivity, and freeze–thaw erosion sensitivity, were similarly classified into five sensitivity levels: extremely sensitive, highly sensitive, moderately sensitive, slightly sensitive and insensitive. They were then converted into wind power construction suitability levels: unsuitable, low suitability, moderate suitability, high suitability and optimum unsuitable.

Socioeconomic suitability. Similarly, population density and agricultural carrying capacity were classified using the natural breaks method. Higher values correspond to lower ecological suitability for wind power

development.

Spatial overlay zoning

We applied a multi-attribute comprehensive evaluation method that integrates Boolean operations with multivariate computation. This approach supports determining weights using various subjective and objective weighting approaches and performing comprehensive quantitative analysis [48,49].

We first overlaid 19 evaluative indicator layers according to their weights, which were obtained via the entropy method (Table 2). The overlaid evaluative indicators were subsequently reclassified using quantiles adjusted by expert judgement: 20 %, 40 %, 70 %, and 85 %. Next, the QTP was sequentially divided into priority construction zones, suitable construction zones, controlled construction zones, restricted construction zones, and technically prohibited construction zones. Areas identified by exclusionary indicators were designated as policy-prohibited construction zones.

Specifically, priority construction zones exhibit strong resource endowments, favourable construction and operational conditions, minimal social–environmental disturbance, and low ecological protection importance, resulting in the highest degree of construction suitability. These zones exhibit the highest suitability for wind power system development, followed by suitable construction zones and controlled construction zones. Restricted construction zones are characterized by high ecological importance, limited resource advantages, low construction and operational suitability, and substantial social–environmental disturbance, making them inappropriate for large-scale wind energy development. Prohibited zones (technical and policy level) should retain their pristine habitats and be entirely excluded from renewable-energy development activities.

Results

Avian suitability distribution modelling

Environmental variables

Following Pearson’s correlation analysis, variables exhibiting strong pairwise correlations ($r > 0.8$) were excluded (Table A-4 in Appendix A). The ultimate variables used in the MaxEnt model included annual mean temperature, monthly mean diurnal temperature range, isothermality, temperature seasonality (coefficient of variation), annual precipitation, precipitation of the driest month, precipitation seasonality (coefficient of variation), and precipitation of the coldest quarter.

Avian suitability distribution

The suitability distribution for Class I key protected species on the QTP is shown in Fig. 3, with the distribution results for Class II species presented in Appendix A, Fig. A-4. The AUC values used for model evaluation for all 66 key protected bird species ranged from 0.765 to 0.995. Overall, 90 % of the models achieved AUC values ≥ 0.80 , including 58 % that achieved values ≥ 0.90 . Species-specific AUC values are reported in Table A-12 in Appendix A.S3.

Among Class I key protected birds on the QTP, as shown in Fig. 3, the optimum and high-suitability areas are concentrated in the eastern and southeastern plateaus. The three main clusters are Qinghai Lake and its

Table 3
Evaluation criteria for selected indicators of construction and operation suitability.

Elevation (m)	Road network density (m/ m ²)	Power grid density (Km/ m ²)	Distance from settlements (Km)	Slope (°)	Distance from bird migration corridors (m) [44]	Score
≤1500	> 0.06	> 0.02	> 25	≤6	>3000	5
1500 ~ 2500	0.04 ~ 0.06	0.01 ~ 0.02	20 ~ 25	6 ~ 12	2500 ~ 3000	4
2500 ~ 3500	0.02 ~ 0.04	0.005 ~ 0.01	15 ~ 20	12 ~ 18	2000 ~ 2500	3
3500 ~ 4500	0.002 ~ 0.02	0 ~ 0.005	10 ~ 15	18 ~ 24	1500 ~ 2000	2
4500 ~ 5500	≤0.002	0	2 ~ 10	24 ~ 30	1000 ~ 1500	1
> 5500	–	–	≤2	> 30	<1000	0

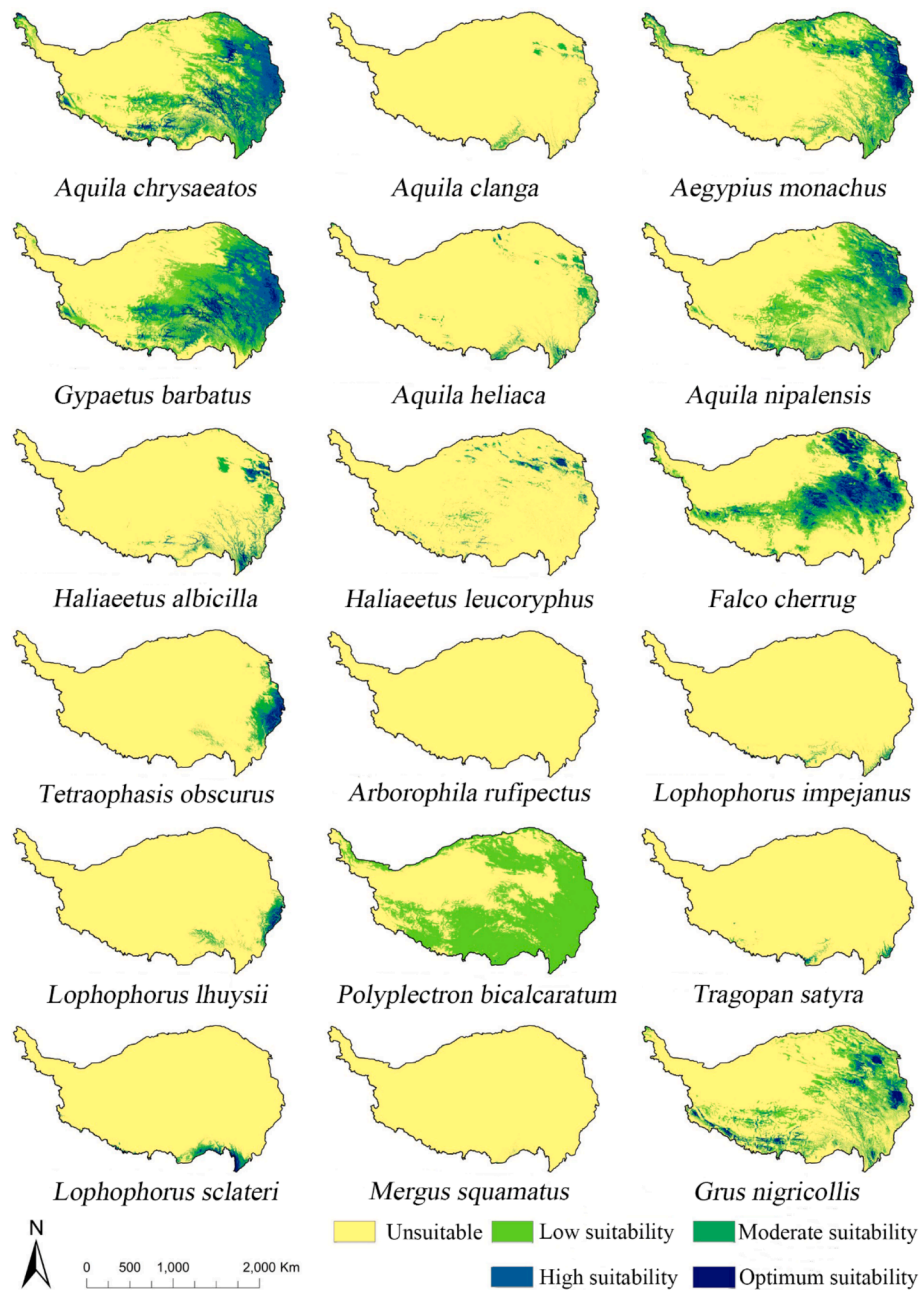


Fig. 3. Simulated spatial distribution of Class I key protected birds.

surrounding regions, the Sichuan-Tibet region, and the Hengduan Mountains with the Three Parallel Rivers region. Golden Eagle, Cinereous Vulture, Bearded Vulture, Steppe Eagle, and Saker Falcon exhibit relatively extensive suitable distribution ranges.

The results indicate that suitable bird habitats are unevenly distributed across the study area, forming three major high-suitability hotspots: the Qaidam Basin – Qinghai Lake – Gonghe Basin – Hehuang Valley, the Sichuan-Tibet Plateau – Hengduan Mountains-Three Parallel Rivers, and southern Tibet regions along the southern Himalayas. These high-suitability regions represent critical areas for biodiversity conservation and should be carefully considered in wind energy planning. These regions serve as critical stopover and wintering sites during migration, allowing birds to replenish energy reserves and safely endure the cold season.

Priority avian conservation areas and migration corridors. The simulated

priority bird conservation areas and migration corridors on the QTP are shown in Fig. 4(a), whereas the size of each priority area is shown in Fig. 4(b). We identified 21 priority bird conservation areas, primarily located across the eastern and southeastern QTP, within the relatively low-elevation regions of Qinghai and Sichuan Provinces. These priority conservation areas serve as key constraints when suitable areas for wind energy development are identified.

Ranked by area, Area 1, covering 165,000 km², is situated around Qinghai Lake and the Gonghe Basin. Area 2, located in the west-central Sichuan province, covers 88,000 km². Several smaller priority zones are distributed across the central plateau and along the southern and northern margins of the QTP. Although smaller in size, these areas often serve as key stepping-stone habitats that maintain ecological connectivity between breeding, wintering, and stopover sites along migration corridors.

A total of 40 bird migration corridors were identified, primarily

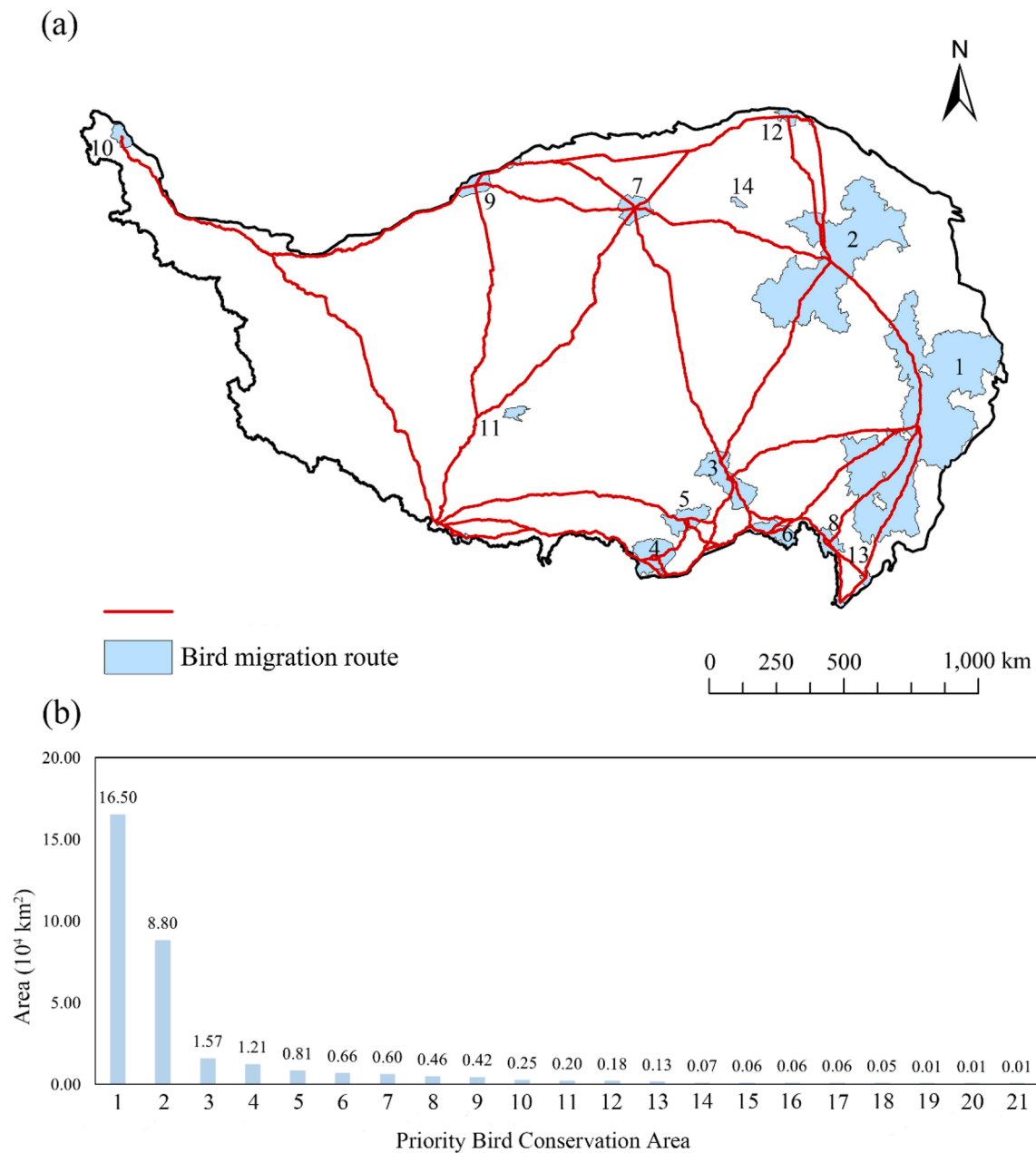


Fig. 4. (a) Spatial distribution of priority bird conservation areas and migration corridors; (b) Area statistics for each priority bird conservation areas.

originating from priority conservation areas in the eastern QTP. These corridors connect with other scattered protected areas to form a comprehensive migration network across the plateau.

Hierarchical evaluation of indicators

The entropy weights of the 19 evaluation indicators are presented in Table A-X. Power grid density received the highest weight (0.0847), followed by elevation (0.0715). Population density and agricultural capacity received the lowest weights, at 0.0371 and 0.0372, respectively. The weight assigned to distance from potential bird migration corridors was 0.0402. A hierarchical evaluation of the 19 indicators for wind power system construction is presented in Fig. 5. For wind energy resource endowment (Fig. 5a), high carrying capacity occurred mainly in the Qiangtang Plateau, the Qaidam Basin, and the southern Qingnan Plateau south of the Kunlun Mountains, while the most stable wind resources were concentrated in the northwestern QTP, the Qaidam Basin,

and parts of the eastern plateau.

Construction and operation suitability (Fig. 5b) was highest in flat, sparsely used areas, particularly in the Qaidam Basin and the Qiangtang Plateau, as well as regions with relatively dense road and power grid networks. In contrast, elevation constraints render most of the Gangdise and Himalayan Mountains unsuitable or technically prohibited for construction. Additionally, southern Tibet and northwestern Yunnan were mainly classified as policy-prohibited zones, encompassing forests, grasslands, croplands, densely populated settlements, and buffer zones along bird migration corridors.

Low development suitability associated with ecosystem function importance are concentrated in northwestern Yunnan and west-central Sichuan (Fig. 5c). Southern Tibet and the Three Parallel Rivers region exhibit extremely high water conservation and soil retention functions. Similarly, the Gonghe Basin in Qinghai and the Qiangtang grasslands play significant roles in terms of windbreak and sand fixation.

With respect to ecological sensitivity (Fig. 5d), high soil-erosion

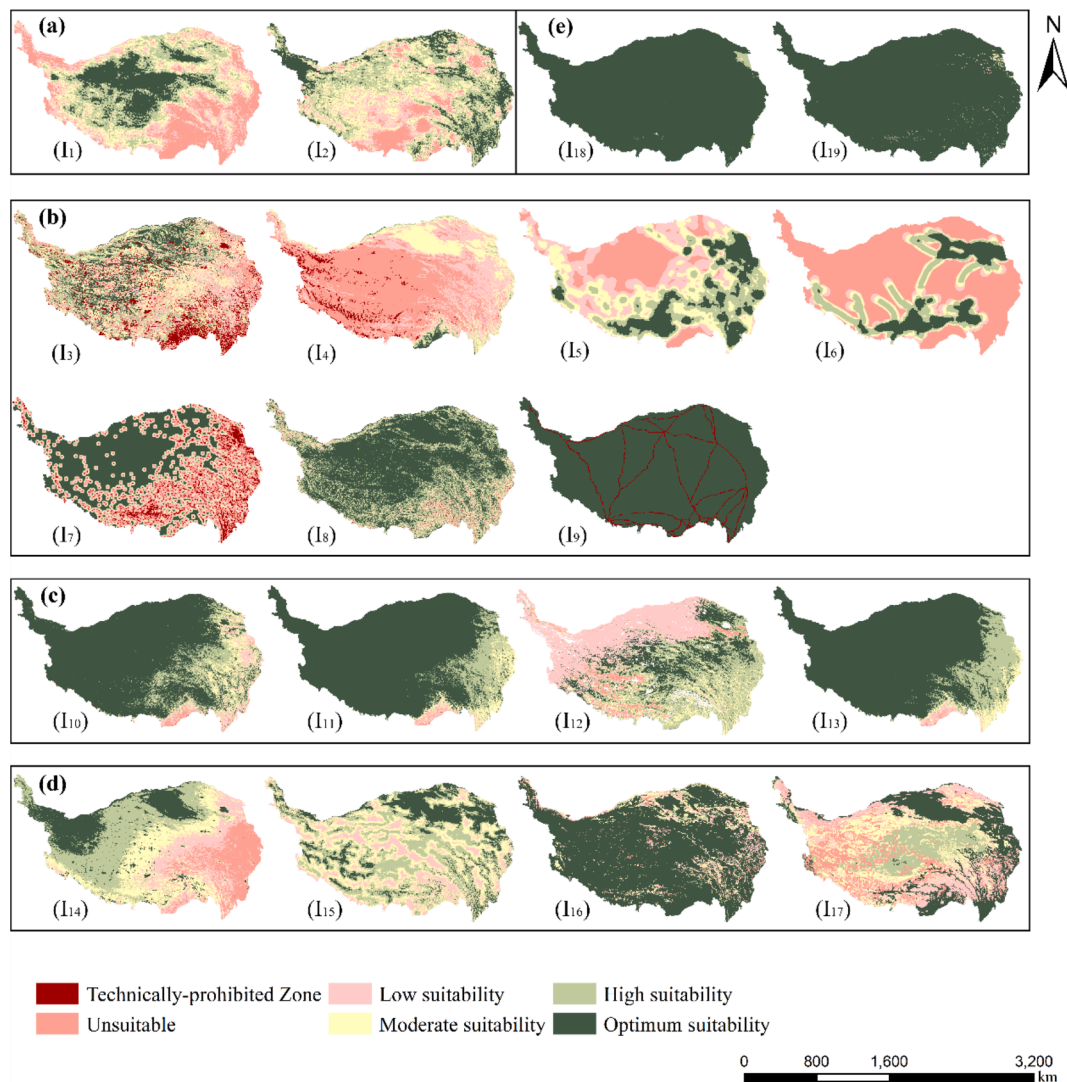


Fig. 5. Classification results of the 19 evaluation indicators used for ecological suitability assessment of wind power development. (a) Wind energy resource endowment indicators (I_1 – I_2); (b) construction and operation suitability indicators (I_3 – I_9); (c) ecosystem function importance indicators (I_{10} – I_{13}); (d) ecological environmental sensitivity indicators (I_{14} – I_{17}); and (e) socioeconomic suitability indicators (I_{18} – I_{19}). All indicator correspond to those listed in Table 2, and were classified into six suitability levels: technically prohibited zone, unsuitable, low suitability, moderate suitability, high suitability, and optimum suitability.

sensitivity was concentrated in southern Tibet and the Three Parallel Rivers area, whereas areas susceptible to rocky desertification are scattered across Qinghai, central-western Sichuan, eastern Tibet, and the Three Parallel Rivers region. Freeze–thaw erosion sensitivity occurred mainly along mountain ranges and high-elevation zones, whereas high landslide sensitivity was concentrated in the Gangdise and Tanggula Mountains, along with river corridors. These environmentally fragile areas are therefore considered unsuitable for large-scale infrastructure development.

From a socioeconomic perspective (Fig. 5e), much of the QTP was classified as highly suitable for wind power development because of its low population density and limited agricultural carrying capacity. Conversely, low-elevation river valleys, such as the Huangshui Valley, are densely populated and have greater agricultural capacity; thus, they are classified as moderate to low-suitability zones that impose certain constraints on wind power development.

Overall, the results reveal a clear spatial differentiation in development potential. Areas with high development suitability are distributed mainly in the Qaidam Basin, the Qiangtang Plateau, and parts of northern Qinghai. These regions possess favourable wind resources, relatively flat terrain, sparse population, and limited ecological

restrictions, making them suitable candidates for future wind power deployment. In contrast, areas with low or restricted suitability are primarily concentrated in southern Tibet, the Three Parallel Rivers region, and central-western Sichuan. These areas provide critical ecosystem services and habitats for numerous species, necessitating stricter protection measures. These contrasting spatial patterns highlight the need to balance wind energy development with ecological conservation across the QTP.

Ecological suitability zoning for wind power system development

Priority zones and suitable zones for wind power construction occupy relatively limited areas, totalling approximately 294,600 km² and accounting for approximately one-tenth of the QTP. Priority zones cover 157,300 km² and are primarily distributed on the northeastern plateau, with smaller scattered areas on the southwestern plateau (Fig. 6). Qinghai and Tibet contain the greatest priority areas, accounting for 106,400 km² and 33,600 km², respectively. Among these regions, the northwestern Qaidam Basin forms a large and continuous priority zone with favourable wind resources, relatively flat terrain, and good grid accessibility. Surrounding these areas, suitable, controlled,

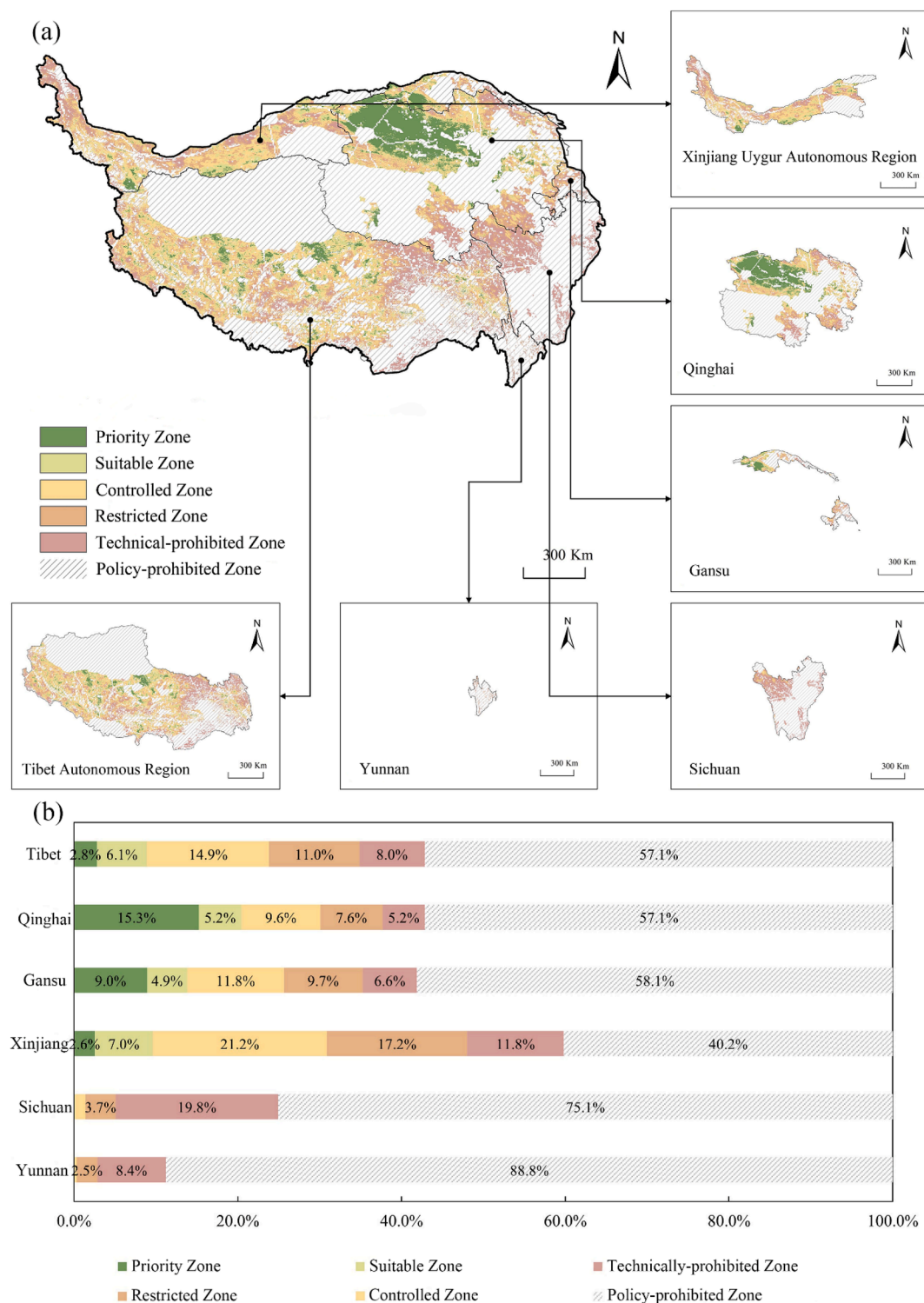


Fig. 6. Ecological suitability zoning of wind power system construction on the Qinghai-Tibet Plateau. (a) Distribution of suitability types by province/region; (b) area proportion of each suitability type by province/region.

and restricted zones are distributed in a gradual spatial transition. The suitable construction zones cover 137,300 km² and are distributed mainly around the priority zones.

The controlled and restricted construction zones cover 328,500 km² and 259,900 km², respectively. These zones are located mainly in the northern and southwestern plateau regions. The policy-prohibited zones, encompassing nature reserves, priority bird conservation areas, bird migration corridors and their buffer zones, water bodies, and urban

land, total 1,497,300 km². Technically inhibited zones are located along the northern edge of the plateau and across most of the Hengduan Mountains in the southeast. This means that more than half of the Qinghai-Tibet Plateau is off-limits for wind power system development.

Across different provinces or regions on the QTP, the spatial distribution of suitability zones varies considerably across provinces. In Tibet, policy-prohibited zones dominate the landscape, accounting for 57.1 % of the region. These areas included large nature reserves, priority bird

conservation areas, and forested lands. In contrast, Qinghai Province contains the most favourable conditions for wind power development, with large priority zones concentrated in the Qaidam Basin. In Gansu and Xinjiang, priority zones are limited to small areas near the margins of the Qaidam Basin, while large proportions of the territory are classified as policy-prohibited or technically prohibited zones. Policy-prohibited zones account for 58.1 % and 45.2 % of the total provincial area, respectively, whereas technically prohibited zones represent 6.6 % and 11.8 %, respectively. In Sichuan and Yunnan, policy-prohibited zones account for 75.1 % and 88.8 % of the total area, respectively, whereas technically prohibited zones represent 19.8 % and 8.4 %, respectively.

Current wind farm distribution

To further evaluate the practical implications of the proposed zoning framework, the distribution of existing wind farms in Qinghai Province was compared with the ecological suitability zoning results (Fig. 7).

Current wind energy projects on the plateau are heavily concentrated in Qinghai Province, particularly within three major development clusters. In the central and northwestern Qaidam Basin (Area 1), most existing wind farms coincide with priority construction zones, indicating a high level of consistency between current development patterns and the assessment results. Notably, three existing wind farms were found to overlap with policy-prohibited zones, specifically encroaching upon priority bird conservation areas and migration corridor buffers (Areas 1, 2, and 3 in Fig. 7). The presence of such conflicts further confirms that current wind farm planning inadequately considers bird migration.

Discussion

Balancing wind-energy potential with avian biodiversity conservation

The zoning results show that areas with high wind-energy potential and favourable engineering conditions do not necessarily remain suitable once avian habitats and movement areas are considered. This spatial mismatch suggests that gross wind-energy potential may overestimate the land available for development with comparatively low ecological risk. On the Qinghai–Tibet Plateau (QTP), wind-rich open landscapes may coincide with breeding, stopover, and movement habitats for sensitive bird species. Avian biodiversity therefore does not merely constitute an external constraint imposed after technical site screening. Instead, it affects how the environmentally developable portion of the wind resource should be interpreted. These findings support the early exclusion or restriction of ecologically sensitive locations and the prioritisation of areas where wind-energy potential and ecological acceptability coincide.

Such early screening is ecologically important because the effects of wind-energy development extend beyond direct collision mortality. Turbine construction, access roads, transmission infrastructure, and repeated human activity may displace birds, fragment habitats, alter movement behaviour, and reduce the functional value of stopover sites. Life-cycle evidence from Norway suggests that disturbance and indirect habitat loss can contribute more strongly to bird-diversity impacts than collisions alone [50].

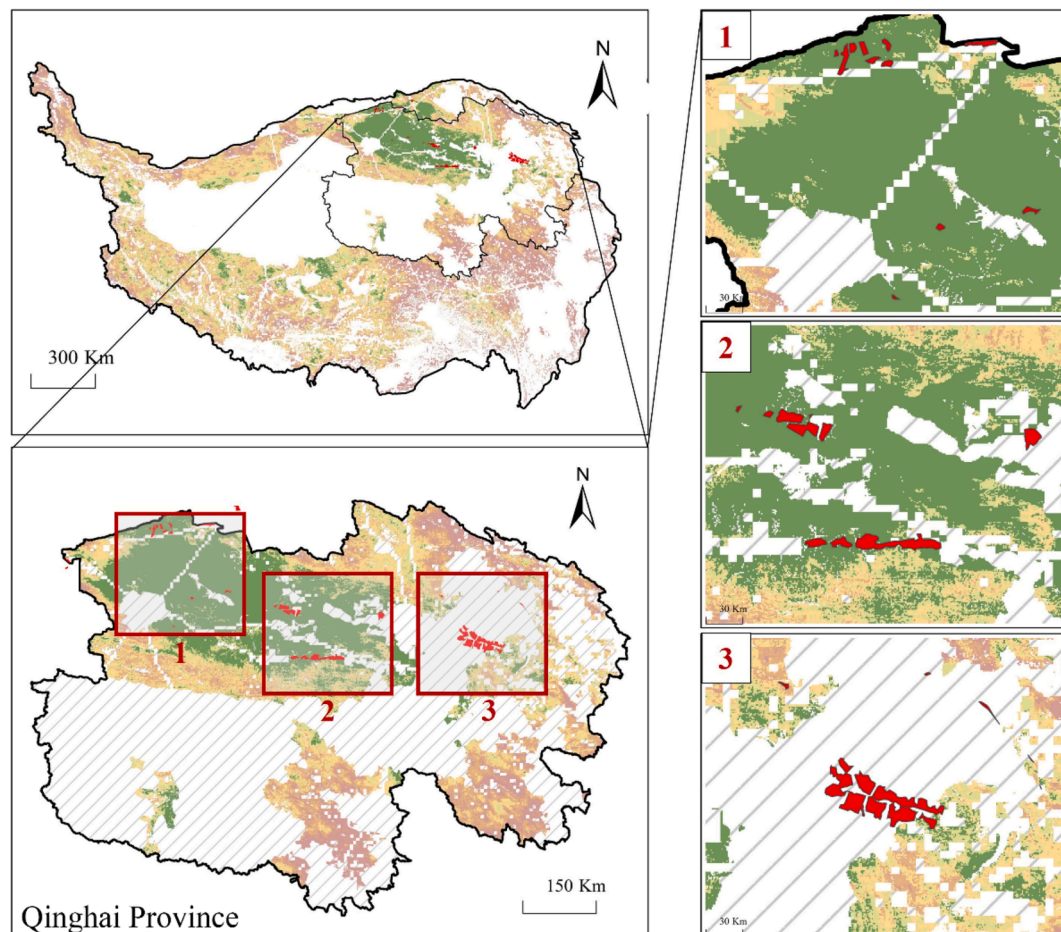


Fig. 7. Comparison of wind farms and ecological suitability zones for wind power system construction in Qinghai Province.

Added value of incorporating modelled potential avian migration corridors

Conventional wind-siting assessments commonly represent biodiversity through protected areas, known breeding sites, or static habitat patches while overlooking the ecological connections between them. As a result, unprotected transition landscapes may receive favourable energy-suitability scores simply because they lie outside reserve boundaries. This was particularly evident in the transition zone between Qinghai Lake and the Qaidam Basin and in high-elevation grasslands and valleys of the central QTP, where favourable wind conditions overlap potential migration routes. These findings are consistent with previous evidence showing that wind-energy facilities can overlap important bird habitats and that migratory birds may avoid wind-energy infrastructure during stopover-site selection [51–53]. One of the main methodological contributions of this study is the incorporation of potential migration corridors as both exclusionary and evaluative criteria, thereby reducing the risk that areas otherwise favourable in terms of wind resources, terrain, and infrastructure are classified as suitable despite their potential role in connecting seasonal habitats.

The ecological relevance of the modelled corridors is supported by their qualitative correspondence with external tracking. Satellite tracking of Black-necked Cranes (*Grus nigricollis*) has identified migration corridors and key stopover areas across the QTP and the Yunnan–Guizhou Plateau [54]. Tracking studies of Bar-headed Geese breeding at Qinghai Lake documented repeated use of stopover sites along routes towards the south [55], while Ruddy Shelducks (*Tadorna ferruginea*) used a broad passage zone across central Qinghai [56]. The correspondence does not imply that the simulated corridors reproduce individual flight paths. Rather, it indicates that the resistance-based approach captures landscape-scale connectivity patterns relevant to strategic screening.

Uncertainty and transferability

Uncertainty arises from both the ecological and energy components of the framework. Habitat-suitability models depend on the selected predictors and background data, and corridor outputs are sensitive to resistance values, source areas, and movement assumptions. On the energy side, indicator weights, data vintage, and the representation of grid access can alter relative suitability, while future changes in turbine dimensions, transmission infrastructure, storage, and market conditions may shift which resources are technically or economically attractive. Suitability classes should therefore be interpreted as comparative decision support rather than deterministic forecasts.

The framework is transferable because its architecture is modular: energy-resource, socioeconomic, legal, habitat, and connectivity layers can be updated independently and combined through the same screening logic. The parameter values themselves are not directly transferable. Applications in other regions should recalibrate species models, movement resistance, exclusion thresholds, infrastructure indicators, and stakeholder priorities to local ecological processes and energy systems. Seasonal migration patterns, land-use change, and climate-driven shifts in habitat should also be represented where data permit.

Limitations

Several potentially relevant indicators, such as distance to substations and turbulence intensity, were not included because of data limitations. Transmission line data were available only for networks above 330 kV in Qinghai and above 110 kV in Tibet, which may distort the apparent spatial pattern of grid accessibility. In addition, the 1 km grid is suitable for regional comparison but cannot resolve turbine-level terrain, wake effects, access-road alignments, or small habitat features. Because the assessment ranks regional spatial suitability rather than project-specific technical and economic performance, it should

complement, rather than replace, detailed techno-economic analysis and environmental impact assessment.

The ecological analysis is likewise model-based and primarily static. Predicted habitat and corridor locations require validation through systematic field surveys, multi-season telemetry, and long-term monitoring, particularly where wind resources and movement connectivity overlap. Species differ in flight height, avoidance behaviour, sensitivity to disturbance, and demographic vulnerability; these differences are not fully represented by a common regional corridor layer. Future assessments should integrate species-specific collision and displacement risk, interannual movement variability, cumulative-development scenarios, and higher-resolution energy-system data. These additions would improve both the ecological realism of the connectivity analysis and the reliability of wind-energy technology assessment at the project scale.

Conclusion

This study develops an integrated ecological suitability zoning framework that provides a spatially explicit tool for optimizing wind energy layout on the QTP, enabling planners to identify and avoid high-risk areas at the strategic planning stage. Three key conclusions emerge. First, 66 nationally protected bird species form three high-suitability habitat clusters, which are interconnected by 21 priority conservation areas and 40 migration corridors that together constitute a plateau-scale migratory network. Second, only 11.3 % of the plateau is suitable zones (priority and suitable construction zones), and these areas are tightly concentrated in Qinghai Province, particularly the Qaidam Basin. In Sichuan and Yunnan, priority zones are nearly absent, and policy- and technically prohibited zones reach 95 and 97 percent, respectively. Third, verified spatial overlap between operational wind farms and priority habitats or migration buffers confirms that ecological risk has been systematically underestimated under current planning practice, demonstrating the diagnostic value of the framework.

These results indicate that integrating bird conservation and dynamic migration into early-stage spatial planning for wind power development is both feasible and necessary as renewable energy deployment accelerates. Such early-stage spatial zoning is essential for reducing ecological conflicts and supporting the reconciliation of energy transition goals with avian biodiversity conservation.

CRedit authorship contribution statement

Jiaqi Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Ruijia Zhang:** Writing – original draft, Visualization, Data curation. **Bingran Ma:** Software, Methodology, Data curation. **Liting Wang:** Writing – review & editing, Supervision. **Lixiao Zhang:** Writing – review & editing. **Huaiwu Peng:** Resources. **Xiaohan Li:** Writing – review & editing. **Weihua Zeng:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seta.2026.105479>.

Data availability

Data will be made available on request.

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