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Incorporating Indigenous perspectives: an impact assessment of renewable energy development on wildlife conservation

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ABSTRACT

Transition to renewable energy is crucial for achieving the goal of carbon neutrality for the Tibetan Plateau. However, little is known about the potential impacts of the energy transition on wildlife conservation in the region, especially from the perspective of Indigenous pastoralists. Here, we employ an approach that integrates spatial overlap analysis, household interviews, and localized experiments to assess the impacts of renewable energy development on wildlife from local to regional scales. The results show that current renewable energy infrastructure, including solar and wind farms, rarely overlaps with wildlife distribution, and renewable energy development currently has negligible impacts on wildlife habitats. However, it is likely that original wildlife habitats across large continuous ranges will become fragmented by the increasing use of photovoltaics (PV) and wind farms in the future. Household interviews revealed a striking disparity in the level of concern about the impacts of renewable energy on wildlife between local pastoralists and the results obtained from spatial overlay analyses and site-based empirical assessments. Specially, 65.2 % of local pastoralists concur that renewable energy will damage wildlife habitats, and 65.5 % agree it will impact wildlife migration, which can be attributed to their limited understanding of renewable energy projects and their potential impacts. Random Forest models reveal that factors such as ethnicity, pasture size, and household demographics have a significant influence on regional disparities in pastoralists' attitudes. We recommended a roadmap to integrate policy, action, and research that simultaneously advances wildlife conservation, renewable energy, and socio-economic development. The study advocates the development of management practices promoting the implementation of wildlife-friendly wind and solar farms that are compatible with the perspectives and needs of local pastoralists.

1. Introduction

The world is currently facing a critical juncture that necessitates immediate action to relieve climate change and reverse the trajectory of biodiversity loss (Ashraf et al., 2024). In working towards net-zero carbon emissions and limiting the projected global temperature increase to below 2 °C, replacing both carbon-intensive energy production and consumption processes with clean, renewable energy is essential (Cherp et al., 2021). A total of 290 gigawatts (GW) of renewable energy was built in 2021 globally, with solar energy accounting for half of the expansion, followed by wind and hydropower, while solar and wind energy are predicted to increase capacity by an additional 1120 GW

annually by 2030 (Bouckaert et al., 2021). However, renewable energy development occupies large tracts of land which may be significant for nature conservation, including habitat that is rich in biodiversity, such as remaining wilderness and protected areas for wildlife (Rehbein et al., 2020; Niebuhr et al., 2022). The ultimate aim of expanding renewable energy is to decarbonize the economy by switching from reliance on fossil fuel to cleaner energy sources. However, while this aim is core to achieving the United Nations Sustainable Development Goals (SDGs), especially SDG7 sustainable energy, and SDG13 combating climate change, it also invokes a trade-off by threatening progress in SDG14, life on land.

The exploitation, operation, and maintenance of solar and wind

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power may have direct impacts on wildlife, including habitat fragmentation or altering the fire regime, which may in turn result in barriers to gene-flow (Farfán et al., 2017; Jager et al., 2021; Ferguson et al., 2025). For example, the operation of wind power turbines or transmission lines leads to bird collisions, thereby elevating mortality rates in species such as vultures, bustards, cranes, and other migratory birds (Hall et al., 2012; Troia et al., 2021). It has been estimated that as many as 600,000 birds and 800,000 bats are killed annually due to turbine strikes (Allison et al., 2019). Similarly, wind turbine collisions have been identified as precipitating population decline in the Egyptian vulture (*Neophron percnopterus*), and reducing breeding success and fecundity rates in both the griffon vulture (*Gyps fulvus*) and the white-tailed eagle (*Haliaeetus albicilla*) in Europe (Martínez-Abraín et al., 2012). Additionally, the loss of native plant species can lead to cascade effects, resulting in lower diversity among other trophic groups within the boundaries of solar energy facilities (Bolonio et al., 2024). In Alberta, Canada, the effects of solar energy on wildlife, including ungulates and amphibians, are considered to be predominantly adverse (Alberta Environment and Parks, 2017). In China, the development of onshore photovoltaics (PV) has caused fragmentation and associated loss of wildlife habitats across approximately 3471 km² of various landscapes such as agricultural land, sandy, grassy, and woody areas (Song et al., 2024). Hernandez et al. (2015) emphasize that habitat loss and fragmentation are significant threats to biodiversity arising from solar PV installations, although the extent of these impacts depends on the location and characteristics of the installation. Nevertheless, renewable energy deployment delivers substantial net environmental benefits—most critically, mitigating climate change by displacing fossil fuels, which directly reduces extinction risks for species vulnerable to warming habitats, extreme weather, and ecosystem disruption (Warren et al., 2018; Jager et al., 2021). For example, with appropriate management practices such as planting hedgerows around the perimeter, solar farms in the UK can reverse the decline of certain endangered species (Randle-Boggis et al., 2020). In general, current global research on the effects of wind and solar energy development on wildlife predominantly concentrates on local, direct, and/or short-term impacts (Abramic et al., 2022; Park et al., 2025). More comprehensive effects, including understanding the associated mechanisms operating at multiple scales from a single site to a region, have not been fully explored. This shortcoming is especially relevant in ecologically fragile and vulnerable regions, such as the Tibetan Plateau.

By 2022, China's installed capacity of new energy, led by wind and PV power, reached 758 gigawatts, accounting for 29.6 % of the total installed capacity of electricity (Wang et al., 2023c). Following the goal of "doubling global renewable energy capacity by 2030", the installation speed of wind and solar power in China needs to be further accelerated in the next five to six years, reaching a total installed capacity of 2200–2400 gigawatts by 2030 (Yang et al., 2024). The Tibetan Plateau accounts for 38.5 % and 45.6 % of China's potential for wind and solar PV energy, respectively (Tang et al., 2023). It is evident that both the global and national communities hold high expectations for the forthcoming expansion of renewable energy production on the Tibetan Plateau. To achieve carbon emission reduction targets, local governments in the Tibetan Plateau are eager to support the rapid implementation of new energy projects. According to the Qinghai Province's "14th Five-Year" energy plan, a generation of approximately 45.8 million kilowatts of PV power and 16.5 million kilowatts of wind power is expected by 2025 (www.seetao.com/details/144137.html). The Tibetan Plateau is home to a wide range of ecosystems, including forests, grasslands, wetlands, and deserts, and is an essential center of wildlife diversity (Sun et al., 2020). Conservation of this wildlife faces a combination of challenges due to ongoing and future fundamental energy transformation involving a steady influx of infrastructure for solar parks, wind turbines, and power lines that threaten to fragment natural habitats and pose a risk, especially to endangered species (Lu and Huntsinger, 2023). Currently, the complex connections between the development of renewable energy resources in the region and wildlife

protection are unclear, and there is to date inadequate understanding of the nature of any trade-offs. Moreover, given the significance of Indigenous herders in the economy of the Tibetan Plateau, the paucity of systematic research on their interactions with wildlife protection, represents a critical research gap, particularly in the context of the emerging energy transition.

The United Nations General Assembly has declared 2026 as the international year of rangelands and pastoralists, and called for pastoralists to be at the core of global rangeland management (Norderhaug et al., 2023). For millennia, Tibetan people have cultivated a holistic and intrinsic relationship with their natural environments, and they have also developed Indigenous knowledge systems and management practices that contribute to wildlife conservation and sustainable use of their land (Sun et al., 2024). In Yushu, Qinghai Province, a study conducted through local herder households' interviews revealed that snow leopards (*Panthera uncia*), which have historically inhabited the Nianbaoyuze Mountain, have a special meaning for local herders and that the relationship between them has consistently been characterized by peaceful coexistence, associated with minimal conflict (Liu et al., 2019). In addition, as conservation measures and efforts in nature reserves have been progressively enhanced, wild animal populations have exhibited notable recovery and significant increases (Lu and Huntsinger, 2023). For example, the number of Tibetan antelopes (*Pantholops hodgsoni*) increased from less than 70,000 in the 1980s and 1990s to approximately 200,000 by 2015 and has since surged to around 300,000 in 2021 (Yang et al., 2024). This wildlife recovery, combined with increases in domestic livestock numbers, has intensified competition for resources between them. This competition results in niche overlap and contributes to the overgrazing of grasslands (Lu and Huntsinger, 2023). Crucially, while livestock are the primary driver of grazing pressure (with a grazing capacity pressure index of 0.93 when considered alone), wildlife contribute a relatively small portion (7.5 %). When both are considered together, the total grazing pressure index increases to 1.01 (Cai et al., 2022). Nomadic grazing by Indigenous people has been harmoniously adapted to an environment characterized by diverse natural resources and climate variability (Miehe et al., 2014). This grazing regime also offers indispensable ecosystem services for wildlife by improving soil fertility, facilitating seed dispersal, and shaping landscapes (Wang et al., 2018). On the Ganjia grasslands of Gansu Province, herders implement traditional ecological knowledge through seasonal rotation grazing and quota-based grazing practices, enabling both livestock and wildlife to adapt to and integrate with the changing natural environment (Hu et al., 2021). Other examples include the savanna of central Kenya, where the coexistence of livestock and wildlife is associated with a reduction in tick populations, an enhancement in the quality of forage plants, and an increase in residents' income through wildlife tourism and the production of meat and milk (Goheen, 2018). However, renewable energy projects alter land use and household energy structure, influence pastoral culture and livelihoods, and decrease the resilience of the pastoral ecosystem (Zhuang et al., 2020). Thus, renewable energy development projects need to fully incorporate the specific social and cultural context, including the attitudes, situations, social demographics, and individual experiences of Indigenous pastoralists. Through such integration, pastoralists can be better prepared for, and even gain from, the energy transition, while simultaneously ensuring that ensuing impacts are not deleterious to wildlife conservation.

In this study, we utilize an approach that integrates spatial overlap analysis at the regional scale, household interviews among pastoralists at the transect scale, and localized experiments (thirteen sites) at the site scale (Fig.S1) to investigate the effects of renewable energy development on wildlife on the Tibetan Plateau. Specifically, we (i) present the potential overlap of existing and future solar and wind power development on wildlife distribution areas; (ii) analyze the potential impacts of solar and wind energy development on wildlife habitats based on network analysis; and (iii) investigate the attitudes, and their underlying factors, that affect the willingness of Indigenous herders to consider the

possible impact of renewable energy development on wildlife conservation. Our study aims to highlight management practices that promote the installation of wildlife-friendly wind and solar farms, particularly tailored to the perspectives and needs of local pastoralists.

2. Materials and methods

We employed a comprehensive approach integrating spatial overlap analysis at the regional scale, household interviews among pastoralists at the transect scale, and localized experiments at the site scale (Fig. S1) to investigate the effects of renewable energy development on wildlife on the Tibetan Plateau. This comprehensive approach significantly enhances the overall validity of the study compared to using any single method. It achieves this by encompassing the full spectrum from broad patterns through community-level processes to direct cause-and-effect at specific locations (Fig. S1). For example, spatial overlap analysis typically depends on objective data sources, which are founded on scientific measurements and mapping methodologies. Household interviews may mention cultural or traditional aspects related to wildlife that can influence the overall understanding of the impacts of renewable energy development. Additionally, local experiments are conducted under controlled conditions, allowing for the establishment of a causal link between renewable energy development and wildlife responses.

2.1. Spatial overlap analysis

(1) Renewable energy data.

Wind and solar energy data from the Tibetan Plateau were sourced from the dataset compiled by [Dunnett et al. \(2020\)](#), which is considered the most comprehensive dataset currently available for wind and solar infrastructure globally. These datasets were generated by extracting pertinent features from OpenStreetMap, a collaborative open-source global mapping initiative. Specifically, data were derived from OpenStreetMap entries tagged to indicate the presence of either wind turbines or solar photovoltaic installations.

The current and future data regarding solar and wind energy in Haixi Prefecture were sourced from the “Haixi Prefecture 14th Five-Year Plan for Clean Energy Development” (<http://www.cnste.org/html/zixun/2022/0922/9527.html>).

(2) Wildlife distribution data.

The spatial distribution of wildlife on the Tibetan Plateau was sourced from the dataset compiled by [Sun et al. \(2020\)](#). Data was collected from published books and papers. Specifically, it primarily encompasses eight wildlife species: the Tibetan antelope (*Pantholops hodgsonii*), the kiang (*Equus kiang*), the Tibetan brown bear (*Ursus arctos pruinosus*), the wild yak (*Bos mutus*), the argali (*Ovis ammon*), the snow leopard (*Panthera uncia*), the bharal (*Pseudois nayaur*), and the white-lipped deer (*Przewalskium albirostris*). The majority of these species are under national protection on the Tibetan Plateau.

(3) Spatial overlap analysis.

Spatial analyses of spatial overlaps between renewable energy installations and wildlife distribution areas were conducted in ArcMap 10.8.1 (Fig. S1). The data underwent reprojection to the Mollweide equal-area projection to ensure consistent area comparability across all latitudes. Spatial overlaps were assessed using the ‘*st_contains*’ predicate, which specifically identifies installations fully contained within protected areas. This approach was chosen to minimize the potential for boundary inaccuracies that could incorrectly indicate overlaps where only an intersection occurs between an installation and a protected area.

2.2. Structured household-level interviews

The data used for this study were collected from structured household-level interviews conducted in the pastoral area across the Tibetan Plateau (TP) from July to August 2023 (Fig.S1). To ensure that the research results accurately reflect the local situation, the

questionnaire was distributed in a random sampling manner. Of the total questionnaires, 190 were found to be valid, indicating a high response rate (95 %). Among those interviewed, 55 were from the Qilian Mountain National Park, 27 were from the Qaidam Basin, 24 were from the Gonghe Basin, 50 were from the Sanjiangyuan National Park, and 59 were from the Chang Tang Plateau (Fig.S2). The content of the household survey includes two aspects (S3 Questionnaire): one is the basic information of households, including family population, age, nationality, degree of education, area of pasture and numbers of livestock; And the other is energy transition and wildlife conservation, including judging whether renewable energy destruct the wildlife habitats, impact on wildlife migration, increase extreme climate events; and understanding/awareness among pastoralists of renewable energy.

The questionnaire was administered in 20 counties of Tibetan Plateau by a five-member research team. The team members were knowledgeable about wildlife conservation and renewable energy policies implemented in Tibetan Plateau. Integrated training was conducted before implementing the investigations to reduce the uncertainty of the survey results to some extent. Prior to commencing the interviews, we elucidated to the respondents the objective of the study, solicited their consent to partake in and record the interview, apprised them of their prerogative to abstain from responding to any inquiries they found discomforting, assured them of their right to terminate the interview at any juncture (which none exercised), and affirmed that all provided responses would be anonymized for subsequent analysis ([Wang et al., 2023a](#)).

2.3. Localized experiments

2.3.1. Sites selection and experimental design

A total of 13 representative photovoltaic (PV) power stations were selected to establish an observation network that encompasses three distinct grassland ecosystems: alpine desert steppe, alpine steppe, and alpine meadow. This observation network includes PV stations with operational and maintenance records spanning 1 to 10 years, with a median of 4 years. Further details are provided in Table S2.

Within each PV stations, survey plots were established in three distinct treatments: Outside (reference zones beyond the PV arrays), Gap (zones between the PV panels), and Under (sheltered zones beneath the PV panels). Each treatment was replicated three times. Within each survey plot, three quadrats (2 m × 2 m) were randomly established to assess vegetation characteristics and soil properties in August 2023.

In contrast to the PV survey spanning multiple stations, wind farm impacts were investigated through an intensive case study focused on the representative Delingha Wind Power Farm. Within this wind farm, three survey sites adjacent to wind turbines were selected. Each survey site comprises five sampling plots positioned at distances of 0, 100, 200, 300, and 400 m from the wind turbines (Fig. S4a; 4b). Within each sampling plot in the wind farm area, three 10 m × 10 m quadrats were randomly established to evaluate vegetation characteristics, soil properties, and the abundance of desert lizards. This larger-scale quadrat design is well-suited for capturing the spatial heterogeneity inherent in desert shrublands ([He et al., 2006](#)). In contrast, the 2 m × 2 m quadrats employed in PV areas are tailored to the limited spaces between and beneath solar panels.

2.3.2. Field and laboratory sampling and analysis

To characterize the community within each quadrat, we recorded the species richness, abundance, and the maximum stem height for each plant species. Vegetation cover for all species was estimated based on the vertical projection of aboveground plant organs. Soil water content and soil temperature of the surface layer were measured using a Field-Scout TDR-100 probe in each quadrat. Soil bulk density was determined using the cutting ring method. Soil samples were extracted from the center of each 0.5 × 0.5 m quadrat using a soil auger, placed in mesh bags (2-mm mesh size), and air-dried outdoors for approximately one

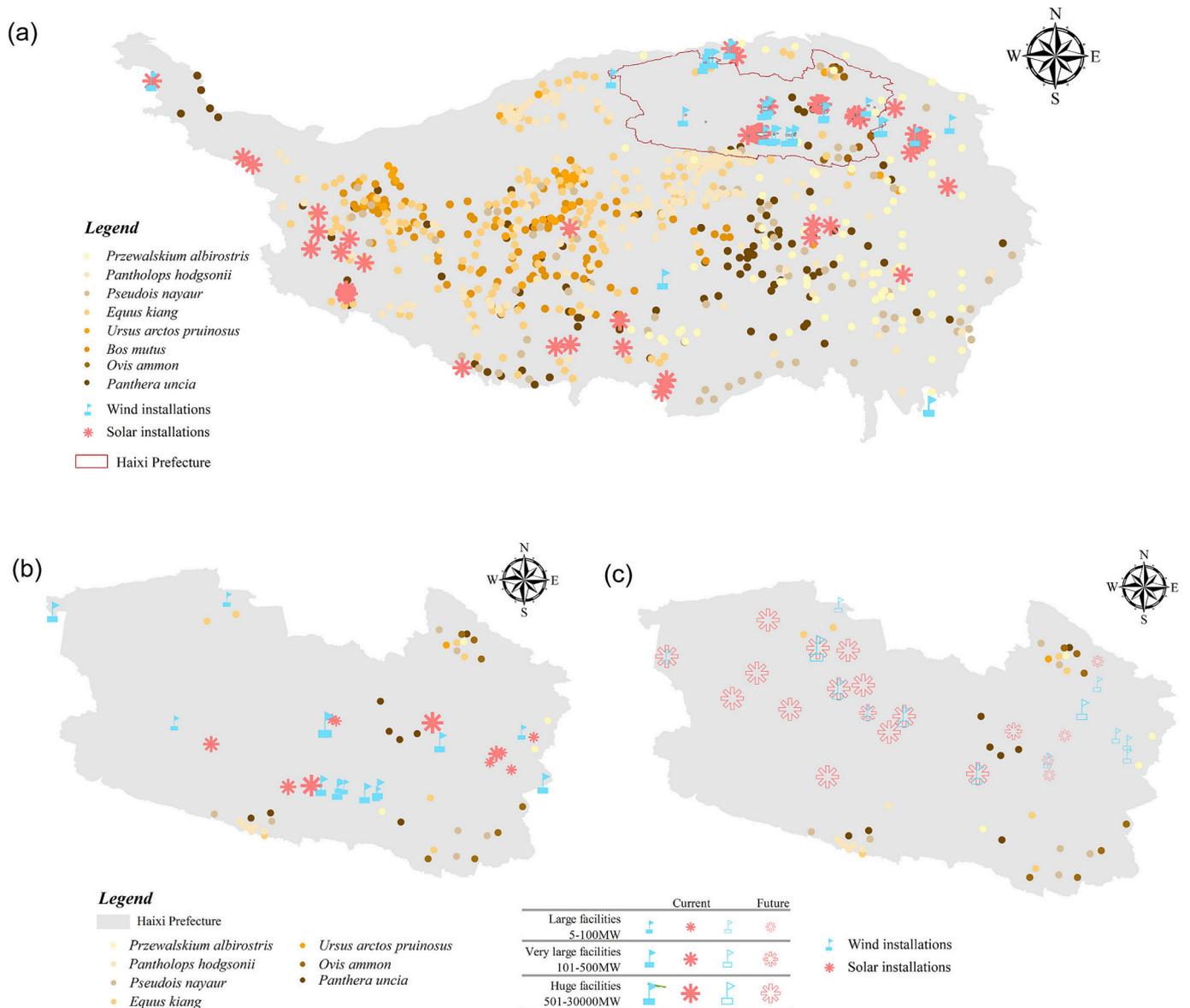


Fig. 1. (a) Spatial overlap between developed solar, wind installations and wildlife distribution on the Tibetan Plateau. (b) Spatial overlap between solar, and wind installations operational and wildlife distribution in the Haixi Prefecture. (c) Spatial overlap between planned solar, and wind installations and wildlife distribution in the Haixi Prefecture.

month. After drying, samples were divided into root and soil subsamples.

The soil subsamples were further dried in the laboratory at room temperature and sieved through a 0.2-mm mesh screen to remove stones and roots. Soil total carbon and soil total nitrogen concentrations were analyzed using an elemental analyzer. Soil total phosphorus, nitrate nitrogen, ammonium nitrogen, and available phosphorus concentrations were determined using the molybdate colorimetric method following digestion with perchloric acid. Soil microbial analysis encompasses two primary objectives: assessing soil microbial diversity and determining the enzyme activities that govern soil carbon, nitrogen, and phosphorus cycles.

2.4. Statistic analysis

We constructed ecological networks to explore the coordination of multiple indicators within and among plant characteristics, soil physical and chemical properties, soil enzymes, and soil microbe diversity in different PV arrays treatments. Within the network, plant, soil

indicators, and their Spearman correlations were represented as nodes and edges, respectively. Statistically significant relationships among indicators were graphically represented using the Gephi 0.10. Then, we calculated a series of network topological properties (e.g. edge, average degree, average path length, density, betweenness, modularity, and hub) in the network (Felipe-Lucia et al., 2020). One-way ANOVA with the LSD multiple comparison was used to analyze the effects of renewable energy farm treatments on ecosystem multifunctionality, vegetation characteristics, soil properties, desert lizard burrows, and network structure index. These treatments included the distances from wind turbines and the deployment of PV arrays. A repeated measures linear mixed model was used to examine the significant regional variations in pastoralists' perceptions regarding the influence of renewable energy development on wildlife. Correlation analysis, regression analysis, and Random Forests analysis (increase in Node Purity) to reveal the driving factors of interviewees perception on the effects of renewable energy on wildlife. The Random Forest algorithm was implemented using the 'randomForest_4.6-14' package (Cutler et al., 2007). Random Forest addresses issues with highly collinear predictors by assigning variable

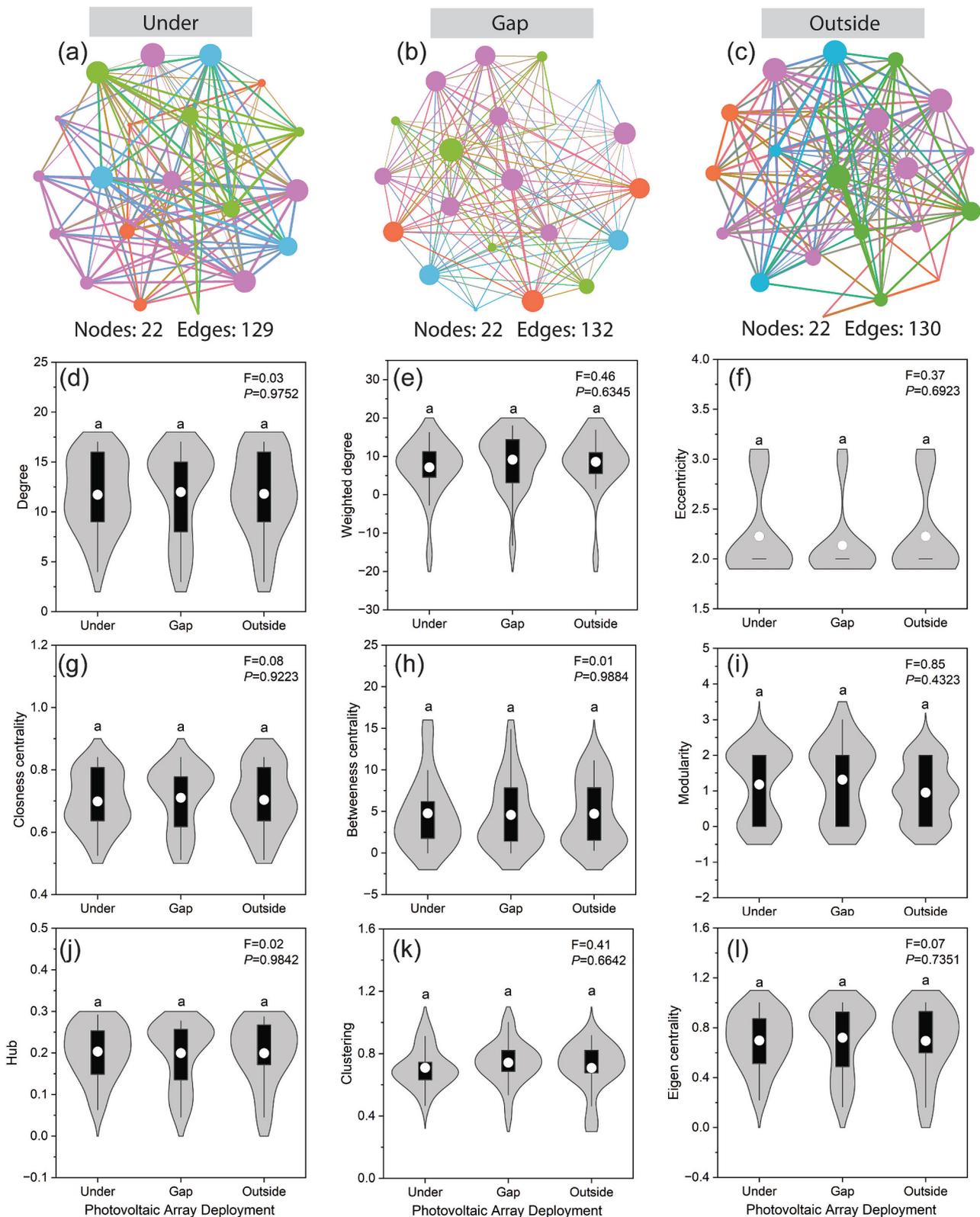


Fig. 2. Networks across ecological indicators (plant characteristics, soil physical and chemical properties, soil enzymes and soil microbe diversity) in different experimental zones (Outside, the reference zones outside the PV arrays; Gap, the zones between the PV panels; and Under, the sheltered zones under the PV panels). Only significant correlations are shown ($P < 0.05$), with the strength of the correlation being represented by edge thickness. The red, purple, blue and green circles denote plant characteristics, soil physical and chemical properties, soil enzymes and soil microbe diversity, respectively. Different letters in the violin diagram represent significant differences among PV arrays treatments ($P < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

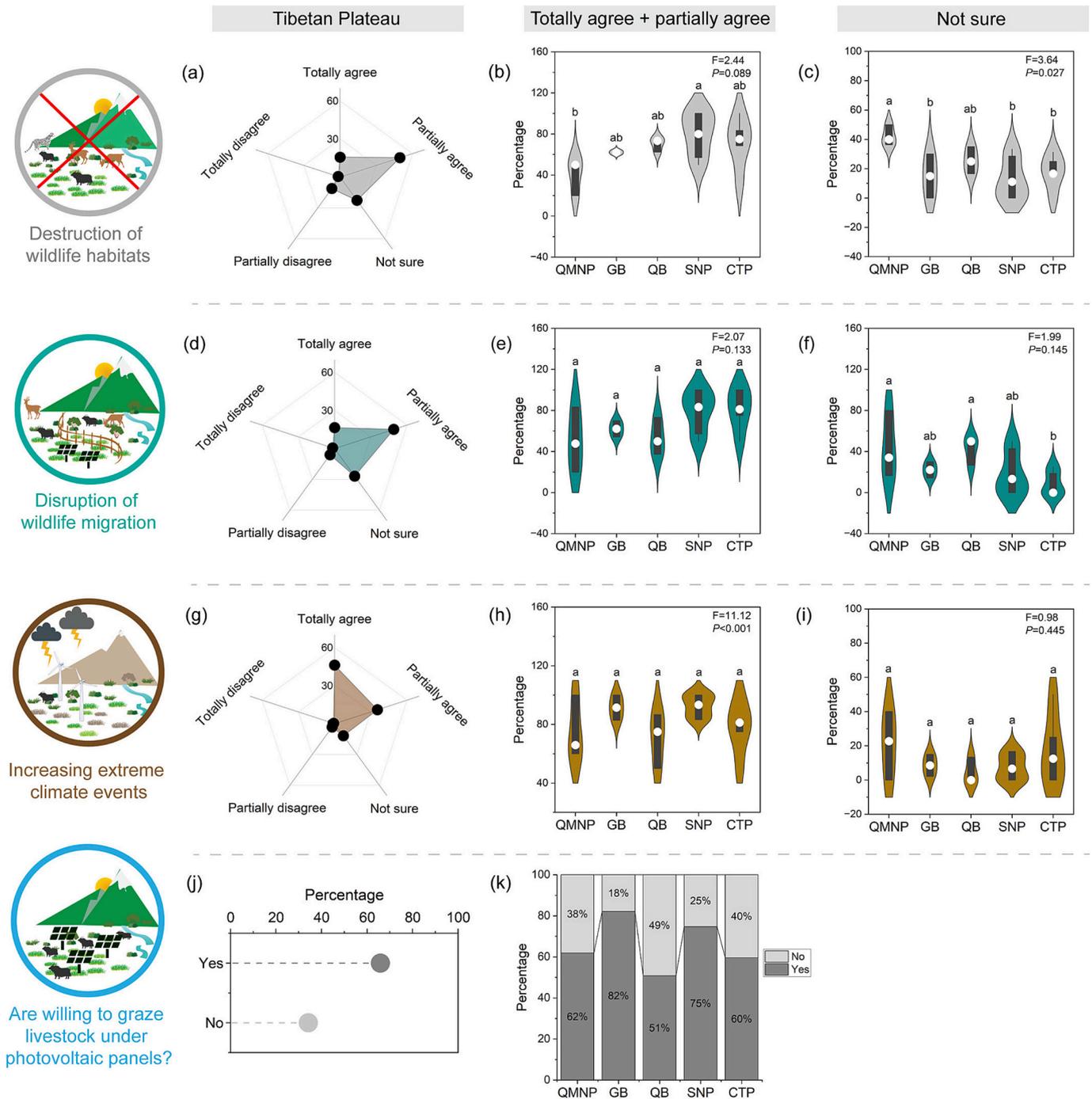


Fig. 3. Perceptions of interviewees on the effects of renewable energy development on wildlife in the transect on the Tibetan Plateau. (a-c) Destruction of wildlife habitats. (d-f) Disruption of wildlife migration. (g-i) Increased frequency of extreme climate events. (j-k) Willingness to graze livestock under PV panels. QMNP: Qilian Mountain National Park, GB: Gonghe Basin, QB: Qaidam Basin; SNP: Sanjiangyuan National Park, CTP: Chang Tang Plateau.

importance across all variables. All statistical analyses were conducted using R statistical software, version 4.3.2 and all figures were drawn using Origin 2023b software.

3. Results

3.1. Spatial overlap between renewable energy facilities and wildlife distribution areas

We investigated the spatial distribution of wildlife distribution areas and operational solar PV, and onshore wind on the Tibetan Plateau

(Fig. 1a). There are approximately 110 solar PV installations and 50 onshore wind installations in the region. Currently, solar PV installations are distributed mainly in the northwestern and southwestern parts of the Tibetan Plateau, the Gonghe Basin, and the Qaidam Basin, while wind installations are mainly located in the Gonghe Basin and the Qaidam Basin (Fig. 1; Fig.S2-S3). The current scale of renewable facilities (solar PV and wind installations) is relatively small and rarely overlap with the wildlife distribution areas (Fig. 1b), suggesting they will likely have little impact on wildlife within those areas. However, looking more closely and taking planned future developments into consideration, the data for Haixi Prefecture suggest that the area of wind

power and solar power farms will increase by 10.0 times and 49.9 times respectively (Fig. 1c; Fig. S3d). The proportion of wildlife distribution areas that contain wind and solar facilities under development is expected to be relatively high (Fig. 1c).

3.2. Effects of renewable energy facilities on wildlife habitats: Evidence from localized experiments

PV arrays treatments had a negligible effect on the proportion of connectivity between the nodes (plant, soil indicators), namely, there were 129, 132, and 130 significant relationships under Outside, Gap, and Under zones of the PV arrays (Fig. 2a-c). Also, no significant difference was observed for the module composition and hub identity of the network between Outside, Gap, and Under zones in the PV arrays (Fig. 2). In addition, ecosystem multifunctionality increases significantly with increased distance from wind turbines (Fig. S4b). Taking the desert lizard (*Phrynocephalus vlangalii*) as an example, and showed that the occurrence of lizard burrows decreased by 43.5 %, 56.5 %, 65.2 %, and 95.7 % respectively as the distance from the wind turbines increased (Fig. S4c). In contrast, there was no discernible distance effect on plant species richness or vegetation cover ($P > 0.05$; Fig. S4d, S4e).

3.3. Interviewee perceptions regarding the effects of renewable energy on wildlife

Interviewees were requested to evaluate whether they thought renewable energy infrastructure would result in wildlife habitat loss. Fig. 3a illustrates the proportions of agreement, disagreement, and uncertainty as 65.2 %, 12.7 %, and 22.1 %, respectively (Fig. 3a). There are regional differences in responses, whereby the Sanjaingyuan National Park (80.7 %), Chang Tang Plateau (72.1 %) and the Qaidam Basin (70.3 %) areas elicited the highest level of responses suggesting agreement that wildlife would be impacted negatively, while this outcome was lowest among respondents from the Qilian Mountains National Park (40.8 %) (Fig. 3b). The proportion of respondents expressing uncertainty in the Qilian Mountain National Park was significantly higher ($P < 0.05$) than that in the other four regions (Fig. 3c). The survey also focused on the impact of renewable energy on wildlife migration. A substantial proportion of interviewees (65.5 %) considered that renewable energy development would have a substantial impact, while only 7.8 % suggested that the effect would be minimal (Fig. 3d). In the Chang Tang Plateau and Sangjiangyuan National Park, the proportion of respondents assuming that wildlife migration would be markedly impacted was highest (81.2 % and 79.9 %; Fig. 3e-f).

When we asked about whether extreme climate events around their residence have been exacerbated in the last 20 years, 81.6 % of the interviewees suggested that there had indeed been an increase, while only 4.2 % of the interviewees felt that such events had declined (Fig. 3g). Regionally, respondents around the Sanjaingyuan National Park exhibited the highest level of agreement with the increased scenario (92.7 %), followed by the Gonghe Basin (91.4 %) and the Chang Tang Plateau (77.9 %), while only 70.6 % of respondents in the Qaidam Basin agreed (Fig. 3h). Asked whether they would graze livestock under PV panels, 65.8 % of all interviewees agreed, with the remainder indicating otherwise (Fig. 3j). In the Gonghe Basin, Sanjaingyuan National Park, and Qilian Mountain National Park, respectively 82.1 %, 74.7 %, and 61.9 % of interviewees expressed their willingness to graze livestock in such circumstances. Conversely, in the Qaidam Basin and the Qiangtang Plateau, almost half of the respondents (49.1 and 40.4 %, respectively) would not graze livestock under PV panels (Fig. 3k).

4. Discussion

4.1. Renewable energy development and wildlife conservation

While the expansion of wind and solar energy infrastructure globally

may not interfere with wildlife conservation priorities as much as feared (Dunnnett et al., 2022), the current and near-term future overlap of these two land uses remains ambiguous on the Tibetan Plateau. Our investigation of the spatial distribution of wildlife distribution areas, and operational renewable energy infrastructure on the Tibetan Plateau (Fig. 1a) reveals the presence of approximately 100 solar PV installations and 43 wind farms in this region. At present, solar PV installations are predominantly situated in the northwestern and southwestern regions of the Tibetan Plateau, as well as in the Gonghe Basin and the Qaidam Basin. Conversely, wind energy installations are primarily concentrated in the Gonghe Basin and the Qaidam Basin (Fig. 1a). In general, the scale of existing operational renewable energy facilities is relatively limited, and there is a minimal spatial overlap between these facilities and wildlife distribution areas (Fig. 1a). The relatively limited number of wind and solar power facilities on the Tibetan Plateau to date is in part due to the priority given to ecological protection of the region (Law of the People's Republic of China on Ecological Protection of the Tibetan Plateau, 2023). Moreover, there are technical challenges relating to the fact that, compared to other regions in China, there are higher construction costs on the Tibetan Plateau, as well as lower levels of local electricity consumption and poor grid interconnectedness with other regions (Tang et al., 2023). In recent years, the above-mentioned limitations have been greatly alleviated through the construction of a new generation of power systems (Zhou et al., 2021). Also, under the national "Dual Carbon" goals (i.e., peak carbon emissions by 2030 and carbon neutrality by 2060 in China), solar and wind power are touted to become the main power supply for power grids in alignment with the Tibetan Plateau "14th five-year" energy plan. Predictably, the large-scale exploitation of new renewable energy in the near term is likely to have an impact on existing protected areas and wildlife habitats. Here, we further analyze the spatial overlap between solar, wind installations (current and those under planned development to be completed by 2035) and wildlife distribution areas in the Qaidam basin. The results indicate that wind and solar energy development, amounting to 1003 km² of wind facilities and 458 km² of solar farms at present, has not thus far encroached on the areas for wildlife distribution in the Qaidam Basin (Fig. 1b). Indeed, our spatial overlay analysis reveals that existing large, contiguous wildlife habitats will become fragmented by renewable energy facilities (Fig. 1c). Such habitat fragmentation creates barriers to wildlife movement, thereby affecting populations.

Our network analysis of 22 plant and soil indicators across 13 PV stations demonstrated that PV development had no significant effect on the structural integrity and resilience of the ecological network (Fig. 2). Previous studies have primarily focused on the impacts of renewable energy power on wildlife habitat, specifically analyzing the impact on single indicators such as soil, vegetation, and water resources, with varied conclusions (Leskova et al., 2022). On one hand, wildlife may be influenced by renewable energy facilities and associated infrastructures directly or indirectly due to fragmentation, electromagnetic field generation, and subsequent trophic cascade effects (Fig. 5). Specifically, construction and operation of PV stations and wind farms, along with their related facilities, may result in removal of vegetation and disturbance of biological soil crusts, which in turn may reduce wildlife abundance (e.g., *Gopherus agassizii* (Lovich and Ennen, 2011)). Large fenced-off areas of PV panels and wind farms act as barriers that obstruct wildlife and prevent access to natural roosting locations (Sánchez-Zapata et al., 2016). In addition, changes in microclimate and local hydrology may further alter the habitat, such as the shading effect of solar panels, which contributes to a reduced transpiration rate, partially counterbalancing the impact of moisture interception on soil caused by the panels (Armstrong et al., 2016). On the other hand, solar farms may provide novel habitats to support wildlife (Fig. 5). For example, the increased biomass and diversity of plants between solar panel rows may offer nesting sites, shelter, or facilitate movement (Semeraro et al., 2018). Our survey data in the Qaidam desert suggest that areas with

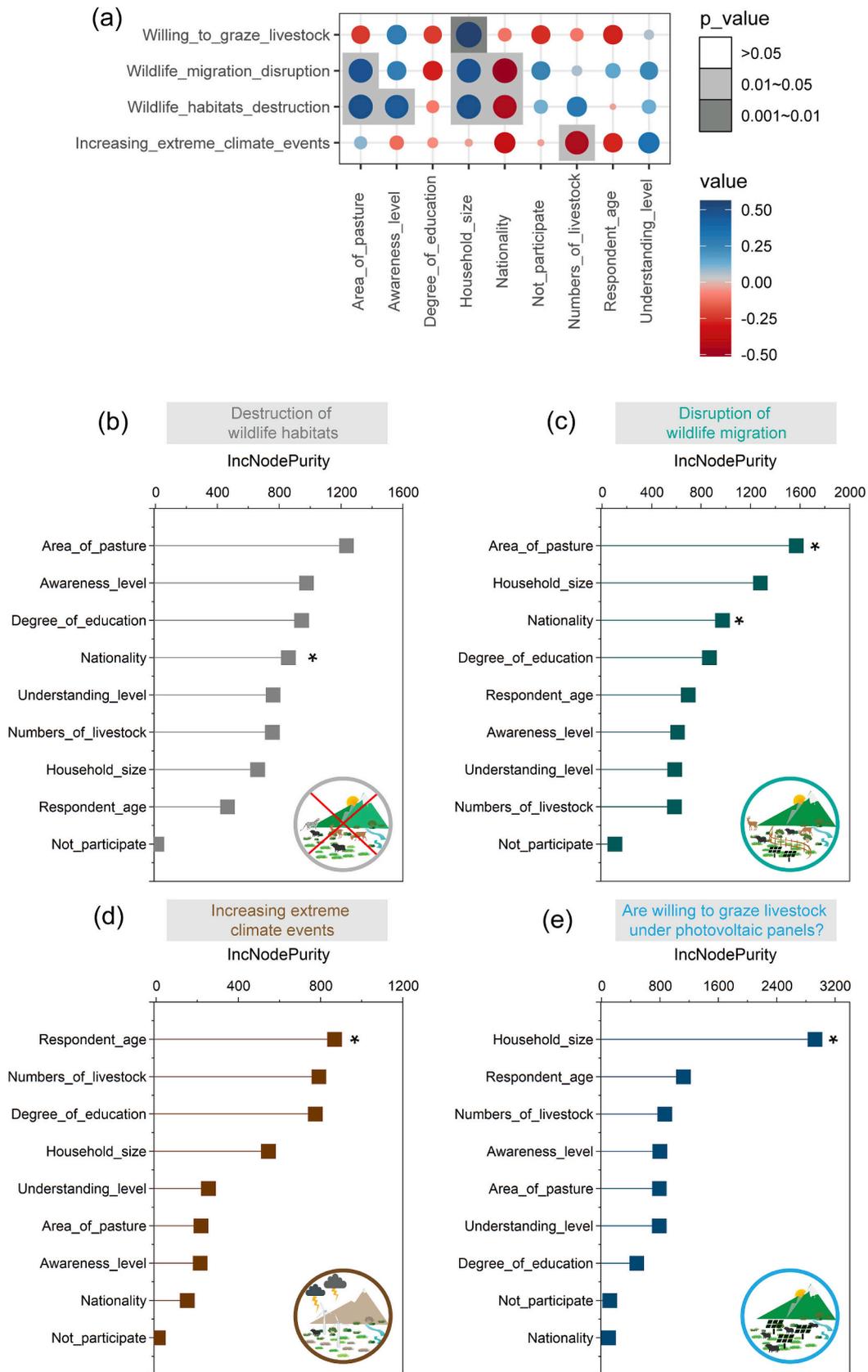


Fig. 4. Correlation analysis (a, Pearson coefficient) and Random Forest analysis (b-e, Variable importance (increase in Node Purity)) to reveal the drivers of interviewee perception on the effects of renewable energy on wildlife.

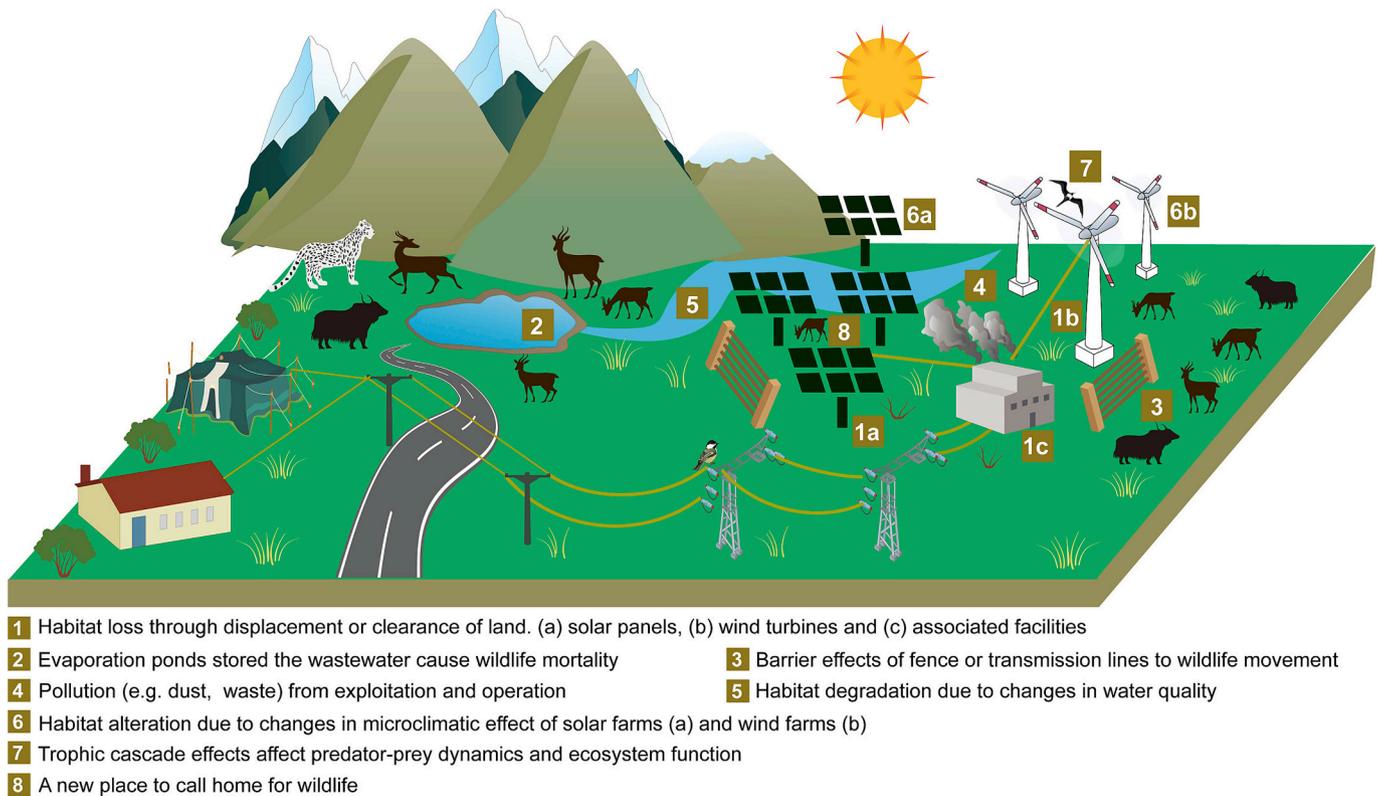


Fig. 5. Potential impact approaches of solar and wind energy developments on wildlife on the Tibetan Plateau.

wind turbines support greater desert lizard populations because of fewer interactions with mean predators (Fig. S4c). These desert lizards were also less wary of predators and exhibited lower stress levels than their counterparts outside the turbine range (Keehn et al., 2019). Other research in the UK provides evidence that well managed solar PV siting can even benefit wildlife, with study installations increasing vegetation diversity and butterfly abundance (Randle-Boggis et al., 2020). Due to the complexity of ecosystems, current research is still dominated by local, direct, short-term impacts or single scales (Goetzberger and Zastrow, 1982; Bianchi et al., 2022; Zhang et al., 2023). The multi-level laws and multi-scale effects of wind resource development on the characteristics, processes, and mechanisms of ecosystems have not been fully understood, and long-term in-depth research is needed.

4.2. Enhancing the participation and awareness of indigenous pastoralists in renewable energy development and operation

Grassland regions on the Tibetan Plateau have been identified as excellent sites for the development of wind and solar energy (Zhuang et al., 2020). Nonetheless, these areas have traditionally been utilized as communal resources by a variety of pastoralist communities over the course of multiple generations (Wang et al., 2023b). For the wildlife conservation community of Tibetan Plateau, especially some local herders, the facilities of solar and wind energy are indeed a novel challenge. Thus, how local herders understand the potential pathways of influence of renewable energy infrastructure on wildlife is vital for the sustainable development of renewable energy sources (Shi et al., 2025). Compared to other individuals (such as scientists, government officials, etc.), these local pastoralists have substantially greater direct investment in the impact of renewable energy development on wildlife. The results of the household interviews in this study show that 65.2 % of local pastoralists concur that renewable energy will damage wildlife habitats and 65.5 % agree it will impact wildlife migration (Fig. 3a; 3d). This suggests that local pastoralists have a relatively high level of concern

about the impacts of renewable energy. Evidently, local perspectives regarding the impacts of infrastructure on wildlife do not align well with the evidence derived from spatial overlay analysis and local experiments. This disparity can be ascribed to the following two factors: firstly, local pastoralists evidently have very low levels of awareness of renewable energy development per se. In the household survey, 82.0 % of respondents indicated a lack of acquaintance with this form of energy (Fig. S5a), while 87.7 % indicated that they were unaware prior to the construction of wind and solar power projects (Fig. S5b). Other studies have also highlighted the lack of information among local pastoralists regarding new project plans during the planning of most renewable energy initiatives, for example in India (Foggin, 2012). Although local pastoralists have a limited understanding of photovoltaic technology itself, investigating their attitudes towards supporting photovoltaic development projects is of great significance. This significance does not depend on local pastoralists' understanding of technical details but rather stems from their roles as direct stakeholders, land users, and environmental observers (Hopping et al., 2016). Secondly, planners of such projects are typically accused of exhibiting a lack of sensitivity towards the "affected local population" and poor awareness of who the local stakeholders are when negotiating land use (Chung and Gagné, 2021). Local government-driven participation can limit opportunities for local pastoralists to participate in decision-making and action (Yeh et al., 2017). Perhaps not surprisingly, herders exhibit very little understanding of the potential impact of renewable energy projects on wildlife, as their primary focus is the condition of their livestock and the status of grassland vegetation, being more concerned with access to pastures, and possible disruptions to seasonal migration routes. Only 9.5 % of respondents have participated in the operation and construction of wind or solar power farms (Fig. S5c), although 65.8 % of respondents are willing to graze livestock under PV panels (Fig. 3j). The minimal engagement of herders impedes their precise understanding of how renewable energy development impacts wildlife, especially in terms of its potential positive effects.

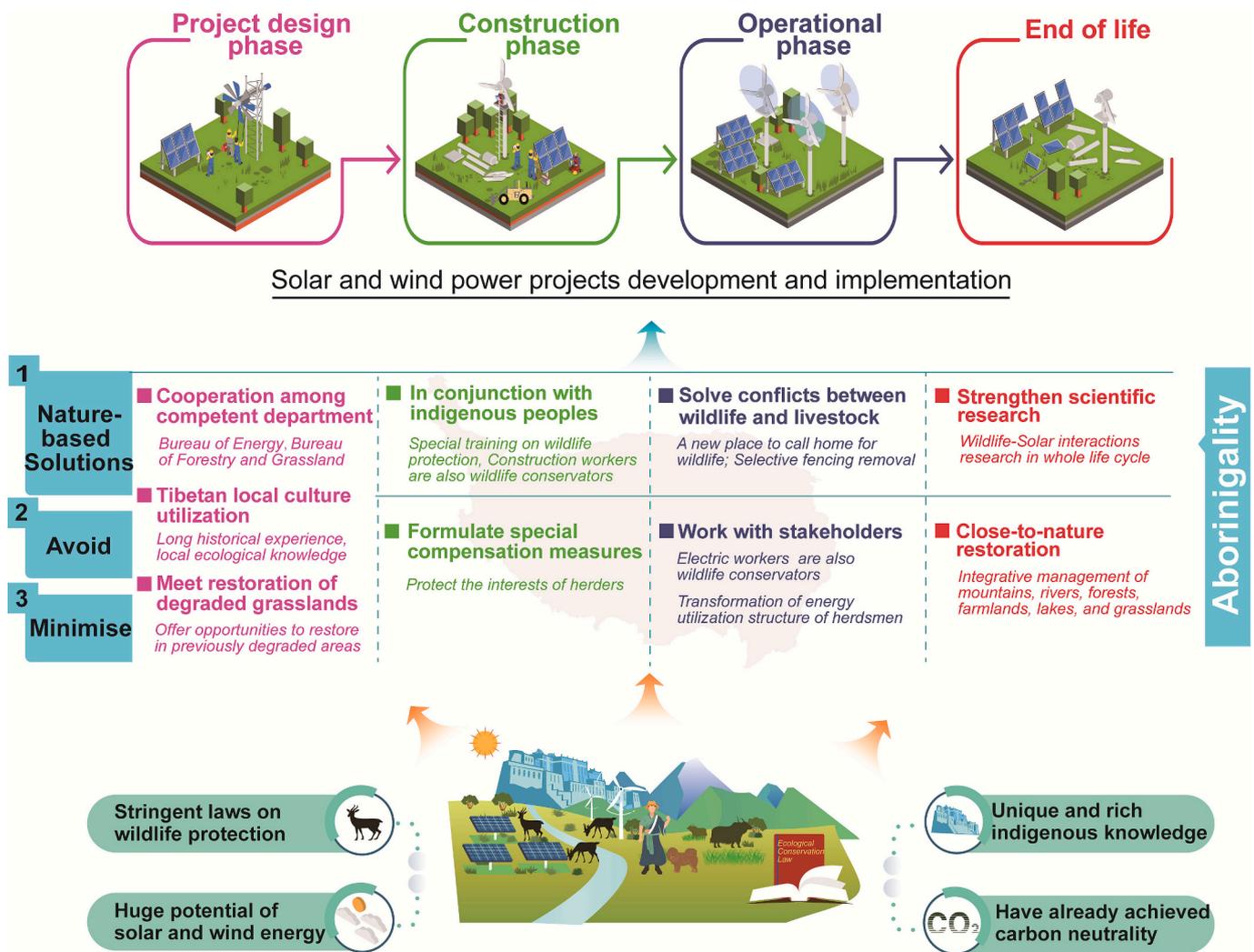


Fig. 6. Mitigation approaches to solar and wind power impact on wildlife across the renewable energy project development cycle on the Tibetan Plateau. In each stage of renewable energy project development (from planning, construction to operation and end of life), it is necessary to consider the potential impact of solar and wind energy on wildlife, take corresponding mitigation measures, and incorporate Indigenous ecological knowledge.

There exists significant regional variation in terms of herder perceptions regarding the influence of renewable energy development on wildlife (Fig. 3b; 3e). These regional disparities are influenced by a range of factors, including their familial circumstances and associated social structures (Wang et al., 2023a). Pastoralists' attitudes towards wildlife impacts correlate significantly with variables such as household size, area of pasture, extent of grasslands, religious beliefs, and awareness levels regarding renewable energy projects across different regions (Fig. S7; S8; S9). In the Sanjiangyuan National Park and Chang Tang Plateau, where Tibetan ethnic groups predominate (Fig. S6c), wildlife conservation is considered highly important in their religious beliefs. It is known that local pastoralists view wildlife as integral to the land and, without wildlife, their land becomes meaningless, they feel empty inside, and lose their connection with the land (Zhao et al., 2020). Indeed, pastoralists, whose livelihoods depend directly on the natural environment, have inherited narratives discouraging them from harming wildlife, while promoting respect for all life forms (Lapinski et al., 2022). In Zado County of the Sanjiangyuan National Park, for instance, despite significant predation of domestic animals by snow leopards, certain herdsmen refrain from engaging in retaliatory hunting practices. This behavior is motivated by their belief that the snow leopard serves as the custodian of the sacred mountain, and its protection is integral to preserving the sanctity of the holy site. Influenced by this ideological framework, local monks and herdsmen have spontaneously established

an association dedicated to environmental protection. This association has undertaken biodiversity monitoring and conservation efforts, implementing a range of strategies to address snow leopard-related issues (Liu et al., 2019). Furthermore, our random forest model demonstrates that the regional variations in the acceptance of grazing livestock beneath PV panels (Fig. 3j) are notably influenced by two crucial factors: the total number of ethnic groups and the available pasture area (Fig. 4). These two factors can directly indicate the extent to which local herders depend on grazing activities. In regions where livelihoods are less dependent solely on pastoralism, such as in the Qilian Mountains National Park and Gonghe Basin, local pastoralists have engaged in the construction and operation of wind and solar farms (Fig. S6k). This higher level of involvement contributes to greater tolerance towards possible renewable energy development (Campos et al., 2020).

4.3. Policy implementations

The development of solar and wind power is already well underway on the Tibetan Plateau, largely driven by the new energy policy reform and rapidly declining costs (Tang et al., 2023). Transitioning to renewable energy, which simultaneously contributes to achieving both carbon neutrality and wildlife conservation is clearly desirable, a goal that could be more efficiently met through engaging with all relevant stakeholders, more especially the Indigenous herders (Jolly and

Thompson-Fawcett, 2021). We argue here for the adoption of synergetic strategies (Fig. 6) across the life-cycle of the project that consider the environmental uniqueness of the Tibetan Plateau, foster wildlife protection, and take advantage of the rich storehouse of Indigenous ecological knowledge (Yeh et al., 2017). In this context, we propose three domains in which policy-making, research efforts and practical actions can be integrated to promote wildlife conservation during the development of solar and wind energy.

Firstly, there needs to be deeper collaboration among relevant government departments. The departments (Bureau of Energy, and Bureau of Forestry and Grassland) of the Tibetan Plateau should support each other on issues of common interest. In the context of the energy sector, there is a need to acknowledge that the main factors constraining the rate of increase in renewable energy is how efficiently the grid can absorb the additional supply (Martinot, 2016; Sturchio and Knapp, 2023). For the natural resources sector, policies are needed that do not automatically assume all human activities are “anti-nature”. Indeed, a series of special management systems for renewable energy development should be formulated by the regional planning committee to facilitate operationalizing energy projects. For example, use remote sensing and GIS technology to map out areas with high - potential for wind or solar energy development, and at the same time, mark critical wildlife corridors. Subsequently, establish buffer zones around wildlife habitats. These zones can serve as a transitional area between energy development sites and wildlife areas.

Secondly, there is a need to meet the goals of degraded grassland restoration, and resolve existing conflicts between wildlife and livestock. Governments and energy developers could focus instead on deploying solar power on degraded landscapes (e.g., alpine grassland). The use of degraded land offers opportunities to improve land condition and provide new habitats for wildlife (Nordberg et al., 2021). Alternatively, low-intensity ‘conservation grazing’ (that is using local livestock such as Tibetan sheep) could be applied for vegetation management in solar farms across alpine regions. Support for local herders could be augmented by leasing solar land for grazing pasture, and simultaneously providing more available habitat for wildlife in other regions where resource competition between wildlife and livestock is more intense.

Thirdly, it is important to place a high value on local Tibetan people and their local culture. Ensure that local pastoralist representatives are included in the decision - making bodies related to energy development projects. For example, have a pastoralist representative on the board of directors of an energy company operating in their area, so that they can directly influence decisions that affect their interests. In the project design phase, developers should consult and cooperate in good faith with local people to consider and adopt their knowledge on wildlife breeding and migration. Moreover, developers should collaborate with herders to jointly map wildlife corridors using participatory GIS. In the construction and operational phase, local Tibetan people could play roles such as construction or electrical workers and wildlife para-conservationists, particularly if appropriate professional training is provided (Darling et al., 2023). The core goal should be to ensure that local Tibetan communities play leading roles in the clean energy future both as beneficiaries and decision-makers.

4.4. Cross-regional applicability and limitations

Globally, the findings of this research have certain universality in regions with similar ecological and social backgrounds, but they need to be applied carefully in combination with specific contexts. At the ecosystem level, when developing renewable energy in biodiversity hotspots (such as the African savanna), there is a widespread risk of habitat fragmentation, which particularly threatens migratory species. At the social level, there is a widespread phenomenon of cognitive differences among local pastoralists. When community participation is insufficient, resource-dependent groups (such as local pastoralists in Mongolia, and the Sahel region) are prone to excessive concerns due to

lack of information. While specific dimensions of our findings demonstrate transferability to other regions, significant limitations persist due to distinct ecological and social contexts. Crucially, the impacts of variables such as ethnic cultural frameworks and pasture size on pastoralists’ perceptions require local empirical verification. Further cross-regional validation is necessary to establish the broader applicability of these findings.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eiar.2025.108143>.

Data availability

Data will be made available on request.

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