Research Progress on the Ecological Suitability of Grassland Photovoltaic Systems (Postprint)

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Abstract

Photovoltaic solar power generation is experiencing rapid large-scale centralized development, effectively reducing the consumption of fossil energy sources such as coal and petroleum, and making significant contributions to climate change mitigation. Grassland photovoltaic ecosystems, built upon photovoltaic solar power station parks (hereinafter referred to as "photovoltaic parks"), aim to achieve integrated solar energy development while systematically protecting grassland ecology. This represents an urgent imperative for promoting the transition of primary energy sources and achieving carbon peak and carbon neutrality objectives. Focusing on the ecological suitability of grassland photovoltaic systems, this study synthesizes research on the impacts of photovoltaic park construction and operation, both domestically and internationally, on local-scale microhabitats (including areas in front of photovoltaic module edges, beneath panels, behind edges, between panels, and outside photovoltaic parks), specifically examining land surface energy transfer, near-surface microclimate, and soil physicochemical properties. It further investigates the adaptive succession of biological communities (plants, animals, and soil microorganisms) within photovoltaic parks in response to disturbed habitats and their role in biogeochemical cycles (carbon cycling). Integrating the contemporary themes of green low-carbon development, digital intelligence, and sustainable development, this analysis examines current deficiencies in ecological suitability research on grassland photovoltaic systems and identifies future development directions, with the aim of providing references for in-depth research on the "grassland photovoltaic +" green development model (such as photovoltaic grass production and grass-light complementarity) and comprehensive desertification control.

Full Text

Preamble

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Abstract: Photovoltaic (PV) solar power generation is developing rapidly through large-scale centralized installations, effectively reducing consumption of fossil fuels such as coal and oil while making important contributions to climate change mitigation. The grassland photovoltaic ecosystem, built upon PV solar power station parks (hereinafter "PV parks"), aims to comprehensively develop solar energy while systematically protecting grassland ecology. This represents an urgent need for driving the replacement of primary energy sources and achieving carbon peak and carbon neutrality goals. Focusing on the ecological suitability of grassland photovoltaic systems, this study summarizes the impacts of PV park construction and operation on local microhabitats (including areas in front of, beneath, behind, and between PV panels, as well as outside the PV park) through alterations in land surface energy transfer, near-surface microclimate, and soil physicochemical properties. We explore the adaptive succession of biological communities (plants, animals, and soil microorganisms) within PV parks in response to disturbed habitats and their role in biogeochemical cycling (particularly carbon cycling). In light of contemporary themes of green low-carbon development, digital intelligence, and sustainability, we analyze current research gaps and future directions for ecological suitability studies of grassland photovoltaic systems, providing references for in-depth research on the green development model of "grassland photovoltaics plus"(such as PV-enabled grass production and grass-light complementarity) and integrated desertification control.

Keywords: grassland photovoltaic system; ecological suitability; desertification control with photovoltaics; PV-enabled grass production; grassland photovoltaic complementary mode; photovoltaic solar power station park

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1 Grassland Photovoltaic System

Since 2009, global photovoltaic solar power generation has grown at an average annual rate of approximately 41%, with installed capacity projected to increase nearly tenfold by 2040. In China, the area of PV parks expanded from 5.86 km^2 in 2010 to 2920 km^2 in 2020, reaching approximately 3712 km^2 by the end of 2022. This growth has already surpassed hydropower capacity (6.6$×10^{4}$ MW), making PV the second-largest energy supply form in China. Globally, PV parks are predominantly located in semi-arid, arid, and alpine regions characterized by abundant solar resources, low precipitation, sparse vegetation, and low population density. The land for these parks is primarily converted from gobi (gravel desert), sandy land, and desert grasslands.

Following PV park construction, PV arrays affect regional microclimate through shading, precipitation interception, and redistribution. This creates spatial variation in near-surface shortwave radiation and photosynthetically active radiation, increases soil moisture, reduces evapotranspiration, and gradually enhances aboveground herbaceous biomass and vegetation coverage over time. In gobi and sandy areas, this phenomenon is termed "PV-enabled grass production," while in desert grasslands it forms the "grass-light complementarity" model. By altering microenvironmental conditions and ecosystem processes, PV parks improve water and nutrient availability for plant growth, enhance vegetation productivity, and promote grassland restoration, thereby establishing the grassland photovoltaic ecosystem [Figure 1: see original paper].

In summary, the grassland photovoltaic ecosystem represents a human-dominated restructuring of microenvironmental conditions in gobi, sandy lands, and desert grasslands. PV parks modify near-surface shortwave and longwave radiation, photosynthetically active radiation, temperature and humidity, and soil temperature and moisture, driving adaptive succession among native plants, animals, and microorganisms. This system constitutes the ecological structure and framework for the "grass-light complementarity" model, representing both a comprehensive utilization of solar and grassland resources and a critical practice for achieving China' s carbon peak and carbon neutrality goals while combating desertification.

2.1 Microenvironmental Characteristics of PV Parks

PV park construction and operation alter microenvironmental factors, creating significant differences in near-surface meteorology, soil properties, and vegetation characteristics compared with surrounding areas. Within parks, microhabitats in front of, beneath, behind, and between PV arrays exhibit distinct differences. Overall, these disturbances manifest as changes in near-surface energy transmission and equilibrium, altered microclimates, and modified soil temperature, moisture, and physicochemical properties.

2.1.1 Land Surface Energy Transfer

PV arrays intercept shortwave radiation, creating localized shading beneath panels that shifts slightly in position and area with solar altitude variations due to Earth’ s rotation and revolution. Shading duration and light intensity follow the pattern: beneath panels > front of panels > between panels. After absorbing shortwave radiation, PV panels alter energy transmission above and below them, dramatically reducing shortwave radiation reaching the ground surface. This changes surface heat flux, sensible heat, and latent heat, subsequently affecting upward and downward longwave radiation and disrupting previous energy transmission patterns. In temperate desert grasslands on the northern slope of the Tianshan Mountains in Xinjiang, Jiang et al. found that PV array installation reduced surface heat flux by 25%-95%, increased sensible heat by 20.9%, and decreased latent heat by 34.4%. Graham et al. reported that PV panels reduced solar radiation by 75% and photosynthetically active radiation by 25%-95% ($P < 0.05$).

2.1.2 Near-Surface Microclimate

Following PV array installation, near-surface meteorological factors including light, temperature, humidity, wind speed and direction, and evapotranspiration undergo changes, creating microclimatic differences between locations within PV parks (front, beneath, behind, and between panels) and surrounding areas. Air temperature between PV arrays is higher than beneath panels, and PV park temperatures are generally higher than surrounding regions. In Arizona, USA, Broadbent et al. observed that daytime maximum temperatures between panels were 1.3°C higher than surrounding areas, while nighttime temperatures were 3-4°C higher. In the UK, Armstrong et al. found that summer temperatures beneath panels were 5.2°C lower than between panels and surrounding areas, while winter temperatures between panels were 1.7°C lower than beneath panels and surrounding areas. In Mediterranean France, Barron-Gafford et al. reported that PV panels lowered soil temperature by 0.75°C and reduced soil moisture.

Precipitation redistribution also occurs, with studies showing that rainfall in front of and between panels is higher than behind and beneath panels. Armstrong et al. found that PV panel shading altered soil temperature and moisture on the Qinghai-Tibet Plateau and Yunnan-Guizhou Plateau. Comprehensive monitoring of PV park construction and operation demonstrates significant differences in soil physicochemical properties and microhabitats compared with native ecosystems.

2.1.3 Soil Physicochemical Properties and Microhabitats

Initial construction activities (compaction, drilling) alter soil physicochemical properties, reducing soil aggregate stability and physical quality. In the Qinghai-Tibet Plateau’ s Talatan PV park (alpine desert grassland), organic matter, total nitrogen, and ammonium nitrogen increased significantly after 1-3 years of operation ($P < 0.05$). PV panel shading and altered precipitation patterns affect soil physicochemical properties and microhabitats, with soil moisture and nitrogen content increasing beneath panels.

2.2 Adaptive Responses of Biological Communities to PV-Disturbed Habitats

2.2.1 Plant Communities

During PV park construction, ground vegetation suffers varying degrees of damage. However, vegetation gradually recovers and undergoes positive succession during PV park operation. MODIS and Landsat 8 data reveal that grassland vegetation in the Qinghai-Tibet Plateau’ s Talatan PV park showed increasing trends after 1-3 years ($P < 0.05$), with similar recovery patterns observed in gobi and desert regions. PV arrays exhibit a “compensatory effect” that enhances grassland productivity and quality.

Within PV parks, plant density, species composition, and diversity change significantly. With increased shading, plant species richness and Margalef index increase substantially ($P < 0.05$). Zhang et al. found that PV arrays affect grassland vegetation differently across China’ s climate zones: in areas with high vegetation cover, PV installation reduces Enhanced Vegetation Index (EVI), while in extremely arid regions, PV arrays slightly increase vegetation coverage. In the southern Songnen Plain, Zhang et al. discovered that total aboveground productivity was higher in front of panels than beneath or behind them ($P < 0.05$). Using simulation experiments, Sturchio et al. found that grazing behavior in PV parks during the growing season (May-September) had a “compensatory effect,” enhancing grassland productivity and quality.

Spatial heterogeneity characterizes plant communities adapting to PV-disturbed microhabitats. In western Songnen Plain, Walston et al. found maximum plant density in front of panels, 34.87% higher per unit area than control areas, while density beneath panels was minimal at only 6.34 plants/m^2, 39.54% lower than controls. In Minnesota, USA, Walston et al. observed 84.8% and 61.4% increases in flowering species richness and floral abundance, respectively. Detailed studies on plant community adaptation to PV-disturbed habitats are summarized in .

2.2.2 Animal Communities

As PV parks operate, animal communities show varying adaptability to PV installations. PV arrays provide shade for livestock, reducing air temperature, body surface temperature, and skin temperature, thereby alleviating heat load (thermoregulation costs). In Brazil' s tropical savanna, Faria et al. found that PV panel shading reduced sheep wool surface temperature by 30.19% and skin temperature by 9.44°C. Fonsêca et al. reported that PV shading decreased sheep skin temperature by 1.5°C. In Minnesota, USA, Walston et al. found that insect quantity, habitat, and community diversity increased over time, with insect group diversity, total insect abundance, and local bee abundance increasing by 44.0%, 63.6%, and 66.7%, respectively, over five years. Studies show that grassland photovoltaic ecosystems enhance bird species richness and diversity. However, the "lake effect" on aquatic birds—where birds mistake PV facilities for water bodies—requires continued monitoring, as this attraction could be fatal. In southern California, Kosciuch et al. found higher bird community diversity indices (including aquatic habitat species) in PV parks than surrounding areas, without observing aquatic bird mortality. Studies on animal community adaptation are detailed in .

2.2.3 Soil Biological Communities (Soil Fauna and Microorganisms)

Soil microbes are direct participants in terrestrial ecosystem biogeochemical cycles and indispensable for maintaining ecosystem services. PV arrays alter soil microbial diversity, though temporal changes vary regionally. In the Qinghai-Tibet Plateau' s Talatan PV park, soil prokaryotic microbial diversity decreased compared with control areas ($P < 0.05$), with reduced community stability. In contrast, soil bacterial diversity increased in southern Songnen Plain PV parks. Ding et al. found that PV arrays increased soil bacterial Chao1 diversity index in Songnen grassland, with spatial variation: Chao1 index increased in front of panels ($P < 0.05$) but showed minimal increase beneath panels, with no differences between panel gaps or behind panels ($P > 0.05$). Soil fungal Chao1 index increased only in front of panels, with no differences elsewhere ($P > 0.05$). Factor analysis identified electrical conductivity and total aboveground biomass as main factors affecting bacterial communities, while available nitrogen and phosphorus primarily influenced fungal communities—both related to increased soil moisture and nitrogen content beneath panels. Soil arthropod diversity beneath panels was higher than between panels and control areas. Studies on soil biome adaptation are summarized in .

2.3 Biogeochemical Cycling in Grassland Photovoltaic Systems

PV parks enhance carbon and nitrogen storage in plants (aboveground, belowground, and litter) and soil. In Songnen Plain PV parks, Zhang et al. found that PV arrays increased plant carbon and nitrogen storage by 17.93% and 0.75%, respectively, and soil carbon and nitrogen storage by 30.19% and 9.44% ($P < 0.05$). Increased soil moisture beneath panels contributes to higher soil carbon and nitrogen storage than surrounding areas. In Ningxia, China, Zhang et al. found that carbon sequestration in PV parks increased nonlinearly by 4.43% annually, with soil temperature and moisture as primary factors affecting greenhouse gas fluxes. Conversely, Armstrong et al. found that PV parks in Colorado, USA, had lower soil carbon and nitrogen than surrounding areas despite vegetation restoration.

PV parks affect greenhouse gas emissions, though impacts vary seasonally. In UK grassland PV systems, Armstrong et al. measured CO_2 flux using infrared gas analyzers (EGM-4), finding that inter-panel grasslands acted as carbon sinks while areas beneath panels were carbon sources. During summer, inter-panel sinks were higher than beneath-panel sinks ($P < 0.05$), but in spring and autumn, control areas showed higher sinks than both inter-panel and beneath-panel areas. Large-scale PV arrays alter near-surface microhabitats (surface albedo, precipitation, atmospheric deposition, wind speed, turbulence), affecting plant-soil carbon cycling. Studies on biogeochemical cycling in grassland PV systems are summarized in .

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3 Research Gaps

Current research reveals that PV park construction and operation alter local microhabitats, affecting near-surface energy transmission, microclimate, soil microenvironment, and biogeochemical cycles, particularly in arid and semi-arid deserts, gobi, and desert grasslands. However, several limitations persist:

1. **Lack of comprehensive observations**: Large-scale centralized PV parks lack long-term, spatially comprehensive, multi-factor integrated monitoring. Current studies are regionally isolated, yielding non-generalizable conclusions without consistent patterns at regional or global scales.
2. **Limited biological research**: Studies on animal, soil fauna, and soil microbial adaptation to PV-disturbed habitats are limited. Research on grassland PV systems as ecological frameworks examining ecological functions and services remains scarce, with unclear spatiotemporal variation characteristics across global regions.
3. **Narrow biogeochemical focus**: Biogeochemical cycling studies concentrate primarily on carbon and nitrogen (gaseous) cycles, with insufficient research on water cycling (e.g., vegetation transpiration, soil evaporation) under PV-disturbed microenvironments. Studies on solid cycles (phosphorus, sulfur) and soil pollution are rarely reported.

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4 Conclusions and Future Directions

By 2060, PV solar power will become China’ s primary energy source, with total installed capacity projected to reach 50$×10^{4}$ MW. Grassland photovoltaic systems will serve as important carbon sequestration carriers in carbon neutrality strategies. Although large-scale centralized PV park construction and operation affect local microenvironments (shortwave radiation, near-surface temperature and humidity, wind speed and direction, soil temperature and moisture), biological communities (plants, animals, and soil microorganisms) demonstrate strong plasticity in response to these disturbances. In arid, semi-arid desert, gobi, and desert grasslands, this has gradually formed a new efficiency-enhancing model of “PV-enabled grass production” evolving into “grass-light complementarity.”

Integrating themes of green low-carbon development, digital intelligence, and sustainability, future research priorities for grassland photovoltaic system ecological suitability should include:

1. **Establishing energy and material flow monitoring systems**: Deploy meteorological and carbon-water flux equipment at regional or transect scales, construct low-altitude, full-spectrum, high-precision monitoring systems, and integrate multi-source remote sensing to develop transparent observation technologies for grassland PV systems. This will expand understanding of energy transmission and material cycling (water cycle, carbon cycle, etc.) and their spatiotemporal dynamics.
2. **Developing carbon sink accounting frameworks**: Quantify carbon emission reduction benefits from PV panel production and park construction/operation. Precisely account for additional carbon sink benefits from vegetation restoration and altered plant-water processes in response to disturbed habitats, advancing key technologies for carbon sink accounting and benefit assessment.
3. **Expanding adaptation research**: Conduct mechanistic analyses of biodiversity, structure, function, and services in grassland PV systems across multiple scales. Analyze impacts and benefits of large-scale centralized PV parks on local climate and ecology, and evaluate PV park suitability in deserts, gobi, desertified lands, and salinized grasslands.

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