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REVIEW ARTICLE

Impacts of centralized photovoltaic power stations on ecosystem components and greenhouse gas emissions: A review

Hao Fu[1†], Jizheng Wu[1†], Yang Liu[1], Xinyu Zhai[1], Xinyu Zhao[1], Wei Fang[1], Panyue Zhang[1]*, Ruiping Li[2]*, Xinming Wang[3], and Guangming Zhang[4]

[1]Key Laboratory of National Forestry and Grassland Administration for Wetland Comprehensive Management, College of Environmental Science and Engineering, Beijing Forestry University, Beijing, China

[2]Ordos Carbon Neutrality Research and Application Co., Ltd., Ordos, Inner Mongolia, China

[3]Ordos Anwei Smart Operation and Maintenance New Energy Co., Ltd., Ordos, Inner Mongolia, China

[4]Institute of Water Pollution Control, School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, China

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***Corresponding authors:**
Panyue Zhang
(panyue_zhang@bjfu.edu.cn);
Ruiping Li (1109065230@qq.com)

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Abstract

Driven by the goal of mitigating global warming, centralized photovoltaic power stations are de-veloping rapidly. While considering their power generation efficiency, a systematic assessment of their comprehensive impact on the ecosystem is necessary. In this review, the impact and driving factors of photovoltaic power stations on ecosystem composition and greenhouse gas (GHG) emis-sions are summarized, as well as the planning and management of photovoltaic power stations. Due to the varying construction scale, construction methods, and geographical locations of photo-voltaic power stations, these power stations show different temporal and spatial changes in impacts on local meteorological conditions, soil characteristics, and biological communities, further affect-ing soil GHG emissions indirectly, leading to an overestimation of carbon emission reduction ca-pacity of photovoltaic power stations. Solar radiation and precipitation distribution are the main factors driving the changes in microclimate, soil properties, biological communities, and GHG emissions. Optimizing the construction mode of photovoltaic power stations not only enhances power generation efficiency but also alters their environmental impact. However, there is still a lack of impact paths and mechanisms of centralized photovoltaic power stations on the abiotic en-vironment and biological communities, the ecological-energy comprehensive assessment system, and the ecological and energy efficiency prediction for different photovoltaic power station con-struction modes. Efforts in these directions will promote the development of eco-friendly photovol-taic systems.

Keywords: Photovoltaic management; Solar energy; Ecology; Environment; Carbon dioxide emissions

1. Introduction

Climate anomalies brought about by global warming, such as continuous heatwaves, rainstorms, forest fires, glacier melting, and sea level rise, not only disrupt the balance of natural ecosystems but also pose an ever-present threat to human survival. Therefore, mitigating global warming has become a priority issue worldwide.[1,2] Carbon dioxide (CO_2) emissions from the combustion of fossil fuels are a major factor contributing to global warming.[3] According to the World Energy Blue Book, coal power generation was the largest source of anthropogenic CO_2 emissions globally, accounting for over one-third of total energy-related emissions worldwide in 2022.[4] Statistics indicated that CO_2 emissions from fossil fuel consumption in China constituted approximately 88% of the country's total CO_2 emissions, with power generation accounting for about 41%.[5] Therefore, implementing carbon emission reduction in the power sector and achieving energy transition within the electricity industries are crucial for both the global community and China in realizing the goals of carbon peaking and carbon neutrality.

Solar energy, being ubiquitous, harmless, vast, and enduring, is the world's most abundant renewable resource. Photovoltaic power generation harnesses the photovoltaic effect at semiconductor interfaces to directly convert sunlight into electricity. In this process, clean energy is produced, making photovoltaics a crucial tool for the power industry to reduce carbon emissions.[6] Photovoltaic power generation has now gained widespread acceptance worldwide.[7] Despite the multiple benefits of solar power generation, including its environmental friendliness and sustainability, the construction of centralized photovoltaic power plants often occupies large areas of land due to the lower power density of photovoltaic generation compared to fossil fuel power generation. Constructing large-scale photovoltaic power stations impacts local ecosystems, for instance, air temperature and solar radiation increase while air humidity reduces, thereby altering vegetation characteristics. Changes in climatic factors like temperature and humidity also influence greenhouse gas (GHG) emissions from ecosystems. Therefore, investigating the ecological and environmental effects of large-scale photovoltaic power stations is crucial for developing eco-friendly photovoltaic facilities and mitigating soil GHG emissions from ecosystems.

Summarizing research on the ecological impacts of centralized photovoltaic power stations is crucial to promoting the construction of ecologically friendly centralized photovoltaic power stations. However, previous reviews primarily focused on the impacts on ecosystem components while paying little attention to related mechanisms and to the effects on soil carbon emissions indirectly caused by ecological alterations. In addition, reviews of research on photovoltaic management from an ecological perspective remain scarce. This review summarizes the impacts of centralized photovoltaic power stations on ecosystems and their indirect effects on soil carbon emissions. The objective of this review is to provide cutting-edge research directions and insights into constructing ecologically friendly centralized photovoltaic power stations and advancing carbon-emission reduction efforts, fully leveraging the environmental benefits of photovoltaic power generation.

2. Impacts of centralized photovoltaic power plants on ecosystems

2.1. Impacts on microclimate

The construction of photovoltaic power stations affects local meteorological conditions. However, the research results vary due to different observation methods. Results of several field observations showed that net radiation and wind speed within the stations decreased by 44% and 38%, respectively. Particularly, the annual average net radiation and wind speed beneath the photovoltaic panels decreased by 92.68% and 50.53%, respectively,[8] compared to those outside the stations, but there was no significant difference in temperature and relative humidity.[9] Several field observation studies indicated that the physical shielding and absorption of solar radiation by photovoltaic panels led to a "photovoltaic heat island effect" by cooling the surface of photovoltaic power stations and heating the ambient air near the photovoltaic panels.[10] At the same time, photovoltaic panels blocked sunlight from reaching the ground,[11] causing the land surface beneath the photovoltaic panels to receive less radiation than that outside the station,[12] with a decrease of ground temperature by approximately 5 °C.[13] The heating/cooling effects varied by season. A field observation study showed that the surface temperature outside the station increased by 1.74 °C during summer, while that within the station decreased by 0.23 °C after the installation of the photovoltaic power station; and in winter, the surface temperatures inside and outside the station rose by 0.4 °C and 1.44 °C, respectively.[14] Remote sensing analysis of 116 photovoltaic power plants worldwide revealed that solar panels resulted in a strong cooling effect on average annual daytime surface temperature and a weaker cooling effect at night. The most significant impact on albedo and daytime surface temperature occurred over barren land, followed by grasslands and farmland.[15] Researchers used models to predict that the reduction in surface albedo caused by photovoltaic panels might trigger positive feedback involving albedo, precipitation, and vegetation, leading to increased temperature and precipitation.[16] Model simulations revealed that photovoltaic power stations in the Gobi Desert of northwest China reduced evaporation and wind speeds,[17] potentially leading to increased humidity within the photovoltaic power stations.[10,18] To simulate the local or regional climate of photovoltaic power stations, a new photovoltaic-related energy balance model was developed to enhance the understanding of interactions between photovoltaic power plants and surface processes, including land surface temperature, downward shortwave radiation, wind speed, sensible heat flux, and latent heat flux.[19]

Currently, field observation, remote sensing interpretation, and model prediction are the core methods for studying the impact of centralized photovoltaic power stations on meteorological conditions. Field observations can provide high-precision, continuous *in situ* micrometeorological data, which is the gold standard for verifying research results, but they have limitations such as poor spatial representativeness and high costs. Remote sensing interpretation offers the advantages of large-scale spatial coverage and long-term sequence dynamic analysis, which can visually present the spatial patterns of meteorological effects on photovoltaic power stations, but it is constrained by the contradiction between temporal and spatial resolution and inversion errors. Model prediction can flexibly simulate the impact characteristics under different photovoltaic layouts and climate backgrounds, and deeply analyze the underlying physical mechanisms, but the accuracy of model prediction highly depends on parameter calibration, and there are technical bottlenecks in multi-scale adaptation. Therefore, coupling analysis with field observations, remote sensing, and model predictions may be highly significant for a deeper understanding of the ecological impacts of photovoltaic power stations.

As shown in Figure 1, the construction of most photovoltaic power stations decreases net radiation, wind speed, evaporation, and surface temperature within the power stations, while increasing air temperature and humidity. However, there are some unusual phenomena: for example, changes in air temperature and humidity at certain photovoltaic power stations show an opposite trend, which is mainly attributed to the differences in research locations and research methods.

2.2. Impacts on soil properties

Most research indicates that the presence of photovoltaic panels directly and indirectly affects soil physicochemical properties.[20,21] In one study, soil water-holding capacity and soil temperature beneath photovoltaic panels were significantly lower than in control areas;[22] soil moisture content within the photovoltaic power station increased by 59.8% to 113.6%, respectively;[22] soil bulk density gradually

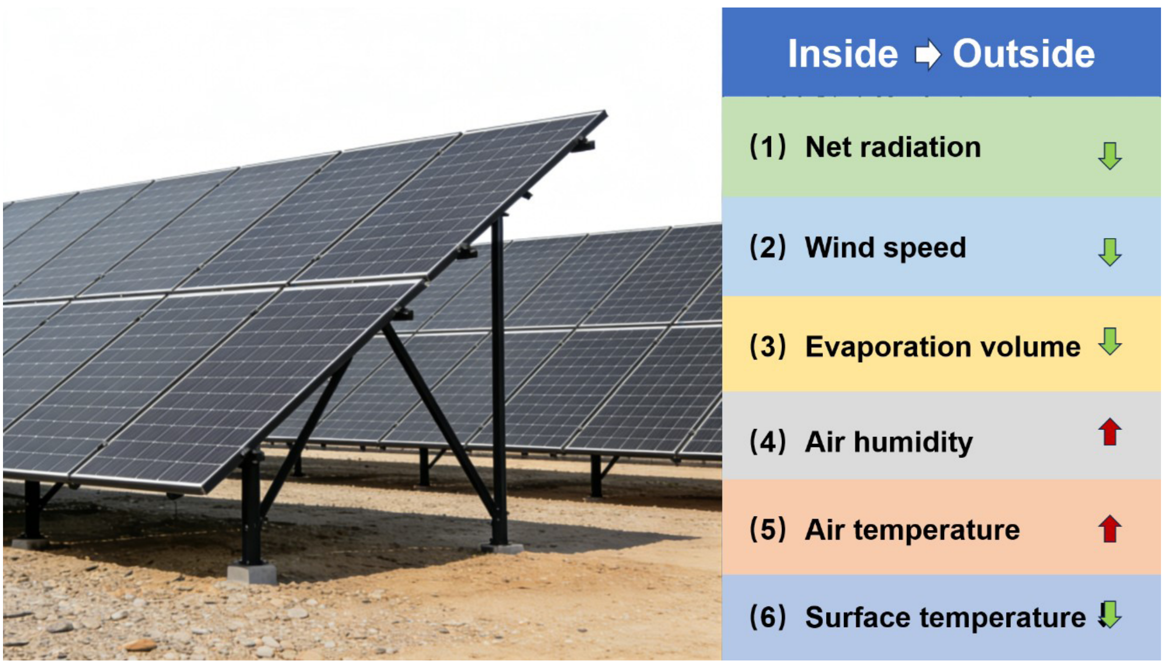

Figure 1. Impacts of centralized photovoltaic power stations on local meteorological conditions. Figure created by authors.

decreased with increasing distance from the center of the photovoltaic power station.[23] A study reported that the soil temperature change induced by photovoltaic panels exhibited seasonal variation, showing a warming effect in winter and a cooling effect from spring to autumn,[24] while electrical conductivity and pH level increased.[25] Photovoltaic power stations have a positive impact on soil fertility under certain conditions,[26] primarily including soil aggregate stability, soil available phosphorus,[27] and organic matter content[28] that increase with the distance from photovoltaic panels.[29] However, a study showed that seven years of photovoltaic coverage reduced soil fertility, with the decrease of total organic carbon and total nitrogen by 61% and 50%, respectively.[25] This may be attributed to differences in the local ecosystems. Additionally, the presence of photovoltaic arrays influences soil carbon and nitrogen cycles. A study showed that photovoltaic arrays increased soil carbon storage by 17.93% and nitrogen storage by 0.75%, and soil pH and bulk density were the primary factors affecting soil carbon and nitrogen storage.[30]

The impacts of photovoltaic power stations on the soil are summarized in Figure 2. It is worth noting that photovoltaic power stations lead to negative effects on soil moisture, soil carbon storage, and nitrogen storage. This might be due to varying soil properties and vegetation growth conditions in different regions, warranting further analysis.

2.3. Impacts on animal community

The photovoltaic power stations may threaten biodiversity,[31] and also impact animal behaviors. Five lambs and six ewes were observed in simulated photovoltaic power stations with two types of shade structures: one with photovoltaic panels and the other with 80% shade cloth. These animals spent less than 1% of their time in the shade cloth, 38% under the photovoltaic panels, and 61% exposed to direct sunlight.[32] A waterbird survey was conducted in wetland areas with floating photovoltaic systems in the Huainan–Huabei coal mining region of the North China Plain. After installing floating photovoltaic systems, waterbird numbers increased, but Simpson's diversity and Pielou's evenness decreased, while species richness showed no significant change.[33]

In conclusion, existing studies have shown that photovoltaic power stations may affect animal activities, thereby affecting biodiversity. However, the studies on the impact of photovoltaic power stations on animal communities were limited, warranting further studies.

2.4. Impacts on plant community

The photovoltaic power stations cause positive or negative disturbances to local vegetation.[34] A study of vegetation at

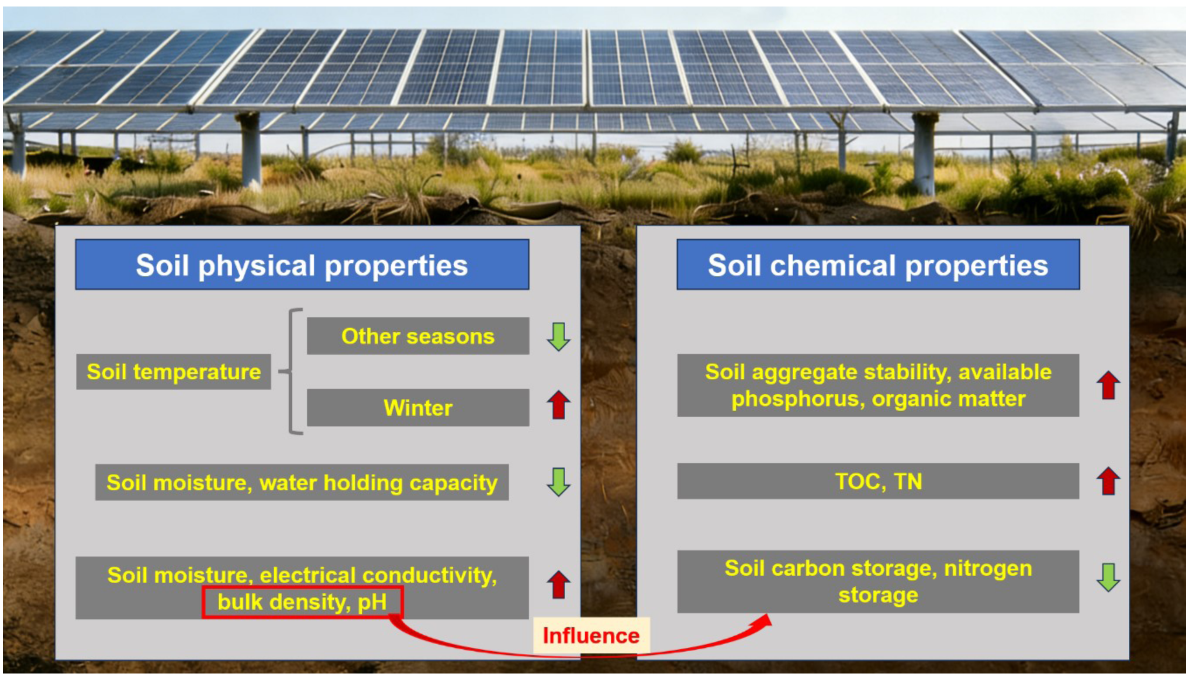

Figure 2. Impacts of centralized photovoltaic power stations on the soil environment. Figure created by authors.
Abbreviations: TN: Total nitrogen; TOC: Total organic carbon.

a desert photovoltaic power station in the Hexi Corridor of Northwest China revealed the differences in aboveground biomass and plant diversity indices, compared to those of the control.[29] Vegetation beneath and around the photovoltaic panels enhanced the performance of ground-mounted photovoltaics; meanwhile, the photovoltaic system created favorable conditions for plant growth.[21,35] Photovoltaic panels can accelerate the pace and quality of vegetation restoration by altering soil surface microhabitats in arid sandy ecosystems, promising unexpected ecological benefits in the future.[36] Remote sensing data revealed that the large-scale implementation of photovoltaic power stations promoted desert greening, primarily due to favorable climate change in photovoltaic desert remediation projects.[37] On the other hand, photovoltaic panels promote vegetation biomass and total soil organic carbon beneath and in front of the panels by redirecting rainwater to the undersides, thereby making a positive contribution to carbon storage.[38] A meta-analysis revealed that photovoltaic power stations promoted vegetation diversity, cover, and biomass, significantly enhancing vegetation productivity. Among different ecosystems, the effect of photovoltaic power stations is most pronounced in desert regions.[39] In grassland ecosystems, the photovoltaic power stations can enhance aboveground plant biomass and vegetation cover. In agricultural and forestry ecosystems, the photovoltaic panels can increase aboveground plant biomass while reducing plant species richness and vegetation cover in forest lands.[27] However, a multidimensional analysis of functional diversity of vegetation within 10 photovoltaic power stations in Italy indicated that lower light levels beneath the photovoltaic panels at higher humidity and lower temperatures resulted in reduced species richness, diversity, and evenness, compared to inter-panel areas and outside the power stations.[40]

The specific impacts of photovoltaic power stations on plant communities are summarized in Figure 3. The positive impact of photovoltaic power stations on plant communities mainly occurs between the two rows of photovoltaic arrays. Beneath the photovoltaic panels, reduced sunlight availability and altered microclimatic conditions can constrain plant growth and diversity, so positive vegetation responses are often stronger in inter-row areas than directly under panels.

2.5. Impacts on microbial community

The photovoltaic power stations also affect the microbial communities in soil and on the surfaces of photovoltaic panels. The abundance of soil microbial communities increases in the photovoltaic power stations.[28] However, a previous study reported that photovoltaic power stations had little impact on the structure of soil archaeal communities in the desert regions, suggesting that niche

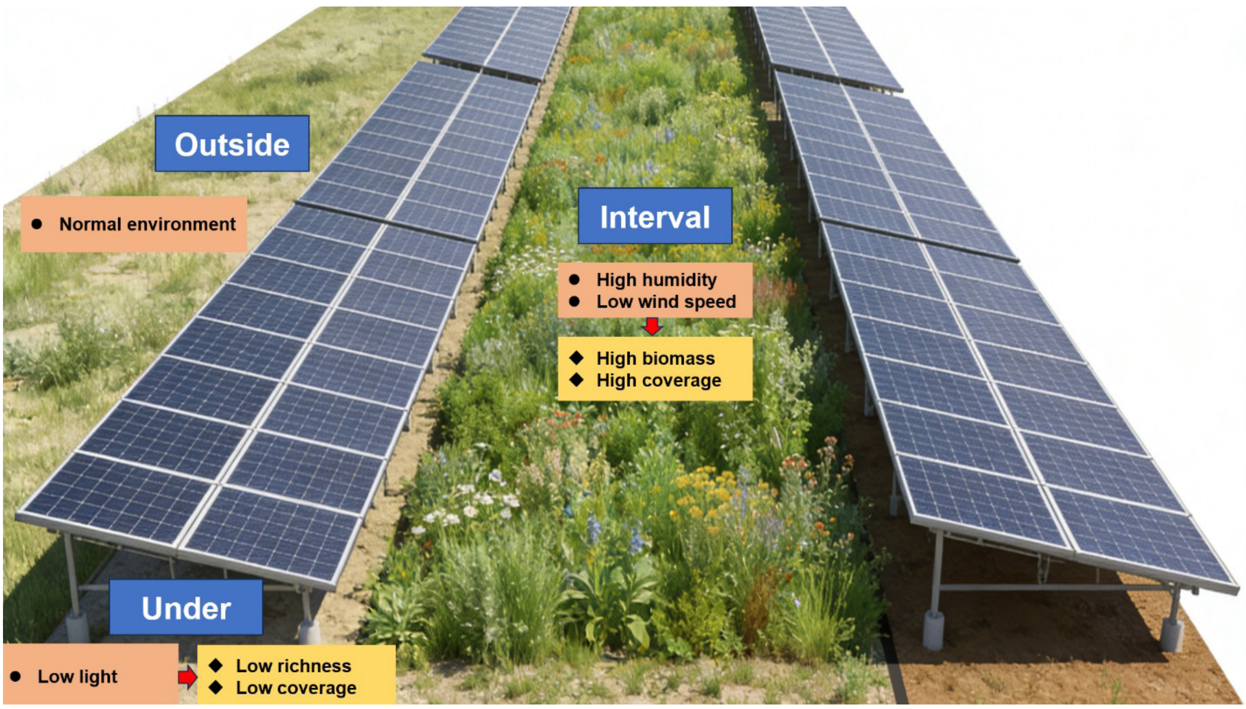

Figure 3. Impacts of centralized photovoltaic power stations on plant communities. Figure created by authors.

selection might play a dominant role in the distribution patterns of soil archaeal communities.[20] The soil bacterial communities within photovoltaic power stations may adopt different survival strategies to cope with small-scale light stress under various vegetation restoration modes.[41] In contaminated soils, such as those with evident fluoride and chloride pollution at photovoltaic sites, elevated fluoride and chloride levels significantly affected the population size and overall biological activity of soil microbial communities.[42] The dominant genera in photovoltaic sites include *Sphingomonas*, Subgroup_6_norank, *Bacteroides strictus*, *Nitrosospira*, *Rhizobium*, and *Acidobacter,*[42] which exhibit resistance to high acidity, elevated fluoride and chloride content, and hypertonic environment. Photovoltaic panels absorb substantial thermal energy and promote the enrichment of thermophilic microorganisms. The microbial diversity on glass surfaces of photovoltaic panels in two tropical cities in southeastern Brazil was investigated, and the taxonomic profiles of two panel types were remarkably similar, dominated primarily by the phyla Proteobacteria and Bacteroidetes, with minor presence of Cyanobacteria, and by the genus *Mycobacterium* and *Methanobacterium-Methanococcus*.[43] However, phototrophic microorganisms were scarce on photovoltaic panel surfaces, with the primary detected microorganisms being melanin-producing hyphal Ascomycetes, pigment bacteria genera, *Bacillus*, and *Tetracoccus*.[44]

Studies have shown that photovoltaic power stations not only alter the diversity of microbial communities but also change the composition of microbial communities, resulting in different functional microorganisms being enriched in different areas. However, the related studies are still relatively few.

2.6. Impacts on soil greenhouse gas emissions

The lifecycle GHG emissions of photovoltaic panels mainly include direct and indirect emissions from manufacturing, transportation, use, and disposal processes, as with other materials.[45] The estimated lifecycle GHG footprints for photovoltaic modules manufactured in Europe and China are 37.3 and 72.2 gCO_2-eq kWh^{-1}, respectively.[46] However, land use change caused by photovoltaic power stations may affect soil properties and plant community characteristics,[47] thereby influencing soil GHG emissions as part of indirect GHG emissions, leading to an overestimation of emission reduction benefits of photovoltaic systems.[49] Research indicated that soil temperature and soil moisture influenced soil GHG fluxes by regulating soil organic matter mineralization, chemical reaction rate, and gas diffusion within the soil, stimulating microbial growth and activity, and altering microbial nitrification and denitrification processes.[48] However, current research has primarily focused on the impact of photovoltaic power stations on soil GHG emissions in grassland ecosystems. Significant variations exist across different ecosystems, and studies exploring the GHG footprint of photovoltaic arrays on different host ecosystems remain relatively scarce.[49]

3. Mechanisms of photovoltaic impacts on ecological components

3.1. Abiotic environment

Solar radiation is the primary environmental factor influencing climate conditions. The direct solar radiation reaching Earth's surface determines whether a region is suitable for constructing photovoltaic power stations and directly impacts the efficiency of photovoltaic power generation. Correlation analysis indicated that direct solar radiation was positively correlated with surface air temperature and wind speed, while negatively correlated with total precipitation, relative humidity, low cloud cover, total cloud cover, and aerosol concentration.[50] Large-scale photovoltaic arrays have the potential to affect surface albedo,[51] leading to a shading effect[52] and precipitation interception.[53] Changes in surface albedo and soil moisture directly or indirectly affect the soil temperature.[24]

However, at present, there is a lack of research on the mechanisms by which centralized photovoltaic power stations affect the meteorological and soil environments. The shortage of monitoring data might be the cause of this issue. In the future, simulation modeling can be developed using previous monitoring data to address this problem.

3.2. Biological community

Remote sensing interpretation and random forest models, specifically through big data mining, have revealed that the implementation of photovoltaic power stations promoted vegetation growth in the vast majority of arid and hyper-arid regions; conversely, photovoltaic power stations have led to reduced vegetation in semi-humid and semi-arid regions. The impact of photovoltaic power stations on vegetation dynamics depends on local environmental conditions. Constructing photovoltaic power stations in areas with sparse vegetation, low humidity, and long sunshine duration is more likely to promote vegetation restoration.[54] Photovoltaic systems can enhance water uptake by the dominant plants from the surface soil and aboveground biomass. This can promote vegetation recovery in semi-arid grassland ecosystems by facilitating water-nutrient coordination and carbon-water coupling.[55] Xia *et al.*[56] quantified the relative contributions of climatic factors and photovoltaic station implementation to changes in the normalized difference vegetation index using multiple regression analysis. Results indicated that vegetation gradually increased since 2000, with the vegetation recovery rate doubling during photovoltaic expansion periods. From 2013 to 2020, climate change was the primary driver of vegetation growth (56%), followed by the expansion of solar photovoltaic infrastructure (44%). Vegetation growth rate within photovoltaic arrays was 1.4 times higher than that outside the photovoltaic arrays, primarily because photovoltaic panels enhanced summer rainfall utilization and mitigated the negative effect of excessive sunlight.

Studies have shown that shade provided by photovoltaic panels promoted soil microbial symbiosis but suppressed the abundance of 16S rRNA gene in soil;[38] increased precipitation reduced the abundance of 18S rRNA gene, while decreased precipitation led to declines in plant aboveground biomass, soil prokaryotic community α-diversity, and dehydrogenase activity beneath photovoltaic panels.[38] Combining quantitative polymerase chain reaction, high-throughput sequencing, and soil property analysis, the responses of soil microbial communities and plant communities to photovoltaic panel installations revealed the critical role of precipitation in maintaining plant and soil microbial diversity within dryland ecosystems, making it essential for predicting risks to local ecological impacts.[57]

There is a lack of systematic observation of the interaction between the abiotic environment and the biological community. Therefore, it is difficult to explain the mechanisms by which centralized photovoltaic power stations affect the abiotic environment and subsequently the biological community, which should be systematically investigated in the future.

4. Drivers of soil greenhouse gas emissions in photovoltaic power stations

4.1 Soil moisture

Soil moisture is the primary factor influencing soil GHG emissions because it governs microbial activity and all associated processes, as illustrated in Figure 4. Research indicated that prolonged drought significantly reduced GHG emissions from soil, with well-structured soils producing higher CO_2 emissions, particularly during warm, dry periods, compared to sandy soils.[62] Soil microorganisms have limited access to carbon and nitrogen within stable soil aggregates (clods, crusts), resulting in lower GHG emissions. Precipitation following prolonged drought can trigger a pulse effect, causing GHG emissions to surge within minutes or hours after rainfall begins and then return to background within days.[63] This is driven by the availability of readily mineralized substrates and easily decomposable materials, which are used to reactivate microbial metabolism.[64] Nitrous oxide (N_2O) emissions tend to be higher in soils with lower total porosity or poor aeration, where oxygen availability is limited and incomplete nitrification or denitrification occurs.[58] While the production of methane (CH_4) requires strict anaerobic conditions and is positively correlated with soil moisture,[59] soil can act as a CH_4 sink under aerobic conditions.[60] Soil moisture is influenced by particle size distribution. Soils with a high proportion of macropores retain less water, thereby promoting the release of GHG produced under aerobic conditions. Conversely, soils dominated by micropores support the formation of CH_4 and N_2O generated under anaerobic conditions.[61]

4.2. Soil temperature

Soil temperature is also a key factor influencing soil GHG emissions. Soil moisture and soil temperature can explain 74% and 86% of N_2O emission variations, respectively.[65] As shown in Figure 5, increases in soil temperature enhance soil respiration rate and increase GHG emissions, representing a positive feedback response to heightened microbial metabolism. As soil temperatures rise, the accelerated soil respiration further promotes CH_4 and N_2O emissions. The temperature dependence of soil GHG emissions can be described by the temperature sensitivity factor Q_{10}. Q_{10} represents the reaction rate change in a chemical or biological system per 10°C change in temperature.[66] The higher the soil temperature, the higher the Q_{10}, and the higher the CH_4 emission, indicating that CH_4 emission is sensitive to temperature change.[67] However, the sensitivity of N_2O to temperature change shows temperature-dependent behavior, and the Q_{10} ranges broadly from 1.7 to 9.3. Specifically, when the temperature exceeds 37 **°C**, N_2O emissions decrease.[68] From the perspective of soil properties, as organic carbon content decreases and soil alkalinity increases, the carbon sequestration capacity of shifting sands gradually becomes more pronounced and intensifies under low-temperature conditions.[69]

4.3. Heavy precipitation

Global warming intensifies the hydrological cycle, leading to a sharp increase in global total precipitation and extreme precipitation events, particularly in arid and semi-arid regions. Total precipitation, precipitation frequency, and precipitation timing are the key factors determining the impact of precipitation pulses on carbon exchange in desert ecosystems. Under long-term conditions of low soil water availability, the carbon sink intensity of desert ecosystems generally increases with increasing rainfall.[20] However, studies also showed that soil CO_2 release significantly increased following desert rainfall pulses,[70] with carbon sink intensity diminishing as rainfall intensity

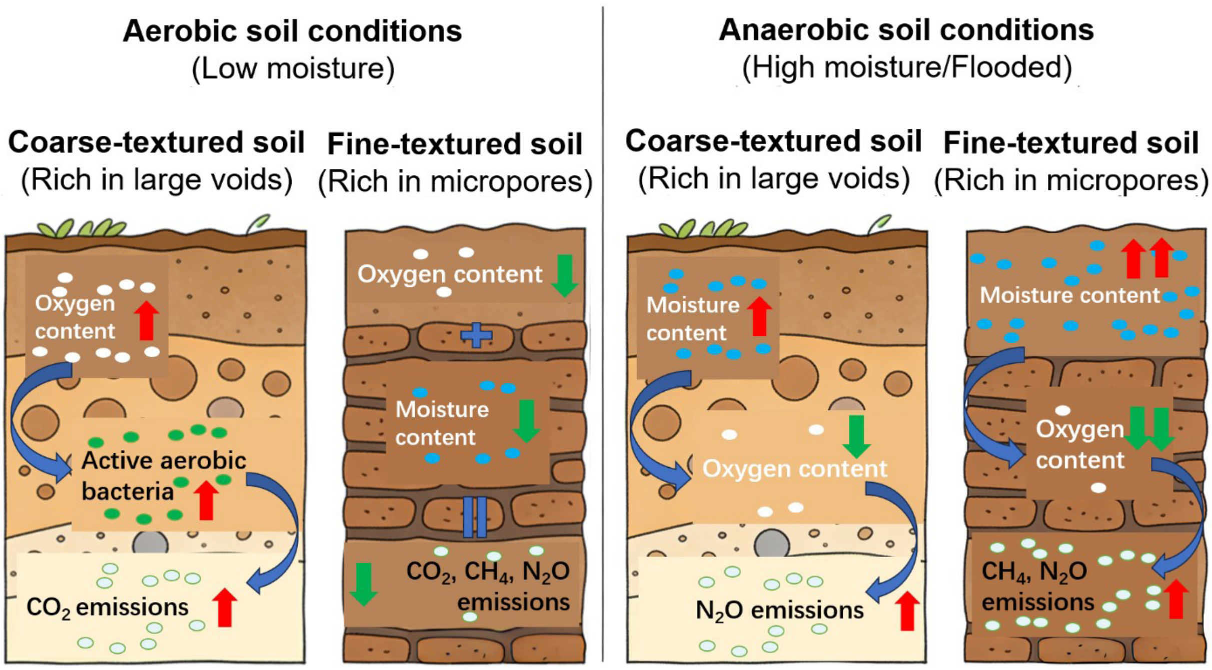

Figure 4. Impacts of soil moisture on greenhouse gas emissions. Figure created by authors.
Abbreviations: CH_4: Methane; CO_2: Carbon dioxide; N_2O: Nitrous oxide.

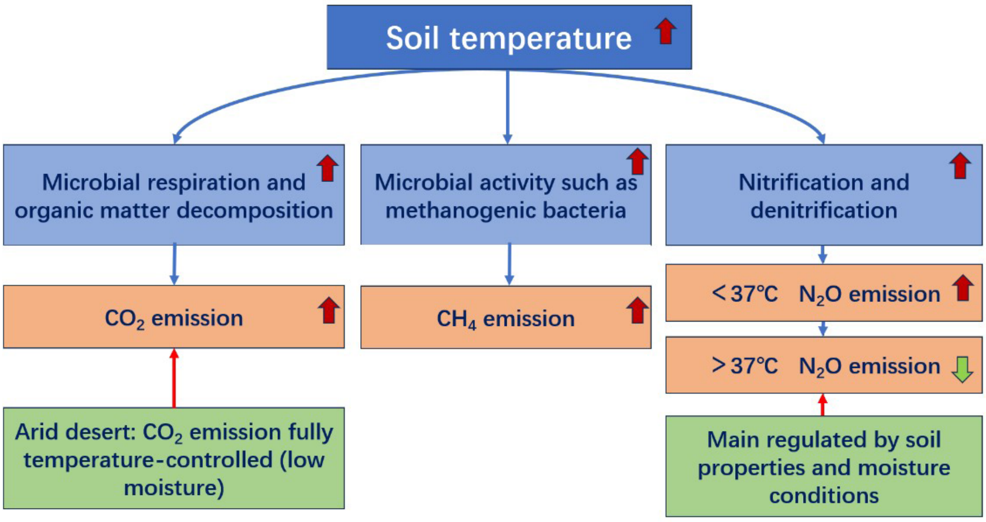

Figure 5. Impacts of soil temperature on greenhouse gas emissions. Figure created by authors.
Abbreviations: CH_4: Methane; CO_2: Carbon dioxide; N_2O: Nitrous oxide.

rose. Precipitation entering shifting sands subsequently influences multiple key processes governing desert carbon budgets, including soil heat transfer, CO_2 dissolution in soil water, soil salinity concentration, microbial abundance and activity, and soil nutrient transport. The long-term arid state of shifting sands can be disrupted following desert precipitation events. When soil moisture remains below a threshold, CO_2 budgets in shifting sands are strictly controlled solely by soil temperature.

4.4. Soil salinity

Soil salinity inhibits microbial activity by lowering the osmotic potential of soil solutions and inducing ion-specific toxicity. Consequently, soil salinity reduces the capacity of soil microorganisms to decompose organic matter, thereby decreasing soil CO_2 emission.[71] Beyond direct effects, salinity can suppress soil CO_2 emission by enhancing the toxic effects of contaminated soils. By forming complexes with toxic metals and inorganic ligands, soil salinity increases the mobility, availability, and toxicity of heavy metals, reducing soil microbial activity and diminishing CO_2 emissions. Studies indicated that soil salinity also reduced CH_4 emission across various ecosystems. This decrease may result from higher salinity, which increases the availability of sulfate ion (SO_4^{2-}). Sulfate-reducing bacteria and methanogens competed for acetate and hydrogen, the primary substrates for CH_4 production. The availability of SO_4^{2-} allowed methanogens with poor competitive ability to exit substrate competition and ultimately, reduced methanogenic activity.[72,73] Studies indicated that within a certain range, soil salinity increased N_2O production in agricultural soils,[74] fallow fields, oasis farms, wetland riparian zones, and coastal ecosystems. The potential processes by which salinization increases N_2O emissions are shown in Figure 6 and include the following: (i) elevated salinity accelerates plant senescence due to salt accumulation in leaves and other plant parts, increasing the input of nitrogen from plant litter into the soil;[75] (ii) salinity exerts a greater inhibitory effect on nitrite oxidizing than on ammonia oxidizing, leading to accumulation of nitrite and subsequent N_2O production; (iii) salinity enhances nitrate-reducing microbial communities, thereby elevating N_2O production rate;[76] (iv) salinization-induced osmotic stress suppresses denitrifying factors responsible for reducing N_2O to N_2;[77] (v) increasing soil salinity stimulates SO_4^{2-} reduction, leading to elevated hydrogen sulfide concentration, which can inhibit N_2O reductase from converting N_2O into nitrogen.

5. Construction and planning management of centralized photovoltaic power stations

The photovoltaic power generation efficiency varies depending on the construction method, not the photovoltaic panels. Li *et al.*[78] reported that the optimal

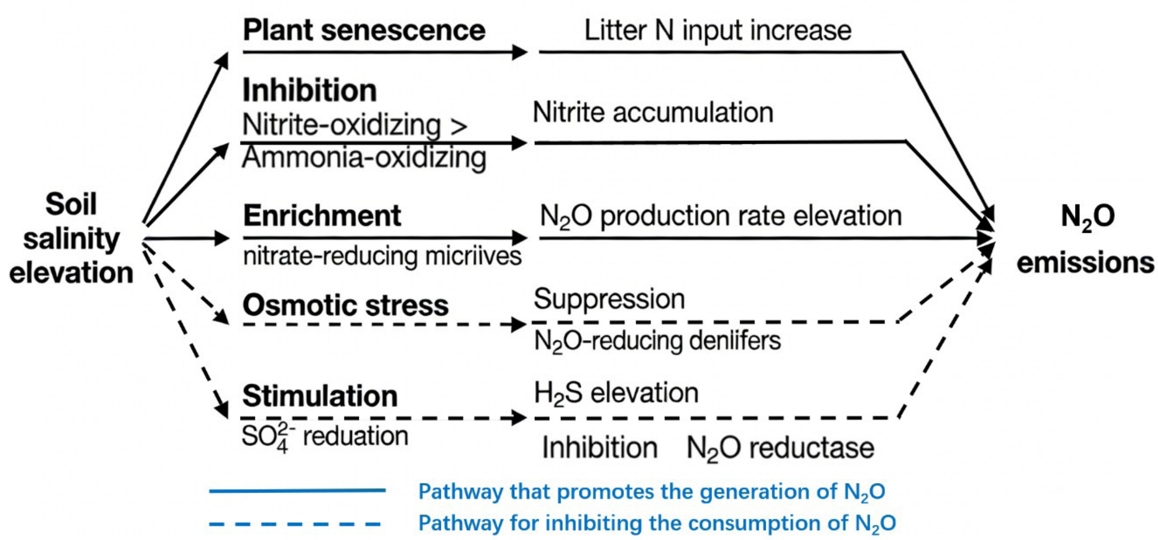

Figure 6. Influence of soil salinity on N_2O emission. Figure created by authors.
Abbreviations: H_2S: Hydrogen sulfide; N: Nitrogen; N_2O: Nitrous oxide; SO_4^{2-}: Sulfate ion.

trajectories for tilt angle and azimuth depend on available solar radiation, solar cell efficiency, tracking system consumption, and optimization constraints. Most investors believe that photovoltaic development should maximize power generation capacity, while paying less attention to adverse effects on expected lifespan or suboptimal tilt angles, such as dust impact, wind pressure, wind cooling effect, construction cost, temperature, and annual water consumption.[79] The solar conversion efficiency of the tracked photovoltaic platform (14.34%) is slightly higher than that of the fixed platform (14.17%),[80] solar tracking can increase the annual solar energy by 28%, boosting electrical output by 29.6%. Barbón *et al.*[81,82] optimized the design plan for photovoltaic power stations by analyzing construction costs and power generation efficiency under different meteorological conditions and tilt angles. Tian *et al.*[83] developed a theoretical model to estimate the power output of curved copper indium gallium selenide modules and compared their performance with flat modules, reporting that flat modules outperformed curved modules at low tilt angles, while curved modules demonstrated advantages in annual electricity generation during summer months at high tilt angles. Mian *et al.*[57] considered numerous variables, including topography, temperature, dust storm, and solar radiation, and integrated various multi-criteria decision-making techniques to ensure the advantages of each method outweigh the disadvantages of others. The results indicated that the most critical factors for selecting photovoltaic sites were solar radiation and sunshine duration. Research also proposed a spatial photovoltaic potential evaluation method integrating aerial photogrammetry with geographic information system (GIS) to assess the photovoltaic potential of buildings.[84]

Through investigating the meteorological and biological impacts of fixed-mounted and tracking photovoltaic systems, Suuronen *et al.*[85] reported that solar tracking technology exerted a lesser influence on microclimate and species composition between sunlight and shade within photovoltaic power stations. Therefore, exploring the planning and management of photovoltaic power station construction is crucial for ecological conservation and involves multi-criteria assessments of factors, such as meteorology, geography, economics, and ecological conditions, as shown in Table 1. Xiao *et al.*[86] analyzed factors influencing the siting of desert photovoltaic stations and established an optimal selection model using the analytic hierarchy process and GIS technology. Khanjarpanah *et al.*[87] proposed a novel algorithm that employs non-radial data envelopment analysis (DEA) and a clustering method, including single-cycle and multi-cycle models, to select optimal locations for photovoltaic site establishment. This algorithm can evaluate the efficiency of candidate sites for photovoltaic power station construction while simultaneously considering their sustainability. Moldovan *et al.*[80] proposed a combined approach integrating DEA, grey analytic hierarchy process (G-AHP), and grey total preference indexed by symmetric performance (G-TOPSIS). This approach considered both quantitative and qualitative efficiency criteria for location evaluation: DEA was employed in the first stage to select efficient locations based on measurable criteria; in the second stage, these locations were further evaluated based on technological, economic, environmental, and socio-political factors. The G-AHP was employed for criterion weighting, while G-TOPSIS ranked the locations. Li *et al.*[78] focused on five land use types: vacant land, bare land, shrubland, woodland, and grassland, excluding disturbed land types, such as construction land, ecological conservation areas, and farmland. They employed the fuzzy analytic hierarchy process to construct a site selection model and analyzed the suitability of locations for photovoltaic power stations, considering 13 factors, including topography, weather, environment, and nearby resources.

Table 1. Comprehensive assessment of photovoltaic power station construction considering ecological and environmental effects

Evaluation content	Research methods	Literature sources
Climate conditions, topography, land cover types, and location	Analytic hierarchy process and GIS technology	86
Power generation efficiency, sustainability	Non-radial data envelopment analysis and clustering methods	87
Technical, economic, environmental, and socio-political	DEA, G-AHP, and G-TOPSIS	80
Terrain, weather, environment, and nearby resources	Fuzzy analytic hierarchy process	78

Abbreviations: DEA: Data envelopment analysis; G-AHP: Grey analytic hierarchy process; GIS: Geographic information system; G-TOPSIS: Grey total preference indexed by symmetric performance.

Nowadays, the pursuit of energy efficiency in photovoltaic power stations is no longer the sole goal. The "photovoltaic +" model has been increasingly explored and gained more attention, for instance, "photovoltaic + agriculture," "photovoltaic + animal husbandry," and "photovoltaic + fishery."[88-91] This indicates that the path of ecological and energy synergy development is the inevitable trend.

6. Conclusion

The construction of centralized photovoltaic power stations indeed impacts ecosystems, including temperature, humidity, soil nutrients, and other factors. However, both abiotic and biotic factors, such as meteorology, soil, animals, plants, and microorganisms, interact indispensably within ecosystems. The ecological impacts of photovoltaic power stations are predominantly attributed to meteorology, soil, vegetation, or microorganisms, yet they have not been systematically investigated. Studies on other ecosystem services, such as carbon sequestration, remain significantly underdeveloped.

Current research on the impact pathways of photovoltaic power stations on ecosystems primarily involves correlation analyses between abiotic and biotic factors based on field monitoring or remote sensing interpretation. This approach fails to elucidate fundamental influence pathways from the perspective of photovoltaic power stations, hindering efforts to restore and protect fragile ecosystems in photovoltaic zones. Globally, research on the mechanisms of soil GHG emissions in photovoltaic areas is limited. It is necessary to investigate how climate change and soil variation influence GHG emissions and to develop mitigation strategies, including nitrification inhibitors, biochar application, and other measures.[92]

Research on photovoltaic power station plan, construction, and management has primarily focused on electricity generation capacity, with several studies addressing cost issues. However, few investigations have examined their ecological impacts, hindering the restoration and protection of fragile ecosystems in these regions and the achievement of harmonious coexistence between humans and nature. Therefore, future research should investigate the impacts of photovoltaic power stations on regional ecosystems under different construction methods and development plans. A comprehensive assessment methodology should be developed to conduct integrated evaluations that achieve the sustainable development of ecologically friendly centralized photovoltaic power stations. A forward-looking life cycle assessment method based on patents and papers can help reliably select the most sustainable solution, rather than merely assessing environmental impacts.[93,94]

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Conflict of interest

Panyue Zhang is the Guest Editor of this special issue, but was not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. Ruiping Li is affiliated with Ordos Carbon Neutrality Research and Application Co., Ltd. (Ordos, Inner Mongolia, China), and Xinming Wang is affiliated with Ordos Anwei Smart Operation and Maintenance New Energy Co., Ltd. (Ordos, Inner Mongolia, China). The remaining authors declare that they have no known competing financial interests or personal relationships that could have influenced thework reported in this paper.

Author contributions

Conceptualization: Hao Fu
Writing–original draft: Hao Fu
Writing–review & editing: All authors

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Not applicable.

Further disclosure

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