land

Article

Response of Vegetation and Soil Property Changes by Photovoltaic Established Stations Based on a Comprehensive Meta-Analysis

Xiaoxin Chen [1,2], Bojian Chen [2,3], Yongdong Wang [1,*], Na Zhou [1,*] and Zhibin Zhou [1]

1 National Engineering Technology Research Center for Desert-Oasis Ecological Construction, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
* Correspondence: wangyd@ms.xjb.ac.cn (Y.W.); zndesert@ms.xjb.ac.cn (N.Z.); Tel.: +86-0991-7823138 (Y.W.); +86-152-7660-5122 (N.Z.)

Abstract: Since the commencement of Sustainable Development Goals (SDGs), renewable energy has faced many challenges in reaching the target of SDGs, while the potential ecological impact on the environment cannot be ignored. The expansion of photovoltaic (PV) networks is raising concerns regarding the potential impact of large-scale PV power stations on local ecosystems. However, a comprehensive understanding of the specific responses of vegetation and soil factors to PV construction across different study locations is still lacking. To address this knowledge gap, we conducted a comprehensive meta-analysis of 28 studies internationally representing 31 observational points that evaluated 432 different vegetation and soil factor responses to the installation of PV power stations. We used piecewiseSEM to explore the responses of predictors/factors to the eco-logical environment. This study investigated the geographical and environmental conditions associated with PV construction and their responses to vegetation and soil factors, considering the advantages and disadvantages of PV power station construction in different ecosystems. The results indicate that (1) the response of the ecosystems to PV power station construction increased by 58.89%. Among these, the most significant improvement is in the desert, which accounts for 77.26%. Improvement in temperate regions is 59.62%, while there is a decrease of 19.78% in boreal regions. Improvement in arid regions is 84.45%, while improvement in humid regions is 9.84%. (2) PV construction promotes SWC, vegetation diversity, vegetation coverage, and vegetation biomass, significantly enhancing vegetation productivity. (3) Among the different ecosystems, PV power station effects were most significant in deserts, while showing negative impacts on croplands. (4) Compared to below-panel treatments, between-panel treatments were more effective in improving ecological conditions. The study contributes to mitigating adverse effects associated with photovoltaic site development, offering insights into site selection planning for solar power stations and the advancement of the renewable energy sector.

Keywords: desert; ecological impact; soil; vegetation; photovoltaic power station; piecewiseSEM

Citation: Chen, X.; Chen, B.; Wang, Y.; Zhou, N.; Zhou, Z. Response of Vegetation and Soil Property Changes by Photovoltaic Established Stations Based on a Comprehensive Meta-Analysis. *Land* **2024**, *13*, 478. https://doi.org/10.3390/land13040478

Academic Editor: Cezary Kabala

Received: 19 February 2024
Revised: 29 March 2024
Accepted: 29 March 2024
Published: 8 April 2024

1. Introduction

Under the Sustainable Development Goals (SDG) framework, the overarching goal is to reduce adverse impacts on the environment and mitigate carbon emissions while improving efficiency. Solar energy is a clean and secure energy source compared with fossil fuels [1].

PV resources are widely acknowledged as clean energy sources, but existing PV technologies have potential environmental impacts, including landscape fragmentation, local biota extinction, alterations in microclimate and biotic community composition, and significant environmental factors, such as surface albedo [2]. Nonetheless, PV power stations can also have a negative impact on ecosystems. The establishment of PV power stations leads to vegetation destruction and influences soil conditions. Research indicates that the implementation process of PV systems can exert diverse impacts on the landscape and biodiversity, posing a potential contradiction to the overarching objective of mitigating global warming [3]. Numerous environmental impacts of PV power stations were considered in various ways, encompassing both negative and positive impacts. Compared with other substantial construction projects, the establishment of utility-scale PV projects necessitates adept management to address various potential environmental impacts. Bai, et al. [4] delved into the impact of photovoltaic panel installation on grassland ecosystem functions. They emphasized that photovoltaic panels may induce complex and profound changes in soil microbial communities through their effects on abiotic factors. In addition, establishing PV power stations in desert areas offers several unique advantages. Meanwhile, the infrastructure for PV generation requires extensive land use [5–7]. However, desert ecosystems are inherently fragile and undergo degradation or alteration owing to disturbances or climate change [2,5]. Regions with a high PV potential frequently encompass fragile ecosystems that are susceptible to disturbances and are challenging to restore [8]. Our understanding of the impact of PV systems on the soil environment is evolving, and our understanding of changes in the microclimate, soil (carbon cycle, soil microbial community composition, and SWC), and vegetation is continually advancing. Additionally, changes in the ecological environment may vary with environmental influences, such as ecosystem type [9].

Numerous studies have highlighted that the development of PV has the potential for significant environmental benefits, especially in degraded areas with minimal conservation value that may be subject to fewer negative environmental impacts. Zhang conducted a meta-analysis and found that the construction of photovoltaic power stations reduces local temperatures, photosynthetically active radiation, and effective radiation, while increasing vegetation coverage and biomass [9]. However, other studies have reported on elevated temperatures down the gradient from large PV facilities [10,11]. A study by Wall et al. found that vegetation is a major carbon source for decomposer microorganisms [12], and that solar panels may also indirectly alter soil conditions by changing the vegetation community composition [5,13]. PV panels can enhance SWC, creating favorable conditions for the growth of flora [14]. Through Lambert, et al. [15] experimental treatments, various configurations of photovoltaic panel setups resulted in diverse ecological responses, revealing increased nutrient interactions in the between-panel configuration compared to the external and below-panel configurations. Through a comparison of photovoltaic (PV) power stations with different years of establishment, Zhang found that PV power stations with longer operational lifespans exhibit higher species diversity [16]. Overall, the PV power stations enhanced the soil conditions and vegetation diversity. The impact of photovoltaic power stations depends on their construction location and the specific effects on specific ecosystems. Under this background, selecting construction sites wisely is crucial.

Our meta-analysis-based study on the response of vegetation and soil factors to established PV stations holds significant global importance, contributing to the advancement of sustainable development, environmental protection, and land management optimization. As the installed capacity of PV systems continues to increase and the scale of PV power stations expands, there is growing societal concern regarding their potential impact on the local environment and ecosystems. The environmental influence of PV power stations is both gradual and long-term. Although these stations contribute positively to energy conservation and emission reduction, it is crucial not to overlook their ecological and climatic impacts [17]. To mitigate the impact of PV arrays on the environment, site selection must be based on both a biological and engineering approach [18], ensuring a comprehensive understanding of environmental conditions within and around these arrays. This approach acknowledges the potential positive impacts of PV power stations, such as altering soil conditions and influencing local flora and fauna.

On a global scale, solar energy is progressively employed for electricity generation, but the environmental ramifications of constructing and operating PV have not been thoroughly examined. Therefore, a comprehensive analysis of the environmental impacts of solar power stations is essential [6,19]. Nevertheless, only a limited number of field investigations have been undertaken, and they have not offered a comprehensive understanding of the intricate connections between PV arrays and vegetation growth. Simultaneously, owing to the intricate nature of the terrestrial carbon cycle, there are research gaps concerning the effects of PV arrays on vegetation-soil processes and their influence on vegetation species diversity and ecological functioning across various site types. Researchers thus have incomplete insights into the effects of PV arrays on vegetation-soil processes and their influence on vegetation species diversity and ecological functions across various site types [19,20]. Even fewer studies have examined the effect of large scale PV systems on animals and their habitats [21]. Moreover, the pace of land-use changes for power generation is rapidly increasing, and the global expansion of PV is expected to continue. Limited understanding exists regarding the implications of this expanding land-use change on the vegetation-soil processes crucial for sustaining key terrestrial ecosystem services [19].

Meta-analysis is a statistical analysis method, also known as meta-analysis or synthesis analysis. The basic method of meta-analysis is to collect specific literature in a specific database using specific design and statistical methods for analysis, and to synthesize and compare the results of studies with different design methods and sample sizes. Compared to other statistical analysis methods, meta-analysis is more scientifically rigorous, applicable to a wider range, and yields more accurate conclusions with increasing data. Since the 1990s, meta-analysis has been introduced into ecological research and has received considerable attention and significant development [22–25]. Meta-analysis is widely employed in the field of ecology today [26–29].

Therefore, the primary objective of this study was to examine the effects of varying climatic contexts and years of PV establishment on vegetation and soil characteristics, discerning trends of increase, decrease, and stability. Our study selected 28 articles representing 31 observational points and one on-site observation point, incorporating 432 data points on PV panel research. We measured the relevant response variables of the soil and vegetation characteristics and conducted a comprehensive meta-analysis to analyze the impact of PV power stations on vegetation-soil interactions within typical PV power stations, to better understand their impact on ecosystem functions. Focusing on soil conditions and vegetation characteristics, this study explored changes in vegetation and soil factors, revealing the influence of environmental factors. In summary, our aim is to explore the responses of vegetation and soil factors to established PV power stations, with the goal of enhancing site selection and implementing adaptive management strategies for them.

2. Materials and Methods

2.1. Co-Occurrence Network of Keywords

To better understand the research dynamics and emerging trends regarding the response of PV power stations to the ecological environment, a search was conducted in the Web of Science (WOS) database using the keywords "Photovoltaic panels" and "Ecological effects(response)". Subsequently, using the literature data visualization software CiteSpace (6.2.2), 31 English articles were subjected to keyword co-occurrence analysis, producing visualizations of the co-occurring keywords (see Figure 1). The visual representation indicates that prominent co-occurring keywords in the English literature include "environmental impacts", "soil moisture", "diversity", "responses", "impacts", and "desert area". Building on this analysis, the subsequent sections primarily delve into the effects of PV power stations on the ecological environment, with a specific focus on vegetation and soil aspects, to provide a theoretical foundation for the site selection of PV power stations.

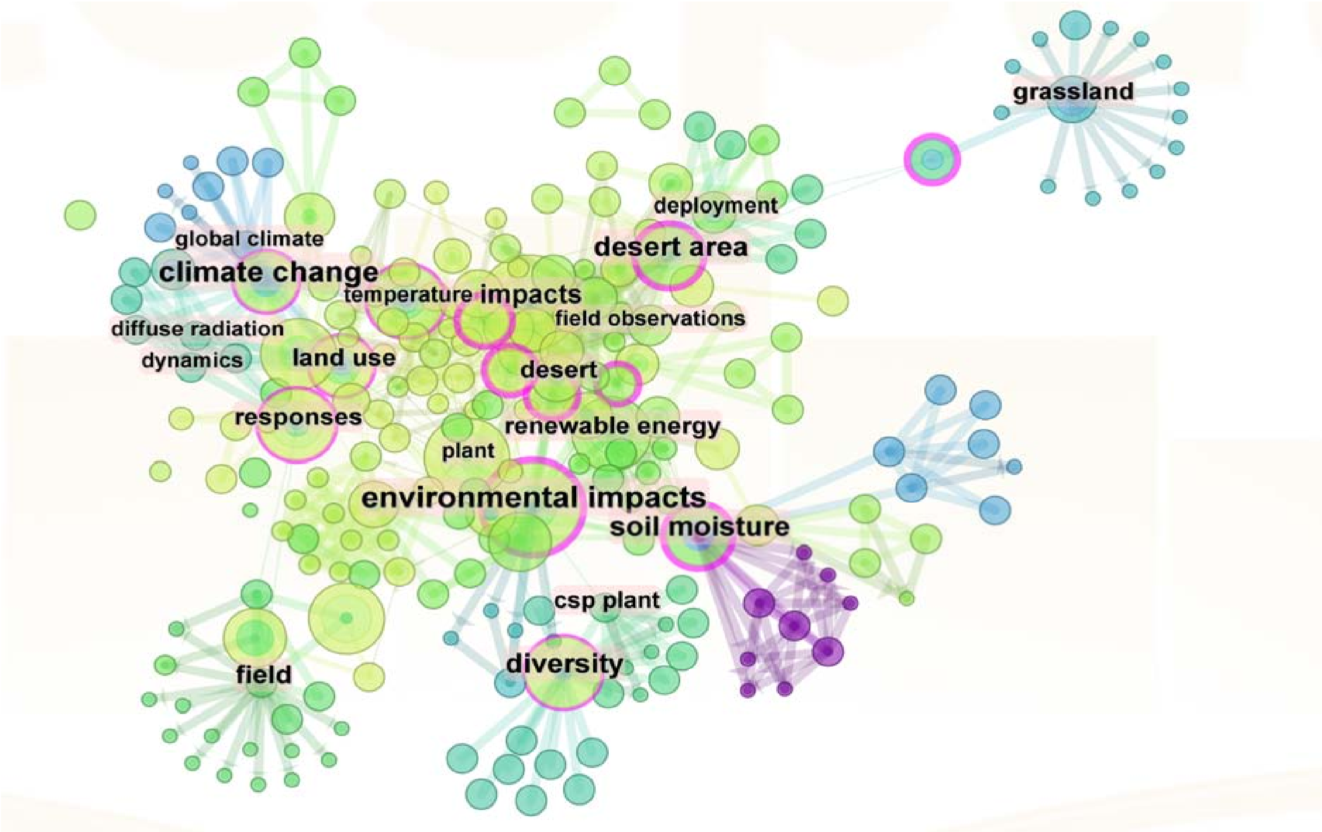

Figure 1. Co-occurrence network of keywords for ecological response study of established PV power stations research based on Web of Science search results. Note: The size of the circles containing keywords reflects their frequency of occurrence and research popularity in the literature, with larger circles indicating more prevalent and popular topics in the research field.

2.2. Data Collection and Processing

An extensive search was conducted on the Web of Science (WOS) Core Collection (2000–2023) to obtain ecological impact data related to the construction of PV power stations. The search query was formulated as follows: (TS=(environment) OR TS=(ecology system) OR TS=(biodiversity) OR TS=(local) OR TS=(microclimate) OR TS=(soil nutrient) OR TS=(geography) OR TS=(geomorphology) OR TS=(landform) OR TS=(vegetation) OR TS=(microhabitat) OR TS=(soil temperature) OR TS=(desert) OR TS=(wilderness) OR TS=(arid) OR TS=(sandy) OR TS=(drought) OR TS=(soil) OR TS=(soil moisture) OR TS=(cropland) OR TS=(forest)) AND (TS=(photovoltaic) OR TS=(solar power)). Research papers and review articles were selected, resulting in a preliminary search result of 47,294 studies.

To avoid bias during article selection, three basic criteria were followed to further filter suitable studies: (1) Clear ecological and environmental impacts, including at least one indicator related to soil conditions and vegetation characteristics; (2) Experimental design involving control and experimental groups, and each group contained at least three replicates; (3) Directly providing or allowing the calculation of mean values, standard deviation (SD), standard error (SE), and sample size based on the information provided. Finally, 28 studies with 31 observational points were included in the meta-analysis (Figure 2). To supplement this data, we conducted an investigation into the ecological conditions of established solar power stations in the arid northwestern desert of Xinjiang, China, by surveying one PV power station.

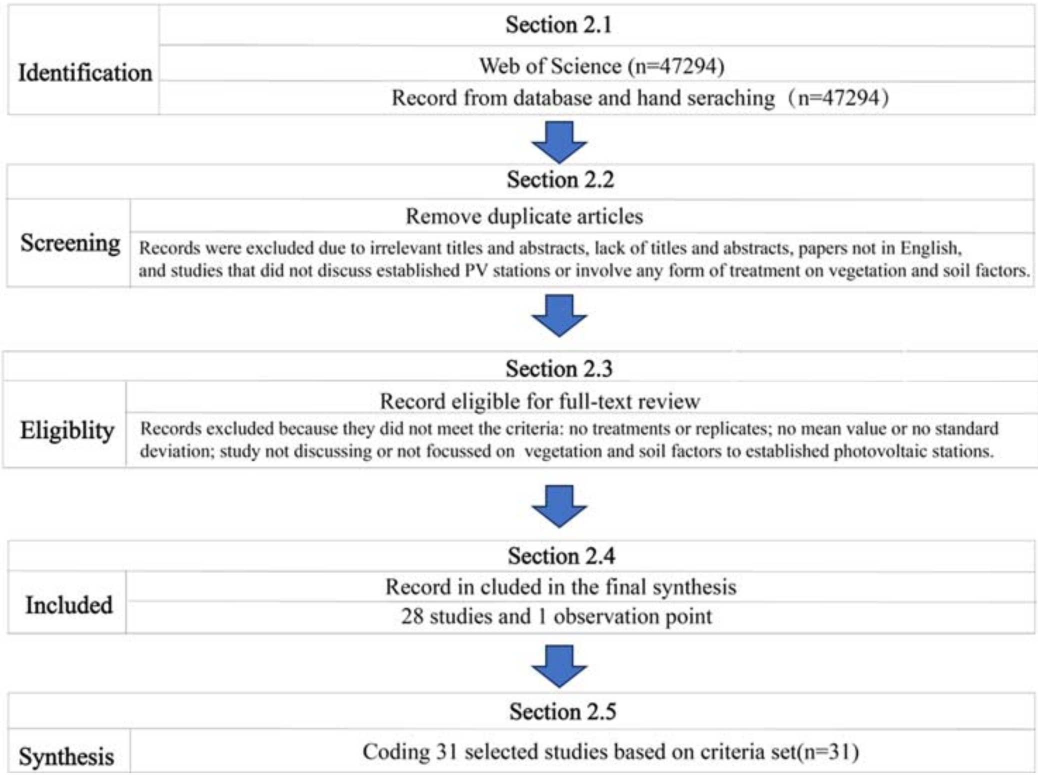

Figure 2. Flow of information through the different phases of a systematic review [30].

If the collected papers did not directly provide the mean and standard deviation or error of the selected variables, WebPlotDigitizer 4.2 software was used to extract data from the figures [31]. Data were extracted, and all standard errors (SE) were converted into standard deviations (SD). If the longitude and latitude were not provided in the articles, detailed geographical information was obtained from Google Maps based on the described study locations. If annual mean precipitation (MAP), and annual mean temperature (TMP) were not provided in the articles, detailed geographical information was obtained from Google Earth Engine (GEE) based on the ERA5 Land; solar radiation (SRAD) data also from ERA5 Land, snow water equivalent (SWE) data from TerraClimate, and slope data from SRTM. Subsequently, the extraction of data in our research relies on dependable source data, including experimental results from authors' papers. Because of the varying number of variables related to soil environment and vegetation dynamics provided in the articles, the sample sizes for each indicator differed. Where necessary, attempts were made to contact the authors to do precise statistical analysis.

The 28 studies selected were predominantly conducted in China, with sporadic contributions from North America, Europe, and Japan. Geographical and environmental data were extracted for each study, including latitude, longitude, altitude, annual mean temperature (TMP), annual mean precipitation (MAP), ecosystem type, climatic zone, slope, snow water equivalent (SWE) and climatic level (Figure 3). We categorized the study locations into dry (<400 mm) and humid (≥400 mm) based on environmental precipitation levels. Additionally, we classified the study sites into tropical (0–25° latitude), temperate (25–50°), and northern (>50°) zones (Table S1) [32,33]. Refer to Table S1 for details. Soil depth described in the included literature was separated into four categories: 0–5 cm, 0–10 cm, 0–20 cm, and 0–30 cm. Referring to [34], the classification of solar radiation, we categorized solar radiation into three classes: ≥6300 ZFRH (Most Abundant), 5040–6300 HFRH (very Abundant), and 3780–5040 FRCH (Abundant). To assess the influence of different PV panel placements on the outcomes, we categorized studies based on their position, i.e., below-PV panels, between-PV panels, and off-site control sites. Here, 'below-PV panels' refers to the area beneath the PV arrays, 'between-PV panels' indicates the space between the PV arrays, and 'control areas' are external locations without PV arrays, left undisturbed or subject to natural growth, serving as control areas. Given the lack of universally recognized classification standards for the lifespan of operational durations of PV arrays, and to mitigate subjective biases, we employed the natural break method to categorize studies based on their duration into 1–2 years, 3–4 years, 5–7 years, and above. The natural break method has been widely applied in numerous studies for classification purposes [35–37]. To assess the impact of different operational durations of PV arrays on the outcomes, we categorized studies based on the time since their construction into short-term (1–2 years), medium-term (3–4 years), and long-term (5 years and more) (Table S1). We therefore investigated the impacts of different geographic contexts or various PV array treatments on the soil environment and variables related to vegetation and environmental characteristics (increasing, decreasing, and unchanged).

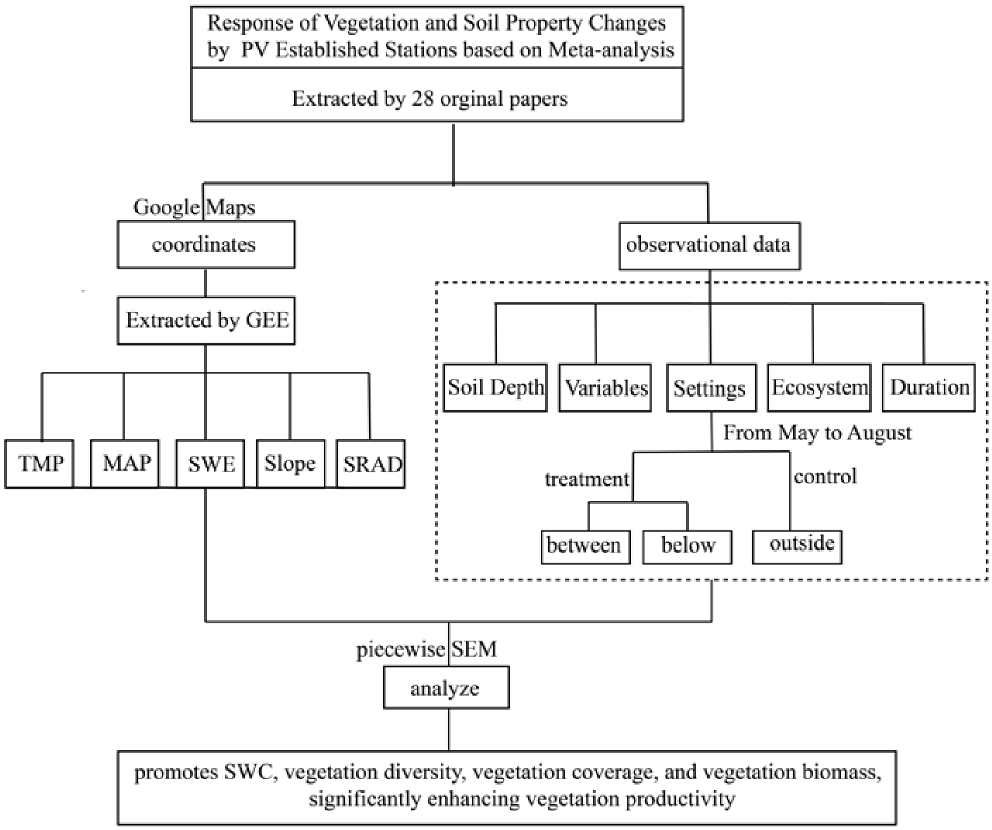

Figure 3. Workflow diagram of the study.

During the observation period, our research concentrated on the growing season (May to October), with soil depths categorized into the four levels described above. The restoration of vegetation at PV power stations primarily involves the use of indigenous vegetation. Our own field study selected a typical PV power station in Xinjiang Province and investigated its impact on the soil environment and vegetation using a combination of location observations, patrol monitoring, and analysis of soil and water conservation monitoring data. During our survey, a soil moisture meter was used to measure the SWC in the PV panel area. The basic information on the 31 PV power stations is presented in Tables S5 and S6.

2.3. Statistical Analysis

The response of various vegetation and soil variables to established PV power stations was calculated using the natural logarithm of the response ratio (lnRR) [38]. x_t and x_c represent the mean values of the experimental and control groups, respectively. The lnRR is employed to quantify the response to the environmental effect, assessing the differences between the control and experimental groups. A positive or negative lnRR value indicates a positive or negative impact on vegetation and soil characteristics after the construction of the PV power stations [33].

$$\text{lnRR} = \ln\left(\frac{\overline{x_t}}{\overline{x_c}}\right) = \ln(\overline{x_t}) - \ln(\overline{x_c}) \tag{1}$$

As explained above, data provided as SE was transformed to SD using the following formula [33]:

$$SD = SE \times \sqrt{n} \tag{2}$$

For each study, we calculated the variance as follows [33]:

$$v = \frac{SD_t^2}{n_t \overline{x_t^2}} + \frac{SD_c^2}{n_c \overline{x_c^2}} \tag{3}$$

Here, SD_t^2 and SD_c^2 represent the variances, whereas n_t and n_c correspond to the sample sizes of the experimental and control treatments, respectively.

If the 95% confidence interval (CI) did not overlap with zero, we considered the overall impact of the experimental treatment (with PV panels) on the given response variable to be significant. For clarity and descriptive purposes, the percentage change was calculated using the following formula [33,39]:

$$\text{Percentage change } (\%) = (e^{\text{lnRR}} - 1) \tag{4}$$

We employed the "rma" function from the R package "metafor" [40] to compute the weighted mean response ratio and 95% confidence intervals (CIs), aiming to quantify the effect size of PV power station construction on vegetation and soil factors (Tables S2 and S4). Subgroup analyses were conducted to assess the impact of categorical moderator variables (such as the time since construction of PV facilities, soil depth, solar radiation, PV array settings, ecosystems, climatic zone, climatic level, and vegetation and soil factors) on various vegetation and soil factors (Table S3). In cases where the standard deviation (SD) for individual data points was missing, we used the "Bracken1992" method to estimate it using the "metagear" package in R 4.3.2 software [41]. The relative importance of each predictor/factor in influencing ecological responses was examined using the "glmulti" package, with a critical threshold set at 0.8 to distinguish between essential and non-essential predictor variables. This analysis aimed to compare the effects of environmental factors, PV array settings, and the established years of PV facilities on different ecosystems [33,42]. Furthermore, we used the "piecewiseSEM" package to account for random effects of sampling sites, providing "marginal" and "conditional" contribution of predictors [43,44]. The "map" package was employed to visualize the distribution of sampling points (Figure 4a), and the "plot biomes" package was utilized to depict the Whittaker biomes (Figure 4b). The R-squared and *p*-values for the data were obtained using the linear regression function in the SciPy package. To assess publication bias in the meta-analysis, the Rosenthal fail-safe number of 25,049 far exceeded the critical threshold of 5N+10, validating the reliability of the paper's data results [38]. All statistical analyses were performed in R version 4.3.2 and Python version 3.7.

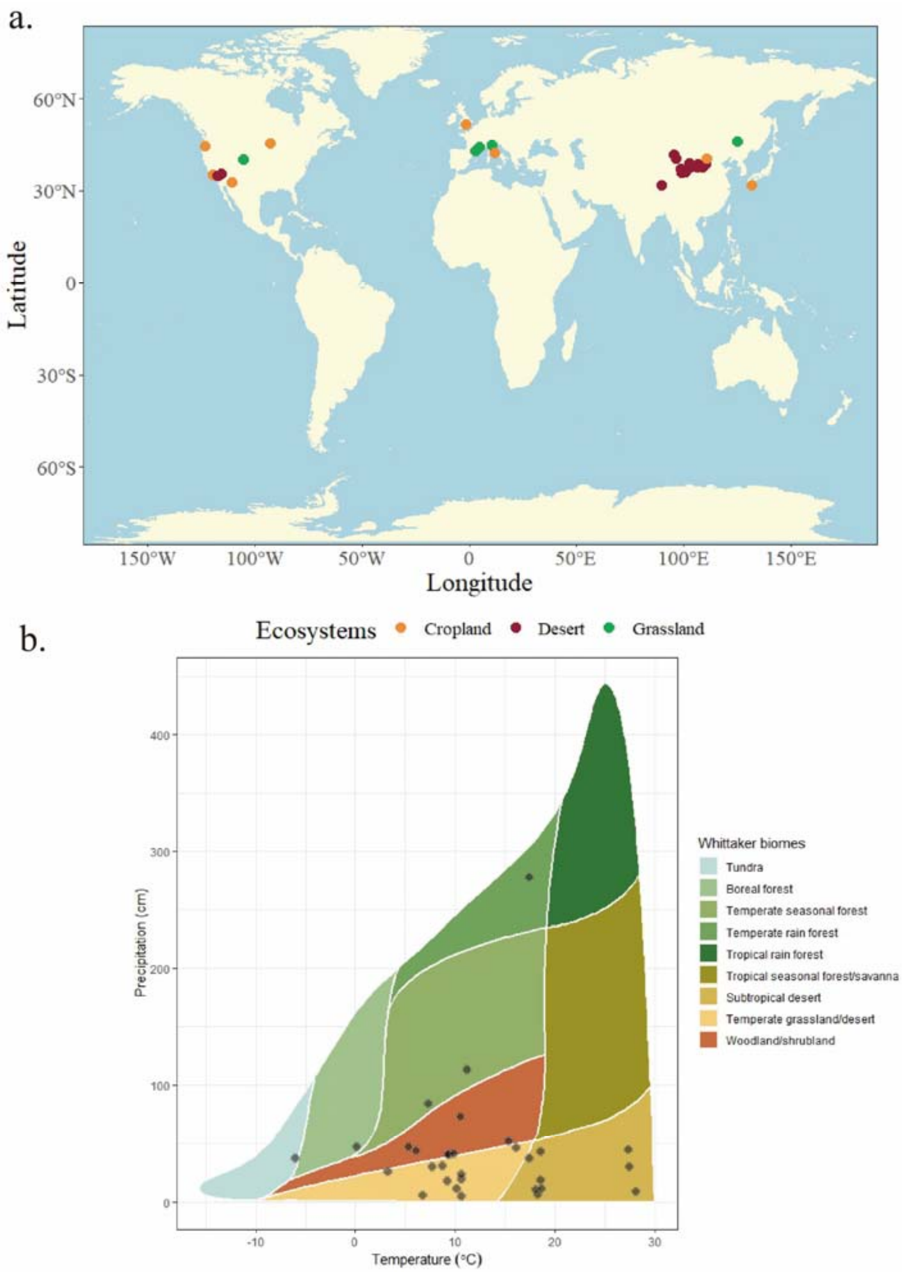

Figure 4. Global distribution map of the 31 established PV power stations studies analyzed here. (**a**) Global distribution map of the 31 established PV power stations studies analyzed here. (**b**) Distribution of studies along temperature and precipitation gradients, overlaid with the different biome types, as defined by Whittaker [45].

3. Results

3.1. Geographical Distribution of Studies

In this study, 28 articles were included in the meta-analysis, encompassing 28 relevant research studies involving a single field measurement site. Most of these studies were conducted across East Asia (primarily China), Europe, and North America (Figure 4a). Despite this geographical bias, the research sites were reasonably well distributed along major temperature and precipitation gradients, covering various global biomes (Figure 4b).

The annual mean temperature of the study sites ranged from −6.02 to 27.5 °C, and the annual precipitation varied between 55.14 and 2778 mm (Figure 4b). The studied ecosystems included cropland, grassland, and desert environments of types (Figure 4a).

3.2. Effects of Photovoltaic Power Stations on Different Factors

This study revealed the significant positive impact of established PV power stations on the ecological environment, including vegetation characteristics and soil environmental factors (Figure 5). These improvements depended on factors such as soil depth, duration since PV construction, configuration of PV panels, and intensity of solar radiation (Figure 5). For example, the influence of PV power station construction on vegetation characteristics was generally positive. Regarding solar radiation, ZFRH and FRCH exhibited significant positive and negative effects, respectively, whereas the effect of HFRH was not significant. Therefore, meaningful results were derived from moderate-scale studies conducted in the short- to medium-term, especially in areas with intense solar radiation.

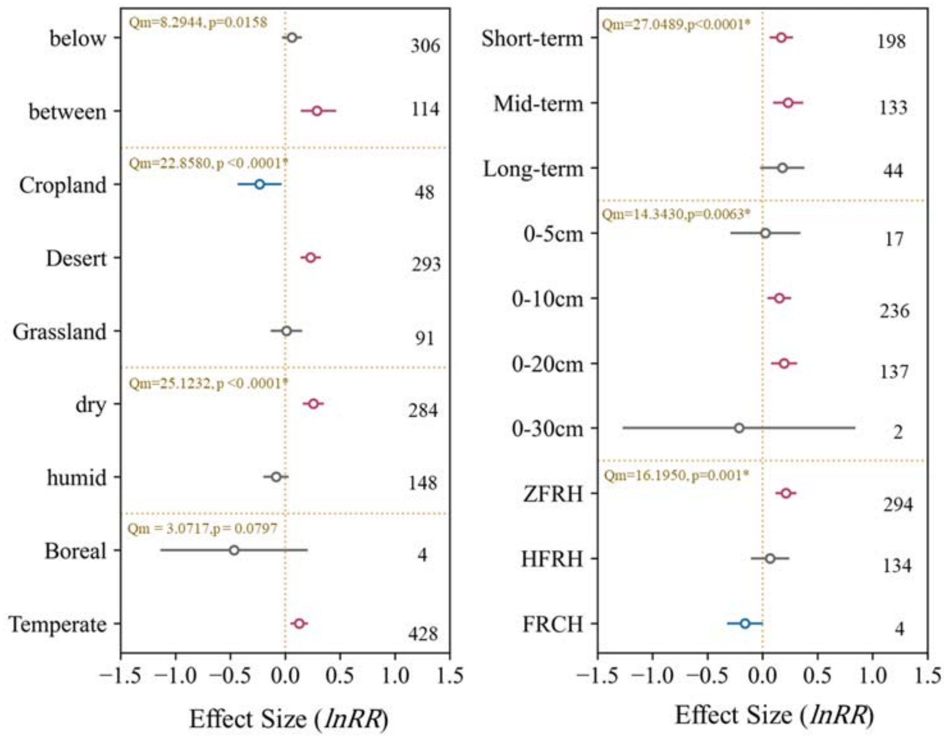

Figure 5. Response of PV power stations to the vegetation and soil factors under different environmental contexts. PV array configurations: below-panel, between-panel; Ecosystem types: cropland, desert, grassland; Climatic level: arid, humid; Climatic zone: northern, temperate; PV power station construction time: short-, medium-, or long-term; Soil depth: 0–5 cm, 0–10 cm, 0–20 cm, 0–30 cm; Solar radiation levels: ZFRH, HFRH, FRCH. Solid red points, solid blue points, and hollow black points represent significant positive, negative, and non-significant effects, respectively. The numbers indicate the quantity for each response. * $p < 0.01$.

In croplands and deserts, there were significant negative and positive effects, respectively, whereas the response in grasslands was not significant. In the temperate, arid, and desert experiments, the between-panel setting of PV arrays demonstrated the most favorable impact on the ecological environment. Specifically, soil depths of 0–5 cm and 0–30 cm showed non-significant effects, while soil depths of 0–10 cm and 0–20 cm exhibited significant positive effects. Concerning the duration since the construction of PV facilities, the short-to medium-term showed a significant positive effect, whereas the long-term did not (Figure 5).

Our meta-analysis found a significantly increased response of ecological environments to PV power station construction. Different configurations of PV arrays (below- and between-panel) and various vegetation and soil factors showed different positive or negative effects on LnRR, influencing diverse responses in different ecosystems under varying environmental conditions.

Figure 5 illustrates the climatic impacts of PV power stations on the ecological environment in different regions and climatic zone. This study found no significant impact on the ecological environment in cold and humid regions. However, in studies conducted in temperate, arid, and desert ecosystems, PV power stations positively influenced the ecological environment.

Based on previous studies [46–48], the soil physicochemical properties were selected as depicted in Figure 6. The results indicated that apart from SWC, which showed a significant positive response to PV power stations, soil physicochemical properties were not significant. Following the construction of PV power stations, there were significant positive effects on vegetation characteristics, including biomass, vegetation coverage, richness, and diversity indices. Conversely, there were significant negative effects on soil evaporation, respiration, and germination rates. The ecological response to the soil environmental impact of PV power station construction was relatively modest. Except for soil moisture content, which showed a significant positive effect, and soil evaporation and respiration, which exhibited significant negative effects, the other soil physicochemical properties did not show notable responses.

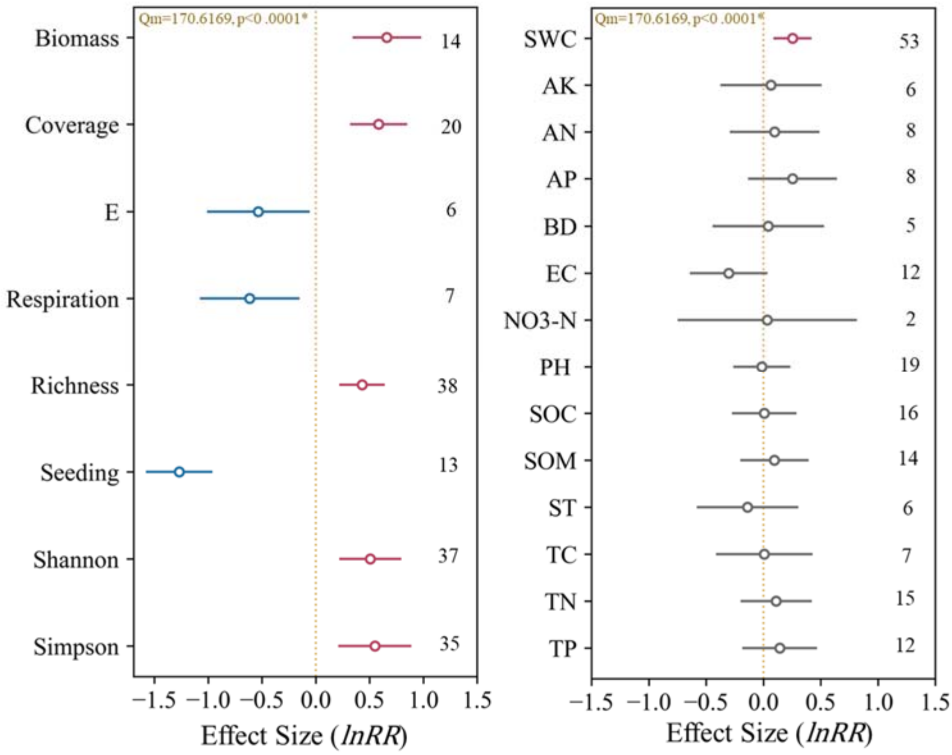

Figure 6. Significant vegetation and soil factors (Biomass, Coverage, E, Respiration, Richness, Seeding, Shannon, Simpson). Other vegetation characteristics are not displayed as they were found to be non-significant. Soil physicochemical properties (SWC, AK, AN, AP, BD, EC, NO3-N, pH, SOC, ST, TC, TN, TP). * $p < 0.01$.

Regarding geographical factors (Figure 7), our findings indicate a positive correlation between altitude and ecological environmental response to various vegetation and soil factors. In other words, as altitude increases, the improvement in the ecological environment due to PV power stations tends to strengthen. Due to the multi-factorial nature of LnRR, analysis of its relationship with individual influencing factors may result in a relatively low R^2 (coefficient of determination).

This study revealed that the impact of PV power station construction on vegetation characteristics was significant, which is consistent with previous subgroup and correlation analyses [9]. The climatic zone, altitude, ecosystem type, soil depth, solar radiation intensity, and time since PV construction exert considerable influence on the vegetation and soil factors under the PV array. This aligns with the results of the subgroup and correlation analyses (Figure 5).

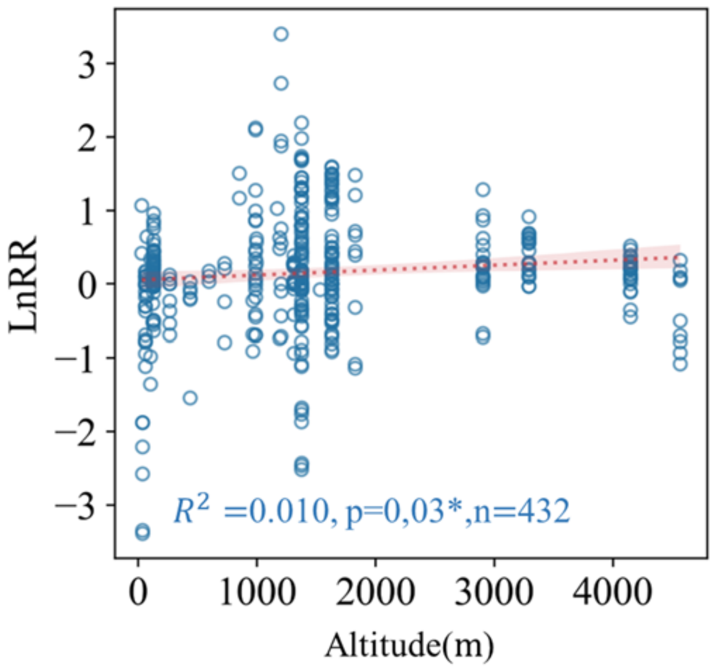

Figure 7. The response of various vegetation and soil factors to established PV power stations correlates with altitude (meters). Asterisks (*) indicate significant effects.

Regarding the climatic factors (Figure 8), as the TMP and MAP increased, the impact of PV power stations on the ecological environment decreased. Moreover, particularly the MAP, was shown to have a higher negative correlation. Therefore, the influence of PV power stations construction is more pronounced in arid regions with less rainfall. Regions with high horizontal solar radiation exhibited more significant positive responses to the construction of PV power stations (Figure 9).

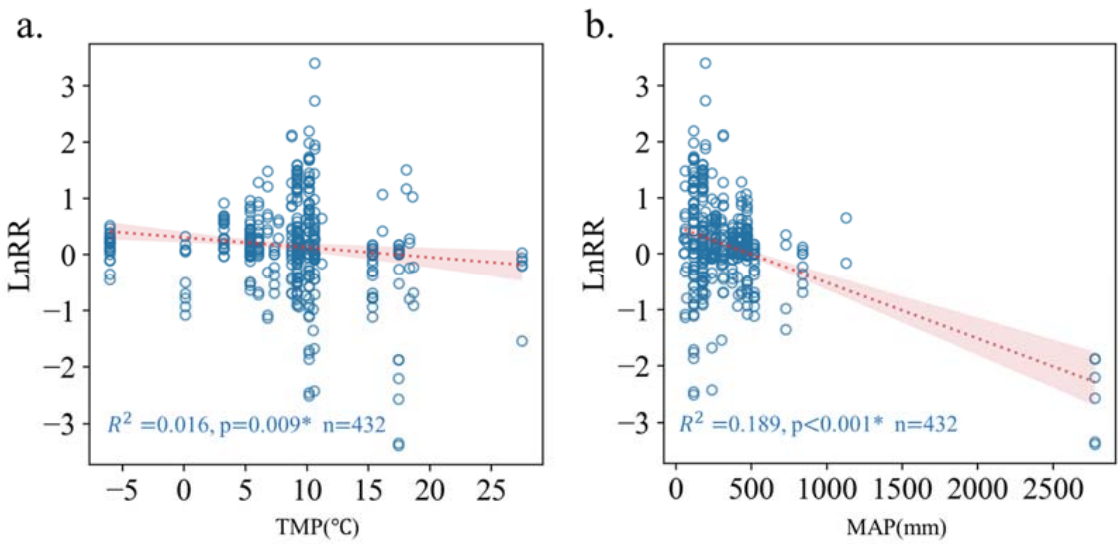

Figure 8. The response of various vegetation and soil factors to established PV power stations correlates with climatic factors. (**a**) TMP (°C) and (**b**) MAP (mm). Asterisks (*) denote significant effects.

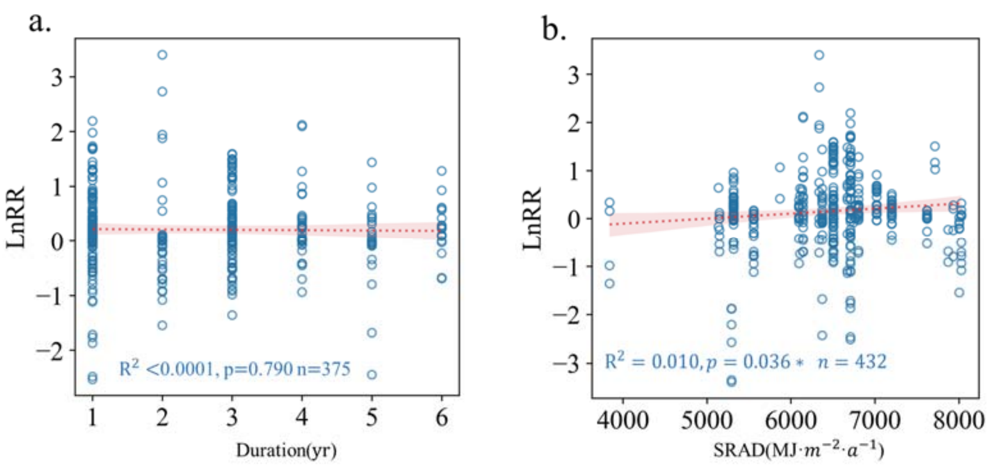

Figure 9. The response of various vegetation and soil factors to established PV power stations correlates with the (**a**) Duration (yr) and (**b**) SRAD (MJ·m^{-2}·a^{-1}). Asterisks (*) denote significant effects.

After the construction of PV power stations, the ecological response to established PV power stations exhibited the following trend under different extents of solar radiation: ZFRH (76.40%) > HFRH (22.81%); in contrast, the FRCH decreased by 19.78%. The results of the ecological improvement effect model showed that vegetation and soil factors were minimally affected by publication bias.

The research findings indicate that the type of ecosystem, solar radiation, soil depth, climatic zone, and duration of PV construction significantly influence vegetation factors within PV facilities. Similarly, duration since PV construction, TMP, and photovoltaic panel settings also play a crucial role in the response of soil factors within PV facilities. This conclusion is supported by sub-group analyses and correlation studies (Figure 10).

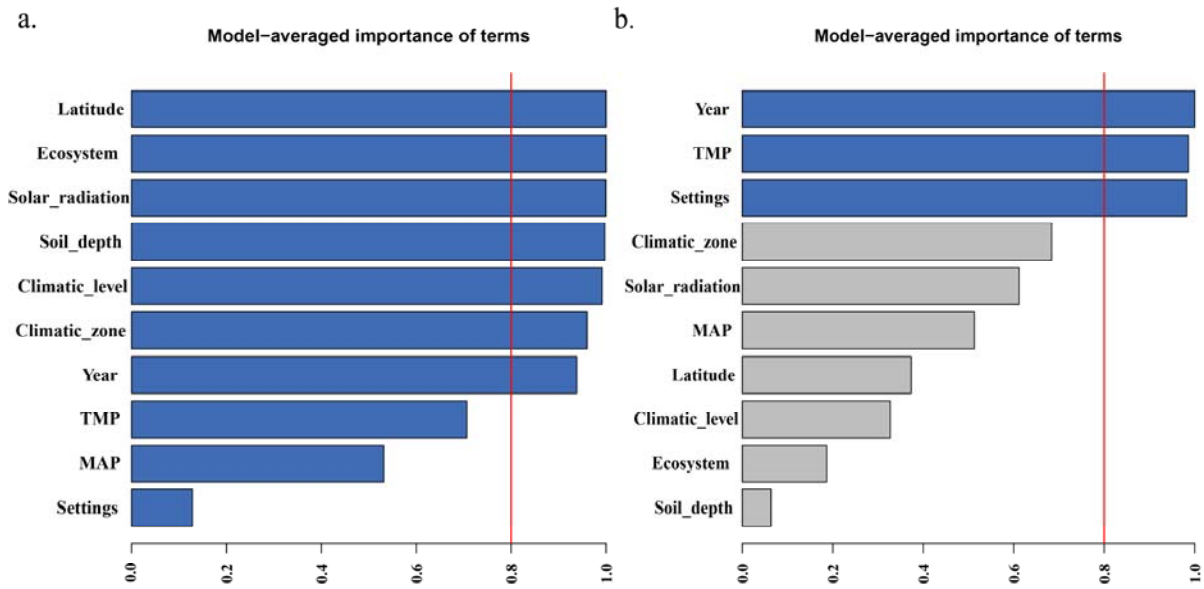

Figure 10. The model displays the importance of predictors/factors for the PV power station construction effects on (**a**) vegetation and (**b**) soil. The significance is determined by the cumulative Akaike weights derived from model selection. A cutoff at 0.8 (depicted by the red solid line) is applied to distinguish the most influential moderators, as illustrated by the blue column.

Our piecewiseSEM results revealed that, relative to the responses of vegetation and soil factors to PV construction, geography, duration since PV construction, environment, and vegetation and soil variables preferentially directly affect the LnRR. Moreover, vegetation and soil variables were shown to impact LnRR by strongly responding to key environmental factors (Figure 11). Our piecewiseSEM results also revealed that setting, duration, environment, Geography and soil depth indirectly affect the LnRR by altering vegetation and soil variables. See each predictor value on LnRR in Figure 12.

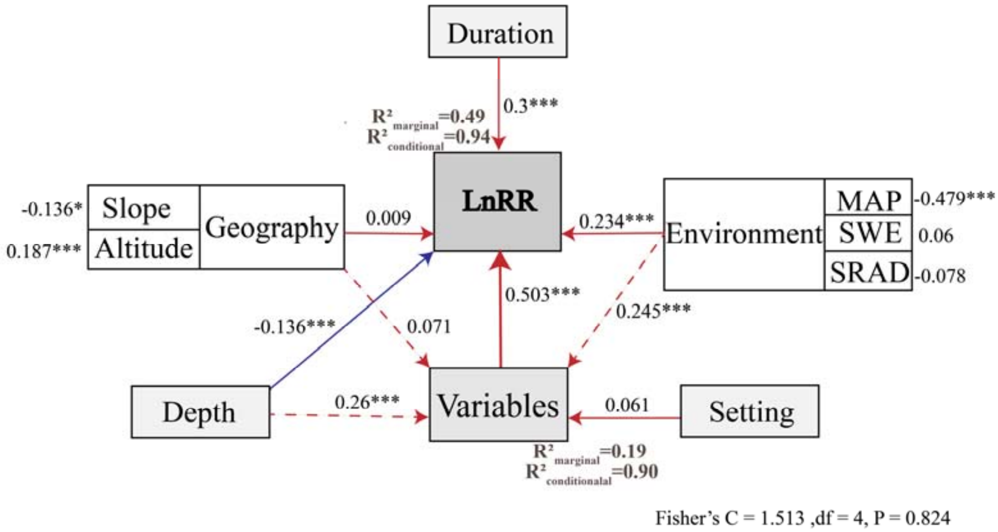

Figure 11. Pathways of environmental and anthropogenic factors impacting the influence of established PV power stations on vegetation and soil factors. PiecewiseSEM accounts for the direct and indirect effects of variables, geography, environment, soil depth, duration, and setting on the response of the established PV power stations at the global scale. The geography and environment were divided into composite variables. Geographical variables consist of slope and altitude; environmental variables include snow water equivalent (SWE), precipitation (MAP), and solar radiation (SRAD). Numbers adjacent to measured variables are their coefficients with composite variables. Numbers adjacent to arrows are path coefficients, representing the directly standardized effect size of the relationship. The thickness of the arrow represents the strength of the relationship. The red and blue lines represent positive and negative relationships, respectively. Total standardized effects of variables on ecosystem stability are shown in marginal and conditional R^2, representing the proportion of variance explained by all predictors/factors without and with accounting for random effects of the "sampling site". Significance levels of each predictor/factor are * $p < 0.05$, *** $p < 0.001$.

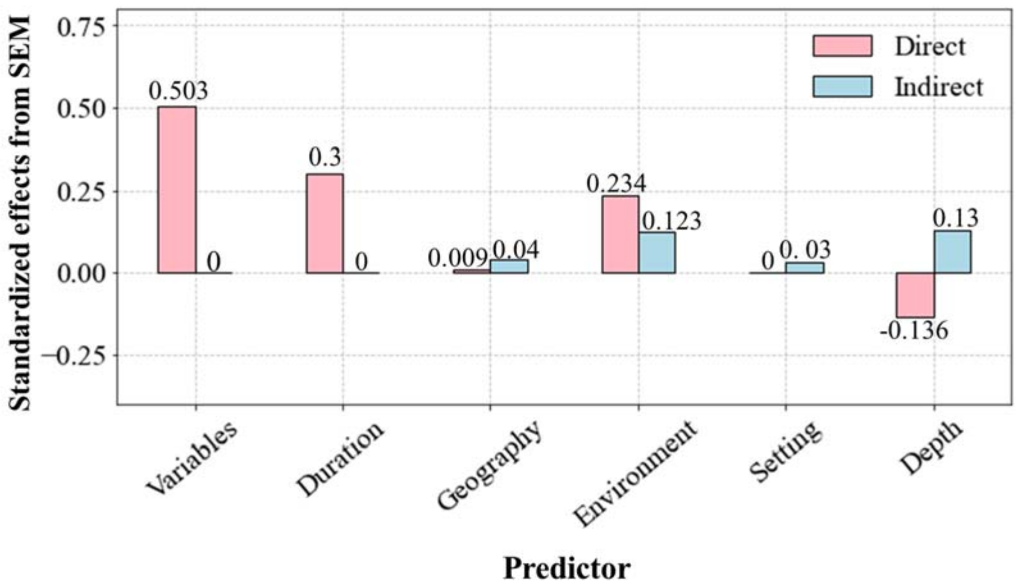

Figure 12. Standardized Direct and Indirect Effects in PiecewiseSEM.

4. Discussion

Our meta-analysis found the duration of established power stations may affect the observed responses. Short-to medium-term installations may have favorable effects on vegetation and soil factors, improving the ecological environment. Notably, medium-term installations demonstrate more significant impacts compared to short-term ones [16]. Conversely, long-term installations might not affect the ecological environment significantly. Overall, the PV power stations enhanced the soil conditions and vegetation diversity. Additionally, changes in soil conditions and vegetation diversity may vary with environmental influences, such as ecosystem type [9]. Lambert et. al. found more nutrient interactions in the between-panel configuration than in the external and below-panel configurations [15], which aligns with the findings of our study. Notably, the significant variation in the SWC is consistent with the results of previous studies [49–51]. Our results indicated a significantly increased response of vegetation and soil factors following the construction of PV power stations compared to the control group. Different PV array configurations (below- and between-panel) exhibit varying significant or insignificant effects on different vegetation and soil factors, thereby influencing responses across diverse environments and ecosystems.

Researchers have suggested that reducing soil water evaporation can accrue soil carbon content and soil porosity, facilitating water storage and increasing SWC [52,53]. Notably, Solar panel technology transfers a portion of absorbed solar radiation into electricity, effectively redistributing energy from the sun [54]. Shading by the PV panels reduced the annual solar irradiance by 58.4% [55]. Moreover, the installed photovoltaic components themselves cast a certain extent of shading on the ground, leading to a reduction in soil water evaporation and thus enhancing water saving within the covered area of the photovoltaic array [56]. Researchers have demonstrated that PV panels intercept and redistribute precipitation inputs and alter the spatial pattern of evapotranspiration by casting shadows underneath the panels [57–59]. In addition to the reduction in soil water evaporation, the increase in SWC may also be associated with the melting of accumulated snow and the regular cleaning of photovoltaic panels. Owing to the influence of photovoltaic components, the melting rate of snow is slowed down, and the meltwater from the accumulated snow becomes a crucial source of SWC at the Earth's surface. Furthermore, the wastewater generated from the regular cleaning of photovoltaic components, when absorbed by the ground, contributes to an increase in SWC [60]. This may result in increased SWC, fostering favorable conditions for the growth of biota [14]. Ultimately, the increase in SWC contributes to enhanced vegetation productivity [14]. Soil water content (SWC) is the basic condition for the survival of terrestrial vegetation. Insufficient SWC can affect the stomatal conductance of vegetation, limiting productivity and even threatening vegetation survival [61]. Under the conditions of future climate change, increased productivity of vegetation can only be promoted through the timely replenishment of SWC [62]. A meta-analysis revealed a significant increase in vegetation productivity (above-ground biomass) and vegetation coverage due to PV power station construction, which is consistent with the results of our study [9]. These results underscore the positive impacts of PV power station construction on the ecological environment. The ecosystems selected for this study were predominantly situated in croplands, grasslands, and deserts, showing changes in land use. This aligns with MacKay's findings [63]. The findings of this study indicate that the construction of PV power stations has a negative impact on croplands, whereas the impact on grasslands is not significant. Therefore, it can be directly influenced by the type of ecosystem (desert, cropland, or grassland).

However, demographic and economic expansion has intensified land competition, with approximately 12% of the globe's land surface dedicated to crop production. Limited land availability leads to biodiversity pressures and rising food prices [30]. Meanwhile, agrivoltaism emerges as a future solution amidst climate change and food and energy challenges [64]. Some scholars propose a technology for dual land use through agricultural and solar energy production to address this issue. Integrated farming and energy production offer positive economic, social, and environmental benefits, providing feasible solutions to the growing competition for land resources [30].

Furthermore, the construction of PV power stations can also affect the response of the ecological environment by directly or indirectly affecting vegetation characteristics and soil factors. Moreover, the impact on adjacent ecosystems is probably more important than the response of the altered PV ecosystem. During both construction and operation, photovoltaic power stations may impact local microclimates, as well as the growth, activity, and life cycles of plants, animals, and microorganisms, to varying degrees. These effects could ultimately lead to changes in ecosystem functions such as carbon sequestration potential [65,66].

Notably, the spatial expansion of PV power stations poses a threat to essential croplands, and the conversion of croplands to PV power stations may jeopardize food production. There is consequently a need to vigorously develop desert PV power station while safeguarding croplands and grasslands. The global photovoltaic power stations cover an area of over 92,000 km^2, prompting an urgent need to address the "conflict competition" between energy development and land [67]. Photovoltaic power stations can evidently enhance the land-use-efficiency of arid area [68]. Governments worldwide should encourage the prioritized use of unproductive land, such as deserts, abandoned mines, artificial water channels, reservoirs, and rooftops, to deploy PV power stations [69]. However, some desert ecosystems have significant biodiversity hot spots that need to be protected [70,71]. Land cover change owing to solar energy has received increasing attention over concerns related to conflicts with biodiversity goals and greenhouse gas emissions [71]. By proactively identifying and resolving these conflicts or issues, sustainable solutions can be sought to minimize the negative impacts of the rapid development of solar energy and ensure the timely achievement of global carbon neutrality goals [67].

Our limitation lies in the absence of soil type data and subsoil data extracted from the original authors' studies. We recommend that it is crucial to collect data on the land characteristics of photovoltaic power stations in the future to prevent structural conflicts in land resource utilization [72–74]. We recognize that the next step is to assess plant-animal interactions in these modified ecosystems [11].

5. Conclusions

1. The responses to soil and vegetation to the construction of PV power stations exhibit significant differences between studies, which are related to the different environmental contexts across ecosystems. Desert, cropland, and grassland ecosystems demonstrated significant positive, genitive, and insignificant effects, respectively.
2. The construction of PV panels generally increases SWC, vegetation diversity, coverage, and biomass. Among these, biomass experienced the most substantial growth.
3. Although the construction of PV power stations does not significantly affect soil physicochemical properties, it suppresses soil respiration and evaporation and significantly enhances vegetation productivity and coverage in the Northern Hemisphere.

In studies conducted in temperate, arid, and desert regions, the between-panel treatment of PV arrays had the most significant impact on the ecological environment. PV panel construction promotes the response of arid desert ecosystems and influences small-scale ecological environments. There was no clear improvement in the ecological environment in response to PV power stations in croplands and grasslands.

Owing to geographical variation, the responses of vegetation and soil factors to PV power stations differ, requiring a comprehensive assessment and analysis of the ecological impact of PV power stations across different ecosystems. In the future, we also suggest promptly recognizing and addressing the issues surrounding contradictory results, diligently seeking solutions, and minimizing the negative and insignificant effects of the rapid expansion of cropland and grassland PV power stations. Additionally, policies should target the environmental performance of energy structures, which is crucial for the photovoltaic industry and many others. Continued active pursuit of this goal is essential to avoid environmental degradation [75].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13040478/s1, Table S1: Identities, levels and description of moderator variables used in this meta-analysis; Table S2: Summary table for subgroup analysis of vegetation variables to PV established stations; Table S3: Summary table for environmental subgroup analysis of vegetation and soil factors to PV established stations; Table S4: Summary table for subgroup analysis of soil variables to PV established stations; Table S5: Master table for country, latitude, longitude, elevation, type of ecosystem, SWE, threatened organisms; Table S6: Master table for MAP, TMP, Duration, Soil depth, SRAD, slope, kind of PV system.

Author Contributions: X.C. was the main contributor to this work; X.C.: Methodology, Software, Investigation, Writing—original draft, Writing—review and editing.; B.C.: Software, Writing—review and editing; Y.W.: Conceptualization, Funding acquisition; N.Z.: Data curation, Funding acquisition; Z.Z.: Investigation, Data curation. All authors commented on the previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by Key Research and Development Projects of the Xinjiang Uygur Autonomous Region (grant numbers 2021B03002-1) and the "Silk Road Economic Belt" Ecological Construction Technology Demonstration National Base for International Science and Technology Cooperation.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tsoutsos, T.; Frantzeskaki, N.; Gekas, V. Environmental impacts from the solar energy technologies. *Energy Policy* **2005**, *33*, 289–296. [CrossRef]
2. Turney, D.; Fthenakis, V. Environmental impacts from the installation and operation of large-scale solar power plants. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3261–3270. [CrossRef]
3. Semeraro, T.; Pomes, A.; Del Giudice, C.; Negro, D.; Aretano, R. Planning ground based utility scale solar energy as green infrastructure to enhance ecosystem services. *Energy Policy* **2018**, *117*, 218–227. [CrossRef]
4. Bai, Z.; Jia, A.; Bai, Z.; Qu, S.; Zhang, M.; Kong, L.; Sun, R.; Wang, M. Photovoltaic panels have altered grassland plant biodiversity and soil microbial diversity. *Front. Microbiol.* **2022**, *13*, 1065899. [CrossRef]
5. Hernandez, R.R.; Easter, S.; Murphy-Mariscal, M.L.; Maestre, F.T.; Tavassoli, M.; Allen, E.B.; Barrows, C.W.; Belnap, J.; Ochoa-Hueso, R.; Ravi, S. Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.* **2014**, *29*, 766–779. [CrossRef]
6. Hernandez, R.R.; Hoffacker, M.K.; Field, C.B. Efficient use of land to meet sustainable energy needs. *Nat. Clim. Change* **2015**, *5*, 353–358. [CrossRef]
7. Trainor, A.M.; McDonald, R.I.; Fargione, J. Energy Sprawl Is the Largest Driver of Land Use Change in United States. *PLoS ONE* **2016**, *11*, e0162269. [CrossRef] [PubMed]
8. Stoms, D.M.; Dashiell, S.L.; Davis, F.W. Siting solar energy development to minimize biological impacts. *Renew. Energy* **2013**, *57*, 289–298. [CrossRef]
9. Zhang, Y.; Tian, Z.; Liu, B.; Chen, S.; Wu, J. Effects of photovoltaic power station construction on terrestrial ecosystems: A meta-analysis. *Front. Ecol. Evol.* **2023**, *11*, 1151182. [CrossRef]
10. Barron-Gafford, G.A.; Minor, R.L.; Allen, N.A.; Cronin, A.D.; Brooks, A.E.; Pavao-Zuckerman, M.A. The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Sci. Rep.* **2016**, *6*, 35070. [CrossRef]
11. Devitt, D.A.; Apodaca, L.; Bird, B.; Dawyot, J.P.; Fenstermaker, L.; Petrie, M.D. Assessing the Impact of a Utility Scale Solar Photovoltaic Facility on a Down Gradient Mojave Desert Ecosystem. *Land* **2022**, *11*, 1315. [CrossRef]
12. Wall, D.H. *Soil Ecology and Ecosystem Services*; Oxford University Press: Oxford, UK, 2012.
13. Lambert, Q.; Bischoff, A.; Cueff, S.; Cluchier, A.; Gros, R. Effects of solar park construction and solar panels on soil quality, microclimate, CO_2 effluxes, and vegetation under a Mediterranean climate. *Land Degrad. Dev.* **2021**, *32*, 5190–5202. [CrossRef]
14. Wu, Z.; Hou, A.; Chang, C.; Huang, X.; Shi, D.; Wang, Z. Environmental impacts of large-scale CSP plants in northwestern China. *Environ. Sci. Process. Impacts* **2014**, *16*, 2432–2441. [CrossRef] [PubMed]
15. Lambert, Q.; Bischoff, A.; Enea, M.; Gros, R. Photovoltaic power stations: An opportunity to promote European semi-natural grasslands? *Front. Environ. Sci.* **2023**, *11*, 1137845. [CrossRef]
16. Zhang, Z.; Shang, W.; Wang, Q.; Fu, G.; Zhang, W.; Wan, X. Biodiversity of Herbaceous Species under Large Photovoltaic (PV) Power Stations in Desert Region of Hexi Corridor. *J. Northwest For. Univ.* **2020**, *35*, 190–196, 212.

17. Li, P.; Gao, X. The impact of photovoltaic power plants on ecological environment and climate: A literature review. *J. Plateau Meteorol.* **2021**, *40*, 702–710.
18. Hernandez, R.R.; Armstrong, A.; Burney, J.; Ryan, G.; Moore-O'Leary, K.; Diédhiou, I.; Grodsky, S.M.; Saul-Gershenz, L.; Davis, R.; Macknick, J.; et al. Techno-ecological synergies of solar energy for global sustainability. *Nat. Sustain.* **2019**, *2*, 560–568. [CrossRef]
19. Armstrong, A.; Ostle, N.J.; Whitaker, J. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ. Res. Lett.* **2016**, *11*, 074016. [CrossRef]
20. Heimann, M.; Reichstein, M. Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* **2008**, *451*, 289–292. [CrossRef]
21. Chock, R.Y.; Clucas, B.; Peterson, E.K.; Blackwell, B.F.; Blumstein, D.T.; Church, K.; Fernández-Juricic, E.; Francescoli, G.; Greggor, A.L.; Kemp, P. Evaluating potential effects of solar power facilities on wildlife from an animal behavior perspective. *Conserv. Sci. Pract.* **2021**, *3*, e319. [CrossRef]
22. Gurevitch, J. A meta-analysis of field experiments on competition. *Am. Nat.* **1992**, *140*, 539–572. [CrossRef]
23. Arnqvist, G.; Wooster, D. Meta-analysis: Synthesizing research findings in ecology and evolution. *Trends Ecol. Evol.* **1995**, *10*, 236–240. [CrossRef] [PubMed]
24. Curtis, P. A meta-analysis of leaf gas exchange and nitrogen in trees grown under elevated carbon dioxide. *Plant Cell Environ.* **1996**, *19*, 127–137. [CrossRef]
25. Gurevitch, J.; Curtis, P.S.; Jones, M.H. *Meta-Analysis in Ecology*; Elsevier: Amsterdam, The Netherlands, 2001.
26. Feng, Y.; Schmid, B.; Loreau, M.; Forrester, D.I.; Fei, S.; Zhu, J.; Tang, Z.; Zhu, J.; Hong, P.; Ji, C. Multispecies forest plantations outyield monocultures across a broad range of conditions. *Science* **2022**, *376*, 865–868. [CrossRef] [PubMed]
27. Hua, F.; Bruijnzeel, L.A.; Meli, P.; Martin, P.A.; Zhang, J.; Nakagawa, S.; Miao, X.; Wang, W.; McEvoy, C.; Peña-Arancibia, J.L. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. *Science* **2022**, *376*, 839–844. [CrossRef] [PubMed]
28. Xu, C.; Silliman, B.R.; Chen, J.; Li, X.; Thomsen, M.S.; Zhang, Q.; Lee, J.; Lefcheck, J.S.; Daleo, P.; Hughes, B.B. Herbivory limits success of vegetation restoration globally. *Science* **2023**, *382*, 589–594. [CrossRef]
29. Lundgren, E.J.; Bergman, J.; Trepel, J.; le Roux, E.; Monsarrat, S.; Kristensen, J.A.; Pedersen, R.Ø.; Pereyra, P.; Tietje, M.; Svenning, J.-C. Functional traits—Not nativeness—Shape the effects of large mammalian herbivores on plant communities. *Science* **2024**, *383*, 531–537. [CrossRef] [PubMed]
30. Al Mamun, M.A.; Dargusch, P.; Wadley, D.; Zulkarnain, N.A.; Aziz, A.A. A review of research on agrivoltaic systems. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112351. [CrossRef]
31. Burda, B.U.; O'Connor, E.A.; Webber, E.M.; Redmond, N.; Perdue, L.A. Estimating data from figures with a Web-based program: Considerations for a systematic review. *Res. Synth. Methods* **2017**, *8*, 258–262. [CrossRef]
32. Wang, Z.; Huang, H.; Wang, H.; Peñuelas, J.; Sardans, J.; Niinemets, Ü.; Niklas, K.J.; Li, Y.; Xie, J.; Wright, I.J. Leaf water content contributes to global leaf trait relationships. *Nat. Commun.* **2022**, *13*, 5525. [CrossRef]
33. Han, H.; Li, C.; Liu, R.; Jian, J.; Abulimiti, M.; Yuan, P. Warming promotes accumulation of microbial- and plant-derived carbon in terrestrial ecosystems. *Sci. Total Environ.* **2023**, *905*. [CrossRef] [PubMed]
34. Gu, W.; Jiapaer, G.; Yin, H.; Jiang, L.; Zang, X. Spatial and temporal distribution characteristic and division research of solar energy resources in southern Xinjiang. *Arid. Land Geogr.* **2021**, *44*, 1665–1675.
35. Yang, G.; Gui, Q.; Liu, J.; Chen, X.; Cheng, S. Spatial-temporal evolution and driving factors of ecological security in China based on DPSIR-DEA model: A case study of the Three Gorges reservoir area. *Ecol. Indic.* **2023**, *154*, 110777. [CrossRef]
36. Yuan, Y.; Bai, Z.; Zhang, J.; Huang, Y. Investigating the trade-offs between the supply and demand for ecosystem services for regional spatial management. *J. Environ. Manag.* **2023**, *325*, 116591. [CrossRef] [PubMed]
37. Zhang, D.; Wang, X.; Qu, L.; Li, S.; Lin, Y.; Yao, R.; Zhou, X.; Li, J. Land use/cover predictions incorporating ecological security for the Yangtze River Delta region, China. *Ecol. Indic.* **2020**, *119*, 106841. [CrossRef]
38. Hedges, L.V.; Gurevitch, J.; Curtis, P.S. The meta-analysis of response ratios in experimental ecology. *Ecology* **1999**, *80*, 1150–1156. [CrossRef]
39. Liu, C.; Lu, M.; Cui, J.; Li, B.; Fang, C. Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Glob. Change Biol.* **2014**, *20*, 1366–1381. [CrossRef]
40. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* **2010**, *36*, 1–48. [CrossRef]
41. Bracken, M. Statistical methods for analysis of effects of treatment in overviews of randomized trials. In *Effective Care of the Newborn Infant*; Oxford University Press: Oxford, UK, 1992; pp. 13–20.
42. Chen, J.; van Groenigen, K.J.; Hungate, B.A.; Terrer, C.; van Groenigen, J.-W.; Maestre, F.T.; Ying, S.C.; Luo, Y.; Jorgensen, U.; Sinsabaugh, R.L.; et al. Long-term nitrogen loading alleviates phosphorus limitation in terrestrial ecosystems. *Glob. Change Biol.* **2020**, *26*, 5077–5086. [CrossRef]
43. Tian, P.; Liu, S.; Zhao, X.; Sun, Z.; Yao, X.; Niu, S.; Crowther, T.W.; Wang, Q. Past climate conditions predict the influence of nitrogen enrichment on the temperature sensitivity of soil respiration. *Commun. Earth Environ.* **2021**, *2*, 251. [CrossRef]
44. Lefcheck, J.S. piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics. *Methods Ecol. Evol.* **2016**, *7*, 573–579. [CrossRef]
45. Whittaker, R.H. *Communities and Ecosystems*; Macmillan Company: London, UK, 1975.
46. Jiang, B.; Zhang, B.; Li, L.; Zhao, Y.; Shi, Y.; Jiang, Q.; Jia, L. Analysis of microbial community structure and diversity in surrounding rock soil of different waste dump sites in fushun western opencast mine. *Chemosphere* **2021**, *269*, 128777. [CrossRef] [PubMed]

47. Li, Y.; Zhou, W.; Jing, M.; Wang, S.; Huang, Y.; Geng, B.; Cao, Y. Changes in Reconstructed Soil Physicochemical Properties in an Opencast Mine Dump in the Loess Plateau Area of China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 706. [CrossRef] [PubMed]
48. Liu, D.; Huang, Y.; An, S.; Sun, H.; Bhople, P.; Chen, Z. Soil physicochemical and microbial characteristics of contrasting land-use types along soil depth gradients. *Catena* **2018**, *162*, 345–353. [CrossRef]
49. Chang, Z.; Liu, S.; Zhu, S.; Han, F.; Zhong, S.; Duan, X. Ecological Functions of PV Power Plants in the Desert and Gobi. *J. Resour. Ecol.* **2016**, *7*, 130–136.
50. Li, S.; Gao, Q.; Wang, X.; Lan, L.; Yang, Z. Characteristics of Vegetation and Soil Property Changes by Photovoltaic Plant Interference in Alpine Desert Steppe. *J. Soil Water Conserv.* **2016**, *30*, 325–329.
51. Wu, C.; Liu, H.; Yu, Y.; Zhao, W.; Liu, J.; Yu, H.; Yetemen, O. Ecohydrological effects of photovoltaic solar farms on soil microclimates and moisture regimes in arid Northwest China: A modeling study. *Sci. Total Environ.* **2022**, *802*, 149946. [CrossRef] [PubMed]
52. Basche, A.D.; Kaspar, T.C.; Archontoulis, S.V.; Jaynes, D.B.; Sauer, T.J.; Parkin, T.B.; Miguez, F.E. Soil water improvements with the long-term use of a winter rye cover crop. *Agric. Water Manag.* **2016**, *172*, 40–50. [CrossRef]
53. Wang, F.; Wang, Y.; Lyu, H.; Fan, Z.; Hu, F.; He, W.; Yin, W.; Zhao, C.; Chai, Q.; Yu, A. No-tillage mulch with leguminous green manure retention reduces soil evaporation and increases yield and water productivity of maize. *Agric. Water Manag.* **2023**, *290*, 108573. [CrossRef]
54. Hu, A.; Levis, S.; Meehl, G.A.; Han, W.; Washington, W.M.; Oleson, K.W.; Van Ruijven, B.J.; He, M.; Strand, W.G. Impact of solar panels on global climate. *Nat. Clim. Change* **2016**, *6*, 290–294. [CrossRef]
55. Li, Z.; Sun, X.; Zhou, J.; Wu, L.; Bi, D.; Zhao, J.; Zhu, R.; Christie, P. Sustainable phytoextraction of metal-polluted agricultural land used for commercial photovoltaic power generation. *J. Clean. Prod.* **2023**, *391*, 136093. [CrossRef]
56. Amaducci, S.; Yin, X.; Colauzzi, M. Agrivoltaic systems to optimise land use for electric energy production. *Appl. Energy* **2018**, *220*, 545–561. [CrossRef]
57. Armstrong, A.; Waldron, S.; Whitaker, J.; Ostle, N.J. Wind farm and solar park effects on plant-soil carbon cycling: Uncertain impacts of changes in ground-level microclimate. *Glob. Change Biol.* **2014**, *20*, 1699–1706. [CrossRef] [PubMed]
58. Valle, B.; Simonneau, T.; Sourd, F.; Pechier, P.; Hamard, P.; Frisson, T.; Ryckewaert, M.; Christophe, A. Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Appl. Energy* **2017**, *206*, 1495–1507. [CrossRef]
59. Weselek, A.; Ehmann, A.; Zikeli, S.; Lewandowski, I.; Schindele, S.; Hoegy, P. Agrophotovoltaic systems: Applications, challenges, and opportunities: A review. *Agron. Sustain. Dev.* **2019**, *39*, 35. [CrossRef]
60. Zhou, M.; Wang, X. Influence of photovoltaic power station engineering on soil and vegetation: Taking the Gobi Desert Area in the Hexi corridor of Gansu as an example. *Sci. Soil Water Conserv.* **2019**, *17*, 132–138.
61. Jin, J.; Cai, Y.; Guo, X.; Wang, L.; Wang, Y.; Liu, Y. Decoupled driving forces of variabilities of transpiration in Chinese subtropical vegetation based on remote sensing data. *J. Geogr. Sci.* **2023**, *33*, 2159–2174. [CrossRef]
62. Yue, D.; Zhou, Y.; Guo, J.; Chao, Z.; Guo, X. Relationship between net primary productivity and soil water content in the Shule River Basin. *Catena* **2022**, *208*, 105770. [CrossRef]
63. MacKay, D.J. Solar energy in the context of energy use, energy transportation and energy storage. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2013**, *371*, 20110431. [CrossRef]
64. Elamri, Y.; Cheviron, B.; Lopez, J.M.; Dejean, C.; Belaud, G. Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. *Agric. Water Manag.* **2018**, *208*, 440–453. [CrossRef]
65. Liu, Y.; Zhang, R.-Q.; Huang, Z.; Cheng, Z.; Lopez-Vicente, M.; Ma, X.-R.; Wu, G.-L. Solar photovoltaic panels significantly promote vegetation recovery by modifying the soil surface microhabitats in an arid sandy ecosystem. *Land Degrad. Dev.* **2019**, *30*, 2177–2186. [CrossRef]
66. Tian, Z.-Q.; Zhang, Y.; Liu, X.; Chen, S.-Y.; Liu, B.-L.; Wu, J.-H. Effects of Photovoltaic Power Station Construction on Terrestrial Environment: Retrospect and Prospect. *Huan Jing Ke Xue = Huanjing Kexue* **2024**, *45*, 239–247.
67. Zhang, N.; Duan, H.; Shan, Y.; Miller, T.R.; Yang, J.; Bai, X. Booming solar energy is encroaching on cropland. *Nat. Geosci.* **2023**, *16*, 932–934. [CrossRef]
68. Stern, R.; Muller, J.D.; Rotenberg, E.; Amer, M.; Segev, L.; Yakir, D. Photovoltaic fields largely outperform afforestation efficiency in global climate change mitigation strategies. *PNAS Nexus* **2023**, *2*, pgad352. [CrossRef] [PubMed]
69. Li, Z.B.; Zhang, Y.; Wang, M. Solar energy projects put food security at risk. *Science* **2023**, *381*, 740–741. [CrossRef] [PubMed]
70. McClung, M.R.; Moran, M.D. Minimizing Impacts of Future Renewable Energy Development on the World's Desert Ecosystems. *Front. Sustain.* **2022**, *3*, 900468. [CrossRef]
71. Hernandez, R.R.; Hoffacker, M.K.; Murphy-Mariscal, M.L.; Wu, G.C.; Allen, M.F. Solar energy development impacts on land cover change and protected areas. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 13579–13584. [CrossRef]
72. *Technical Guidelines for Environmental Impact Assessment—Ecological Impact*; Ministry of Ecology and Environment of People's Republic of China: Beijing, China, 2020; Volume HJ 19-2022, pp. 1–25.
73. Needham, B. *Dutch Land-Use Planning: The Principles and the Practice*; Routledge: London, UK, 2016.

74. Schützenberger, J. *OÖ Photovoltaik-Strategie 2030: Eine Machbarkeitsstudie über die Errichtung einer PV-Freiflächenanlage auf einem rekultivierten Quarzsandtagebau*; Westsächsische Hochschule Zwickau: Zwickau, Germany, 2023.
75. Stamford, L.; Azapagic, A. Environmental impacts of photovoltaics: The effects of technological improvements and transfer of manufacturing from Europe to China. *Energy Technol.* **2018**, *6*, 1148–1160. [CrossRef]