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Peer Review File

Small reduction in land surface albedo due to solar panel expansion worldwide

Corresponding Author: Professor Zhenzhong Zeng

Version 0:

Decision Letter:

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Dear Professor Zeng,

Your manuscript titled "Observation-based assessment of photovoltaics-laying effect on land surface albedo" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

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We hope to receive your revised paper within six weeks; please let us know if you aren’t able to submit it within this time so that we can discuss how best to proceed. If we don’t hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Sylvia Sullivan, PhD
Editorial Board Member
Communications Earth & Environment

Martina Grecequet, PhD
Associate Editor
Communications Earth & Environment
@CommsEarth

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript by Wei et al “Observation-based assessment of photovoltaics-laying effect on land surface albedo” used MODIS albedo product and a global inventory of PV sites to quantify the impact of PV on albedo and RF. The environmental impact of PV has attracted growing attention nowadays, and the topic of the study is worth investigating. Overall, the manuscript is well-written, and the results are clear.

Major comments:
1. The argument that climate models overestimate the albedo effect of PV is not supported by the analysis. Although the average albedo of PV is 0.16 by satellite data in this study, which is larger than 0.1 assumed in climate models, it is not necessarily that climate models overestimate the albedo difference without knowing the background albedo in climate models. If the background albedo in climate is also higher than that from satellite data, the albedo change could still be similar to that in satellite data. Also, the albedo difference is related to how PV is parametrized in climate models. Some PV parametrizations include variable albedo of PV (e.g., Heusinger 2019; Chang 2022).
2. Comparison with other studies on the albedo impact of PV can be made, e.g., with recent literature (Jiang 2022; Xu 2024). The largest albedo difference of PV observed in open shrubland is different from other studies. I wonder the reason. Additionally, some earlier papers explored the radiative forcing of the albedo of PV, which is worth mentioning (Nemet 2009).

Specific comments
L105 -109: PV albedo varies in different bands at different times (hours, seasons) and is affected by many factors (Ying 2022). As for PV parameterization in climate models, there are constant (0.1) or variable in complicated schemes (Heusinger

2019; Chang 2022).

L115-117. This can be compared with the albedo effect estimated by Xu 2024, who quantified the albedo effect of PV using many sites.

Fig 2. Please add a zero tick on panel c and d.

L136-137. The largest albedo decrease in open shrubland is unexpected. As seen from table S3, albedo change is largest over barren land.

L202-208.This argument is not convincing. If a constant albedo of 0.1 is applied in climate models, it is unclear how much albedo changes are in models relative to its background albedo. The analysis only shows albedo change from satellite data.

L368-375: What would the results be if PV grid fractions were not considered? What if directly comparing the albedo differences?

References:

Chang, R., Yan, Y., Luo, Y., Xiao, C., Wu, C., Jiang, J., & Shi, W. (2022). A coupled WRF-PV mesoscale model simulating the near-surface climate of utility-scale photovoltaic plants. Solar Energy, 245, 278–289. https://doi.org/10.1016/j.solener.2022.09.023
Heusinger, J., Broadbent, A. M., Sailor, D. J., & Georgescu, M. (2020). Introduction, evaluation and application of an energy balance model for photovoltaic modules. Solar Energy, 195(September 2019), 382–395. https://doi.org/10.1016/j.solener.2019.11.041
Li, S., Weigand, J., & Ganguly, S. (2017). The Potential for Climate Impacts from Widespread Deployment of Utility-Scale Solar Energy Installations: An Environmental Remote Sensing Perspective. Journal of Remote Sensing & GIS, 6(1), 1–5. https://doi.org/10.4172/2469-4134.1000190
Nemet, G. F. (2009). Net radiative forcing from widespread deployment of photovoltaics. Environmental Science and Technology, 43(6), 2173–2178. https://doi.org/10.1021/es801747c
Xu, Z., Li, Y., Qin, Y., & Bach, E. (2024). A global assessment of the effects of solar farms on albedo, vegetation, and land surface temperature using remote sensing. Solar Energy, 268, 112198. https://doi.org/10.1016/j.solener.2023.112198
Ying, J., Li, Z., Yang, L., Jiang, Y., Luo, Y., & Gao, X. (2022). The characteristics and parameterizations of the surface albedo of a utility-scale photovoltaic plant in the Gobi Desert. Theoretical and Applied Climatology. https://doi.org/10.1007/s00704-022-04337-5

Reviewer #2 (Remarks to the Author):

Review - 1:
Observation-based assessment of photovoltaics-laying effect on land surface albedo
Authors: Sihuan Wei et al., 2024

Considering the need to increase the electrical supply to the humanity growing demand sharply, and at the same time to reduce fossil fuel emitted greenhouse gasses to the atmosphere, currently a major source of CO2 emission, the importance of green alternative energy becomes a necessary solution. Large-scale photovoltaic (PV) field installations in sunny regions could become primary electricity production sources. However, it is now well recognized that large scale, land cover changes, could have direct effects on the land- atmosphere energy exchanges that affect the Earth's radiative forcing and the climate system. The driven effects by the land cove changes could contradict the CO2-suppressing cooling impact on the climate.
In his paper Sihuan Wei et. al., assess the radiative forcing balance, result from existing PV installation fields by comparing the eliminating CO2 emission due to the green electrical manufacturing vs. the albedo change effect of the installed dark PV sheets over that surface. For their analyzing assessments, the authors used the electrical output of the study sites to calculate the alternative CO2-prevented emission against the change in the surface albedo calculated by remote sensing techniques. The strength of this study is in the large areas it has performed: area-wise, of about 20% of the identified PV sites in their survey, and the use of remote sensing to identify the sites' areas, and to calculate the albedo change by the PV cover over the PV site.
It is an interesting paper and clear, but it suffers from several major drawbacks:

1. In the calculation of the Carbon suppression, the difference between the carbon uptake by the surface before the PV installation to the carbon 'uptake' by the PV field should be considered. This presumable, for most sites, will extend the breakeven duration.
2. For future assessment of the climatic impact of a site at a given location for possible PV installations and for comparing the RF among sites and other uses, the relative forcing effect per unit of area is needed. Please reconsider the conclusions drawn in Line (L) 186.
3. Unclear are the significant Albedo differences among countries (e.g., Figure 3)? Is it because of the PV's types, the installation procedure, by the different ecosystem types, or? Otherwise, why will it be a country-dependent variable?
4. Throughout the calculations, the time scale of the albedo change for the radiative forcing-driven values is unclear

(Methods part). For example, are R↓_SR and the ΔAlbedo averages in equation 6 annually average? Have those values weighted by seasonal and daily RSR changes?
5. The term μWm-2 needs explanation. It is likely the projected global average (all Earth's surface, annually, and for which year?) RF penalty of PV installation? Then, consider presenting this against the benefit of CO2 suppression by the PV's.
6. The PV field albedo value depends on the spacing area between PV rows and the PV sheets' angles, which affect the electricity production efficiency per unit area at a given site. Since it is a global-scale study that may served decision-makers, prior to PV installation decisions in future work, it is recommended that the authors elaborate more on electrical output per a unit area of PV field.
7. This study concentrated on the albedo change radiative forcing; however, PV also has other RF impacts, as well as environmental and ecological aspects that must consider as well (e.g., https://doi.org/10.1093/pnasnexus/pgad352) before converting an area to a PV site.

Minor comments:
L. 188. Unclear are the 'relatively concentrated variations' and the connection to Fig. 2.c.
L. 204-7. Is 0.16 not more pronounced than 0.1 (Δalbedo) of the previous sentence there? And the meaning of 'with an area ratio of 1' is unclear.
L 375-6. Unclear Point 2 is.
Provide the R↓SR source.
L. 437. Cap value is unclear. Note, the value seems to be kind of ½ h annually on average.

Author Rebuttal letter: The author's response to these comments can be found at the end of this file.

Version 1:

Decision Letter:

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Dear Professor Zeng,

Your manuscript titled "Observation-based assessment of photovoltaics-laying effect on land surface albedo" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Sylvia Sullivan, PhD
Editorial Board Member
Communications Earth & Environment

Martina Grecequet, PhD
Associate Editor,
Communications Earth & Environment
@CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors did a good job of revising the manuscript. I do not have further comments and it can be accepted.

Reviewer #2 (Remarks to the Author):

I want to thank the paper's Authors for the detailed and systematic answers to all the comments.
I'm satisfied with them most and ask to address the following:
1. When comparing the carbon emission reduction gained by PV installation, which includes the life cycle (LC) assessment, the ecosystem gross primary production (GPP) is not to be compared but the net ecosystem (carbon) exchange (NEE). I may not be precise enough when I wrote that comment in the first round.
2. Figure 10 caption is unclear.
And, that a larger PV area has a greater RF effect is trivial; it is better not to repeat this often.
3. The explanation for the countries' effect on the PV sites' Albedo (China, India vs. USA) is unclear. If it is a different climate, please show that and explain instead. Consider not including fig. R11.d.

I am sure those comments do not need much effort, and I wish the authors luck with the paper submission.

Author Rebuttal letter: The author's response to these comments can be found at the end of this file.

Response to the reviewers (COMMSENV-24-0408-T)

Reviewer #*1* (Remarks to the Author):

Reviewer #*1* General Comments: *The manuscript by Wei et al "Observation-based assessment of photovoltaics-laying effect on land surface albedo" used MODIS albedo product and a global inventory of PV sites to quantify the impact of PV on albedo and RF. The environmental impact of PV has attracted growing attention nowadays, and the topic of the study is worth investigating. Overall, the manuscript is well-written, and the results are clear.*

[Response] We are grateful for your high compliments on the broad interest of our paper. Your constructive suggestions have enhanced the clarity and coherence of our study. We believe that all your concerns and comments have been well taken care of in the revised manuscript.

[*Reviewer #1* Major comments 1] *The argument that climate models overestimate the albedo effect of PV is not supported by the analysis. Although the average albedo of PV is 0.16 by satellite data in this study, which is larger than 0.1 assumed in climate models, it is not necessarily that climate models overestimate the albedo difference without knowing the background albedo in climate models. If the background albedo in climate is also higher than that from satellite data, the albedo change could still be similar to that in satellite data. Also, the albedo difference is related to how PV is parametrized in climate models. Some PV parametrizations include variable albedo of PV (e.g., Heusinger 2019; Chang 2022).*

[Response] Thank you for your constructive comments. We acknowledge the importance of incorporating both the background albedo and the albedo of PV site when comparing the observation-based albedo change with climate modeling settings. In the revision, we have carefully summarized previous modeling studies focused on deploying PV panels on the natural ground (Table R1), providing background albedo and albedo change information in their experiment designs to support our argument.

Our satellite-observed albedo changes are much smaller than those projected changes in ESMs, implying that the assumptions in these modeling may inadequately represent the albedo and corresponding change at locations where PV panels are deployed. On the one hand, we note that some PV parameterization assumptions may not align well with real-world conditions by assigning a constant albedo for PV site, assuming solar panels cover the entire area of interest. For example, in some global-scale climate simulations deploying PVs in desert areas, PV sites are assumed to have an albedo of 0.1 (PV panel reflectivity) without accounting for the typically higher background albedo in gaps between PV arrays, leading to an underestimation of albedo at PV sites (Table R1). On the other hand, the determination of background albedo in climate models relies on assuming fixed values on land-cover type (look-up tables) or process-based calculations. Therefore, we have further computed the satellite-based background albedo of the study areas in the modeling studies for comparison. The results indicate that, for comparable background albedo conditions, the discrepancy in albedo change between satellite data and climate model assumptions arises from the underestimated albedo of PV sites (Li et al., 2018; Lu et al., 2020) (Table R1). Meanwhile, our comparison with Chang *et al.* (2022) highlights discrepancies in albedo values, emphasizing the potential need for adjustments of albedo values in regional climate modeling by using observation-based data (Table R1).

Table R1 (also Supplementary Table 1 in the revised manuscript). Previous studies modeling the climate feedbacks from deploying solar panels on natural ground. The values enclosed in brackets represent the satellite-based shortwave albedo of the study area in modeling studies. With the exception of Chang *et al.*[5], whose study region aligns with one of our PV sites, the remaining values are only the mean albedo of 2019, aimed at minimizing computational burdens.

Scale	Model	Albedo		Albedo Change		Land Cover	Source
		Background	PV Site	Absolute	Relative		
[a]Global	UMD –ICTP	0.34 (0.3337)	0.1	-0.24	-71%	Desert	Li *et al.*[1]
[a]Global	EC-Earth	~0.2 to ~0.4 (0.3337)	0.1	~-0.1 to ~-0.3	~-50% to ~-75%	Desert	Lu *et al.*[2]
[a]Regional	WRF	~0.21 (0.2186)	0.05	~-0.16	~-76%	Desert	Millstein *et al.*[3]
Regional	[b]WRF	[c]0.38 [d]0.38	[c]0.16 [d]0.21	[c]-0.22 [d]-0.17	[c]58% [d]55%	Barren or Sparsely Vegetated	Chang *et al.*[4]
Regional	[b]WRF	[c]0.25 [d]0.30 (0.1915)	[c]0.13 [d]0.15 (0.1794)	[c]-0.12 [d]-0.15	[c]48% [d]50%	Shrubland	Chang *et al.*[5]

[a]: Assuming solar panels cover the interested place with 100 % coverage.

[b]: The background albedo values are found from look-up table.

[c]: Maximum albedo.

[d]: Minimum albedo.

We have clarified related contents in the revised manuscript:

“Previous studies have simulated the effects of PV deployment on climate[10-16]. Despite advancements in PV parmeterization[10-17], many modeling studies[12-16], when characterizing the PV’s effects on the surface energy budget, ideally assign overall terrestrial albedo values to regions featuring PV panel arrays, based on simplistic assumptions.” (Page 3, Lines 62-65 in the clean version of the revised manuscript).

“Besides, the satellite-observed albedo changes are much smaller than those projected changes in ESMs[14-15] (Fig. 2c,d; Supplementary Table 1). These disparities suggest that the assumptions in these modeling may inadequately represent the albedo and corresponding change at locations where PV panels are deployed.” (Page 4, Lines 112-116).

“Understanding the unintended climate impacts of widespread solar panel deployment is crucial for tackling climate change. It's essential to practically characterize the albedo changes at PV sites to refine climate models at both global and regional levels. The overall surface mixed albedo of a PV farm reflects both the reflectivity of solar panels and that of the natural surface, accounting for the required spacing between arrays (ref. [36]; Supplementary Fig. 16). Given that the albedo of most land cover types exceeds 0.1 (ref. [37]), neglecting the background albedo in spacing in some global-scale ESM-based simulations[14-15], which utilized simplified fixed albedo of 0.1 to represent PV sites over the desert, can lead to lower mixed albedo at PV sites compared to observations (Supplementary Tables 1-2). This, in turn, results in a larger relative albedo change from the background (up to 75% decrease; refs. [14-15]), and thus an overestimated climate response.” (Page 7, Lines 211-221).

Furthermore, we acknowledge the advancements in PV parameterization in climate models (Taha et al., 2013; Masson et al., 2014; Chang et al., 2020; Chang et al., 2022; Heusinger et al., 2020), which now often include variable albedo. However, uncertainties arise due to scale mismatches when only a few field observations are used to represent the entire site's average albedo (e.g., Chang et al., 2022). Our analysis could provide a valuable reference to address these complexities by examining mixed albedo at PV sites (Table R2) and exploring the related albedo changes when conducting simulations at both regional and global scales. Moreover, in our study, we have investigated the influence of climate regime, background land cover, and soil moisture. We agree that further investigation into the environmental factors and PV installation characteristics is needed to fully explore the temporal dynamics. The above discussions have been added to the revised manuscript (Pages 8, Lines 222-233).

Table R2 (Supplementary Table 4). The albedo of PV sites over the same specific land cover under different climate conditions. Q25 and Q75 are 25th and 75th percent interval quantiles, respectively.

Type	Number of sites	Median	Q25	Q75
OS-BWh	14	0.1915	0.1784	0.2094
OS-BWk	7	0.1908	0.1854	0.1966
OS-BSk	5	0.1662	0.1488	0.1714
OS-Csa	13	0.1708	0.1474	0.1786
WSa-Cfb	3	0.1236	0.1139	0.1370
Sa-Cfb	12	0.1180	0.1051	0.1309
Gr-BWk	29	0.1731	0.1644	0.1877
Gr-BSk	9	0.1484	0.1333	0.1616
Gr-Csa	69	0.1604	0.1486	0.1717
Gr-Cfb	3	0.1265	0.1133	0.1375
Gr-Dwb	12	0.1488	0.1227	0.1585
Gr-Dwc	10	0.1600	0.1557	0.1642
Gr-Dfc	4	0.1250	0.1157	0.1623
Cr-Aw	11	0.1253	0.1197	0.1391
Cr-BWh	3	0.1788	0.1638	0.1813
Cr-BSk	5	0.1453	0.1306	0.1525
Cr-Csa	6	0.1561	0.1431	0.1810
Cr-Cwb	3	0.1398	0.1302	0.1441
Cr-Cfb	7	0.1234	0.1001	0.1363
Cr-Dwb	15	0.1442	0.1386	0.1492
Cr-Dfc	7	0.1443	0.1361	0.1504
Ba-BWh	15	0.1991	0.1648	0.2276
Ba-BWk	59	0.1867	0.1709	0.2037
WB-Cfb	3	0.0971	0.0861	0.1003
WB-Dwb	4	0.0805	0.0758	0.0938

[*Reviewer #1* Major comments 2] *Comparison with other studies on the albedo impact of PV can be made, e.g., with recent literature (Jiang 2022; Xu 2024). The largest albedo difference of PV observed in open shrubland is different from other studies. I wonder the reason. Additionally, some earlier papers explored the radiative forcing of the albedo of PV, which is worth mentioning (Nemet 2009).*

[Response] Thank you for the great suggestions. Accordingly, we have added more comparisons and discussions with other recent literatures in the revision, and updated the following Table R3 (also Supplementary Table 2 in the revised manuscript).

Table R3 (Supplementary Table 2). The comparison of shortwave albedo between our study and other studies.

Longitude (°)	Latitude (°)	Satellite		In-situ observations		Land cover	Source
		Background	Change	Background	Change		
95.233	36.503	[a]0.2102	[a]-0.0162	0.26	-0.07	Barren	Yang *et al.*[6]
100.588	36.136	[a]0.1664	[a]-0.0216	0.179	0.005	Barren	Chang *et al.*[7]
-111.284	32.555	-	-	0.3	-0.09	Barren	Broadbent *et al.*[8]
119.793	32.303	-	-	0.101	-0.019	Water body	Li *et al.*[9]
87.660	44.410	[a]0.1916	[a]-0.0100	0.23	-0.09	Barren	Li *et al.*[10]
87.660	44.410	[a]0.1916	[a]-0.0100	[b]0.22	-0.08	Barren	Ying *et al.*[11]
35.059	29.965	-	-	0.38	-0.21	[c]Barren	Stern *et al.*[12]
94.250	40.000	[a]0.1905	[a]-0.0145	-	-	Barren	Hua *et al.*[13]
		0.2216	-0.0287	-	-		
[d]Comprehensive sites		-	[a]-0.024	-	-	-	Zhang *et al.*[14]
		-	-0.036	-	-	-	
[e]Comprehensive sites		-	[a]-0.0126	-	-	Grass-lands	Xu *et al.*[15]
		-	-0.014	-	-		
		-	[a]-0.0142	-	-	Barren	
		-	-0.025	-	-		
		-	[a]-0.0102	-	-	Crop-lands	
		-	-0.010	-	-		

[a]: Our study.

[b]: The background for comparison is not near the PV site.

[c]: This site is located in a typical desert land under hot and arid climate conditions.

[d]: Zhang *et al.*[14] selected 23 PV plants (1 km resolution satellite-based albedo data), but only 17 plants exist or have high accuracy in the PV dataset used in our study. In order to compare with their results, here the albedo change we calculated is the mean value of the 17 PV plants.

[f]: Xu *et al.*[15] selected 116 solar power plants (both PV and concentrated solar power (CSP) plants with area larger than four 1-km pixels to reduce the effect of mixed pixels) and only calculated the white-

sky albedo. Here we didn't select the sites they used for a detailed comparison, but rather conducted a general albedo change comparison of sites over different land use types.

Regarding the observed largest albedo difference of PV in open shrubland, it is attributed to our samples' distribution. Albedo change is influenced not only by background characteristics but also by the proportion of the PV panel area to the total area at each site (packing factor). Among the valid samples of our analyses, barren sites in the Northern Hemisphere, with higher latitudes, have PV panels inclined at steeper angles to optimize solar radiation (Fig. R1). This inclination necessitates wider gaps between arrays to minimize shading, resulting in a smaller packing factor and consequently, a less pronounced reduction in albedo. Therefore, PV sites in shrubland typically have a larger proportion of the total area covered by PV panels compared to sites in barren landscapes. We have mentioned this in the manuscript: "Contrary to recent findings favoring greater albedo changes in barren areas (Supplementary Table 2; ref. [28]), we uncover a larger overall albedo decrease in shrubland sites. This likely stems from barren sites being situated at higher latitudes (Supplementary Fig. 7), resulting in steeper solar panel angles, wider PV array spacing, and ultimately, a smaller fraction of the site covered by PV panels, leading to a reduced albedo change." (Page 5, Lines 141-146).

Additionally, thank you for recommending this important reference. We have compared our results with Nemet *et al.* in the manuscript (Page 8, Lines 245-250): "By 2050, according to the projected installed solar PV capacity of exceeding 18,200 GW (~37 fold the capacity in 2018) in the IRENA's 1.5°C Scenario[7], the global RF would potentially reach more than 1,135 μW m^{-2} (equivalent to anthropogenic carbon emissions of approximately 426 Tg C), compared with 3,300 μW m^{-2} obtained from the idealized assessment under a similar scenario of PV installation capacity (Nemet, 2009)."

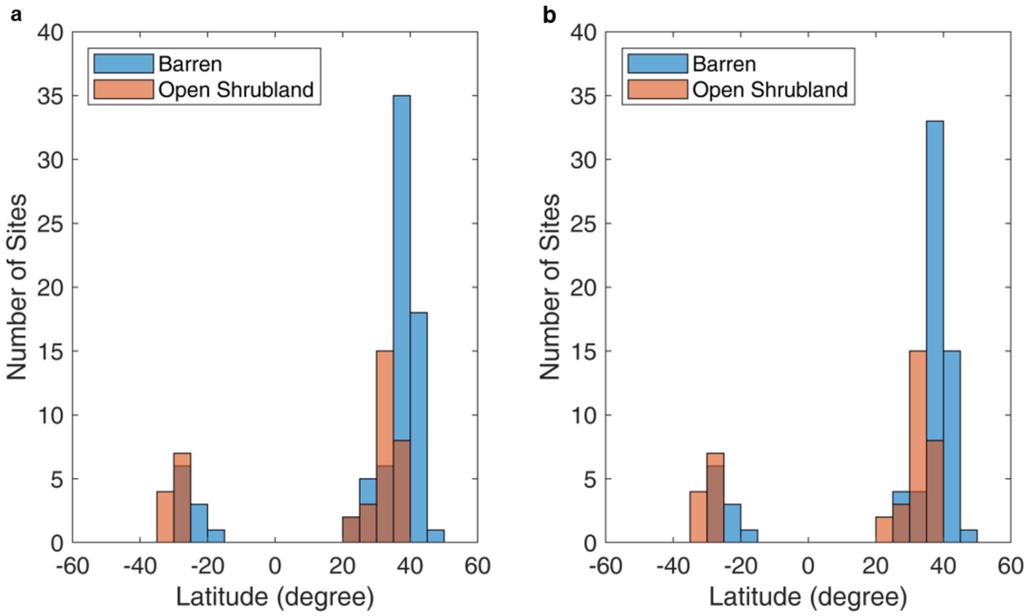

Fig. R1 (Supplementary Figure 7). The latitude pattern comparison of PV sites over open shrublands and barren. a, The latitude pattern of all PV sites over open shrublands (n = 39) and barren (n = 77). **b**, The latitude pattern of sites over open shrublands (n = 39) and filtered sites over barren (n = 67). The barren sites included in **b** have been selectively filtered to ensure that their background albedo falls within the range observed for sites over open shrublands, providing a consistent comparison of background albedo between the two types of land cover. Most of the PV sites located over barren (38.99°N; median) are positioned at higher latitudes compared to those over open shrublands (34.06°N; median) in the Northern Hemisphere. This implies that PV arrays at these barren sites require greater spacing to mitigate the shading effects on the panel generation.

[*Reviewer #1* Specific comments 1] *L105-109:* *PV albedo varies in different bands at different times (hours, seasons) and is affected by many factors (Ying 2022). As for PV parameterization in climate models, there are constant (0.1) or variable in complicated schemes (Heusinger 2019; Chang 2022).*

[Response] Thank you for your thoughtful comments. Our study focuses on the overall mean impact of PV-induced shortwave albedo change, crucial for understanding radiation energy balance in climate models. We acknowledge the necessity to delve deeper into the temporal variability of PV albedo in regional climate modeling to reflect its variable nature. From a different perspective, our study could also contribute to this discourse by providing empirical data and results regarding environmental factors such as land cover types and climate regimes. These insights can help inform and refine modeling efforts in this area.

We have clarified related contents in the manuscript and provided more discussions (refer to [*Reviewer #1* Major comments 1]).

[*Reviewer #1* Specific comments 2] *L115-117:* *This can be compared with the albedo effect estimated by Xu 2024, who quantified the albedo effect of PV using many sites.*

[Response] Thank you for recommending this important reference. We have added this and other observation-based results in Supplementary Table 2, and the updated table is shown as Table R3 (refer to [*Reviewer #1* Major comments 2]). Additionally, we have revised related contents on Pages 5, Lines 141-146 in the manuscript.

[*Reviewer #1* Specific comments 3] *Fig 2. Please add a zero tick on panel c and d.*

[Response] We have revised this figure by adding grey lines to represent the zero value.

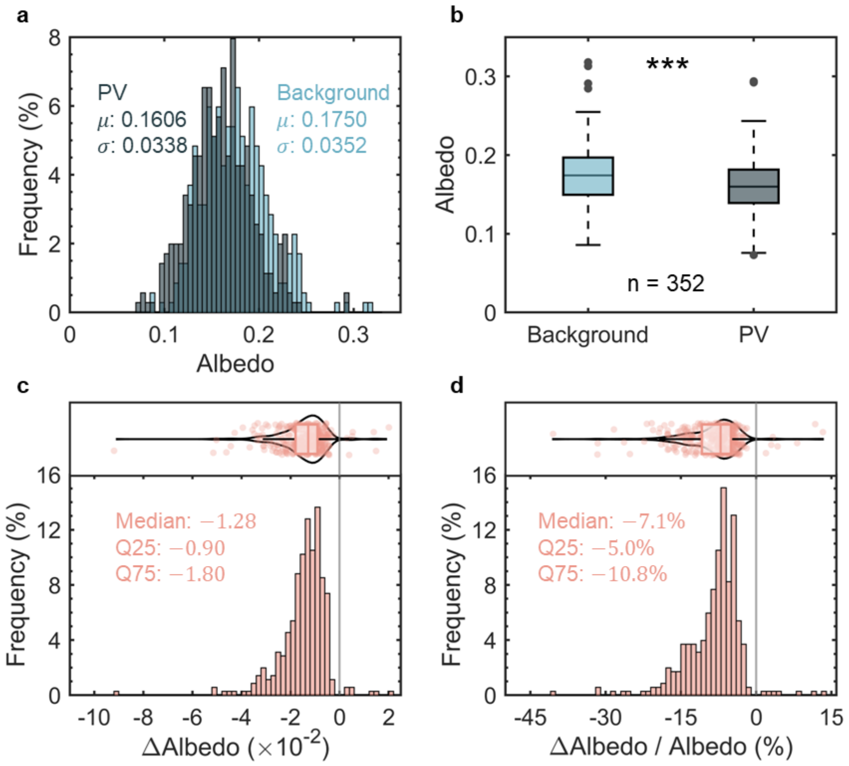

Fig. R2 (Fig. 2). Analysis and comparison of mean albedo at PV sites and their corresponding backgrounds.

[*Reviewer #1* Specific comments 4] *L136-137:* *The largest albedo decrease in open shrubland is unexpected. As seen from table S3, albedo change is largest over barren land.*

[Response] Thank you for highlighting this discrepancy. Indeed, when examining all PV sites collectively, those situated over open shrubland demonstrate the most significant reduction in albedo. This apparent contradiction arises from the geographical distribution of the sample sites, as discussed previously under [Reviewer #1 Major comments 2]. However, when considering sites within a specific country, sites in barren areas exhibit a larger albedo reduction (Supplementary Table 3). We have added detailed descriptions to clarify this point in the manuscript on Page 5, Lines 141-146.

[*Reviewer #1* Specific comments 5] ***L202-208:*** *This argument is not convincing. If a constant albedo of 0.1 is applied in climate models, it is unclear how much albedo changes are in models relative to its background albedo. The analysis only shows albedo change from satellite data.*

[Response] In the revision, we acknowledged the significance of considering both the background albedo and the albedo of PV panels in affecting albedo changes. We compiled background albedo and albedo change information in previous modeling studies concentrating on PV deployment on natural ground (Table R1), revealing substantially higher albedo changes compared to our satellite-observed evidences and observation-based results from other literatures (Tables R2 and R3).

Moreover, we have expanded the discussion by providing potential avenues for refining PV-induced albedo changes in climate models as follows: "Understanding the unintended climate impacts of widespread solar panel deployment is crucial for tackling climate change. It's essential to practically characterize the albedo changes at PV sites to refine climate models at both global and regional levels. The overall surface mixed albedo of a PV farm reflects both the reflectivity of solar panels and that of the natural surface, accounting for the required spacing between arrays (ref. [36]; Supplementary Fig. 16). Given that the albedo of most land cover types exceeds 0.1 (ref. [37]), neglecting the background albedo in spacing in some global-scale ESM-based simulations[14-15], which utilized simplified fixed albedo of 0.1 to represent PV sites over the desert, can lead to lower mixed albedo at PV sites compared to observations (Supplementary Tables 1-2). This, in turn, results in a larger relative albedo change from the background (up to 75% decrease; refs. [14-15]), and thus an overestimated climate response." (Page 7, Lines 211-221).

"Introducing the packing factor, a parameter representing the percentage of interested land covered by panels in the PV site[10,38], into global-scale Earth system simulations offers a straightforward method to address this concern. It enables the mixed albedo of regions with PV installations to more accurately align with observed values and refine the heterogeneity in PV-induced albedo change caused by the underlying background characteristics." (Pages 8, Lines 222-226).

[*Reviewer #1* Specific comments 6] ***L368-375:*** *What would the results be if PV grid fractions were not considered? What if directly comparing the albedo differences?*

[Response] Thank you for your question. Direct comparisons without considering the specific fraction of the grid covered by PV panels (Fig. R3) could substantially underestimate the true impact of the PV installations on albedo changes due to the inclusion of background land cover. Some studies address this uncertainty by imposing constraints on the size of photovoltaic fields (e.g. Xu et al., 2024); however, this approach may still overlook this key concern and could reduce the number of available PV sites for assessing the impact on albedo.

To better understand the extent of this potential underestimation, we analyzed the relative difference between albedo change calculated by our linear parameterization method and that by direct comparisons across 352 selected sites. Our findings show that ~82% of sites exhibit positive differences, with a median value of 37% (Fig. R4), suggesting a notable underestimation in the albedo change calculated by direct comparison. This comparison underscores the potential for substantial underestimation when not accounting for PV grid fractions and validates the robustness of our method. Related revisions in the manuscript are on Pages 13-14, Lines 398-401.

We have added related figures in the SI:

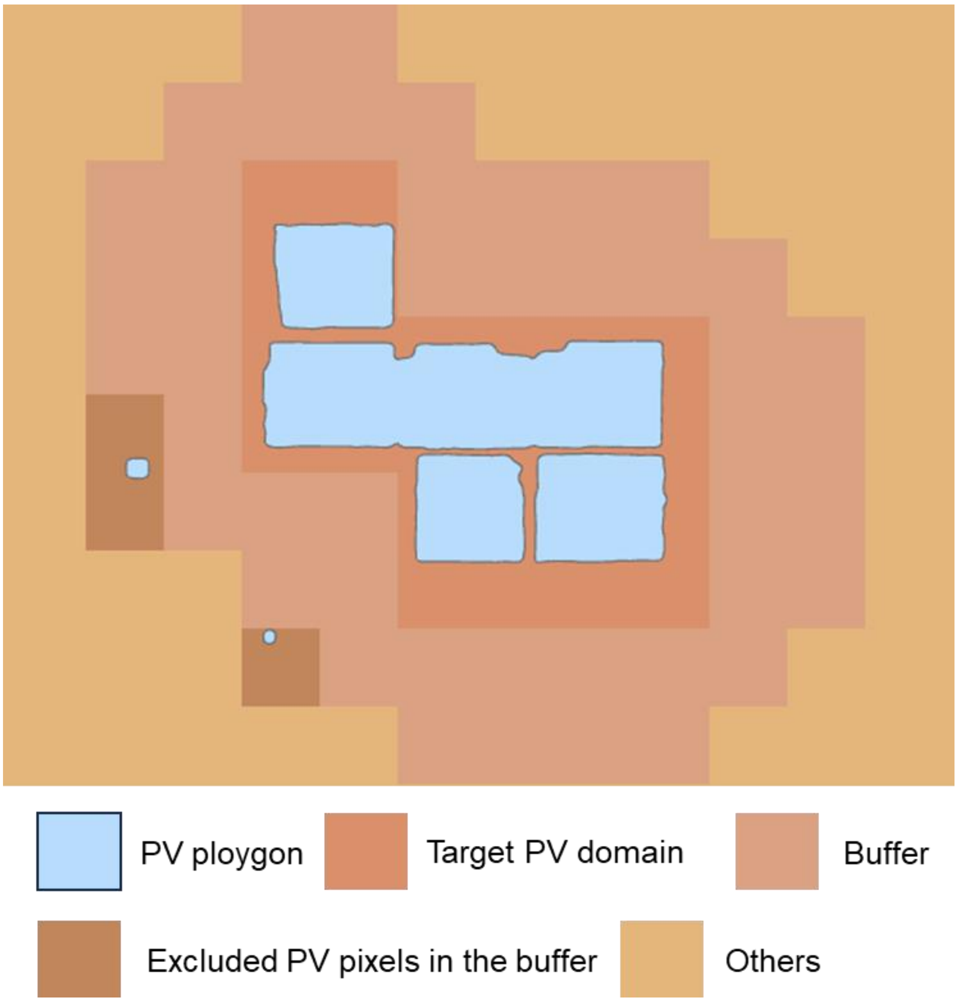

Fig. R3 (Supplementary Figure 20). The diagram of creating a buffer near a target PV domain (site). To create a buffer zone with a width of 2 pixels around a selected PV connected region, a dilation operation is used to enlarge the target PV region by adding two pixels around its edges. Any other PV regions within the buffer zone, apart from the target PV domain, are excluded.

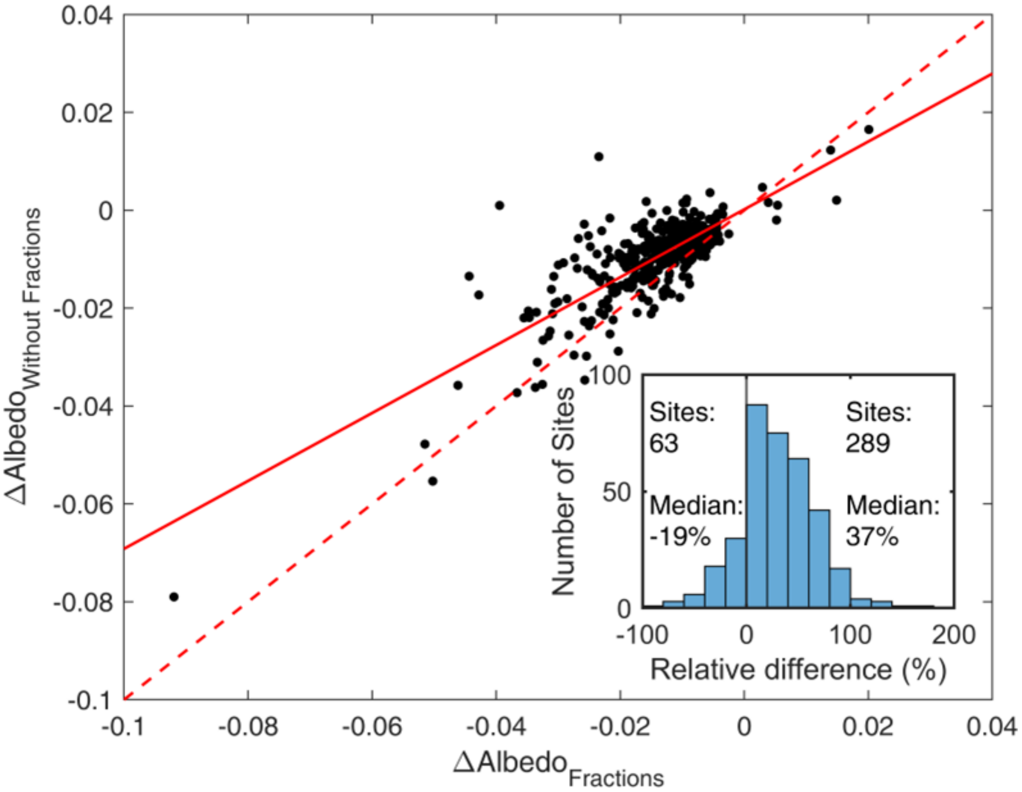

Fig. R4 (Supplementary Figure 21). The comparison of absolute albedo change (ΔAlbedo) over 352 selected PV sites between considering the PV grid fractions and without considering the fractions. The red solid line represents the line of equality (x=y), while the dashed line indicates the fitting line. The inset details the ratio of differences in albedo change with and without PV grid fractions to albedo change with PV grid fractions. A relative difference greater than zero indicates that the albedo change is greater when considering PV grid fractions. Additionally, the inset captions provide the count of sites with relative differences both greater and less than zero, along with their respective median relative difference values.

Finally, thank you for reviewing our paper and for providing your useful comments/suggestions. We have acknowledged this in the paper:

"We acknowledge the anonymous reviewers for their detailed and helpful comments to the original manuscript." (Page 22, Lines 645-647).

References:

Chang, R., et al., 2020. Simulated local climatic impacts of large-scale photovoltaics over the barren area of Qinghai, China. Renewable Energy. 145, 478-489.

Chang, R., et al., 2022. A coupled WRF-PV mesoscale model simulating the near-surface climate of utility-scale photovoltaic plants. *Solar Energy*, **245**, 278–289.

Heusinger, J., et al., 2020. Introduction, evaluation and application of an energy balance model for photovoltaic modules. *Solar Energy.* **195**, 382–395.

Li, S., et al., 2017. The Potential for Climate Impacts from Widespread Deployment of Utility-Scale Solar Energy Installations: An Environmental Remote Sensing Perspective. *Journal of Remote Sensing & GIS*. **6**, 1–5.

Masson et al., 2014. Solar panels reduce both global warming and urban heat island. Frontiers in Environmental Science. 2, 14.

Stern, R., et al., 2023. Photovoltaic fields largely outperform afforestation efficiency in global climate change mitigation strategies. *Proceedings of the National Academy of Sciences Nexus*. **2**, pgad352.

Taha, H., 2013. The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas. Solar Energy. 91, 358-367.

Xu, Z., et al., 2024. A global assessment of the effects of solar farms on albedo, vegetation, and land surface temperature using remote sensing. *Solar Energy*. **268**, 112198.

Reviewer #2 (Remarks to the Author):

Reviewer #2 General Comments: *Considering the need to increase the electrical supply to the humanity growing demand sharply, and at the same time to reduce fossil fuel emitted greenhouse gasses to the atmosphere, currently a major source of CO2 emission, the importance of green alternative energy becomes a necessary solution. Large-scale photovoltaic (PV) field installations in sunny regions could become primary electricity production sources. However, it is now well recognized that large scale, land cover changes, could have direct effects on the land- atmosphere energy exchanges that affect the Earth's radiative forcing and the climate system. The driven effects by the land cove changes could contradict the CO2-suppressing cooling impact on the climate.*

In his paper Sihuan Wei et. al., assess the radiative forcing balance, result from existing PV installation fields by comparing the eliminating CO2 emission due to the green electrical manufacturing vs. the albedo change effect of the installed dark PV sheets over that surface. For their analyzing assessments, the authors used the electrical output of the study sites to calculate the alternative CO2-prevented emission against the change in the surface albedo calculated by remote sensing techniques. The strength of this study is in the large areas it has performed: area-wise, of about 20% of the identified PV sites in their survey, and the use of remote sensing to identify the sites' areas, and to calculate the albedo change by the PV cover over the PV site.

It is an interesting paper and clear, but it suffers from several major drawbacks:

[Response] We highly appreciate your approval of our work. We also sincerely thank you for the insightful comments and suggestions that greatly helped us to improve this study. Following these suggestions and comments, we have substantially revised the manuscript. We have provided a more explicit explanation of the primary objective of our study, added a more detailed description of the methodology, and involved additional analyses and discussions. We believe these revisions have substantially improved the manuscript, addressing the issues you highlighted and enhancing the overall quality of our study.

[*Reviewer #2* Specific comments 1] *In the calculation of the Carbon suppression, the difference between the carbon uptake by the surface before the PV installation to the carbon 'uptake' by the PV field should be considered. This presumable, for most sites, will extend the breakeven duration.*

[Response] Thank you for emphasizing the importance of accounting for pre-installation carbon sequestration levels in our PV carbon suppression analysis. In response, we've conducted a comprehensive examination to assess how PV installations affect the land's inherent carbon sequestration capability, with a specific focus on the carbon avoidance (CA) from PV generation and changes in Gross Primary Production (GPP). Details of the methods of additional analyses have been provided in the Supplementary Materials (Pages 2-3, Lines 45-65 in the SI).

The additional analyses reveal that while GPP generally decreases at PV sites (Fig. R5a), the magnitude of this reduction is minimal (within a range of ±5%) compared to the carbon emissions avoided (CA) by using solar energy instead of coal-fired electricity (Fig. R5b). Clean electricity generation from PV systems at most sites (Fig. R6) offsets their adverse albedo impacts within a single year, indicating a relatively short breakeven duration (Fig. R7). This suggests a cooling effect in subsequent years of PV operation, emphasizing the positive role of deploying PV panels in mitigating global warming. These findings and their associated discussions have been incorporated into the revised manuscript (Pages 8-9, Lines 251-260 in the clean version of revised manuscript).

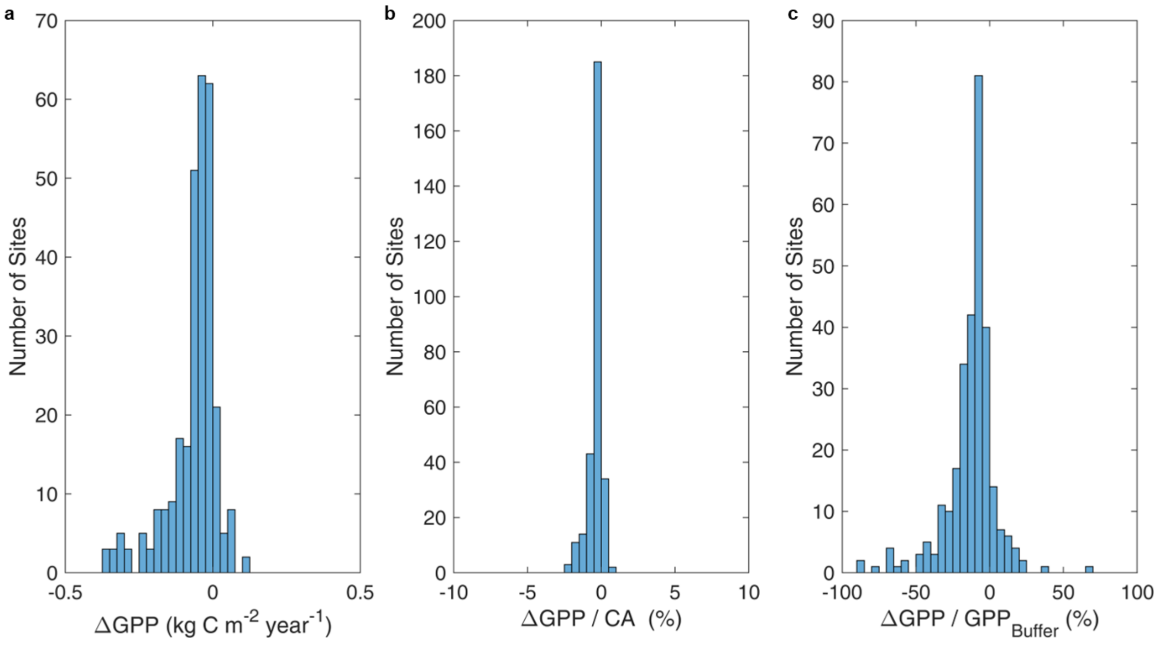

Fig. R5 (also Supplementary Figure 19 in the revised manuscript). The influence of PV installation on Gross Primary Productivity (GPP). a, The GPP difference between the PV site and the corresponding buffer zone. **b**, the comparison between the changed GPP and carbon avoidance (CA; Supplementary *Methods*) by PV generation. **c**, The ratio of GPP change value to the buffer zone’s GPP.

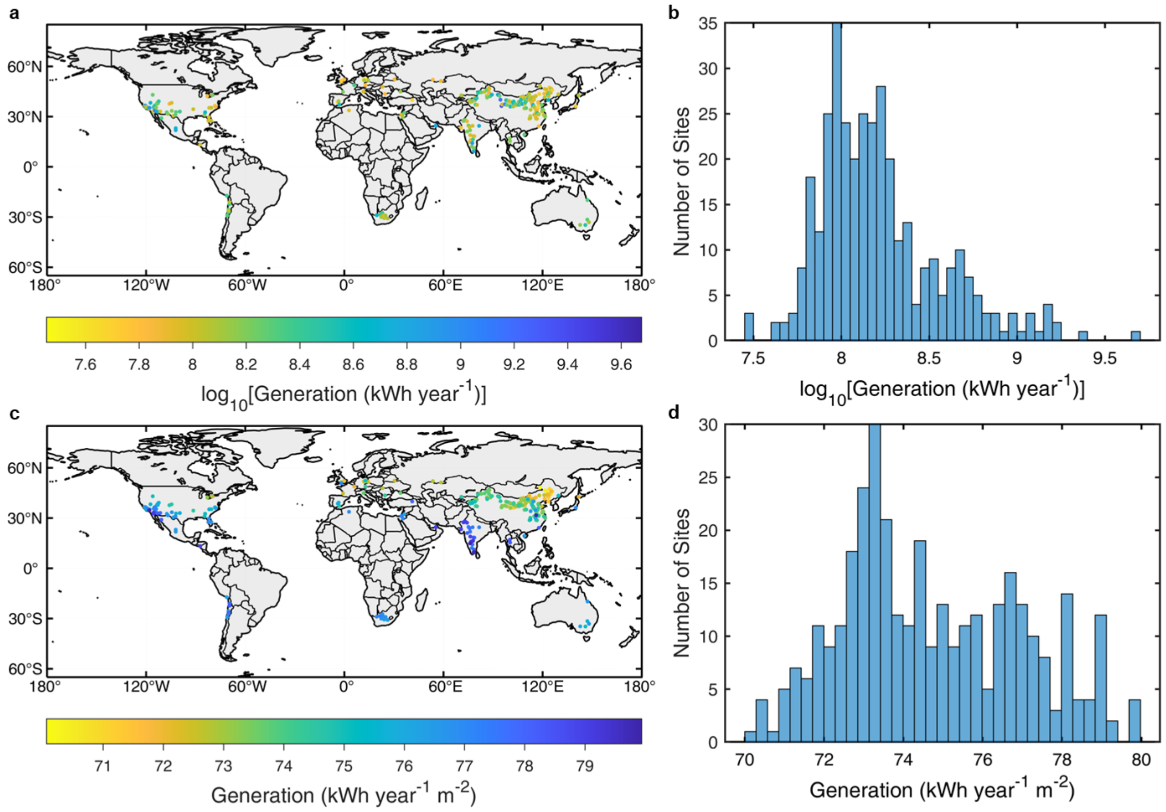

Fig. R6 (Supplementary Figure 17). The yearly total generation and generation per unit of each PV site. a and **b** show the spatial pattern and histogram of the total generation per PV site, while **c** and **d** show the generation per unit of each PV site.

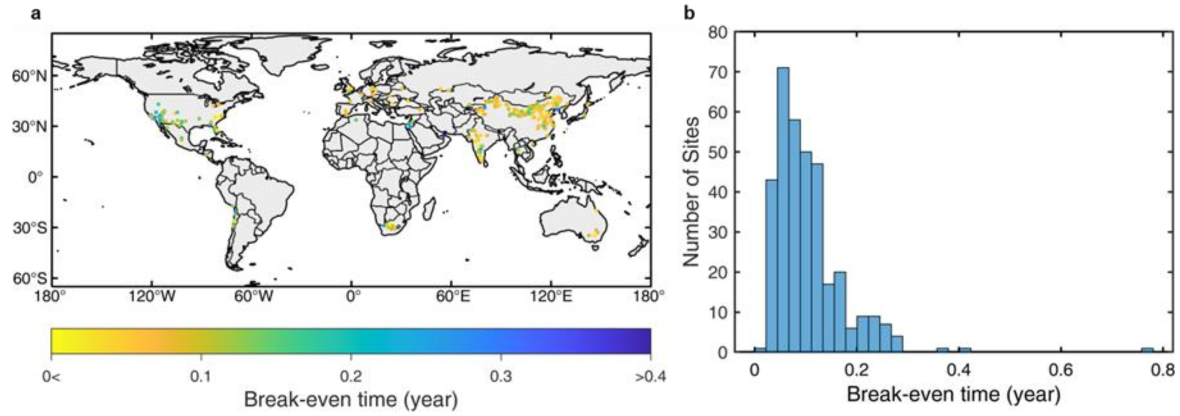

Fig. R7 (Supplementary Figure 18). The break-even time of each PV site. a, Spatial pattern of sites' break-even time. **b**, The frequency distribution histogram of PV sites' break-even time. Only positive values are shown.

[*Reviewer #2* Specific comment 2] *For future assessment of the climatic impact of a site at a given location for possible PV installations and for comparing the RF among sites and other* *uses, the relative forcing effect per unit of area is needed. Please reconsider the conclusions drawn in Line (L) 186.*

[Response] Thank you for your valuable comments regarding the importance of assessing the climatic impact of PV installations in terms of relative forcing per unit area.

Initially, we primarily focused on global-scale radiative forcing (global RF, derived from local RF) at the top of the atmosphere (TOA). This approach of calculating global RF and the related carbon equivalence allowed us to make land-surface albedo change comparable to changes in atmospheric CO_2 concentrations (Nemet, 2009; Bright et al., 2013; Bright et al., 2016). We now recognize the importance of local radiative forcing (local RF) in understanding regional climatic impacts. Therefore, we have included an analysis of local (relative) RF, accounting for constant atmospheric transmittance factor ($T_{SR}^{\uparrow}$), as depicted in Figs. R8 and R9). Details of the methods of additional analyses have been provided in the *Supplementary Materials* (Page 2, Lines 35-43 in the SI).

The related analyses and descriptions have been added in the revised manuscript: "We further examine the local RF (Supplementary *Methods*), crucial for regional energy budget, which ranges from -4.48 W m^{-2} to 20.56 W m^{-2} (Fig. R8). Notably, the desert site in the United Arab Emirates exhibits the most significant positive local RF value, because of its exceptionally large albedo change compared to other sites (Supplementary Figs. 5, 15 and 16), suggesting that deploying PV on desert land could lead to a larger temperature disturbance." (Page 7, Lines 202-207).

Regarding the relative importance of the three impact factors on global RF, we have found that the area's impact on RF is more pronounced due to its extensive variability across multiple orders of magnitude, compared to albedo change and radiation (Fig. R10). Additionally, concerning the factors influencing local RF, we found that albedo change plays a more dominant role compared to radiation (Fig. R9). We have modified these conclusions and updated these figures in the revised manuscript (Page 7, Lines 194-202).

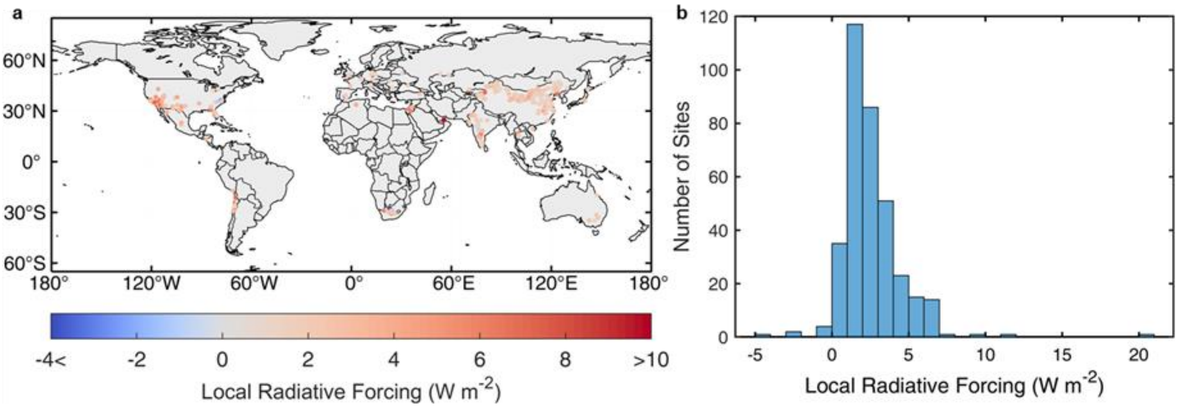

Fig. R8 (Supplementary Figure 14). The local radiative forcing (RF) of the 352 PV sites. **a**, Spatial pattern of sites' local RF. **b**, The histogram of corresponding local RF in the 352 PV sites.

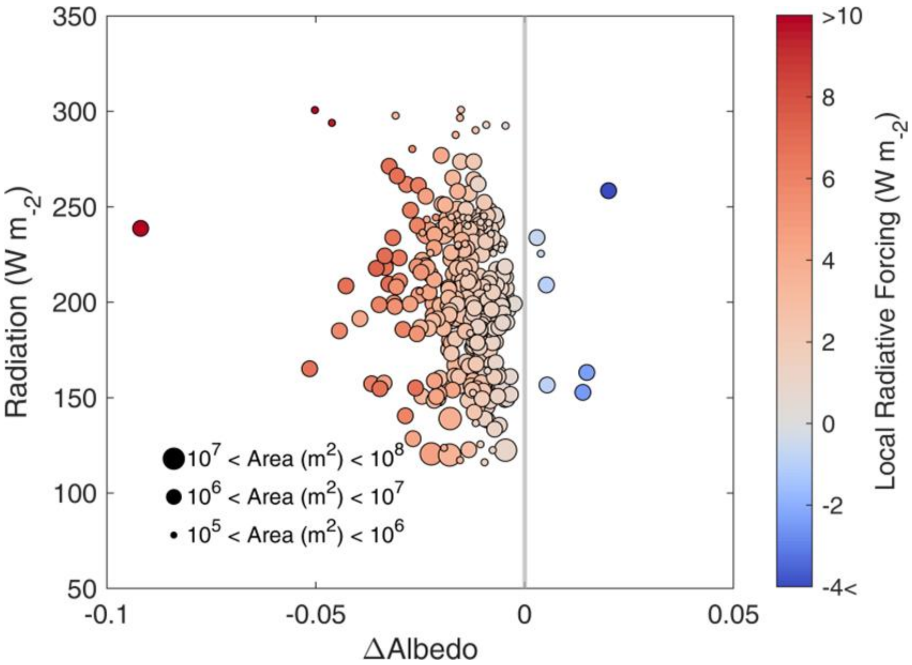

Fig. R9 (Supplementary Figure 16). Drivers influencing local radiative forcing (RF). The grey line shows the zero value of albedo change. The greater the deviation from the zero line, the more significant the change in shortwave forcing, highlighting the dominant role of albedo change compared to radiation.

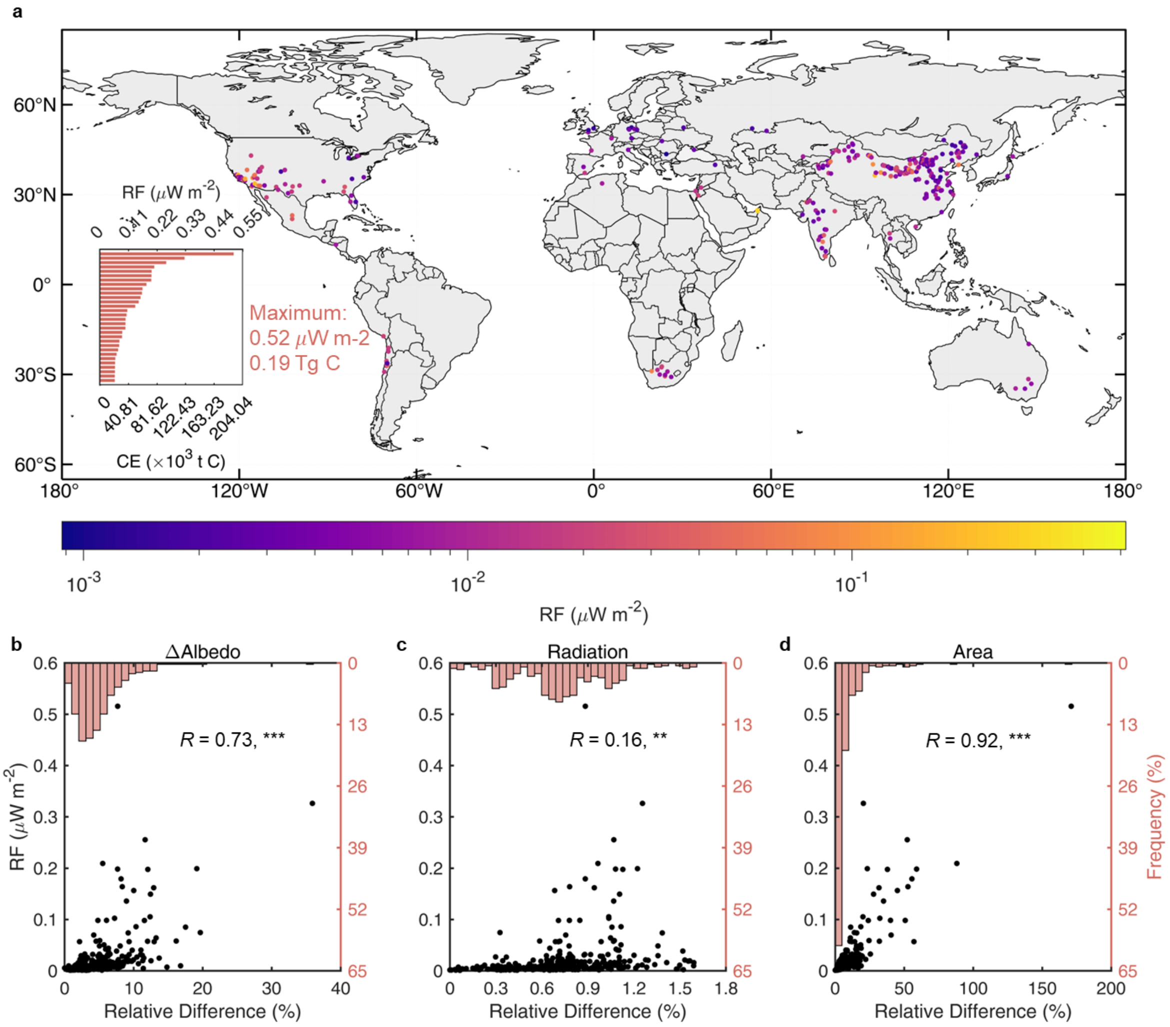

Fig. R10 (also Fig. 5 in the manuscript). The global radiative forcing (RF) and carbon equivalence (CE) due to albedo change. a, The spatial pattern of the global RF caused by PV deployment. The insert shows the top 30 sites' RF values alongside corresponding anthropogenic carbon equivalence. **b-c**, Three key variables determining the global RF at the top of the atmosphere. The relative differences are expressed as the absolute percentage changes of each variable relative to its respective minimum absolute value. The captions show the Pearson partial correlation coefficients between RF and each variable (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$), respectively. 7 sites with negative RF are not shown in the figure above.

[*Reviewer* #2 Specific comment 3] *Unclear are the significant Albedo differences among countries (e.g., Figure 3)? Is it because of the PV's types, the installation procedure, by the different ecosystem types, or? Otherwise, why will it be a country-dependent variable?*

[Response] Thank you for your comments regarding the observed significant albedo differences among countries. Our findings demonstrate varied albedo changes across different land cover types and notable variations among countries with the same land-cover type. This suggests additional factors beyond land cover influence these changes. Therefore, we further discuss the influence from other factor, like climate regimes and soil moisture. Our results highlight the significant role of climate regime in influencing albedo changes, shedding light on the phenomenon of country-dependent albedo differences.

We have refined and expanded related contents in the manuscript: “Moreover, we find that the categories of sites in different land-cover types from the United States significantly differ from those of China and India (Fig. 3d). This indicates that, despite consistent land-cover types, the reduction in albedo at PV sites exhibits notable spatial variation, suggesting the influence of factors beyond land-cover types.

Further analysis reveals that climate regime plays a pivotal role in influencing albedo changes, even when considering the same land cover type (Fig. 4 and Supplementary Fig. 8).” (Page 6, Lines 153-159).

We have also modified the previous Fig. 3 (Fig. R11) to enhance the logic flow of the description and improve the clarity of our results.

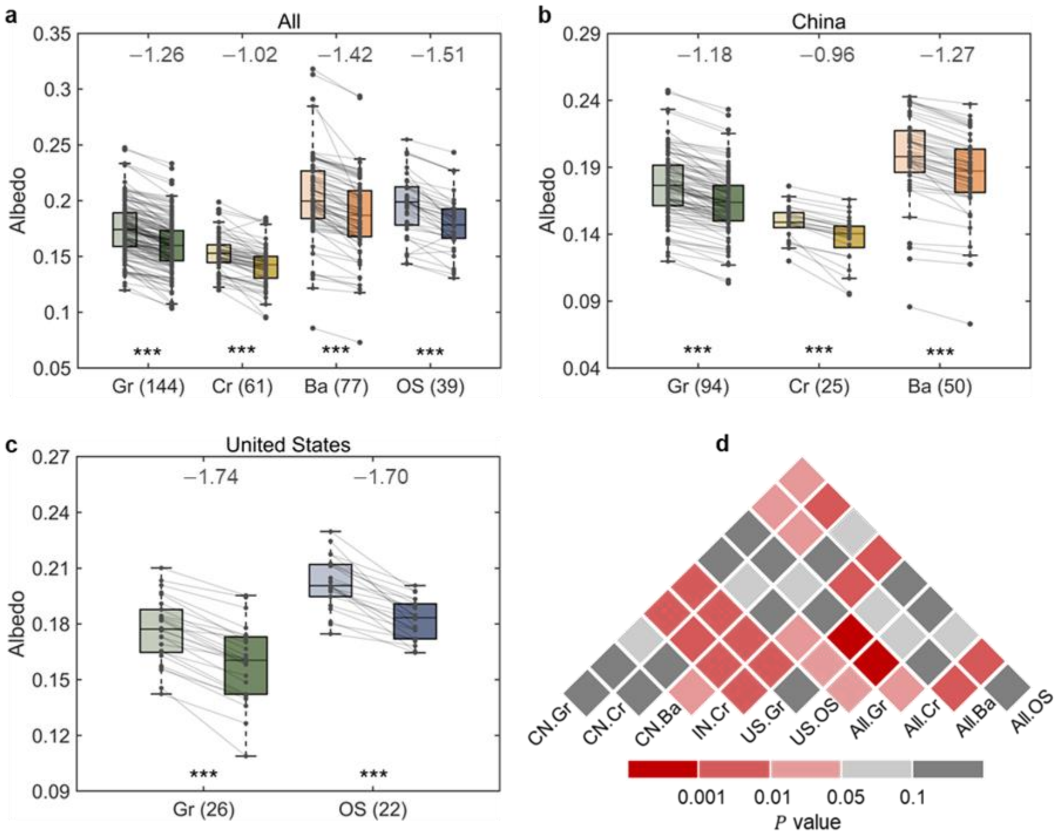

Fig. R11 (Fig. 3). The albedo change of sites covered by PV panels in different land-cover types and countries. a-c, Boxplots of the background albedo (higher transparency) and the albedo in the site covered by PV panels (lower transparency) for different land-cover types with the paired points connected by gray line. The captions show the median values of absolute albedo change. Gr, Cr, Ba, and OS represent sites in grasslands, croplands, barren and open shrublands, respectively. The numbers in parentheses after land-cover types represent the corresponding number of samples. Paired t-test is used to test the significant difference between the PV site's mean albedo (with 100% coverage of PV facilities) and background albedo (with 0% coverage of PV facilities) (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$). **d**, Illustration of the significant-difference-level of albedo change between two groups of sites (by using Wilcoxon rank sum test) in specific land-cover type from the corresponding country in **a**-**c**, respectively. All and US represent sites in the United States and all the countries, respectively.

[*Reviewer #2* Specific comments 4] *Throughout the calculations, the time scale of the albedo change for the radiative forcing-driven values is unclear (Methods part). For example, are R↓_SR and the ΔAlbedo averages in equation 6 annually average? Have those values weighted by seasonal and daily RSR changes?*

[Response] Thank you for highlighting the need for clarity regarding the time scale in our calculations. The $\bar{R}_{SR}^{\downarrow}$ and the ΔAlbedo averages in equation 6 are three-year averages (2019-2021), although we treat the albedo RF as an instantaneous event. Here ΔAlbedo values are calculated from three-year weighted albedo averages, the calculation of which considers the daily and monthly radiation variations. Specifically, we first calculate the daily mean blue-sky albedo, which is then used to derive monthly weighted albedo values. These monthly values are weighted by corresponding daily downward shortwave radiation, reflecting daily radiative dynamics. Subsequently, we aggregated these monthly weighted albedo values into three-year weighted averages, utilizing the monthly downward shortwave radiation for weighting, which are then used in the linear parameterization method to calculate albedo change.

Here we have provided more details in the methods: "The hourly land-surface shortwave radiation values were derived by scaling the daily average radiation, as provided by the BESS radiation product[47], against the daily average extraterrestrial radiation. This ratio adjusts the daily radiation values to an hourly scale, reflecting variations in extraterrestrial radiation throughout the day, under the assumption of consistent atmospheric conditions[29]" (Page 12, Lines 349-353).

"The hourly grid albedo values were subsequently used to derive daily, monthly and three-year (2019-2021) weighted averages by utilizing corresponding time-scale downward shortwave radiation." (Page 13, Lines 368-370).

"We assume that the global effect of PV RF due to albedo change is instantaneous[29]. Nevertheless, the characterization of instantaneous RF relies on the mean albedo change (2019-2021), derived through the linear parameterization method based on the three-year weighted grid albedo values (2019-2021). Hence, the RF of radiance imbalance from albedo change can be quantified as follows:

$$RF_{\overline{\Delta Albedo}} = -\frac{\bar{R}_{SR}^{\downarrow}\overline{\Delta Albedo}T_{SR}^{\uparrow}A_{PV}}{A_E} \qquad (6)$$

where $\bar{R}_{SR}^{\downarrow}$ is the three-year average incident shortwave radiation (2019-2021) at the terrestrial surface (W m^{-2}), $\overline{\Delta Albedo}$ is the mean albedo change due to PV deployment, which is calculated from the three-year weighted average grid albedo (2019-2021) by using the linear parameterization method (Fig. 1e), A_{PV} represents the scope area covered by PV facilities in a PV site, A_E denotes the Earth's surface area (510 × 10^6 km^2), and $T_{SR}^{\uparrow}$ is the upward transmittance constant, set at 0.854 (ref. [60])." (Page 15, Lines 446-457).

[Reviewer #2 Specific comments 5] *The term µWm-2 needs explanation. It is likely the projected global average (all Earth's surface, annually, and for which year?) RF penalty of PV installation? Then, consider presenting this against the benefit of CO2 suppression by the PV's.*
[Response] The term µWm^{-2} denotes microwatts per square meter, a unit measuring the intensity of radiative forcing over a given area. In our study, the global PV-albedo radiative forcing (global RF) at the top of the atmosphere (unit: W m^{-2} or µWm^{-2}) demonstrates the global effect of PV installation that is assumed to take place instantaneously, not at an annual scale or a specific year. We have further clarified related contents more in the manuscript (refer to [Reviewer #2 Specific comment 2] and [Reviewer #2 Specific comments 4]).

The approach of calculating global RF and the related carbon equivalence allowed us to make surface albedo changes comparable to changes in atmospheric CO_2 concentrations. Additionally, we have further compared it with the benefit of CO_2 suppression by calculating the reduced carbon emissions (CE_{gen}) and the carbon avoidance (CA) by PV generation (Page 16, Lines 458-473 in the manuscript; Page 2, Lines 45-51 in the Supplementary *Methods*). Our analysis shows that compared to the coal-fired plants, the clean electricity generation from PV generation in most sites (Fig. R6) offsets their adverse albedo impacts within a single year (break-even time; Fig. R7). This indicates a cooling effect in the subsequent years of PV operation, emphasizing the positive role of deploying PV panels in mitigating global warming.

[Reviewer #2 Specific comments 6] *The PV field albedo value depends on the spacing area between PV rows and the PV sheets' angles, which affect the electricity production efficiency per unit area at a given site. Since it is a global-scale study that may served decision-makers, prior to PV installation decisions in future work, it is recommended that the authors elaborate more on electrical output per a unit area of PV field.*

[Response] Thank you for your valuable suggestions. We acknowledge the influence of the spacing area between PV rows and the PV sheets' angles on PV field albedo, which has been discussed more on Page 5, Lines 141-146 in the revised manuscript.

Additionally, we have analyzed the electrical output per unit area of the PV field (Fig. R6, also Supplementary Fig. 18). We have added related results in the manuscript: "Annual generation at PV sites varies from 2.84 × 10^7 to 4.74 × 10^9 kWh year^{-1}, while electrical output per unit area ranges from 70.06 to 79.94 kWh year^{-1} m^{-2}(Supplementary Fig. 18)." (Pages 8-9, Lines 254-256).

In terms of related implications, it would be helpful to use more efficient solar panels to improve PV generation per unit in future deployment, thus reducing the break-even time and enhance PV's climatic benefits. We have also added related contents in the manuscript: "Transitioning lands to PV farms requires optimizing PV generation per unit area and minimizing the albedo reduction to shorten break-even times. Utilizing more efficient solar panels increases electrical output per area and land-use efficiency[39], thereby reducing the break-even time through enhanced carbon avoidance (Supplementary *Methods*) and decreased positive global RF due to smaller land requirements." (Page 9, Lines 275-278).

[Reviewer #2 Specific comments 7] *This study concentrated on the albedo change radiative forcing; however, PV also has other RF impacts, as well as environmental and ecological aspects that must consider as well (e.g., https://doi.org/10.1093/pnasnexus/pgad352) before converting an area to a PV site.*

[Response] Thank you for your valuable comments. We acknowledge that PV also have other RF impacts like longwave forcing, which may extend the break-even time. We have added related contents in the Discussion part: "However, our estimation of break-even time is idealized and does not include several specific factors that could potentially prolong this period. These factors include the omission of other PV-related radiative forcing, such as longwave forcing, and the use of idealized PV generation calculations involving overlooking the degradation of PV generation efficiency over time. Additionally, we do not consider the carbon sequestration changes in natural lands caused by PV installations, as these are relatively minor compared to the carbon offsets at the PV site (Supplementary Fig. 19)." (Page 9, Lines 261-270 in the manuscript).

Additionally, we have also refined and expanded the final part of the Discussion to highlight the environmental and ecological aspects regarding PV deployment:

"However, the deployment of PV panels also carries potential environmental and ecological risks[24]. Changes in carbon sequestration from PV installations on natural lands, though might be minor compared to the carbon avoidance of generation, are unneglectable compared to the land's original state (Supplementary Fig. 19a,c). This is mainly due to landscape reshaping[38], influencing local native vegetation dynamics and soil microbial characteristics[43]. Consequently, ecologically rich lands and vital ecosystems should be avoided by the energy industry[44]. Additionally, in certain croplands requiring high solar radiation or day-night temperature difference, the shading of solar panels reduces crop yield and quality[45,46]. Floating PV systems may also influence water quality[42], warranting comprehensive impact studies. In relative terms, converting highly degraded barren to a solar farm, despite suffering from its positive radiative forcing and potential extension of energy payback time, may be more cost-effective when considering land and ecosystem service values, making it a suitable priority target for conversion. Therefore, future PV expansion requires careful consideration to maximize the climatic benefits and minimize ecological disruptions and environmental influences." (Page 10, Lines 287-301).

[Reviewer #2 Minor comments 1] *L. 188. Unclear are the 'relatively concentrated variations' and the connection to Fig. 2.c.*

[Response] Thank you for your feedback. We have revised related contents in the manuscript for clarity: "In contrast, changes in albedo and radiation exhibit narrower ranges of variation (Fig. 2c and Supplementary Fig. 13), making their impacts on the RF less substantial compared to that of the area." (Page 7, Lines 194-196). Additionally, we have updated Fig. 5 (Fig. R9) to illustrate this more clearly.

[Reviewer #2 Minor comments 2] *L. 204-7. Is 0.16 not more pronounced than 0.1 (Δalbedo) of the previous sentence there? And the meaning of 'with an area ratio of 1' is unclear.*
[Response] Thank you for pointing out the potential confusion in our manuscript. To clarify, the values 0.16 and 0.1 refer to the observed mean albedo at PV sites and the albedo assumed in some previous studies (e.g., Li et al., 2018), respectively, and not changes in albedo (ΔAlbedo). We acknowledge that the original presentation could lead to misunderstanding, so we have revised this section to enhance clarity (Page 7, Lines 208-218; Supplementary Tables 1-3).

The term 'with an area ratio of 1' might not be immediately clear to readers as it is indeed a technical term. This phrase was intended to describe the scenario in our linear parameterization method where the entire grid cell is completely occupied by a PV site. In the revision, we have removed this description.

[Reviewer #2 Minor comments 3] *L 375-6. Unclear Point 2 is. Provide the R↓SR source.*
[Response] We have made Point 2 clearer: "(2) the difference between the maximum and minimum area ratio values across all pixels within an individual PV site should be larger than 0.5;" (Page 14, Lines 405-407).

Regarding the R↓SR source, it is cited on Page 11, Lines 311-313 of the manuscript, which is also included in the section of data availability (Page 16, 483-490).

[Reviewer #3 Minor comments 4] *L. 437. Cap value is unclear. Note, the value seems to be kind of ½ h annually on average.*
[Response] We have clarified Cap value more in the manuscript: "CI is the carbon dioxide intensity (900 g CO_2 kWh^{-1}) of coal-fired plants in 2018 (ref. [62]), CF is the mean capacity factor (0.11) of solar PV in the world[63] and Cap (kW) is the total capacity of a PV site, which is the sum of estimated nominal peak alternating current generating capacities of each solar generating units in the site. Each solar generating unit corresponds to a vector polygon in the

global PV dataset, where the capacity of each unit has been evaluated based on its size, the efficiency of the solar panels, and other factors[30]." (Page 16, Lines 475-481).

Additionally, as for the '½ h', if you are referring to the operating of PV only in the hours of daytime, here the yearly generation of each PV site is calculated by utilizing capacity factor (CF), which has involved the considerations of '½ h', and therefore the total annual hours of operation are 8760 h (Eq 2 in Lee et al., 2022).

Finally, thank you for reviewing our paper and for providing your useful comments/suggestions. We have acknowledged this in the paper:

"We acknowledge the anonymous reviewers for their detailed and helpful comments to the original manuscript." (Page 22, Lines 645-647).

References:

Bright, R. M., et al., 2013. Technical Note: Evaluating a simple parameterization of radiative shortwave forcing from surface albedo change. *Atmospheric Chemistry and Physics*. **13,** 11169-11174.

Bright R. M., et al., 2016. Carbon-equivalent metrics for albedo changes in land management contexts: relevance of the time dimension. *Ecological Applications*. **26**: 1868-1880.

Li, Y., et al., 2018. Climate model shows large-scale wind and solar farms in the Sahara increase rain and vegetation. *Science*. **361,** 1019-1022.

Lee N., et al., 2020. Hybrid floating solar photovoltaics-hydropower systems: Benefits and global assessment of technical potential. *Renewable Energy*. **162**, 1415-1427.

Nemet, G. F., 2009. Net Radiative Forcing from Widespread Deployment of Photovoltaics. *Environmental Science & Technology*. **43,** 2173-2178.

Response to the reviewers (COMMSENV-24-0408A)

Reviewer #1 (Remarks to the Author): *The authors did a good job of revising the manuscript. I do not have further comments and it can be accepted.*

[Response] Thank you for your positive feedback and for acknowledging our revisions. We appreciate your support and valuable suggestions throughout the review process.

Reviewer #2 (Remarks to the Author): *I want to thank the paper's Authors for the detailed and systematic answers to all the comments.*

I'm satisfied with them most and ask to address the following:

[Response] Thank you for acknowledging our responses to your comments. Moreover, we have revised related contents to address your remaining concerns. We appreciate your valuable suggestions and believe that these changes have further improved our manuscript.

[*Reviewer #2* Specific comments 1] When comparing the carbon emission reduction gained by PV installation, which includes the life cycle (LC) assessment, the ecosystem gross primary production (GPP) is not to be compared but the net ecosystem (carbon) exchange (NEE). I may not be precise enough when I wrote that comment in the first round.

[Response] Thank you for pointing this out. We attempted to use NEE to compare the carbon emission reduction gained by PV installation. However, because of the small PV site areas, there are currently no publicly available satellite-based NEE data with sufficient spatial resolution for analysis. In our revised manuscript, we've compared the carbon emission reduction grained by PV with the net primary production (NPP) for instead. The results show that the change in NPP is small compared to the carbon avoidance from PV generation (Fig. R1b). Since NEE is smaller than NPP (NEE = NPP - soil respiration), the change in NEE is relatively smaller compared to the carbon avoidance achieved by PV installations.

Details of the methods of additional analyses have been revised in the Supplementary Materials (Page 2, Lines 46-66 in the Supplementary Methods).

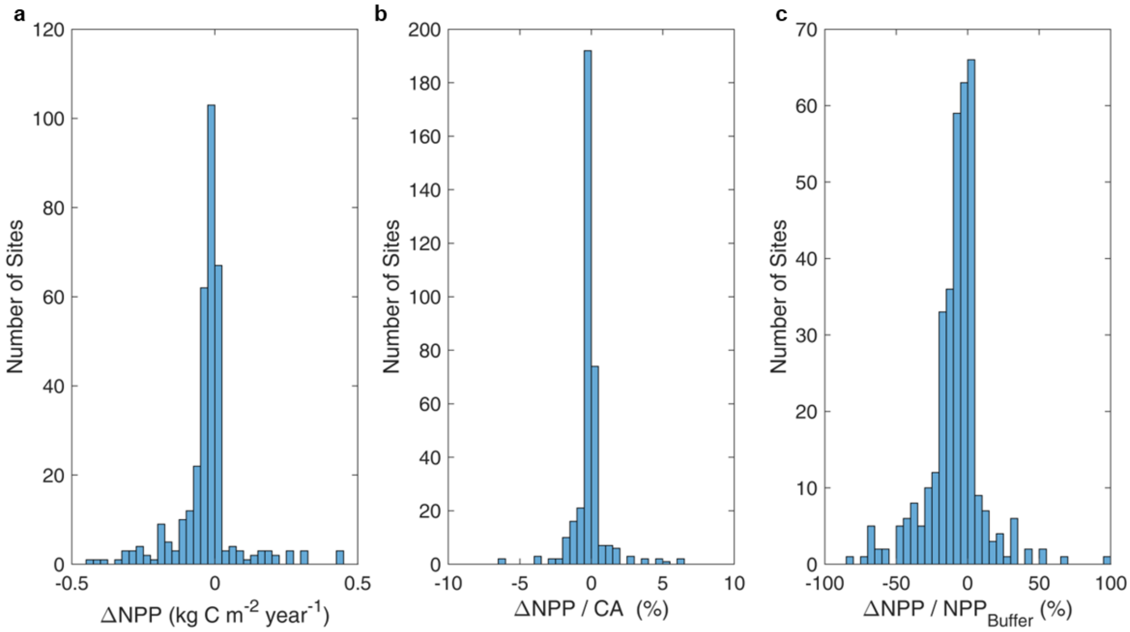

Fig. R1 (also Supplementary Figure 20 in the revised manuscript). The influence of PV installation on Net Primary Productivity (NPP). a, The NPP difference between the PV site and the corresponding buffer zone. **b**, The comparison between the changed NPP and carbon avoidance (CA; Supplementary Methods) by PV generation. **c**, The ratio of NPP change value to the buffer zone's NPP.

[*Reviewer #2* Specific comments 2] *Figure 10 caption is unclear.*

[Response] Thank you. We have made it clearer.

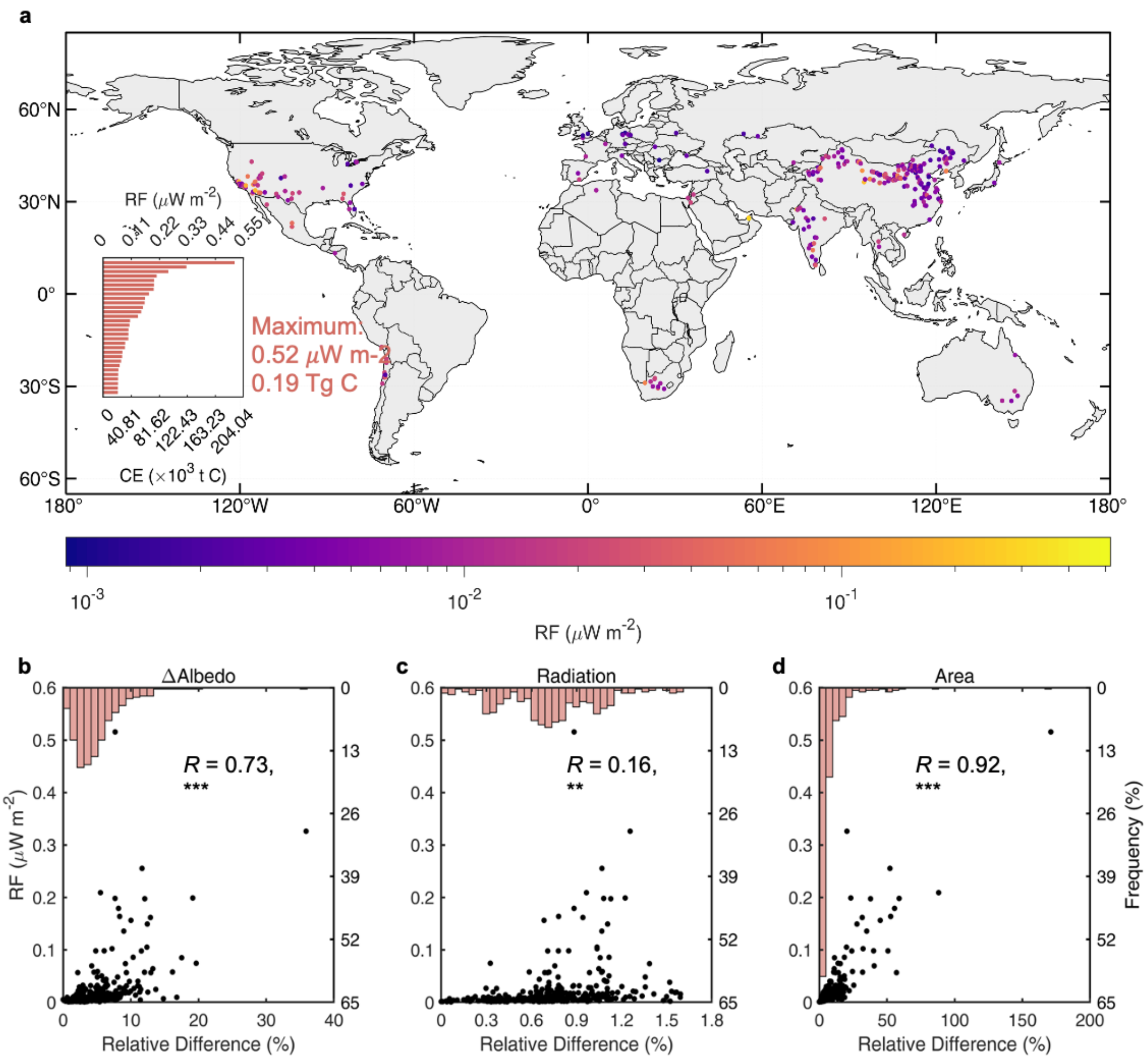

Fig. R2 (also Fig. 5 in the manuscript). The global radiative forcing (RF) and carbon equivalence (CE) due to albedo change. a, The spatial pattern of the global RF caused by PV deployment. The insert shows the top 30 sites' RF values alongside corresponding anthropogenic carbon equivalence. **b-d**, The relationship between three key variables—albedo change, mean downward shortwave radiation, PV site area—and the global RF at the top of the atmosphere. The relative differences are expressed as the absolute percentage changes of each variable relative to its respective minimum absolute value. The black scatters show the relationship between RF and relative difference of corresponding variable, while the upper bars represent the frequency distribution of relative difference. The captions show the Pearson partial correlation coefficients between RF and each variable (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$), respectively. 7 sites with negative RF are not shown in the figure above.

[*Reviewer #2* Specific comments 3] *And, that a larger PV area has a greater RF effect is trivial; it is better not to repeat this often.*

[Response] Thank you for your great advice. We agree that a lager PV area has a greater global RF effect is trivial. We have revised related contents to be more concise: "The area's impact on RF is more pronounced due to its extensive variability across multiple orders of magnitude, compared to albedo change and radiation (Fig. 5b-d)." (Page 7, Lines 195-196 in the manuscript). Meanwhile, we have also removed the relevant content from the discussion section in the manuscript (Page 8, Lines 230-240 in the manuscript).

[*Reviewer #2* Specific comments 4] *The explanation for the countries' effect on the PV sites' Albedo (China, India vs. USA) is unclear. If it is a different climate, please show that and explain instead. Consider not including fig. R11.d.*

[Response] Thank you for highlighting this point. We have further compared grassland sites between China and United States, where enough samples are available, to explore whether different climates cause varying albedo change across countries. We found that their climates are not identical (Fig. R3a,b). Additionally, even under the same climatic conditions, the albedo change of the sites may vary due to differences in PV panels arrays spacing caused by latitude (Fig. R3c), the influence of which has been mentioned on Page 5, Lines 136-139 in the manuscript. Moreover, we have excluded Fig. R11d (also Fig. 3d in the manuscript).

Related contents have been revised in the manuscript (Page 6, Lines 159-168): "We also explore whether different climates cause varying albedo changes across countries. A comparison of sites over grasslands in China and the United States, where sufficient samples are available, reveals that nearly 25% of PV sites over grasslands in China are located under cold and dry winter conditions (Dwa, Dwb, and Dwc regimes; Supplementary Fig. 9a,b), with a median albedo change of -1.02×10^{-2}. In contrast, no such sites exist in the United States, potentially contributing to the lower albedo change at PV sites over grasslands in China. Nonetheless, even for grassland sites under similar climatic conditions (e.g., BSk regime), the albedo changes at PV sites in the two countries differ (-1.27×10^{-2} in China; -1.74×10^{-2} in the United States). This disparity could be attributed to the different PV array spacing induced by variations in latitude (Supplementary Fig. 9c).”

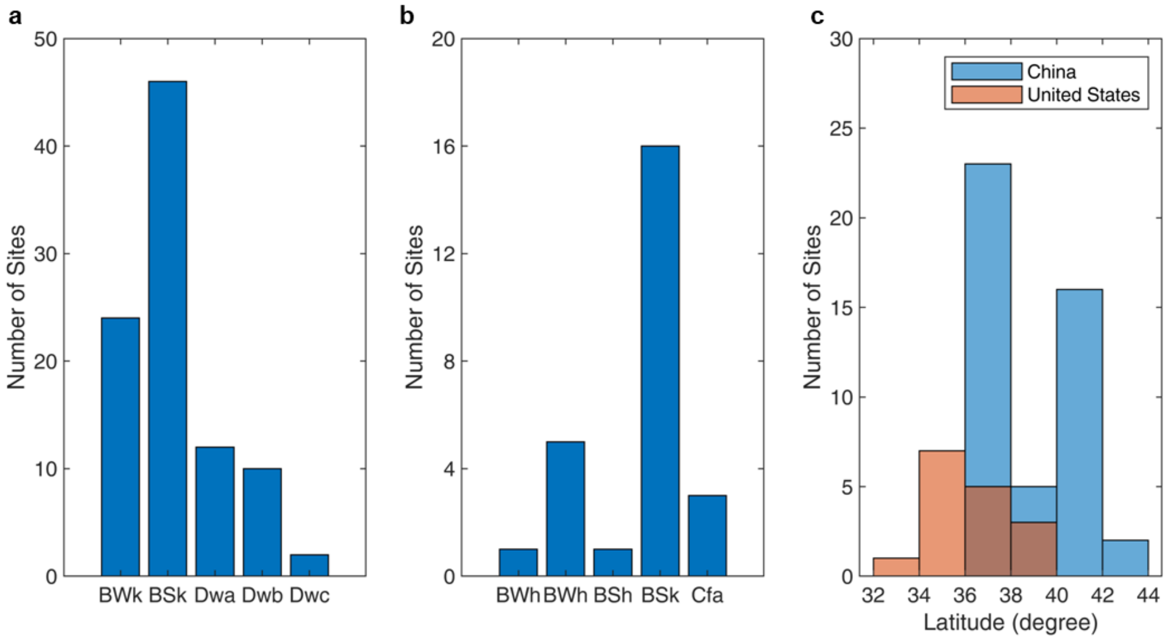

Fig. R3. (also Supplementary Fig. 9 in the manuscript) The comparison of albedo change over grassland PV sites between China and the United States. a, The counts of grassland PV sites under different climate regimes in China. **b**, The counts of grassland PV sites under different climate regimes in the United States. **c**, The latitude distributions of grassland PV sites under BSk regime in China and the United States, respectively.