Photovoltaic drives 100× carbon reduction and albedo-driven cooling exceeding forestation in climate mitigation

Qi Yuan [1], Bin Zhao [1]*, Haiqiang Guo [1]

[1] Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, Institute of Biodiversity Science and Institute of Eco-Chongming (SIEC), School of Life Sciences, Fudan University, Shanghai 200438, China.

Corresponding author: Bin Zhao, zhaobin@fudan.edu.cn

Supplementary Information

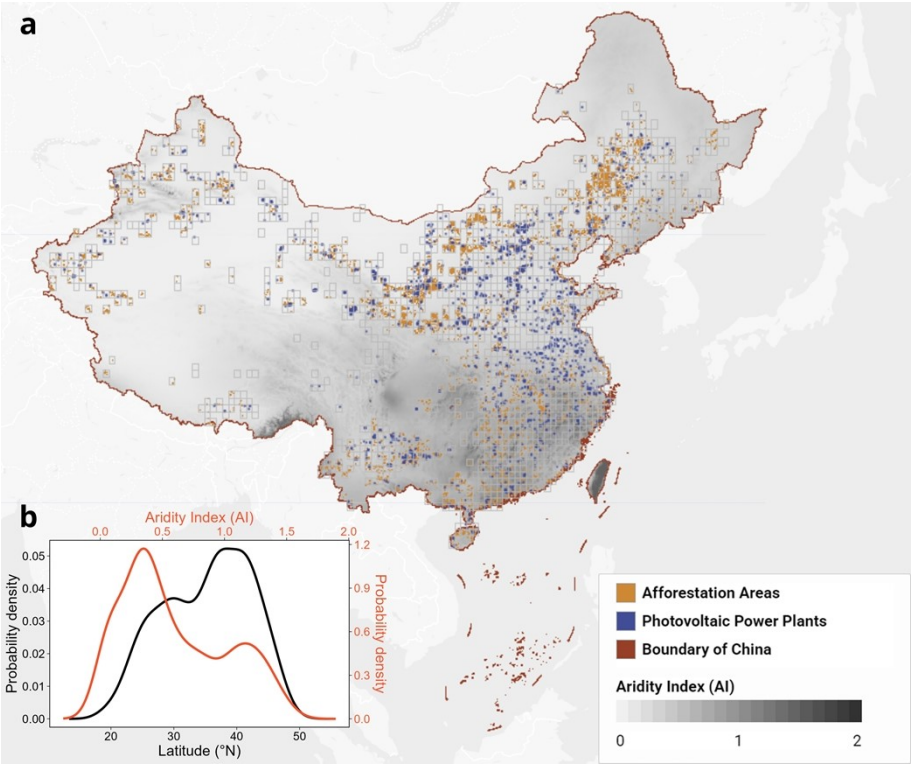
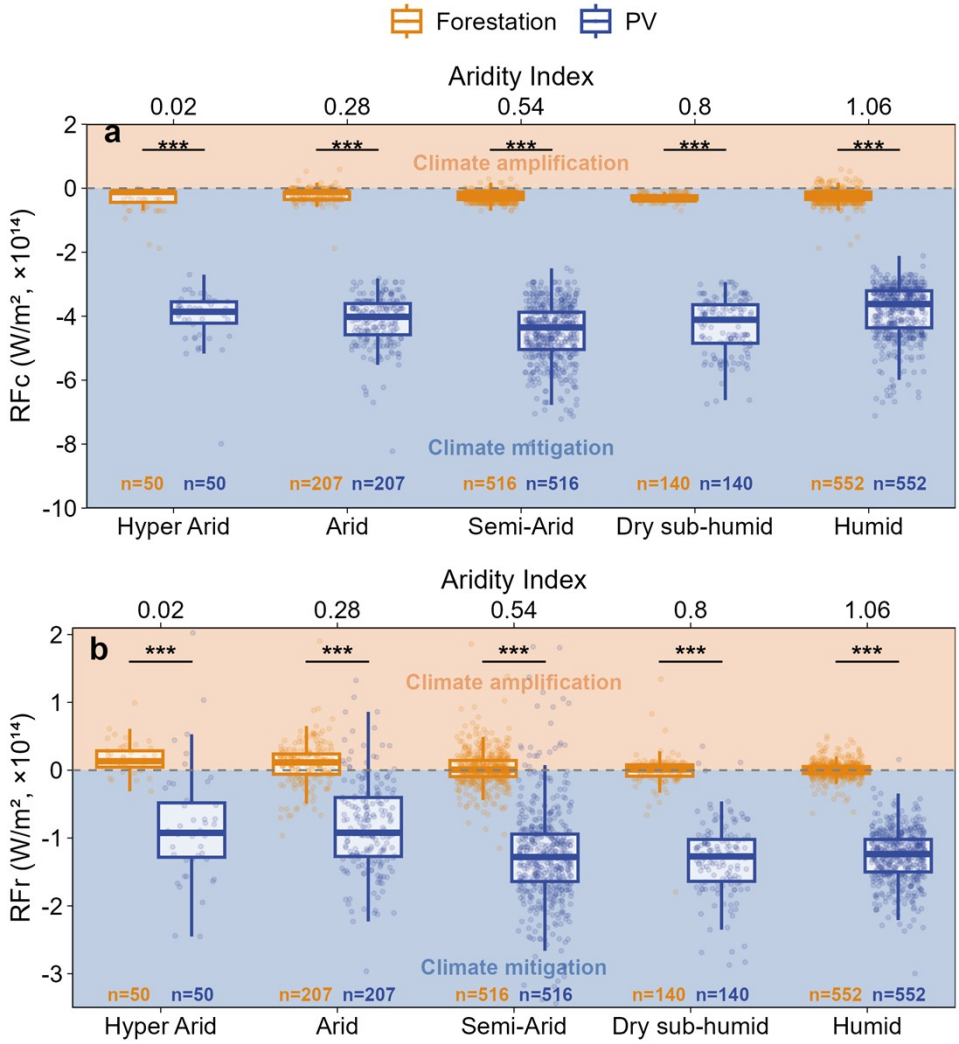


Figure S1. Spatial distribution of the anthropogenic forestation and solar photovoltaic (PV) power plants. a, Spatial distribution of sample grids cells (0.5°×0.5°), where both PV and forestation coexist. The gray-scale background indicates the aridity index (AI, which is the ratio of annual average precipitation to annual average reference

17 evapotranspiration). b, Kernel density curves of sample grids cells' latitude (black line)
18 and AI (red line)
19



20

21 Figure S2. Radiative forcing of forestation and PV. a, CO_2-induced radiative forcing
22 (RFc). b, Energy-budget-induced radiative forcing (RFr). The RFc of forestation
23 represents CO_2 absorption resulting from the cumulative growth of vegetation over a
24 decade. Blue shaded background indicates climate mitigation benefit (RFc or RFr <
25 0), while red shaded background indicates climate amplification effect (RFc or RFr >
26 0). "*" indicates $p < 0.05$, "**" indicates $p < 0.01$, "***" indicates $p < 0.001$, and "ns"
27 indicates not significant. AI classification: Hyper Arid (<0.03), Arid (0.03-0.2), Semi-

Arid (0.2-0.5), Dry Sub-Humid (0.5-0.65), Humid (>0.65). Boxes show the interquartile range (25th–75th percentiles) of climate attributes across AI classification, with central lines marking medians, whiskers extend to ±1.5×IQR. n is the sample size.

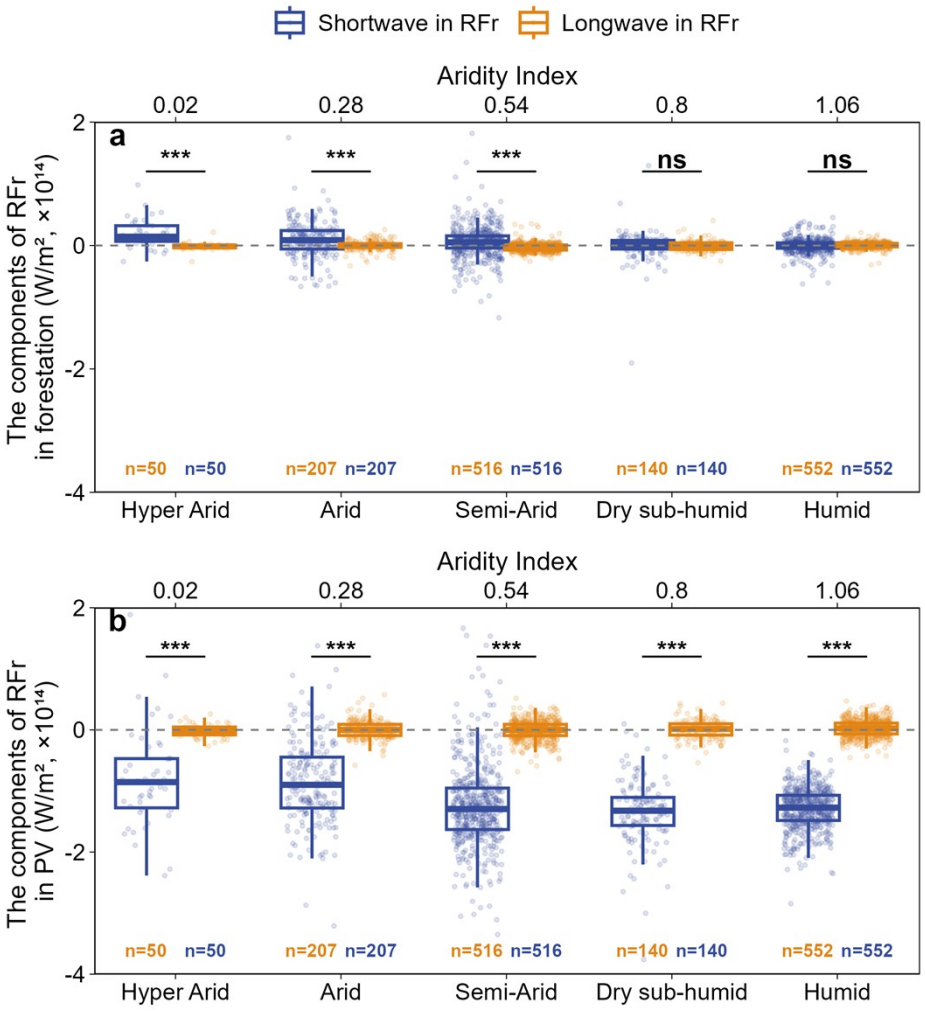


Figure S3. Radiative forcing components of PV and forestation. a, The components of RFr in forestation. b, The components of RFr in PV. "*" indicates $p < 0.05$, "**" indicates $p < 0.01$, "***" indicates $p < 0.001$, and "ns" indicates not significant. Boxes show the interquartile range (25th–75th percentiles) of climate attributes across AI classification, with central lines marking medians, whiskers extend to ±1.5×IQR. n represents the sample size. We adjusted the magnitudes of decadal ΔC from vegetation

growth ($^{RF_{c_vge}}\cdot$10year^{-1}) to align with the magnitudes scale of PV-induced radiative forcing ($^{RF_{c_PV}}\cdot$year^{-1}), ensuring both metrics are comparable in terms of time and area dimensions.

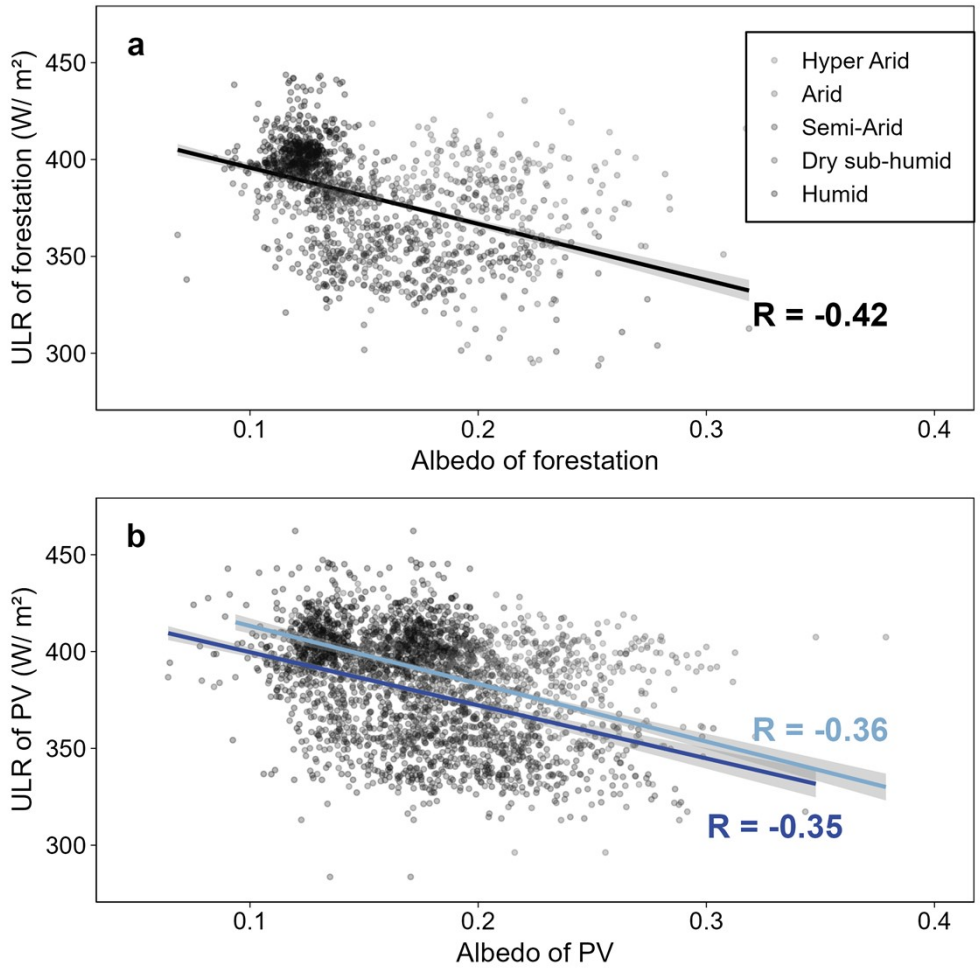


Figure S4. The relationship between the URL and albedo of PV or forestation. a, Relationship between the URL and albedo of forestation. b, Relationship between the URL and albedo of PV. The dark blue fitting curve indicates the actual albedo of PV, while the light blue one represents the effective albedo of PV. R represents the Pearson correlation coefficient.

Table S1. Robustness of PV effective albedo change

Group	GTI slop	Effective albedo change slop ($\times 10^{-3}$)	GTI mean ($kWh \cdot m^{-2}$)	Effective albedo change mean	GTI relative change (%/deg)	Effective albedo relative change (%/deg)	Sample size
15°	-36.88 ***	-0.28 *ns*	1338.07	-0.042	-2.76	0.67	127
30°	51.94 ***	1.16 ***	1664.21	-0.039	3.12	-2.97	357
45°	-5.71 *ns*	2.87 **	1932.41	-0.032	-0.30	-8.89	217

Note: Statistical significance: "**" indicates $p < 0.01$, "***" indicates $p < 0.001$, and "*ns*" indicates not significant. The tilt groups represent PV panels at optimum tilt for maximum annual yield (±4° tolerance across adjacent grid cell). The slopes of GTI (Global irradiation) or effective albedo change reflect their linear response to tilt angle. The relative change is calculated as (slope / group-specific mean) × 100 (%/deg) to eliminate dimensional bias, quantifying tilt sensitivity.

Table S2. The statistic of carbon emission reduction rate (CES) for PV and forestation ($kgC \cdot m^{-2} \cdot year^{-1}$)

Climate classification	Sample size	Type	Mean	Median	Standard deviation	Min	Max	Range
Hyper arid	50	PV	14.52	13.97	2.87	9.81	28.89	19.07
		Forestation	0.12	0.06	0.14	0.01	0.66	0.64
Arid	207	PV	14.90	14.43	2.77	10.28	29.26	18.98
		Forestation	0.07	0.05	0.07	-0.21	0.66	0.87
Semi-arid	516	PV	16.28	15.80	3.23	9.14	28.88	19.75
		Forestation	0.09	0.08	0.05	-0.12	0.25	0.37
Dry sub-humid	140	PV	15.50	14.73	3.07	10.69	24.16	13.47
		Forestation	0.10	0.10	0.04	0.02	0.24	0.22
Humid	552	PV	13.76	13.00	2.90	7.54	25.57	18.03
		Forestation	0.09	0.09	0.08	-0.21	0.69	0.90
Total	1465	PV	15.00	14.63	3.21	7.54	29.26	21.72
		Forestation	0.09	0.08	0.07	-0.21	0.69	0.90