# Supplementary Material

**Response of vegetation and soil property changes by photovoltaic established stations based on a comprehensive meta-analysis**

**Xiaoxin Chen[a,b], Bojian Chen[b,c], Yongdong Wang[a,*], Na Zhou [a,*] and Zhibin Zhou[a]**

a. National Engineering Technology Research Center for Desert-Oasis Ecological Construction, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
b. University of Chinese Academy of Sciences, Beijing 100049, China
c. State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
*. Corresponding author. phone.: +86- 0991-7823138. E-mail: wangyd@ms.xjb.ac.cn
*. Corresponding author. phone.: +86- 15276605122. E-mail: zndesert@ms.xjb.ac.cn

Table S1 Identities, levels and description of moderator variables used in this meta-analysis.

| Moderators | Subgroup | Description |
|---|---|---|
| Settings | below | Below the photovoltaic arrays |
| | between | Between the photovoltaic arrays |
| Solar_radiation | ZFRH | Solar radiation ⩾ 6300/MJ·m$^{-2}$·a$^{-1}$ |
| | HFRH | Solar radiation 5040-6300/MJ·m$^{-2}$·a$^{-1}$. |
| | FRCH | Solar radiation 3780-5040/MJ·m$^{-2}$·a$^{-1}$. |
| Duartion | Short-term | established years 1-2 years |
| | Mid-term | established years 3-4 years |
| | Long-term | established years 5-7 years and above |
| Soil_depth | 0-5cm | 0-5cm soil |
| | 0-10cm | 0-10cm soil |
| | 0-20cm | 0-20cm soil |
| | 0-30cm | 0-30cm soil |
| Ecosystem type | Cropland | Study in cropland |
| | Desert | Study in desert. |
| | Grassland | Study in grassland. |
| Climatic zone | Temperate | Latitude 25-50° |
| | Boreal | Latitude > 50° |
| Gruop | Vegetation | Vegetation characterization factors |
| | Soil | Soil characterization factors |
| Climatic Level | Arid | Mean annual precipitation < 400 mm. |
| | Humid | Mean annual precipitation ≥ 400 mm. |

Table S2 Summary table for subgroup analysis of vegetation variables to PV established stations.

| Variables | n | LnRR | 95% confidence interval |
|---|---|---|---|
| Biomass | 12 | 0.6609 | 0.3526,0.9692 |
| Coverage | 20 | 0.5850 | 0.3314,0.8385 |
| Richness | 38 | 0.4305 | 0.2308,0.6302 |
| Seeding | 13 | -1.2690 | -1.5662, -0.9719 |
| Shannon | 36 | 0.5062 | 0.2297,0.7827 |
| Simpson | 34 | 0.5497 | 0.2208,0.8786 |

Table S3 Summary table for environmental subgroup analysis of vegetation and soil factors to PV established stations.

| Moderators | Subgroup | n | LnRR | 95% confidence interval |
|---|---|---|---|---|
| Settings | below | 305 | 0.0605 | -0.0190, 0.1400 |
| | between | 114 | 0.2898 | 0.1539, 0.4527 |
| Solar_radiation | ZFRH | 294 | 0.2173 | 0.1337, 0.3010 |
| | HFRH | 134 | -0.0366 | -0.1491,0.0758 |

| | | | | |
|---|---|---|---|---|
| | FRCH | 4 | -0.4660 | -1.1166, 0.1845 |
| Year | Short-term | 198 | 0.1704 | 0.0736, 0.2673 |
| | Mid-term | 133 | 0.2326 | 0.1071, 0.3581 |
| | Long-term | 44 | 0.1790 | -0.0114, 0.3694 |
| Soil_depth | 0-5cm | 17 | 0.0255 | -0.2827, 0.3337 |
| | 0-10cm | 236 | 0.1515 | 0.0543, 0.2487 |
| | 0-20cm | 137 | 0.1948 | 0.0864, 0.3031 |
| | 0-30cm | 2 | -0.2139 | -1.2637,0.8360 |
| Ecosystem type | Cropland | 48 | -0.2334 | -0.4231, -0.0437 |
| | Desert | 293 | 0.2314 | 0.1485, 0.3143 |
| | Grassland | 91 | 0.0108 | -0.1219, 0.1435 |
| Climatic zone | Boreal | 4 | -0.4659 | -1.1266,0.1948 |
| | Temperate | 428 | 0.1280 | 0.0599,0.1961 |
| Climatic Level | Arid | 284 | 0.2566 | 0.1715,0.3417 |
| | Humid | 148 | -0.0833 | -0.1877,0.0210 |

Table S4 Summary table for subgroup analysis of soil variables to PV established stations.

| Soil factors | n | LnRR | 95% confidence interval |
|---|---|---|---|
| SWC | 53 | 0.2540 | 0.0974,0.4105 |
| E | 6 | -0.5336 | -1.0003, -0.0669 |
| Respiration | 7 | -0.6139 | -1.0657, -0.1620 |
| AN | 8 | 0.0971 | -0.2835,0.4777 |
| AK | 6 | 0.0663 | -0.3646,0.4973 |
| AP | 8 | 0.2536 | -0.1231,0.6303 |
| BD | 5 | 0.0428 | -0.4343,0.5199 |
| EC | 12 | -0.3033 | -0.6318,0.0252 |
| NO3-N | 2 | 0.0339 | -0.7364,0.8042 |
| PH | 19 | -0.0138 | -0.2520,0.2244 |
| SOC | 16 | 0.0071 | -0.2634,0.2776 |
| SOM | 14 | 0.0963 | -0.1903,0.3828 |
| ST | 6 | -0.1387 | -0.5711,0.2936 |
| TC | 7 | 0.0069 | -0.4037,0.4175 |
| TN | 15 | 0.1114 | -0.1881,0.4108 |
| TP | 12 | 0.1424 | -0.1726,0.4573 |

Table S5 Master table for country, latitude, longitude, elevation, type of ecosystem, SWE, threatened organisms.

| author | country | lon | Lat | Altitude/m | SWE | Climatic level | Ecosystem | Climatic zone | threatened organisms |
|---|---|---|---|---|---|---|---|---|---|
| Adeh et al.,2018 | USA | -123.28 | 44.56 | 75 | 0.036 | humid | Cropland | Temperate | / |
| Armstron | UK | -1.65 | 51.62 | 106 | 0 | humid | Cropland | Boreal | / |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| g et al.,2016 | | | | | | | | | |
| Bai et al.,2022 | China | 124.9 | 46.17 | 132 | 5.46 | humid | Grassland | Temperate | / |
| Choi et al.,2023 | USA | -92.91 | 45.45 | 268 | 27.88 | humid | Cropland | Temperate | / |
| Ding et al.,2021 | China | 100.59 | 36.16 | 2906 | 1.67 | humid | Desert | Temperate | underground microbial community |
| Greg et al.,2021 | USA | -110.85 | 32.58 | 1173 | 0 | humid | Cropland | Temperate | / |
| Hua et al.,2022 | China | 95.5 | 41.58 | 1830 | 1.01 | dry | Desert | Temperate | / |
| Kirimura et al., 2022 | Japan | 131.41 | 31.83 | 39 | 0 | humid | Cropland | Temperate | / |
| Lambert et al.,2022 | France | 2.93 | 43.02 | 63 | 0 | humid | Cropland | Temperate | B. retusum |
| Lambert et al.,2023 | France | 4.83 | 44.36 | 440 | 0 | dry | Grassland | Temperate | the abundance of soil mesofauna and biomass |
| Li et al., 2016 | China | 98.44 | 36.99 | 3293 | 1.88 | dry | Desert | Temperate | / |
| Liu et al.,2019 | China | 106.61 | 38.53 | 1206 | 0.37 | dry | Desert | Temperate | / |
| Liu et al.,2023 | China | 106.13 | 37.61 | 1380 | 0.40 | dry | Desert | Temperate | soil prokaryotes |
| Menta et al.,2023 | Italy | 10.33 | 44.8 | 125 | 0 | dry | Grassland | Temperate | soil arthropods |
| Moscatelli et al.,2022 | Italy | 11.59 | 42.38 | 32 | 0 | humid | Cropland | Temperate | microbial activity |
| Quentin et al.,2021 | France | 2.93 | 43.02 | 63 | 0 | humid | Grassland | Temperate | microbial activity |
| Sinha et al., 2018 | America | -119.86 | 35.19 | 599 | 0 | dry | Cropland | Temperate | Birds |
| Steven et al.,2020 | USA | -115.46 | 35.55 | 855 | 0 | dry | Desert | Temperate | non-bee insect flower visitors |
| Sturchio et al., 2022 | America | -105.13 | 40.12 | 1535 | 3.67 | humid | Grassland | Temperate | / |
| Tanner et al.,2021 | USA | -117.47 | 34.99 | 730 | 0 | dry | Desert | Temperate | Rare plant |
| Tanner et al.,2021 | USA | -116.85 | 34.8 | 968 | 0 | dry | Desert | Temperate | Rare plant |
| Three | China | 96.41 | 40.58 | 1309 | 0.75 | dry | Desert | Temperate | / |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Gorges Guazhou PV station | | | | | | | | | |
| Wang et al., 2016 | China | 108.92 | 37.62 | 1314 | 1.44 | humid | Desert | Temperate | / |
| Yuan et al., 2020 | China | 110.3 | 38.63 | 1194 | 1.43 | humid | Desert | Temperate | / |
| Yuan et al.,2022 | China | 98.9 | 35.77 | 4148 | 19.92 | dry | Desert | Temperate | archaeal communities |
| Zhai et al.,2018 | China | 110.8 | 40.43 | 991 | 4.25 | dry | Cropland | Temperate | / |
| Zhang et al., 2020 | China | 103.13 | 37.75 | 1633 | 0.65 | dry | Desert | Temperate | / |
| Zhang et al., 2020 | China | 102.56 | 38.92 | 1378 | 0.93 | dry | Desert | Temperate | / |
| Zhao et al., 2022 | China | 110.78 | 40.6 | 998 | 4.25 | dry | Grassland | Temperate | / |
| Zhu et al.,2021 | China | 89.58 | 31.67 | 4567 | 2.62 | humid | Desert | Temperate | / |

Note: The Three Gorges Guazhou Photovoltaic Power Station is our observed PV station.

Table S6 Master table for MAP, TMP, Duration, Soil depth, SRAD, slope, kind of PV system.

| author | Settings | MAP/ mm | TMP/ ℃ | Year | Soil depth/cm | SRAD | slope | kind of PV system |
|---|---|---|---|---|---|---|---|---|
| Adeh et al.,2018 | between | 1128.14 | 11.21 | / | / | HFRH | 0.87 | Centralized ground PV power station |
| Armstrong et al.,2016 | between | 728.86 | 10.51 | 3-4 | 0-10 | FRCH | 0.59 | Centralized ground PV power station |
| Bai et al.,2022 | below | 471.57 | 5.39 | 1-2 | 0-20 | HFRH | 0.45 | Centralized ground PV power station |
| Choi et al.,2023 | below | 839.86 | 7.35 | 1-2 | 0-5 | HFRH | 0 | Centralized ground PV power station |
| Ding et al.,2021 | below | 434.57 | 6.06 | >5 | 0-10 | ZFRH | 0.98 | Centralized ground PV power station |
| Greg et al.,2021 | below | 431.14 | 18.6 | / | / | ZFRH | 5.29 | Centralized ground PV power station |
| Hua et al.,2022 | between | 61.71 | 6.81 | / | 0-5 | ZFRH | 0.31 | Centralized ground PV power station |
| Kirimura et al., 2022 | below | 2778 | 17.46 | / | / | HFRH | 2.60 | Centralized ground PV power station |
| Lambert et al.,2022 | below | 519.14 | 15.34 | 3-4 | 0-10 | ZFRH | 3.80 | Centralized ground PV power station |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Lambert et al.,2023 | between | 302.71 | 27.5 | 1-2 | 0-10 | ZFRH | 0.69 | Centralized ground PV power station |
| Li et al., 2016 | below | 263.57 | 3.25 | 3-4 | 0-20 | ZFRH | 8.30 | Centralized ground PV power station |
| Liu et al.,2019 | below | 195.57 | 10.64 | 1-2 | 0-20 | ZFRH | 0.50 | Centralized ground PV power station |
| Liu et al.,2023 | between | 238.86 | 10.6 | >5 | 0-20 | ZFRH | 2.01 | Centralized ground PV power station |
| Menta et al.,2023 | below | 371.71 | 17.49 | / | 0-10 | ZFRH | 0.70 | Centralized ground PV power station |
| Moscatelli et al.,2022 | between | 466.14 | 16.15 | >5 | 0-10 | HFRH | 1.3 | Centralized ground PV power station |
| Quentin et al.,2021 | below | 519.14 | 15.34 | / | 0-10 | HFRH | 3.80 | Centralized ground PV power station |
| Sinha et al., 2018 | between | 371.71 | 17.49 | 1-2 | / | HFRH | 1.13 | Centralized ground PV power station |
| Steven et al.,2020 | below | 110.86 | 18.09 | / | / | ZFRH | 1.92 | Centralized ground PV power station |
| Sturchio et al., 2022 | below | 407.14 | 9.46 | / | / | ZFRH | 0.51 | Centralized ground PV power station |
| Tanner et al.,2021 | below | 71.57 | 18.35 | >5 | / | ZFRH | 0.38 | / |
| Tanner et al.,2021 | below | 0.05 | 0.07 | 3-4 | / | ZFRH | 0.38 | / |
| Three Gorges Guazhou PV station | below | 0.03 | 0.04 | 1-2 | / | ZFRH | 5.75 | Centralized ground PV power station |
| Wang et al., 2016 | below | 55.14 | 10.64 | / | 0-20 | ZFRH | 0.51 | Centralized ground PV power station |
| Yuan et al., 2020 | below | 409 | 9.36 | 3-4 | 0-20 | HFRH | 1.00 | Centralized ground PV power station |
| Yuan et al.,2022 | below | 414.29 | 9.92 | / | 0-10 | HFRH | 2.50 | Centralized ground PV power station |
| Zhai et al.,2018 | between | 376.43 | -6.02 | 1-2 | 0-10 | ZFRH | 6.97 | Centralized ground PV power station |
| Zhang et al., 2020 | below | 313.29 | 8.77 | 3-4 | / | HFRH | 0.51 | Centralized ground PV power station |
| Zhang et al., 2020 | below | 177.71 | 9.21 | 3-4 | 0-10 | ZFRH | 0.93 | Centralized ground PV power station |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Zhao et al., 2022 | between | 117.71 | 10.18 | 1-2 | 0-10 | ZFRH | 1.01 | Centralized ground PV power station |
| Zhu et al.,2021 | between | 299.57 | 7.69 | >5 | 0-20 | HFRH | 0.81 | Centralized ground PV power station |

Note: The Three Gorges Guazhou Photovoltaic Power Station is our observed PV station.

## List of 28 papers involved in the meta-analysis

Armstrong, A., Ostle, N.J., Whitaker, J., **2016.** Solar park microclimate and vegetation management effects on grassland carbon cycling. Environmental Research Letters 11.

Bai, Z., Jia, A., Bai, Z., Qu, S., Zhang, M., Kong, L., Sun, R., Wang, M., **2022.** Photovoltaic panels have altered grassland plant biodiversity and soil microbial diversity. Frontiers in Microbiology 13.

Barron-Gafford, G.; Pavao-Zuckerman, M.; Minor, R.L.; Barnett-Moreno, I.; Dimond, K.; Gerlak, A.; Murphy, P.; Thompson, M.; Winkler, C.; Marston, S. Agrivoltaics in drylands: Co-location has food, water, and renewable energy benefits. In Proceedings of the 2019 ESA Annual Meeting (August 11--16), **2019.**

Choi, C.S., Macknick, J., Li, Y., Bloom, D., McCall, J., Ravi, S., **2023.** Environmental Co-Benefits of Maintaining Native Vegetation With Solar Photovoltaic Infrastructure. Earths Future 11.

Ding, C., Liu, Y., 2021. Effects of Solar Photovoltaic Park Construction on Soil Microbial Community in Alpine Desert of Qinghai Tibet Plateau. Acta Agrestia Sinica 29, 1061-1069.

Hassanpour Adeh, E.; Selker, J.S.; Higgins, C.W. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. PloS one 2018, 13, e0203256.

Hua, Y., Chai, J., Chen, L., Liu, P., 2022. The Influences of the Desert Photovoltaic Power Station on Local Climate and Environment: A Case Study in Dunhuang Photovoltaic Industrial Park, Dunhuang City, China in 2019. Atmosphere 13.

Kirimura, M., Takeshita, S., Matsuo, M., Zushi, K., Gejima, Y., Honsho, C., Nagaoka, A., Nishioka, K., **2022.** Effects of Agrivoltaics (Photovoltaic Power Generation Facilities on Farmland) on Growing Condition and Yield of Komatsuna, Mizuna, Kabu, and Spinach. Environmental Control in Biology 60, 117-127.

Grodsky, S.M.; Campbell, J.W.; Hernandez, R.R. Solar energy development impacts flower-visiting beetles and flies in the Mojave Desert. Biological Conservation **2021**, 263, 109336.

Lambert, Q., Bischoff, A., Cueff, S., Cluchier, A., Gros, R., **2021**. Effects of solar park construction and solar panels on soil quality, microclimate, CO2 effluxes, and vegetation under a Mediterranean climate. Land Degradation & Development 32, 5190-5202.

Hassanpour Adeh, E.; Selker, J.S.; Higgins, C.W. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. PloS one **2018,** 13, e0203256.

Lambert, Q., Bischoff, A., Enea, M., Gros, R., **2023**. Photovoltaic power stations: an opportunity to promote European semi-natural grasslands? Frontiers in Environmental Science 11.

Lambert, Q., Gros, R., Bischoff, A., **2022.** Ecological restoration of solar park plant communities and the effect of solar panels. Ecological Engineering 182.

Li, S., Gao, Q., Wang, X., Lan, L., Yang, Z., 2016. Characteristics of Vegetation and Soil Property Changes by Photovoltaic Plant Interference in Alpine Desert Steppe. Journal of Soil and Water Conservation 30, 325-329.

Liu, Y., Zhang, R.-Q., Huang, Z., Cheng, Z., Lopez-Vicente, M., Ma, X.-R., Wu, G.-L., 2019. Solar photovoltaic panels significantly promote vegetation recovery by modifying the soil surface microhabitats in an arid sandy ecosystem. Land Degradation & Development 30, 2177-2186.
Liu, Z., Peng, T., Ma, S., Qi, C., Song, Y., Zhang, C., Li, K., Gao, N., Pu, M., Wang, X., Bi, Y., Na, X., 2023. Potential benefits and risks of solar photovoltaic power plants on arid and semi-arid ecosystems: an assessment of soil microbial and plant communities. Frontiers in Microbiology 14.
Matthew A.Sturchio, E., J.E., Barron-Gafford, G.A.A., Chen, A., Alderfer, C., Condon, K., Hajek, O.L.L., Miller, B., Pauletto, B., Siggers, J.A., Slette, I.J.J., Knapp, A.K.K., **2022**. Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. Ecosphere 13.
Menta, C., Remelli, S., Andreoni, M., Gatti, F., Sergi, V., **2023.** Can Grasslands in Photovoltaic Parks Play a Role in Conserving Soil Arthropod Biodiversity? Life-Basel 13.
Moscatelli, M.C., Marabottini, R., Massaccesi, L., Marinari, S., **2022.** Soil properties changes after seven years of ground mounted photovoltaic panels in Central Italy coastal area. Geoderma Regional 29.
Sinha, P., Hoffman, B., Sakers, J., Althouse, L., **2018**. Best Practices in Responsible Land Use for Improving Biodiversity at a Utility-Scale Solar Facility. Case Studies in the Environment.
Tanner, K.E., Moore-O'Leary, K.A., Parker, I.M., Pavlik, B.M., Haji, S., Hernandez, R.R., **2021.** Microhabitats associated with solar energy development alter demography of two desert annuals. Ecological Applications 31.
Wang, T., Wang, D., Guo, T., Zhang, G., Zhao, S., Niu, H., Lu, S., Lin, H., 2016. The Impact of Photovoltaic Power Construction on Soil and Vegetation. Research of Soil and Water Conservation 23, 90-94.
Yuan, B., Wu, W., Yue, S., Zou, P., Yang, R., Zhou, X., 2022. Community structure, distribution pattern, and influencing factors of soil Archaea in the construction area of a large-scale photovoltaic power station. International Microbiology 25, 571-586.
Yuan, S., Zhang, Z., Dang, T., Yang, Y., Yuan, F., Bu, C., 2018. Comparative Study of Growth Status of Three Plant Measures and Its Ecological Functions in Photovoltaic Power Station of Mu Us Sandy Land. Research of Soil and Water Conservation 25, 235-239.
Zhai, B., Gao, Y., Dang, X.-h., Chen, X., Cheng, B., Liu, X.-j., Zhang, C., 2018. Effects of photovoltaic panels on the characteristics and diversity of Leymus chinensis community. Shengtaixue Zazhi 37, 2237-2243.
Zhai, B., Gao, Y., Dang, X., Meng, Z., Xu, L., Liu, Z., 2022. MECHanISM OF PHOTOVOLTAIC POWER STATION ON SOIL MOISTURE anD ITS IMPULSE RESPONSE IN GRASSLanD REGION OF CENTRAL INNER MONGOLIA. Acta Energiae Solaris Sinica 43, 49-56.
Zhang, Z., Shang, W., Wang, Q., Fu, G., Zhang, W., Wan, X., 2020. Biodiversity of Herbaceous Species under Large Photovoltaic (PV) Power Stations in Desert Region of Hexi Corridor. Journal of Northwest Forestry University 35, 190-196,212.
Zhao, J., Liu, M., Hao, M., Wang, Q., 2022. Effects of Vegetation Restoration on Soil Aggregate Composition and Organic Carbon of Eco-Photovoltaic Power Station in Arid Area. Research of Soil and Water Conservation 29, 137-143.
Zhu, S.-k., Wang, S., Zhang, J.-t., Gao, D.-d., Sheng, H.-y., 2021. Microclimate characteristics of photovoltaic arrays and their effects on plant growth in a solar power station area.

Shengtaixue Zazhi 40, 3078-3087.