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LETTER

An unexpectedly large proportion of photovoltaic facilities installed on cropland

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Dear Editor,

The global expansion of photovoltaic (PV) installations is critical for achieving carbon-neutral goals but raises pressing land-use challenges. This study examines current PV land-use patterns and explores solutions to reduce land-use conflicts. Satellite-based analyses reveal that cropland accounts for 43% of global PV installations, with European Union countries leading at 81%, exceeding barren land usage despite its greater suitability. Regional disparities in PV land use, shaped by varying population densities and land availability, highlight the importance of developing tailored strategies. Innovative solutions like agrivoltaics and floating PV systems, alongside advancements in solar cell efficiency, offer pathways to minimize ecological impacts and preserve food security. Balancing renewable energy deployment with sustainable land management is essential for a resilient energy future.

INTRODUCTION

The severe reliance on fossil fuels since the Industrial Revolution has contributed to massive greenhouse gas emissions, especially carbon dioxide, catalyzing global warming and thus intensifying terrible climate events. This underscores the urgency of replacing fossil fuels with plentiful carbon-extensive energy, notably wind and solar energy, to achieve carbon-neutral goals, aligning with the Paris Agreement's ambition to keep global temperature rise under 2°C. Photovoltaic (PV) stands out as a key player in the renewable energy system, not only due to its adaptable installation and minimal carbon footprint but also decreasing costs. By 2023, the cumulative capacity of solar PV reached 1,411 gigawatts (GW), accounting for approximately one-quarter of the global renewable capacity.[1] This figure is projected to be more than 5,000 GW by 2030, under the International Renewable Energy Agency's 1.5 °C scenario.[1] Undoubtedly, the widespread installation of solar-oriented infrastructure in the future is bound to become an important component of human society.

However, the rapid expansion of solar projects, especially utility-scale ones, requires substantial land resources. For instance, solar PV arrays, which are required to generate the same amount of energy as a conventional 1-gigawatt power station, typically cover about 80 km^2 of land.[2] This great demand for land raises growing concerns, as global land scarcity, ecosystem service needs, and energy generation requirements have simultaneously increased.[3] Given the unintended environmental impacts of large-scale solar power development—such as soil erosion and biodiversity loss—siting solar projects on barren lands or built-up areas (e.g., rooftops and parking lots) is preferable. Nonetheless, recent regional investigations in California have shown that a large proportion of existing utility-scale solar installations are located on croplands.[3] Meanwhile, projections have highlighted that in future scenarios, certain countries will face significant challenges in allocating sufficient land for PV without negatively impacting agriculture or other ecological landscapes.[4] Despite these, current global patterns of land use conflict caused by solar installations have not been systematically discussed.

Satellite-based observations provide us with a unique lens for examining the complex interplay between energy production and land use at a global scale. Here, we utilize the dataset of global solar PV generating units and land-cover data to analyze this issue. In particular, the global inventory of solar generation facilities, which documents 68,611 generating units built worldwide before September 30, 2018, is derived from Sentinel-2 and SPOT6/7 satellite imagery.[5] To identify the land-cover type before PV facilities deployment, we overlap this dataset with the 30-meter resolution land-use map, GLC-FCS30D, of 2008.[6] The year 2008 is selected due to the limited presence of solar installations prior to this period. In addition, population density is a key factor characterizing both energy demand and land-use conflict. In this study, we further investigate the relationship between population density and the area proportion of different land cover types occupied by solar facilities. The population density data used in this analysis comes from the Gridded Population of the World Revision 11 (GPW v4.11) dataset, which has a spatial resolution of 30 arc-seconds.[7] The gridded data for the year 2020 is specifically selected.

RESULTS AND DISCUSSION

As of September 30, 2018, approximately 4,818 km^2 of land areas worldwide have been directly converted for PV facilities, with the majority located in the Northern Hemisphere. The largest contributors to this land use are China (2,152 km^2; 45% of the total), European Union (EU) countries (746 km^2), and the United States (670 km^2). PV installations predominantly occupy croplands, grasslands, and barren lands, which together account for 70% of the total area. Interestingly, barren land, often considered to be the preferred site for PV installations, accounts for only 30% of the total. In contrast, cropland makes up nearly 2,057 km^2 —about 43% of the global PV land use—a share comparable to the total PV land use in China (Figure 1A).

Land use patterns vary greatly among the three major regions of PV installations. In China, which accounts for the largest share of global PV land use, only 25% of installations are on croplands, compared to 26% on grasslands and 35% on barren land. Most cropland projects in China are concentrated in the central-eastern regions, whereas the northwest and central-northern regions are dominated by installations on barren land and grassland (Figure 1B). In the United States, cropland accounts for approximately 40% of PV deployments, which is primarily located along the east and west coasts as well as in the central-northern regions (Figure 1C). In contrast, EU countries, with a PV land use area amounting to just 35% of China's, place a striking 81% of their installations on cropland (Figure 1D). Many sites of agricultural solar facilities have appeared in Germany, Spain, and Italy.

Population density shows a strong correlation with the land cover that is occupied by PV, highlighting how population distribution shapes land-use decisions for solar deployment. From a global perspective, our analysis reveals that the proportion of PV installations on cropland increases with population density, peaking at 0.62, before declining. In contrast, installations on barren land steadily decrease, while those in built-up areas increase (Figure 1E). Although this general trend is observed across the three major contributors—China, the EU, and the United States—the population densities at which these turning points occur differ obviously. In China, the peak proportion (0.60) of cropland installations occurs at a population density of 500 - 1,000 people km^{-2}, while in the EU and the United States, the peak proportions (0.67 for the EU; 0.54; the United States) occur at much lower densities of 25 - 50 people km^{-2} and 10 - 25 people km^{-2}, respectively (Figure 1F-H). Regional differences in turning points reflect the potential spatial relationship between population distribution and land use, as well as variations in development stages and average population density. Furthermore, at lower population densities, both China and the EU show a higher reliance on barren land for solar installations (nearly 1), while the United States primarily utilizes shrublands and croplands. Notably, while cropland remains a dominant site for PV facilities, there has been an obvious rise in installations on forested land in the EU and the United States, reflecting different land-use strategies for PV deployment.

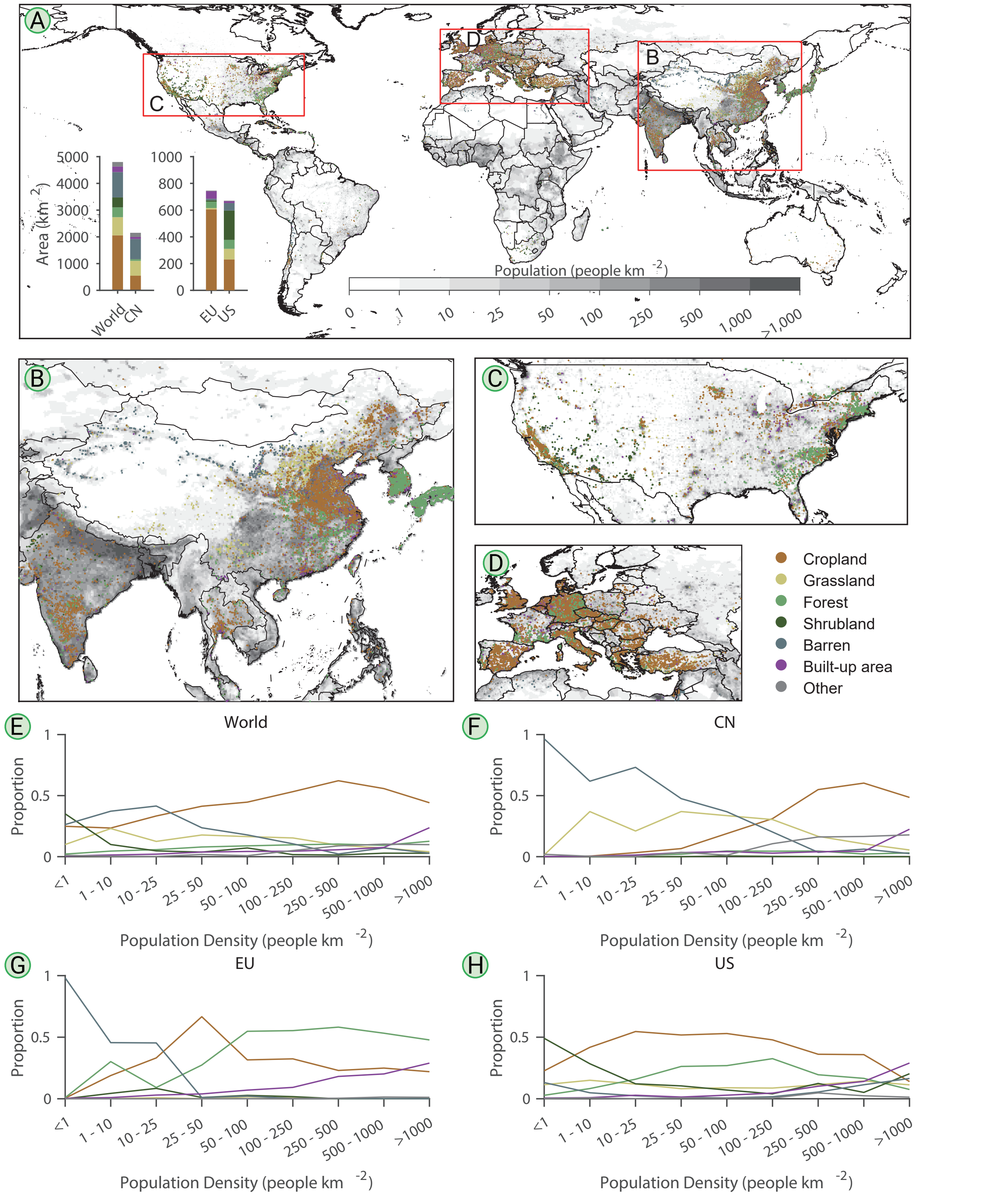

Figure 1. Different land-cover types converted for solar energy use by 2018. A, The spatial pattern of different land covers occupied by PV. The insert in A shows the area counts of three main contributors to global PV installations, China (CN; B), the United States (US; C), and the European Union countries (EU; D). E-H demonstrate the relationship between population density and the area proportion of different land-cover types occupied by PV facilities.

Our results show that PV facilities are widely encroaching on cropland worldwide, even other ecological land cover like forests and shrublands, a phenomenon not limited to specific regions but occurring globally. High population density areas, particularly urban centers, have limited wastelands, making cropland and built-up areas the primary options. Given the high land value in these regions, cropland with low slopes, regular shapes, and large contiguous areas is considered for utility-scale PV projects. Such lands are typically near energy demand centers, minimizing transmission losses and costs. Projections from IRENA's 1.5 °C Scenario[1] suggest that installed solar PV capacity could exceed 18,200 GW by 2050 (approximately 37 times the capacity in 2018). If current trends in utility-scale solar installations continue, this expansion could lead to the conversion of approximately 74,000 km² of cropland —an area comparable to the entire land area of Ireland. These projections underscore the urgent need to balance clean energy development with food security and ecological protection, addressing the trade-offs inherent in this rapid transformation.

Therefore, to address challenges in sustainable land use, improving land-use efficiency is crucial. One promising approach is to strategically deploy solar panels with precious land. Agrivoltaics (APV) offers an innovative solution for policymakers, where PV panels generate electricity above, while agricultural production continues below. This dual use of land alleviates land scarcity and enhances the economic returns from solar projects. Evidence has suggested that installing solar panels in drylands can have positive effects on crop yields, such as chiltepin pepper and cherry tomato,[8] as the shading provided by PV panels reduces surface temperatures and decreases vegetation transpiration, which in turn benefits crop growth. Nonetheless, APV is not universally suitable, as certain crops, such as corn and wheat, which are highly sensitive to radiation, may experience yield losses due to intermittent shading. To maximize benefits, APV projects must account for local climate conditions, crop characteristics, and agricultural needs. Prioritizing low-productivity lands, including abandoned croplands, can further minimize risks to food security while optimizing land use.

Another promising solution is floating photovoltaic (FPV) systems, which are expected to grow rapidly worldwide. By integrating PV panels with water bodies, such as reservoirs and oceans, FPV systems minimize land-use conflicts while providing multiple synergistic benefits. For example, reservoirs are often close to power grids, reducing infrastructure costs associated with electricity transmission. Additionally, the reflective properties of water and natural evaporative cooling can help maintain lower temperatures for PV panels, thereby improving their efficiency. FPV systems can also reduce water evaporation by shading the water surface, contributing to water conservation.[9] However, the wide use of FPV systems in the future requires us to comprehensively understand its consequent impact on the water environment and ecology. One recent field survey has demonstrated that the deployment of FPV will cause a reduction in plankton species and individual density, together with a changed bird community composition.[9] Further research is essential to mitigate these ecological challenges and ensure the sustainable expansion of FPV technology.

Improving energy conversion efficiency is important for enhancing land-use efficiency as well. Higher conversion efficiency allows solar installations to occupy less space while delivering high power output, offering greater flexibility for deployment in urbanized or environmentally sensitive areas with limited land availability. Currently, silicon-based solar cells, including monocrystalline and polycrystalline variants, dominate the global market, but their theoretical efficiency has plateaued at around 29%. Despite their widespread use, this relatively low efficiency requires larger land areas for large-scale installations. Emerging photovoltaic technologies, such as perovskite solar cells, are poised to overcome these limitations. Single-junction perovskite cells can theoretically reach efficiencies of up to 33%, while multi-junction perovskite cells may achieve efficiencies over 40%,[10] greatly surpassing the efficiency limit of silicon-based cells. Moreover, perovskite materials excel in low-light conditions, maintaining high performance during cloudy days or at dawn and dusk. This adaptability further enhances their overall energy generation potential. However, the commercial scalability of perovskite solar cells is hindered by stability issues, particularly long-term durability under varying environmental conditions (e.g., humidity, temperature, and UV exposure). Despite these challenges, ongoing improvements in stability and scalability position perovskite cells as a promising alternative for future solar technologies.

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AUTHOR CONTRIBUTIONS

Z.Z. designed the study. S.W. performed the analysis and led the writing. All authors contributed constructive comments and revisions to the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The global inventory of photovoltaic solar energy generating units is available at https://zenodo.org/record/5005868. The global 30 m land-cover data (GLC_FCS30D), is available at https://doi.org/10.5281/zenodo.8239305, and the global gridded population data (GPW v4.11) can be assessed at https://doi.org/10.7927/H49C6VHW.