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LETTER

Analyzing land characteristics associated with historical large-scale solar photovoltaic deployment in the united states

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**Abstract**

Large-scale solar (LSS) deployment has accelerated rapidly across the United States, yet comprehensive understanding of its siting patterns remains limited. Here, we present a national-scale geospatial assessment of land characteristics converted for LSS development and apply statistical analyses to evaluate whether installations are disproportionately concentrated within specific land types. We find that siting patterns are strongly correlated with high solar irradiance, underscoring the role of resource quality in shaping deployment decisions. LSS projects are disproportionately concentrated on agricultural lands and shrubland. Within agricultural areas, installations predominantly occur on croplands and are strongly associated with irrigated systems. Notably, more than 90% of projects are deployed on agricultural land with Productive, Versatile, and Resilient (PVR) index values of land quality exceeding the national median. These findings highlight the need for strategic siting frameworks that reconcile solar development with the conservation of agriculturally valuable land.

1. Introduction

Solar energy has experienced rapid growth in the United States over the past decade leading to a total of around 150 gigawatts (GW) of utility-scale photovoltaics (PV) (EIA 2026) and approximately 60 GW of small-scale PV installed as of the end of 2025 (EIA 2026). The growth in solar development is propelled by a confluence of technological innovation, cost reductions, and policy support at federal and state levels (Edenhofer *et al* 2012, Silverman and Huang 2021, EIA 2023). U.S. solar capacity is expected to reach between 600 and 1,650 GW by 2050, based on 61 forward-looking scenarios of U.S. electricity sector buildout that account for factors such as fuel prices, demand growth, technology costs, resource availability, transmission conditions, and policy environments (Gagnon *et al* 2024).

Limited rooftop capacity in the United States requires the deployment of ground-mounted solar facilities to meet state-level solar energy deployment estimates (Gagnon *et al* 2016, NREL 2021). LSS or utility-scale solar, systems have become a central component of utility planning processes (Callaway *et al* 2017). Moreover, LSS development supports local economies through job creation (Haerer and Pratson 2015, DOE 2024) and landowner revenue (Wiser *et al* 2020, Buckley Biggs *et al* 2022). As of the end of 2021, more than 4400 LSS facilities (≥ 1 megawatt direct current (MWdc)) were operating nationwide, totaling over 60 GW of installed capacity (EIA 2022).

Land requirements for LSS can vary with geography, system design, environmental constraints and permitting conditions (Bolinger *et al* 2023). Typical installations require approximately 3–10 acres per

MWdc, although solar infrastructure directly occupies only 20%–50% of site area due to panel spacing to prevent inter-row shading (Ong *et al* 2013). LSS facilities are predominantly located in rural regions with large contiguous land parcels, particularly agricultural land and shrubland, which provide flat, open terrain suitable for installation and maintenance. LSS deployment can alter land use and affect vegetation dynamics, microclimates and wildlife habitats (Lovich and Ennen 2011, Zhang *et al* 2023, Xu *et al* 2024), yet it can also generate techno-ecological synergies (Hernandez *et al* 2019) such as land restoration, habitat provision, and agricultural production underneath and between rows of panels (Macknick *et al* 2022, Chopdar *et al* 2024, Widmer *et al* 2024).

In some regions of the United States, LSS deployment has faced public oppositions regarding concerns over agricultural land conversion and broader social-ecological impacts (Carlisle *et al* 2016, Susskind *et al* 2022, Elizabeth Weise 2024). Despite these perceptions, comprehensive geospatial assessments of the characteristics of land converted to LSS remain limited. Our research makes three main contributions. First, prior research has largely focused on land cover and land use (LULC) categories that have converted to solar deployment (Kruitwagen *et al* 2021, Zhang *et al* 2023, Karen Maguire *et al* 2024). Building on this foundation, our analysis began with LULC but extended the characterization to six additional geospatial variables: agricultural land type and quality, cropland type, irrigation lands, soil organic carbon (SOC), and global horizontal irradiance (GHI). This multi-dimensional characterization provides a more detailed understanding of the land resources associated with historical LSS deployment across the contiguous United States (CONUS). Second, we leveraged the United States Large-Scale Solar (LSS) Photovoltaic Database (USPVDB), which provides digitized array boundaries and validated operational and capacity data (Fujita 2023, Fujita *et al* 2023b). This expands upon previous studies that relied on predicted or hypothetical PV boundaries (Kruitwagen *et al* 2021, Karen Maguire *et al* 2024), reducing characterization uncertainties caused by LSS footprints. Third, beyond land characterization, we performed statistical tests to inform whether LSS deployment is disproportionately concentrated within specific land types. The remainder of the paper describes the data and methods (section 2), presents results (section 3), and discusses implications (sections 4 and 5).

2. Methods

2.1. Land variables

Our analysis focuses on the characteristics of land prior to LSS installations—identifying the types of

land converted for LSS—rather than examining land use changes. This focus is due to the lack of datasets on post-installation land management beneath panels. We analyzed seven land variables (table S1), selected for data availability and their relevance to assessing how LSS placement intersects with LULC, particularly agricultural lands.

The analysis began with broad LULC categories, but we used a broader definition of agricultural land including both grazing pasture and cropland for analysis. The cropland category was derived from the annual crop data layer (CDL), while grazing pasture was identified by integrating the CDL with LULC datasets from the Farms Under Threat (FUT) product developed by American Farmland Trust (AFT) (Boryan *et al* 2011, CSP 2020). Specifically, we used the agricultural land-use categories from the FUT-LULC dataset to further distinguish the grassland/pasture class mapped in the CDL into grazing pasture and grassland/pasture not associated with agricultural use. The detailed geospatial processing is in the Supplemental Notes. Then, we evaluated the quality of agricultural land converted for LSS using the productivity, versatility, and resiliency (PVR) dataset developed by the AFT, which integrate factors such as crop yield, climatic conditions, soil properties, topographical features, ecosystem services, and land management practices (CSP 2020). Next, we examined LSS installations occurring on irrigated lands which tend to be disproportionately valuable for production (USDA 2023). Subsequently, we analyzed GHI as a key economic driver of LSS deployment because higher irradiance increases expected energy generation (Sengupta *et al* 2018). Finally, we examined SOC because potential carbon emissions from land conversion depend on baseline SOC levels prior to deployment (van de Ven *et al* 2021). Most of these datasets are available at 30 m resolution, whereas SOC and GHI are provided at coarser scales of 250 m and 4 km, respectively (table S1). Although the datasets differ in spatial resolution, they remain appropriate for this study because our analysis focuses on national-scale patterns of historical LSS deployment rather than fine-scale conditions within individual facilities. Detailed pre-processing applied to each land variable is described in the section 1 of SI.

2.2. LSS datasets

Data on LSS facilities were derived from the USPVDB (Fujita 2023, Fujita *et al* 2023b), developed by the U.S. Geological Survey (USGS) and Lawrence Berkeley National Laboratory. This database contains 3,699 manually digitized and validated LSS facilities (≥ 1 MWdc) mapped using high-resolution remote sensing imagery, with array boundaries and attributes such as installed capacity (in MWdc) and initial operation year ranging from 1986 to 2021 (Fujita *et al* 2023b, Ancona *et al* 2023a). Not all LSS facilities were eligible for this study

because several land datasets used here have limited temporal and spatial coverage. For example, the national-scale CDL (USDA 2016) used for analyzing agricultural land use is only available from 2008 onward. Because our objective is to characterize pre-installation land conditions, we restricted the analysis to projects that began operation during 2009–2021, and because most land datasets are CONUS-only, we focus on facilities within the CONUS. This yields 3,657 projects (> 98% of USPVDB facilities). The number of LSS facilities analyzed varies by land variable because some analyses apply only to subsets of projects (e.g. agricultural land-quality metrics are evaluated only for facilities sited on agricultural lands). The sample size for each variable is reported in table S2.

2.3. Zonal statistics analysis

We conducted a zonal statistics analysis to summarize land characteristics within LSS facility polygons. Zonal statistics is a common approach in geographic information systems (GIS) to aggregate raster values within polygonal zones (Haag *et al* 2020). We implemented two workflows: one for categorical variables (e.g. LULC) and one for continuous variables (e.g. PVR). For categorical variables, we identified the majority land category within each facility. If a single category accounted for $\geq 50\%$ of the facility area, we assigned that category; otherwise, the facility was labeled ‘Mixed.’ We then summarized the number, area, and capacity of facilities by land category. For continuous variables, we calculated the mean value within each facility, assigned the facility to a predefined value bin (e.g. PVR range), and summarized the number, area, and capacity by bin.

This study aims to analyze land characteristics prior to LSS installations; therefore identifying an appropriate reference year representing pre-construction conditions is critical. This reference year determines which year of land dataset is applied to each facility for analysis. However, the USPVDB does not record the installation year and instead provides only the first year of operation. To address this limitation, we implemented a two-step procedure to determine the reference year for each facility. First, we initially assumed that installation occurred in the first year of operation. Under this assumption, the reference (pre-construction) year is defined as one year prior to the assumed installation year. Second, because commissioning may occur at any point within the recorded operation year (e.g. early versus late in the calendar year), the ‘one-year-prior’ period may overlap with site preparation or construction which may not reflect true pre-construction conditions. We therefore used annual LULC as a diagnostic to refine the initial assumption: if the dominant LULC class one year prior to the

first operation year is developed or barren—classes that can plausibly arise from clearing, grading, or construction—we infer that construction likely began earlier. In these cases, we revised the assumed installation year to one year before the first operation year and set the reference year to two years before the first operation year. For each facility, we recorded the resulting reference year and applied it consistently across all land variables to select the dataset year used for zonal analysis.

In addition, temporal coverage differs across land variables, and not every dataset is available annually over the study period. For example, the PVR dataset is available only for 2001 and 2016. For variables with sparse temporal snapshots, we used the assumed reference year to select the nearest available dataset year for analysis. The processing details are documented in section 1 of the Supplementary information (SI). Zonal analysis was conducted at multiple geographical scales—national and regional—to discern the spatial patterns of land characteristics associated with LSS installations. Furthermore, we aggregated the zonal results by the year of operation to delineate temporal patterns associated with LSS installations

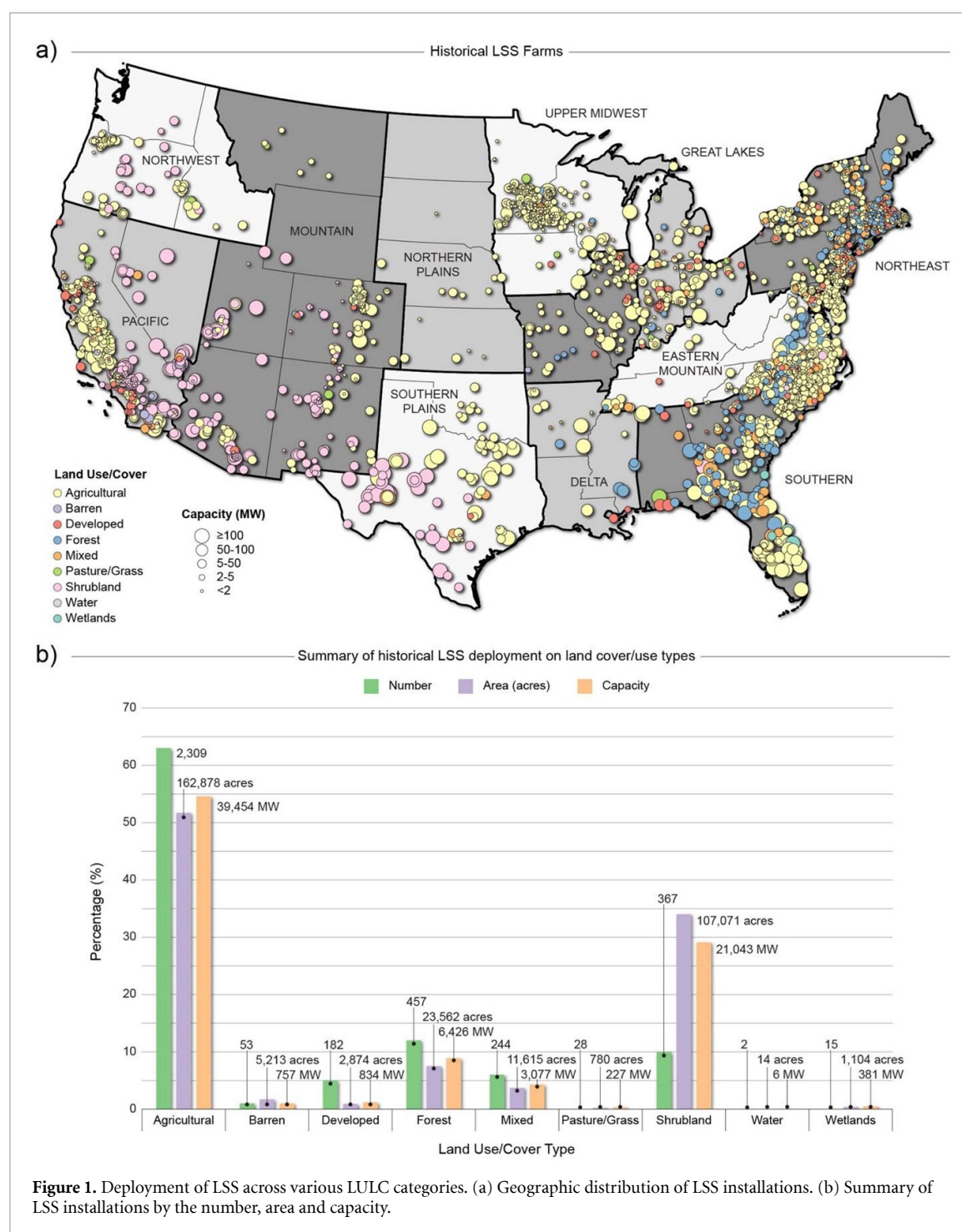
2.4. Hypothesis test

We conducted a chi-square (χ^2) hypothesis test to assess whether LSS deployment is disproportionately within a specific land category (e.g. agricultural land). The null hypothesis assumes that the areal proportion of LSS deployment in a given land category does not significantly differ from the overall CONUS areal proportion of that land category. In contrast, the alternative hypothesis suggests that the areal proportion of LSS deployment in the land category exhibits a statistically significant difference, either higher or lower than the area proportion of the land category. The significance level was set at 0.05. Furthermore, we performed the test at both national and regional scales to understand land characteristics converted for LSS within different spatial contexts. Based on the *P* value, we classified the test results into ‘significantly higher,’ ‘significantly lower,’ or ‘not significant.’

3. Results

3.1. Land use characteristics prior to LSS installation

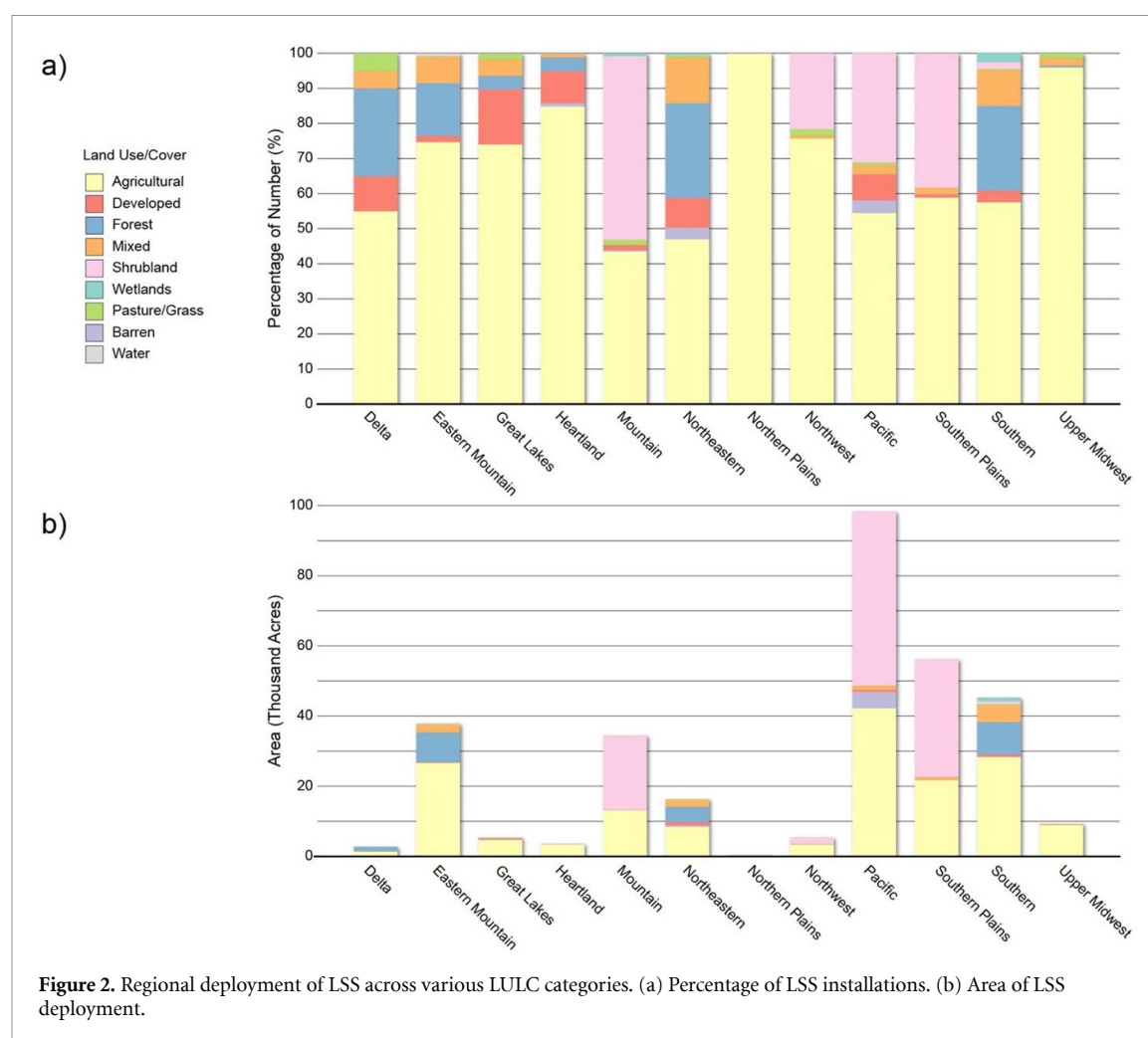
From 2008 to 2021, a total of 3,657 LSS facilities were constructed in the CONUS. Our analysis shows that 63.1% ($n = 2,309$) of the LSS projects were installed on agricultural lands, followed by forests and shrublands, accounting for 12.5% and 10% respectively (figure 1). Shrublands are commonly utilized for LSS in the Southwestern and Mountain U.S. regions while forested land is commonly utilized in the Eastern U.S.



(figure 1(a)). The annual and cumulative growth in the number of LSS installations occurs predominantly on agricultural lands (figure S1). Geographically, most regions except Mountain and Northeastern have deployed over 50% of LSS facilities on agricultural land (figure 2(a)).

LSS projects have been deployed on over 315 111 acres of land for LSS energy, with 51.7% (162,878 acres) located on agricultural lands and 34% (107,071) on shrublands, as illustrated in figure 1(b). This represents the conversion of approximately 0.025% of national agricultural land for

LSS production (table S3). The conversion rate for shrubland is similar, at 0.23 acres per 1,000 acres, or 0.023%. Hypothesis testing results indicate the area proportion of LSS facilities deployed on agricultural land (51.7%) is significantly higher ($p < 0.001$) than the national proportion of agricultural land (33.3%) (table S3). A similar statistically significant ($p = 0.017$) result was also observed for shrubland. Regional analyses of LULC conversion for LSS, as shown in figure 2(b), and hypothesis testing reveals that the LSS deployment on agricultural land is statistically higher ($p < 0.05$) than regional agricultural



land proportion across most regions with the exception of the Southern Plains (Figure S2(a) and table S4). Additionally, LSS deployment on shrubland is statistically higher ($p < 0.05$) in the Mountains and Southern plains regions (Figure S2(b)). Among the 42 states with LSS deployed, 40 states exhibit statistically higher area percentages of LSS deployment on agricultural land relative to their respective agricultural land proportions (table S5 and figure S2(d)). The use of agricultural lands for LSS has gradually increased, with the cumulative installations on agricultural land now exceeding that of any other land-use type (figure 3). Notably, the annual deployment on shrubland has been primarily concentrated in the years of 2016, 2020, and 2021, indicating specific periods of intensified deployment (figure 3(a)).

The patterns and trends observed in the power capacity of LSS are similar to the findings based on land area described above, likely due to the consistency of capacity densities across installations (figure 1(b), figures S3 and S4). Older, smaller-capacity LSS projects are predominantly located along the east and west coasts (figure S5) whereas newer, larger projects are mainly situated in the Southern Plains, Southern regions, and the Great Lakes regions. The CONUS has witnessed a yearly increase in

installed capacity, with a significant surge in 2016 when the installation volume exceeded 10 GW, nearly doubling that of 2015. A similar trend was observed in 2020.

3.2. LSS deployment on agricultural land types: cropland vs. grazing pasture

Agricultural lands are classified into three categories: cropland, grazing-pasture, and mixed agricultural land. Mixed agricultural land generally refers to LSS facilities converted from a combination of cropland and grazing pasture, often alongside some non-agricultural land covers, where neither agricultural land type accounts for more than 50% of the facility area. Among the 2,309 LSS facilities sited on former agricultural land, the majority (80.4%, $n = 1,856$) are located on cropland, followed by grazing-pasture, which accounts for 14.5% ($n = 335$), with the remainder distributed on a combination of these two land types (figure 4). The conversion of cropland for LSS represents around 0.034% of the total cropland area within the CONUS (table S6). Hypothesis testing results demonstrate that area proportion of LSS facilities installed on cropland (73.9%) relative to total agricultural land, is significantly higher ($p < 0.001$) than the share of the total cropland area (54.7%)

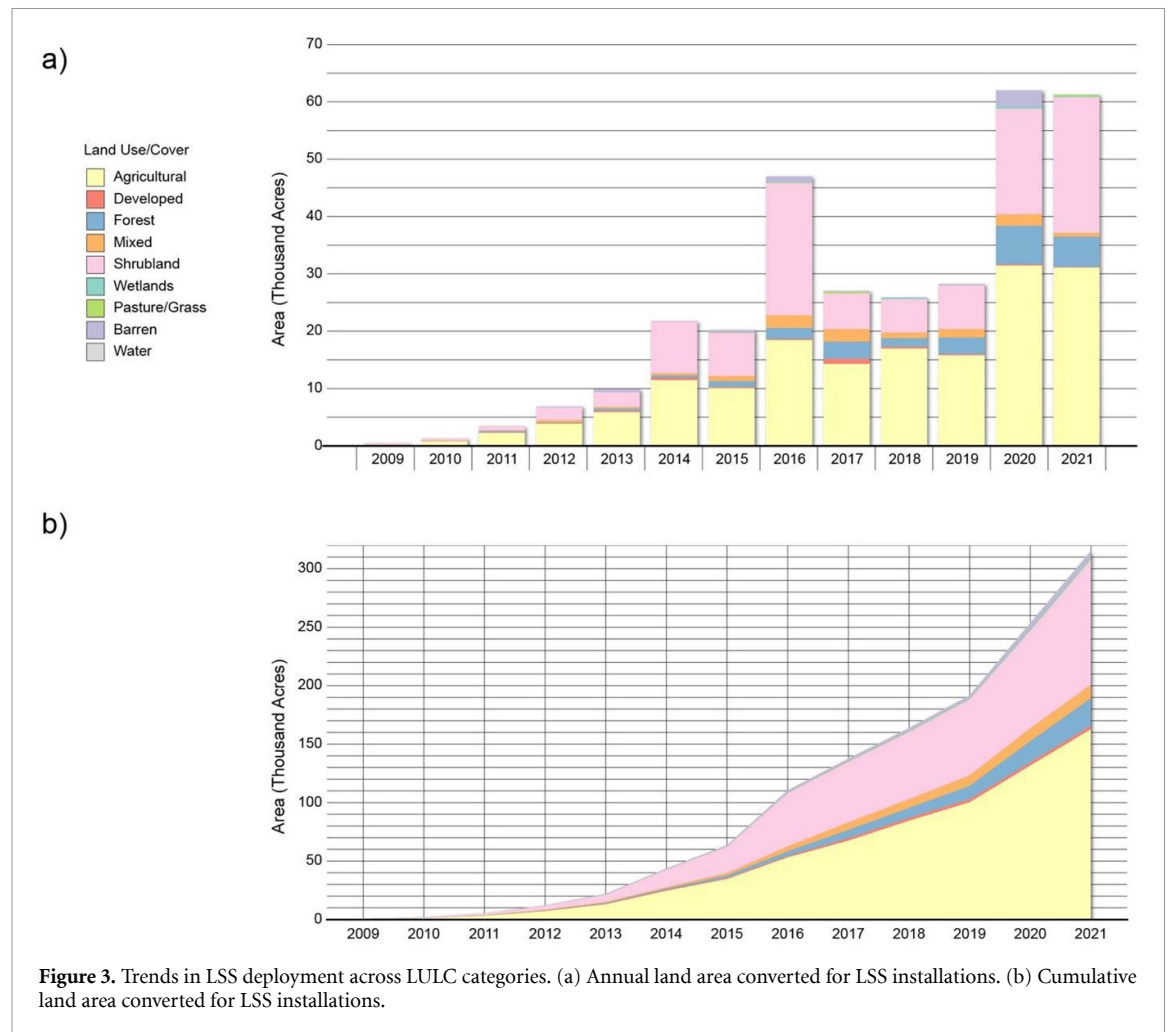


Figure 3. Trends in LSS deployment across LULC categories. (a) Annual land area converted for LSS installations. (b) Cumulative land area converted for LSS installations.

within the agricultural land in CONUS table S6). This statistical pattern of deployment on cropland is consistent across regions while the LSS deployment on grazing-pasture is significantly lower across regions (Figure S2, 2(f) and table S7). Cropland, compared to grazing-pasture, has been the primary agricultural land type utilized for LSS deployment across years and regions (figure 4(c) and S6–S8).

3.3. Agricultural land quality of LSS deployment

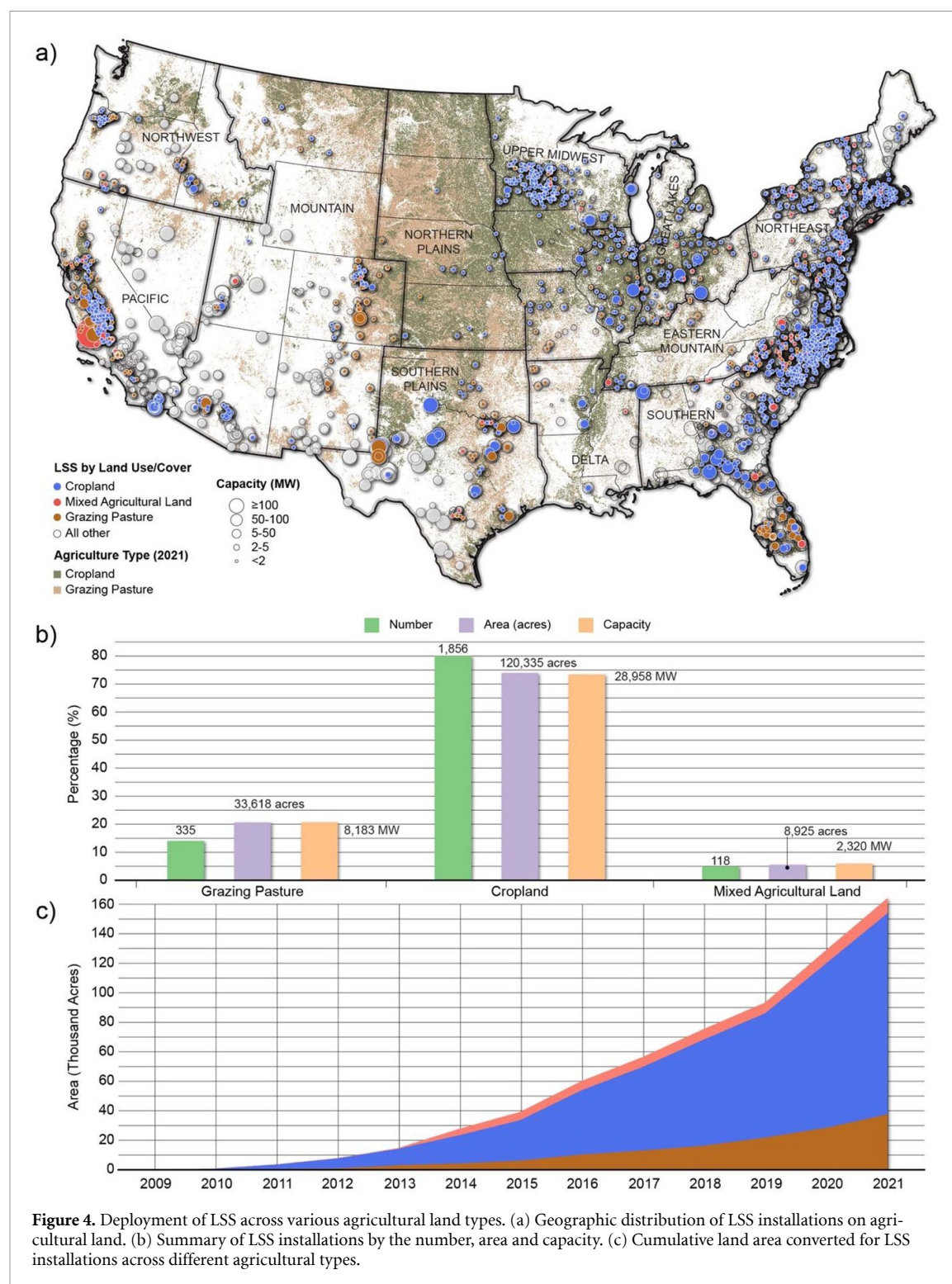
We utilized the PVR dataset (CSP 2020) to analyze the deployment of LSS projects on agricultural lands of varying quality (figure 5). PVR values range from 0 to 1, with higher values indicating superior quality (CSP 2020). To facilitate the analysis, the national-scale PVR dataset was stratified into six categories based on statistical percentiles: below 50%, 50%–60%, 60%–70%, 70%–80%, 80%–90%, and above 90% (figure 5). The analysis focused on LSS facilities installed on agricultural land ($n = 2,309$). However, due to missing PVR values for 216 LSS projects, the final analysis was conducted on the remaining 2,093 projects with total area of 158 442 acres.

Our analysis reveals 90.7% (1,899 out of 2093) of LSS facilities are deployed on agricultural lands with PVR values exceeding the national median (50th

percentile) (figure 5). These installations account for 83.5% (132,482 acres) of the total agricultural land converted for LSS (158,442 acres). Notably, the percentage of LSS area relative to the total agricultural land within a given percentile reaches a maximum of 0.044%, observed in the 60%–70% PVR percentile (table S8). The results of hypothesis testing shows that the proportions of LSS area within PVR percentiles of 50%–60%, 60%–70% and 80%–90%, which are 18.3% (29,004 acres), 25.3% (40,163 acres), and 22.6% (35,819 acres), respectively, are significantly higher ($p < 0.05$) than the corresponding national distribution of agricultural land within these percentiles (table S8). Still, the percentage of LSS area relative to total agricultural land area within these PVR percentiles remains under 0.04%. Regional hypothesis testing reveals that LSS deployment within each of these percentiles is significantly higher ($p < 0.05$) in at least five regions (figure S9 and table S9). Notably, LSS deployment in the Northern Plains region is statistically higher ($p < 0.05$) within the 80%–90% PVR percentile.

3.4. LSS deployment on irrigated land

Of the 2309 LSS facilities sited on agricultural land, 19.4% ($n = 449$) have been established on formerly



irrigated agricultural land. This accounts for 35.1% (57,189 acres) of the agricultural land used for LSS (figure 6). Figure S10 reveals the cumulative LSS installations over irrigated land by number, area and capacity. Hypothesis testing indicates that the proportion of LSS facilities installed on irrigated land (35.1%) is statistically higher ($p < 0.001$) than the overall proportion (14.1%) of irrigated land within the agricultural land in the CONUS (table S10). This statistical pattern of association with irrigated land is

consistent in 8 out of the 12 regions, as detailed in figure S2(g), 11 and table S11.

3.5. LSS deployment on cropland: crop types

We examined crop types on cropland converted for LSS installations utilizing the USDA crop sequence boundaries (CSB) dataset (Abernethy *et al* 2023). Our first analysis aims to understand the frequency of LSS facilities that are associated with a given crop. A crop is linked to a LSS facility if it appeared in the

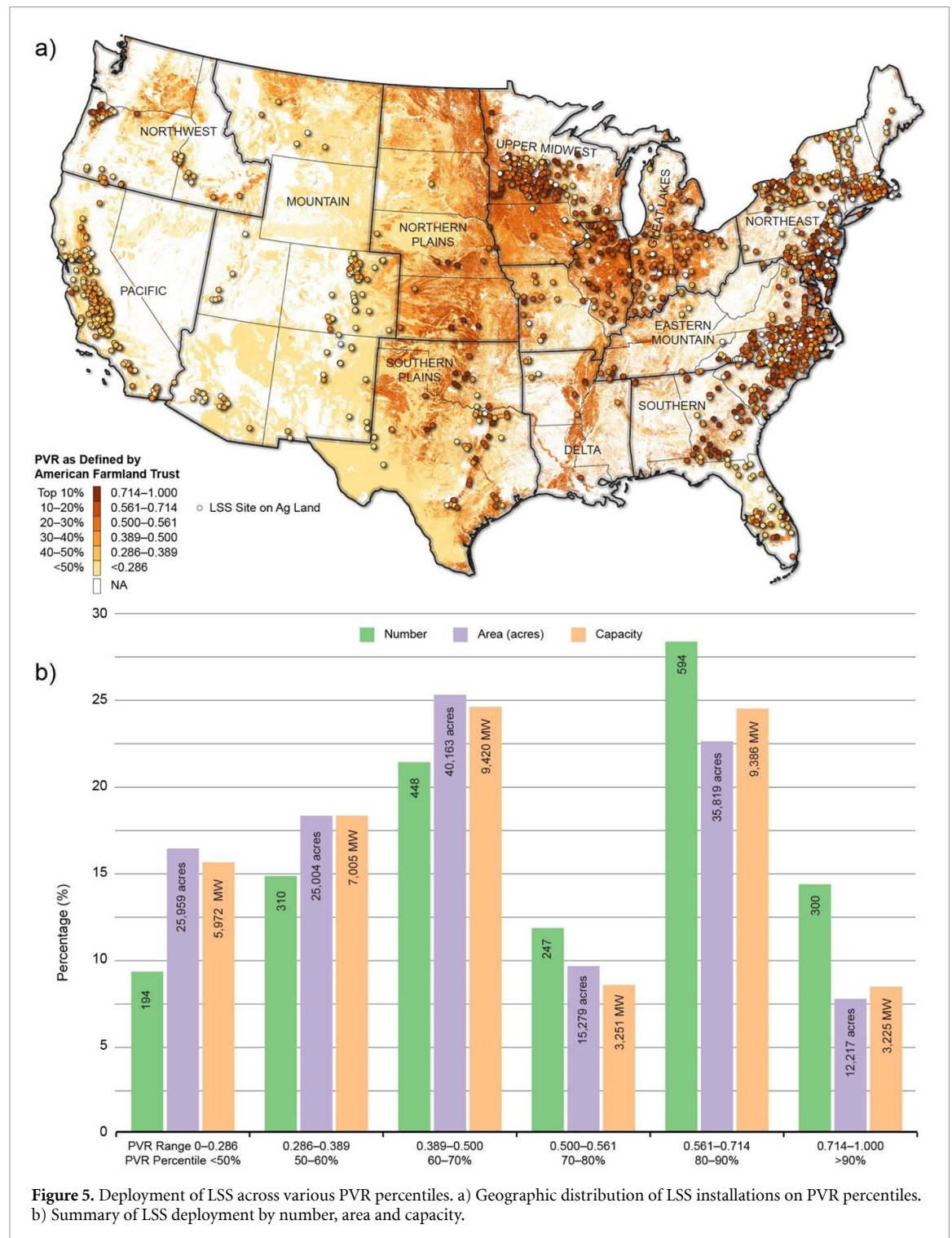


Figure 5. Deployment of LSS across various PVR percentiles. a) Geographic distribution of LSS installations on PVR percentiles. b) Summary of LSS deployment by number, area and capacity.

rotation on the cropland prior to the installation, without accounting for the crop area, as detailed in section 1.6 of the SI. Then, we summarized the number, area, and capacity of LSS facilities associated with each crop type. Figure 7 presents the results for crops associated with at least 5% of LSS facilities. Note that the summed percentages exceed 100%, as multiple crops can be associated with a single LSS facility over the course of historical crop rotation schedules. The results indicate that corn and soybeans are the most prevalent crop types, with 65% of LSS projects

($n = 1,856$) built on cropland involving them in their crop rotations. Additionally, over 50% of the LSS area include fallow/idle cropland, winter wheat, corn, and soybeans (figure 7). The findings on crop types associated with LSS capacity aligns with the patterns observed in LSS area.

Our second analysis evaluates crop cultivation displacement resulting from LSS deployment, accounting for their specific crops' area and frequency grown in crop rotations (figure 8). For a LSS facility associated with multiple crop types, its area and

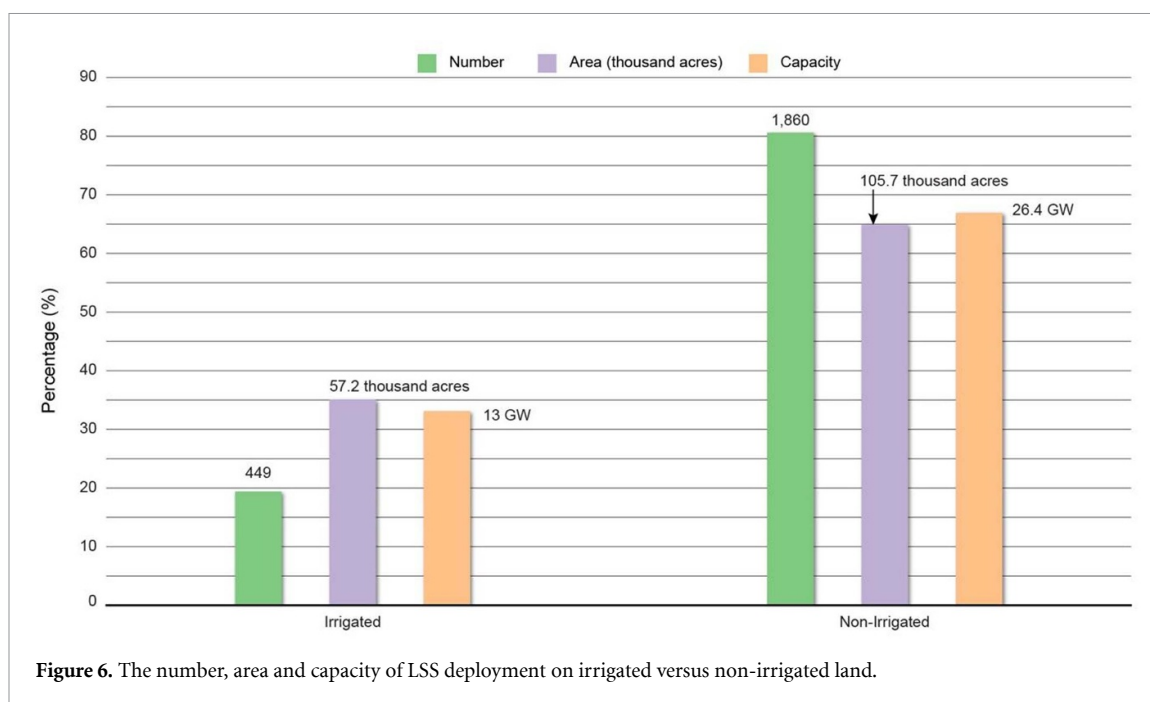


Figure 6. The number, area and capacity of LSS deployment on irrigated versus non-irrigated land.

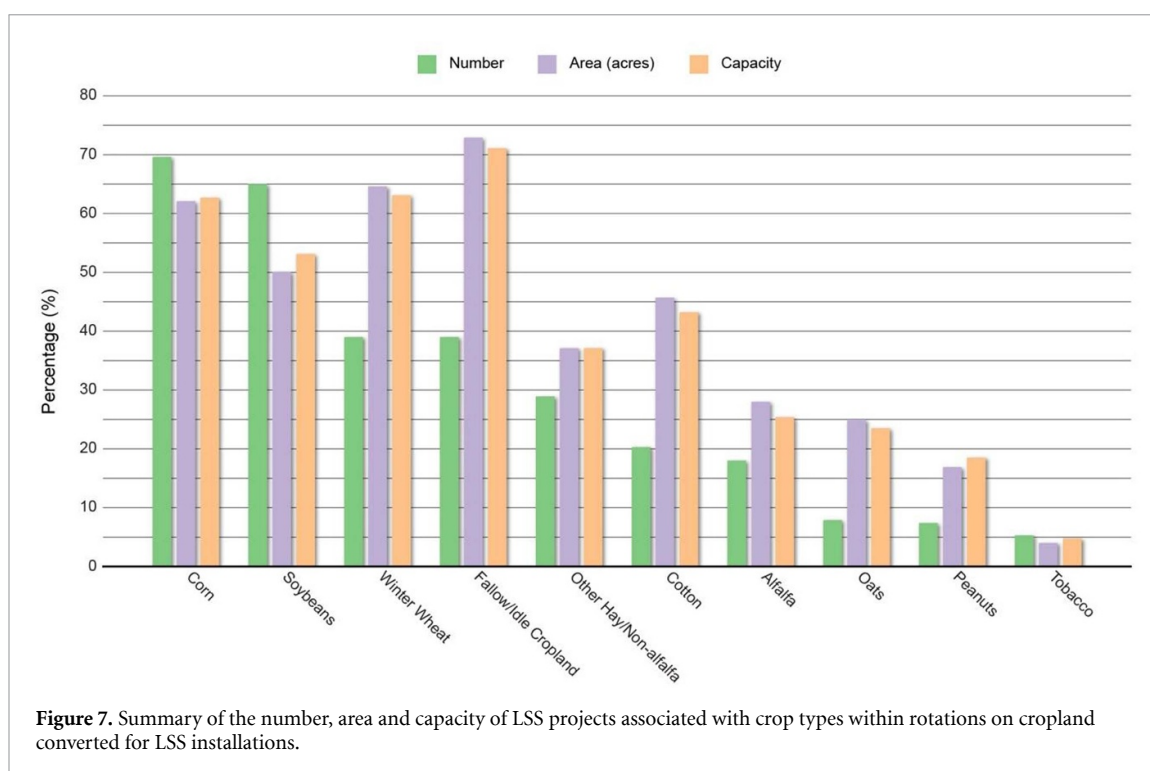
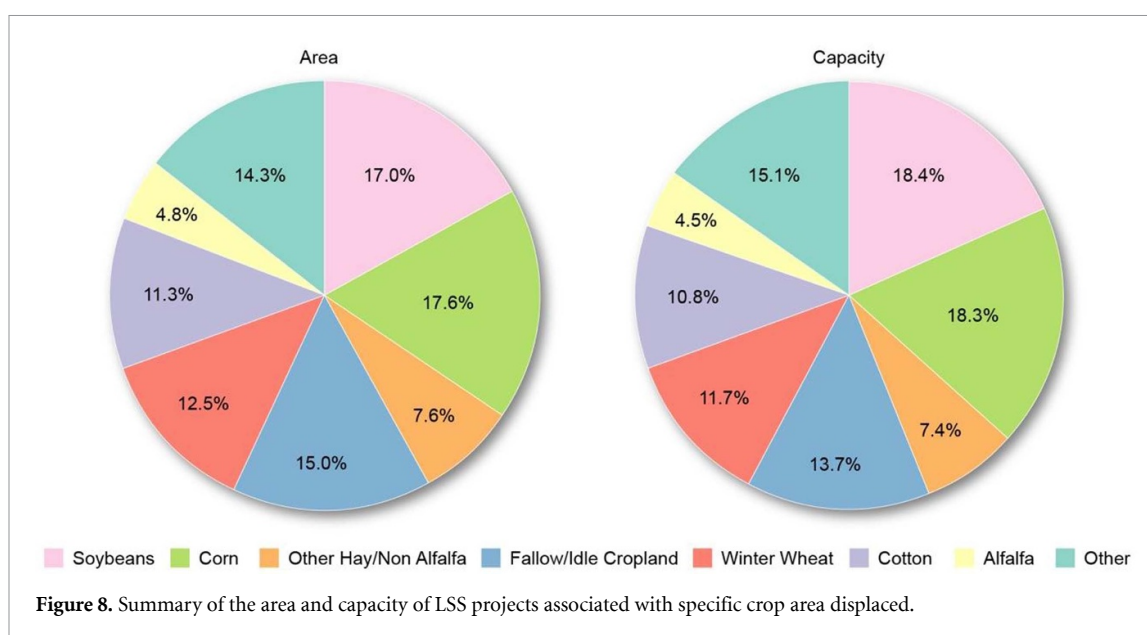


Figure 7. Summary of the number, area and capacity of LSS projects associated with crop types within rotations on cropland converted for LSS installations.

capacity are proportionally allocated to each crop based on its respective share of the area estimated by considering the normalized frequency of each crop within the historical crop rotation and the corresponding cropland area, as detailed in the section 1.6 of SI. Crop types with a converted area proportion of less than 4% of the total cropland area are aggregated and classified as ‘other’. Notably, soybeans and corn are the predominant crops displaced, each accounting for more than 17% of the cropland area utilized for LSS. Corn displaced is estimated to be 18.3 thousand

acres, whereas soybean acreage displaced is estimated to be 17.6 thousand acres, both of which represent less than 0.02% of total area grown of these crops in the United States. Hypothesis testing reveals the proportions of LSS facilities deployed over corn and soybean croplands are not statistically higher than their overall shares of total cropland, which are 26.3% and 25.2%, respectively (table S12). In contrast, the deployment of LSS facilities on former cotton and fallow/idle croplands, representing 11.2% and 15% respectively, is statistically higher than their respective shares of



total cropland, 3.8% and 5.2% (table S12). We did the same analysis for each region, with the results of the crop area proportion and hypothesis testing presented in figure S12 and table S13. The findings on LSS capacity are similar to the results based on crop area (figure 8).

3.6. SOC levels of land converted for LSS

We overlaid the LSS facilities with data on SOC levels, categorizing the results according to different LULC types as shown in figure S13(a). This analysis reveals a notable trend that the SOC levels where LSS are deployed over forest lands are relatively higher compared to installations on other land types, such as shrubland, which exhibit lowest average SOC levels (figure S13(b)). Hypothesis testing demonstrates a statistically higher rate of LSS facilities situated on lands characterized by lower SOC (table S14). This installation pattern was consistently observed across regions as demonstrated by the regional statistical test (figure S14 and table S15).

3.7. GHI levels for LSS installations

Figure S15 presents the results of LSS deployment over GHI, broken down by LULC categories. The results reveal that shrubland areas host the highest average GHI values among various LULC types utilized for LSS deployment, consistent with the geographical distribution of shrubland in the southwest region, which has higher GHI (figure S15a). We found that approximately 95% of the land utilized for LSS installations features a GHI exceeding $4 \text{ kWh m}^{-2} \text{ d}^{-1}$ (table S16). Notably, national-scale statistical test shows that LSS facilities significantly (over 40%) falls within the GHI range of $5.5\text{--}6.5 \text{ kWh m}^{-2} \text{ d}^{-1}$. The regional statistical test also shows a preference for local areas with higher GHI (figure S16 and table S17).

4. Discussion

Our study shows that LSS deployment expanded rapidly between 2009 and 2021, encompassing 315 111 acres which represents 0.016% of CONUS surface area. This also indicates less than 1% of total land cover changes (159.7 million acres) observed between 2001 to 2016 across all other sources of land use change (Homer *et al* 2020). Notably, LSS deployment is disproportionately concentrated on agricultural land and shrubland. However, agricultural land converted for LSS represents 1.5% of the 11 million acres of agricultural land converted by other uses between 2001 and 2016 (CSP 2020). Looking forward, the U.S. Department of Energy's Solar Futures Study projects ground-based PV could reach a maximum of 0.5% of CONUS area by 2050 (NREL 2021). As total land requirements increase, continued concentration within agricultural land and shrubland may increase local land-use competition and intensify environmental pressures. Under such expansion trajectories, strategic siting will become increasingly important, although implementation remains complex given the diversity of landownership structures, regulatory frameworks, and stakeholder priorities. Our study also observes distinctive patterns in both the number and size of LSS projects deployed over agricultural land and shrubland. Agricultural land accommodates a larger number of facilities, but projects tend to be smaller, averaging 70.5 acres per installation—approximately 15% of the average U.S. farm size of 463 acres reported in 2022 (USDA 2024). In contrast, shrubland are selected for larger LSS projects, averaging 291.7 acres per installation. This divergence likely reflects differences in landowner decisions, zoning constraints on agricultural lands and the geographic distribution of GHI. In particular, shrubland in the Southwest—where higher GHI coincides with

extensive contiguous land—tends to host larger-scale developments.

More than 90% of LSS facilities sited on agricultural land are located on lands classified above the median land quality (PVR) grade. While there are many driving factors including the tendency for private lands to be of higher quality and easier to build LSS on than public lands, this allocation of LSS systems on higher quality agricultural lands in the CONUS could raise issues at a state or regional level related to the preservation of available higher quality farmland. In addition, this development emphasizes the importance of integrating LSS installations with agricultural activities thoughtfully to preserve, if not enhance, farm productivity.

Our findings indicate a higher proportion of LSS deployment on croplands relative to grazing-pasture lands, both nationally and regionally. This pattern should not be interpreted as evidence that grazing-pasture lands are unsuitable for LSS development, but could reflect more on the economics and land characteristics of the different agricultural uses as well as the dominant land practices in the states that have seen the highest growth in solar development. LSS deployment on all agricultural land types can provide opportunities for landowners to diversify income streams (Biggs *et al* 2022). Agrivoltaics—co-locating ground-mounted solar with agricultural activities on the same parcel—represents one such approach (Dinesh and Pearce 2016, Barron-gafford *et al* 2019, Macknick *et al* 2022, Chopdar *et al* 2024). Potential benefits include increased land-use efficiency, lowering greenhouse emissions and positive impacts on certain plant and animal species in addition to economic gains (Chopdar *et al* 2024, Widmer *et al* 2024). Current deployment of agrivoltaics in the United States shows nearly 600 projects that represent over 10 GW of installed capacity on 62 000 acres (NREL 2024). Most projects (over 400) involve pollinator habitat, while the largest land-use (49,000 acres) is for sheep grazing. Economic barriers make scaling up this technology for crop production challenging, and despite the potential benefits of agrivoltaic systems for crop production and the prevalence of LSS on croplands, crop agrivoltaics adoption in the United States to-date has been limited.

The results reveal a high percentage of deployment over corn and soybean cropland, two of the most widely grown crops in the United States. However, the proportion of LSS development on these croplands are not statistically significant when compared to their overall share of cropland. In addition, the impact of this on food security is limited, as less than 2% of corn, and less than 15% of soybeans grown in the United States are for direct human consumption (USDA 2015, WRI 2022). Deployment over cotton and fallow/idle land shows a higher

LSS deployment proportion when compared to their national proportions of cropland. Fallow/idle land represents underutilized resources that can be repurposed for LSS energy production without competing directly with active agricultural land. These four uses (corn, soybean, cotton, and fallow/idle land) represent 57% of the cropland displacement of LSS and would have minimal impacts on national food production.

Our study indicates a strong association between LSS installation and irrigated lands that are often more productive for crop yields (Troy *et al* 2015). Although water scarcity could be driving retirement of some agricultural lands, water availability is not likely the primary driver of conversion of these agricultural lands. Instead, the association may reflect other siting-relevant factors such as flat terrain, existing access to electrical infrastructure, aging farmer demographics, and land costs. Still, this intersection could lead to reductions in regional water needs, as that water previously used for irrigation water could be used for other purposes, including supplementing water needs of nearby farms. LSS facilities need some water during construction (e.g. dust suppression) and occasionally for operations (e.g. cleaning), but this represents water use that is orders of magnitude lower than irrigated agriculture (Meldrum *et al* 2013, Bukhary *et al* 2018).

Our study also highlights a significant avoidance of forest, wetlands, and developed land for LSS deployment. Despite 7.9% of LSS projects occurring over forests and wetlands, predominantly in the Delta, Eastern Mountains, Northeast, and Southern regions of the CONUS, LSS are built on these lands in lower percentages than their overall share of land-use in these regions. Conversion of these lands, which generally contain higher SOC, could lead to increased LULC emissions. However, this study did not quantify the SOC change caused by LULC change because of LSS deployment. Further research is needed to understand the long-term impacts of LSS placement on SOC dynamics, as a recent study finds that LULC change, including indirect effects, due to solar deployment may result in a net carbon emission up to 50 gCO₂/kWh (van de Ven *et al* 2021). Future studies can also compare these emissions with emissions offset by displacing fossil generators on the grid. Moreover, LSS installations have generally avoided developed land due to factors such as limited space for development, community opposition, and zoning regulations like structure setbacks (Eisensohn 2023, Lopez *et al* 2023).

This study is subject to several uncertainties that warrant future study. First, our analysis focused exclusively on land characteristics, excluding other critical siting drivers such as proximity to transmission lines, land cost and compliance with

social and environmental regulations (Alanazi *et al* 2020, Lopez *et al* 2023). These factors can significantly influence local decisions regarding utility-scale PV development. Ignoring these factors may affect the null hypothesis in this study—that all LSS projects are distributed proportionally to the land availability and that all lands are developable. Future work could extend this analysis using methods from advanced spatial statistics to identify critical siting drivers and the spatial processes underlying historical LSS deployment patterns. Second, we did not assess the land use characteristics after the LSS installations. The management of land beneath LSS panels may impact various factors, including soil structure, microclimatic conditions, and SOC dynamics—key determinants for ensuring sustainable land use. Third, USPVDB does not include those small-scale PV facilities less than 1 MW and does not cover the installations in 2022 and 2023 at the time of writing, which may lead to an underestimation of land converted for utility-scale PV use. In addition, the database only delineates the LSS array boundaries, not the total land used for LSS facilities (e.g. other land uses such as the road and fencing beyond the area covered by array), which is another factor of underestimation. Fourth, not all land variables have annual mapping covering the temporal range for land use analysis prior to LSS installations. However, we have leveraged the datasets of the highest fidelity available, and we believe they are sufficient to summarize national-scale patterns. Finally, uncertainty may arise from the zonal-statistics approach to summarize land characteristics. For example, applying a majority rule to categorical variables may simplify heterogeneous land compositions within individual facilities; future studies could further quantify the proportional area of each land category converted to LSS.

5. Conclusions

Continued expansion of LSS energy underscores the importance of understanding historical land use deployment patterns and trends in order to better inform future development. Our study reveals that while LSS deployment has expanded significantly in recent years, its overall impact on land use and land cover remains minimal compared to other drivers of land use change in the United States. LSS projects have been disproportionately concentrated on agricultural lands and shrubland compared to those lands' share of total land mass in the United States. Soybeans and corn—the most displaced crop types for LSS—are not disproportionately targeted relative to their overall share of cropland. Notably, the majority of LSS installations on agricultural land occur on areas ranked above the national median in terms of land

quality, raising potential concerns about preserving high-quality farmland. LSS deployment shows a strong association with irrigated lands and regions with higher GHI, reflecting a focus on transforming productive and resource-rich areas. Overall, this work reveals the historical patterns and trends in LSS siting, underscoring the need for strategic siting to balance energy development with land preservation.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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