Solar Land Use Conversion: A Review

Literature review of soil, water, and ecosystem impacts from the land use land cover conversion for utility-scale solar energy photovoltaic facilities.

Abstract

Introduction: Utility Scale Solar Energy (USSE) photovoltaic generation is forecasted to lead the decarbonization strategy of the United States. Models predict that by 2050 up to 40,000 km2 (about twice the area of New Jersey) will be converted to USSE (NREL, 2021). With over 3,600 USSE facilities in operation, it is timely to analyze documented and forecasted ecological impacts from this energy transition.

Methods: This study identified the existing literature for the ecological impacts of LULC for USSE construction and operation. To align with decarbonization goals and valuable ecosystem services, the impacts to 1) biodiversity and 2) carbon sequestration were the focus of this study. The results of the literature review were then analyzed for ecological impacts within the US coastal plain.

Results: Existing research on USSE is concentrated within arid or semi-arid habitats within native grasslands or shrublands habitats. Biodiversity impacts from LULC to USSE are anticipated to negatively influence migratory corridors. Increases in carbon sequestration within the soil and vegetation biomass are anticipated from the LULC conversion to the USSE since LULC conversion to USSE is forecasted to dominate croplands. Further empirical studies on USSE is necessary especially outside of arid or semi-arid habitats.

Keywords: USSE, LULC, Photovoltaic, ecosystem services, biodiversity, carbon sequestration

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Abbreviations List

Abbreviation	Definition
EIA	Energy Information Administration
GW	Gigawatt
LULC	Land Use Land Cover
km	kilometer
MW	Megawatt
NLCD	National Landcover dataset
NLUD	National Landuse dataset
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Lab
PV	Photovoltaic
SEIA	Solar Energy Industries Association
US	United States
USPVDB	United States Large-Scale Solar Photovoltaic Database
USSE	Utility Scale Solar Energy

1.0 Introduction

1.1 Significance

The past decade has seen an exponential increase in utility-scale solar energy (USSE) development across the United States (US) (Hernandez et al., 2014; US Energy Information Administration [US EIA], 2024c). Figure 1 demonstrates the exponential trend in US solar installations across the US dominated by USSE facility installations (Solar Energy Industries Association [SEIA] and Wood Mackenzie, 2024). Solar generation is the current leader in energy *capacity* as depicted in Figure 2. Additionally, solar generation is forecasted to lead in renewable energy *generation* by surpassing hydropower in 2024 (SEIA and Wood Mackenzie, 2024; US EIA, 2023a; US EIA 2023b; Wilson et al., 2020). The trend of exponential growth in installation and the federal decarbonization goals of 2030 and 2050 indicate that USSE deployment will continue to grow for decades (Jenkins et al., 2021; The White House, 2021; The White House, 2023).

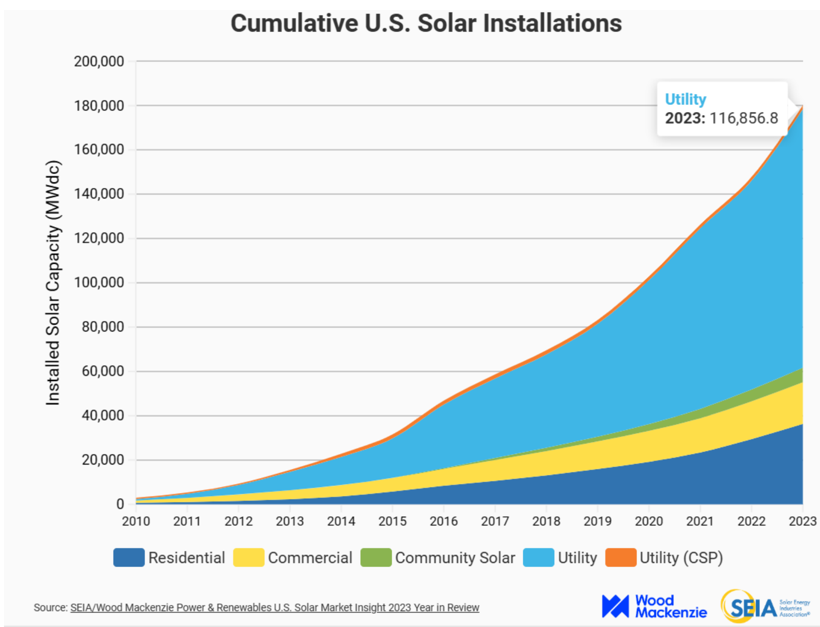

Figure 1 Solar Energy Installation Growth: Exponential growth of solar energy installations from 2010 to 2023 (SEIA and Wood Mackenzie, 2024)

1.2 Utility-Scale Solar Energy Photovoltaic Basics

Two requirements exist for a solar energy-generating facility to qualify as a USSE. First, USSE facilities inject generated electricity into the grid. Second, USSE facilities have a large generation capacity with a nameplate greater than 20 megawatts (MW) but US EIA categorizes USSE as low as 1 MW or greater (US EIA, 2024; Bukhary et al., 2014; Hernandez et al., 2014a; Hernandez et al., 2014b). These two qualities distinguish USSE from rooftop solar or other small commercial and residential solar generating facilities.

USSE are large-scale facilities encompassing several hundred acres with infrastructure to inject the generated power directly into the grid. USSE facilities can include generation from photovoltaic (PV) or concentrating solar power (CSP) with PV projected to dominate in USSE technologies by 2050 at a rate of 190 times more than CSP for land area necessary (NREL, 2021). This study only focuses on PV USSE when referencing USSE. The USSE facility with its many ancillary structures is the footprint. The US Large-Scale Solar Photovoltaic Database (USPVDB) is a remote sensing database updated annually that presently encompasses the footprint of only the photovoltaic arrays of USSE facilities with an operation date between 1986 and 2021. Figure 2 depicts the footprint of a USSE facility as defined by the USPVDB in blue and a footprint that captures the ancillary structures with limits of disturbance from USSE development and operation in pink. The Ancillary structures that dominate the USSE footprint include the stormwater control features, construction laydown yard, inverters, and transmission interconnect facilities (Hernandez et al., 2014b). The arrays of photovoltaic modules provide the generation of the USSE, comprise the largest percentage of the USSE footprint, and are captured by the USPVDB. The total footprint is the land area converted to the land use of a power generating USSE facility.

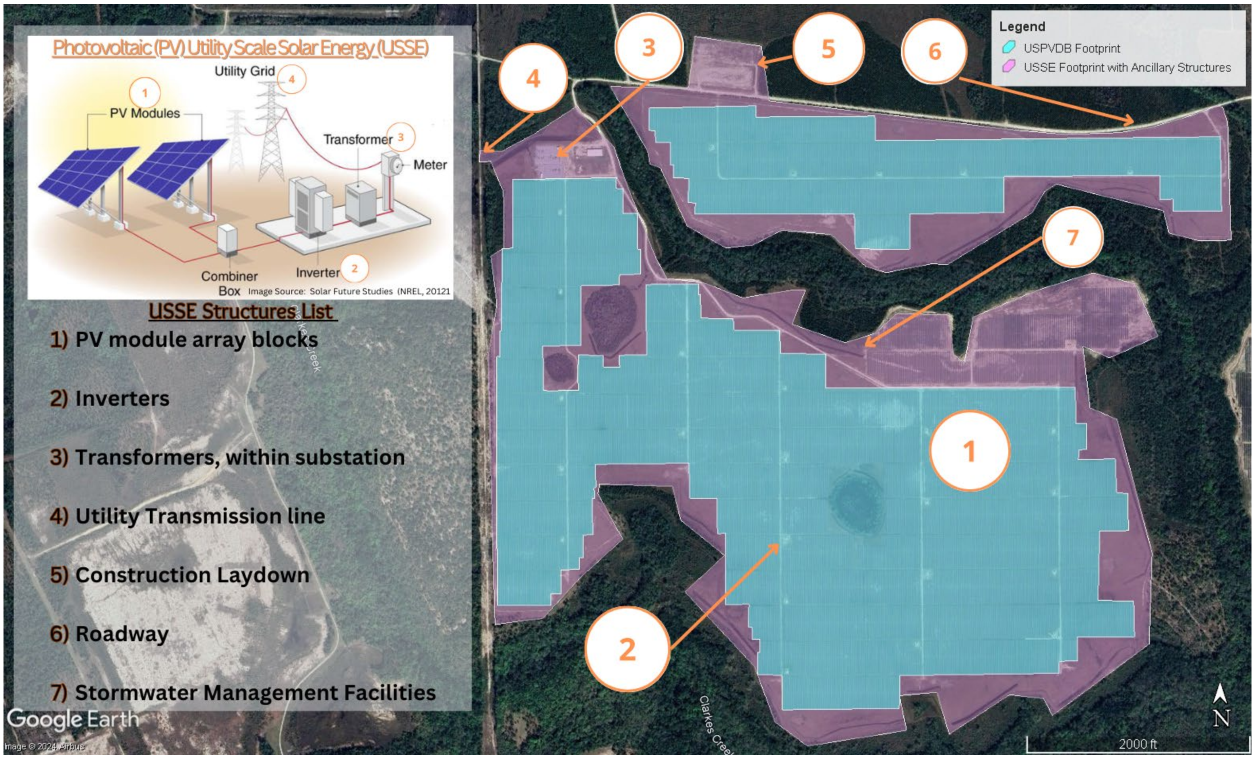

Figure 2 USSE Facility Footprint and Ancillary Structures: Depicting the PV footprint from the USPVDB (blue), aerially identified USSE footprint (pink), and identified ancillary structures of a USSE ground-mounted photovoltaic plant (numbered) (Google Earth, 2022; NREL, 2021; Fujita et al., 2023).

1.3 Land Cover and Land-Use Change Overview and Importance

Land use and land cover (LULC) are major influencers of the ecosystem at local and global scales which in turn influence the ecosystem services and functions of an area. Land cover is defined as the composition of the vegetation or structures which cover an area of land; while land use is the anthropogenic activities of the area (Sleeter et al., 2018). As the global population and demands on natural resources increase, land scarcity and pressures on ecosystem services are also increasing (Kruitwagen et al., 2021). Massive transformations of the LULC are anticipated due to the USSE deployment and “public opposition to large-scale construction impacts and changing landscapes” poses a very real and high risk to the US decarbonization goals (Jenkins et al., 2021). Analyzing LULC for USSE can help educate the public on the scope of USSE impacts and provide sustainable development suggestions to decrease public opposition and preserve ecosystem services.

2.0 Objective

This study explored the ecological impacts of LULC conversion to ground-mounted photovoltaic (PV) USSE through the construction and operation phases of facility development. The literature review was conducted to provide insights for sustainable development in the renewable energy transformation of the US. This study focused on the coastal plain where horizontal irradiance potential indicated strong solar resources and where increased USSE development was forecasted (Jenkins et al., 2021; Sengupta et al., 2018; SEIA, 2024).

3.0 Methodology

The limits of the scope of this review included English-language peer-reviewed, government-issued, or industry literature. There were no publication date restrictions applied to the literature review other than before this March 2024 study. The Web of Science Core Collection database was the core method for obtaining peer-reviewed literature. Since the study focused on USSE within the US, a preference for US government or US industry sources was leveraged. Due to limited available research in the area, the peer-reviewed literature was filtered for content and not by geographic area of study. First a wide national and global lens was applied to the literature review to capture the breadth of LULC. Then the extent was narrowed to the regional and facility level to assess the impacts to 1) biodiversity and 2) carbon sequestration. Finally, the information was extrapolated to the focused Coastal Plain for the four (4) focus areas. The references section includes the complete list of the agencies and sources.

4.0 Results

4.1 Methodologies Used for Ecological Evaluation

Existing studies assessing LULC conversion for USSE relied heavily on remote sensing, and forecast modeling, with a limited number of field studies. Remote sensing techniques were used to map, analyze, and forecast the LULC composition and change globally and nationally. Due to limited available field research on USSE facilities, most studies utilized the results of field investigations upon similar land cover or targeted species to extrapolate to the anticipated impacts of USSE development. The field studies that assessed USSE site conditions and microclimates were similarly designed with three core sample locations (Figure 3). These three core locations were a control sample adjacent to the USSE facility footprint (outside) and two locations within the USSE facility footprint with sample points under the arrays (non-gap) or in the open space of the facility (gap) as depicted in Figure 3 below. The field studies that analyzed wildlife patterns associated with USSE were avian mortality count studies and global positioning service (GPS) tagged ungulate tracking. Desktop studies comprised the core results of LULC conversion for USSE.

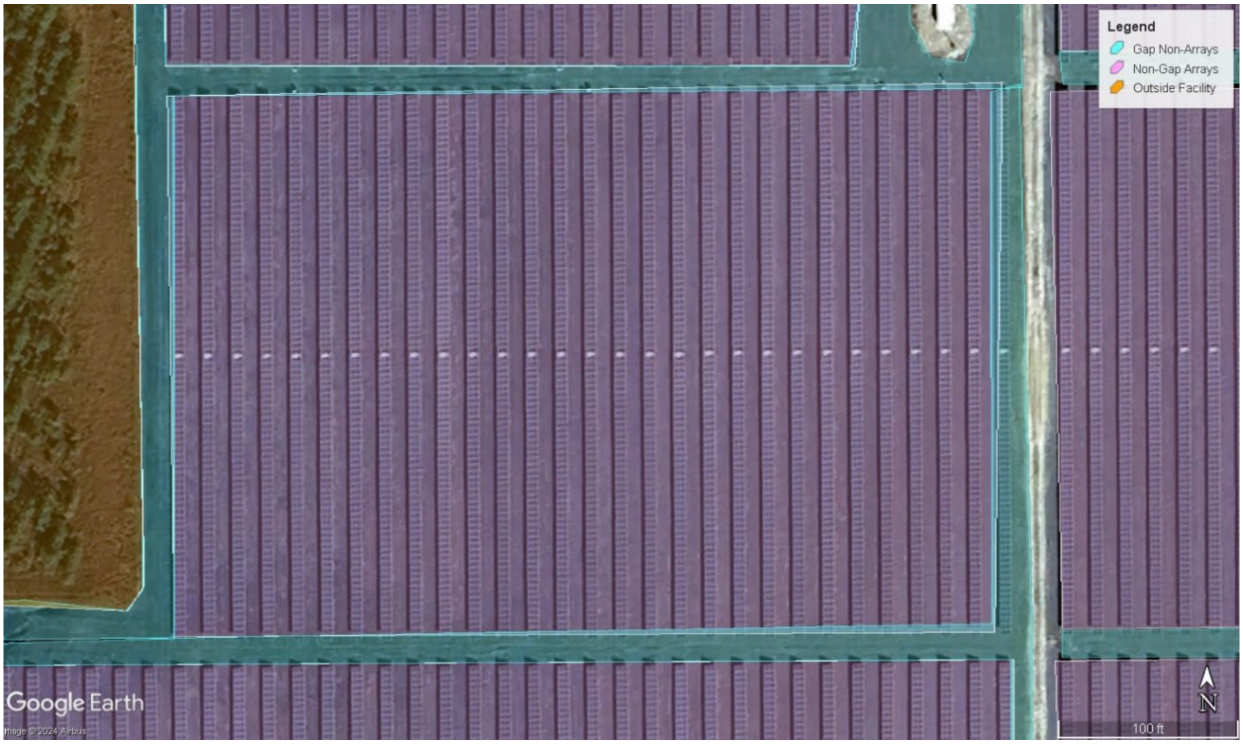

Figure 3 Analyzed Portions of USSE Facilities in Empirical Studies: USSE footprint soil and vegetation studies in the open space of the facility footprint (gap, blue) under the arrays (non-gap, pink or adjacent to facilities (outside, orange) (Google Earth, 2024).

4.2 Land Area Converted and Forecasted for Conversion to USSE

Assessing the breadth of completed and potential ecological impact from USSE development requires first understanding the total area converted and proposed for conversion to USSE. Within the US, maintaining grid reliability requires mandatory reporting to the US EIA on USSE and other utility-scale generation but the reporting does not require the submission of the area of the facility footprint (US EIA, 2023b). Thanks to advances in remote sensing and machine learning, the USPVDB was created to capture the extent of the photovoltaic area of USSE of over 3,900 ground-mounted US PV USSE facilities in operation by 2021 (Fujita et al, 2023). Similar global databases were created that assessed USSE in operation in 2018 or earlier (Kruitwagen et al., 2021). In addition to facility extent, the USGS National Land Cover Dataset (NLCD) contains US land cover assessments since 2001 with the data publications used across many of the desktop studies reviewed in this paper (USGS, 2008). Uniquely, to monitor land use changes, the National Land Use Dataset (NLUD) was created (Sleeter et al., 2018). The results of these LULC datasets were that globally USSE development is predominantly built upon and the greatest potential for future development upon former croplands (Adeh et al., 2019; Kruitwagen et al., 2021).

The forecasting for future USSE coverage in the USSE entailed the creation of models that predicted technological improvements in generation per square meter (energy density) and predictions on policies that will enhance USSE development success (Hernandez et al., 2015; Jacobson et al., 2015; Jenkins et al., 2023; Levin et al., 2023). All models and forecasts agreed that a significant percentage of the US will be converted to USSE due to the US decarbonization goals of 2030 and 2050. Table 1 depicts the model predictions for land area converted to USSE by 2050 which ranges from 14,000 km^2, the size of Connecticut, to 40,000 km^2, between the size of Maryland and West Virginia (Hernandez et al., 2015; Jacobson et al., 2015; Levin et al., 2023; US Census Bureau, 2021).

Referenced Study	2050 USSE estimated capacity (GW)	2050 estimated area converted to USSE (km^2)
Hernandez et al., 2015	500	14,285
Jacobson et al., 2015	2,326	17,383
Levin et al., 2023	1,484	40,000
NREL, 2021	1,570	41,650

Table 1: model predictions for land area converted to USSE by 2050.

4.3 Ecological Features of US Regions with High Potential for LULC to USSE

The Southwest leads in solar resources followed by the Southeast, the Northwest, and finally the Northeast (Jacobson et al., 2015; Sengupta et al., 2018; Figure 4). The NLCD and NLUD provide valuable national-level data on land composition. As depicted in Figure 5, the top two solar resource regions, the southwest and southeast contain contrasting land covers and land uses. The southwest land cover is dominated by 65.9% grassland and shrub habitats followed by 19.5% forestland with a dominant land use of production at 51.2% and a secondary land use of conservation at 36.6% (Sleeter et al., 2018). Meanwhile, the southeast land cover is dominated by 38.2% forestland habitats followed by 21.7% agriculture with a dominant land use of production at 43.5% and a secondary land use of built-up at 36.1% (Sleeter et al., 2018). The southwestern US is dominated by Xeric and Western Mountains ecoregions while the southeastern US is dominated by the Coastal Plains ecoregion (US EPA, 2023; Omernik, 1987). The two regions in the US with the highest solar resource are the Southwest dominated by grassland land cover and preservation land use and the Southeast dominated by forestland land cover and agricultural land use (Figure 5).

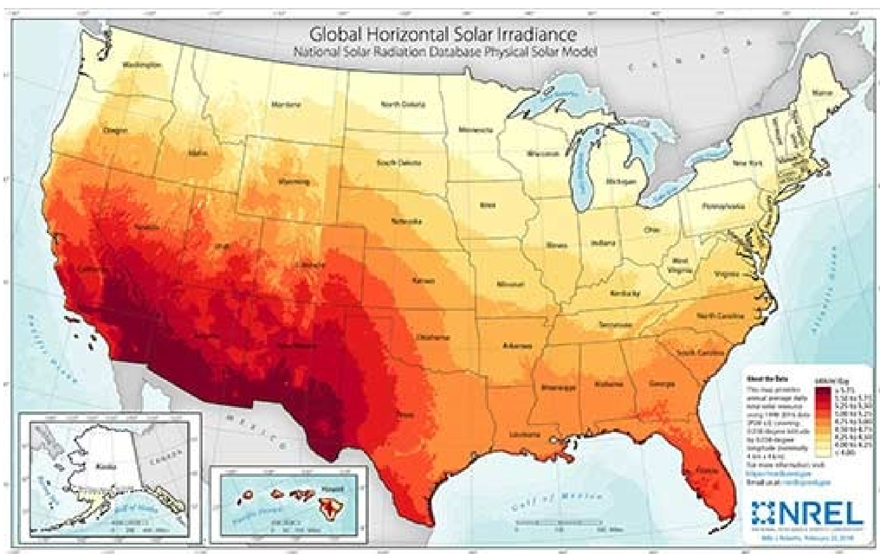

Figure 4 US Solar Resource from Annual Average Global Horizontal Irradiance: The Southwest leads in solar resource followed by the Southeast (Sengupta et al., 2018).

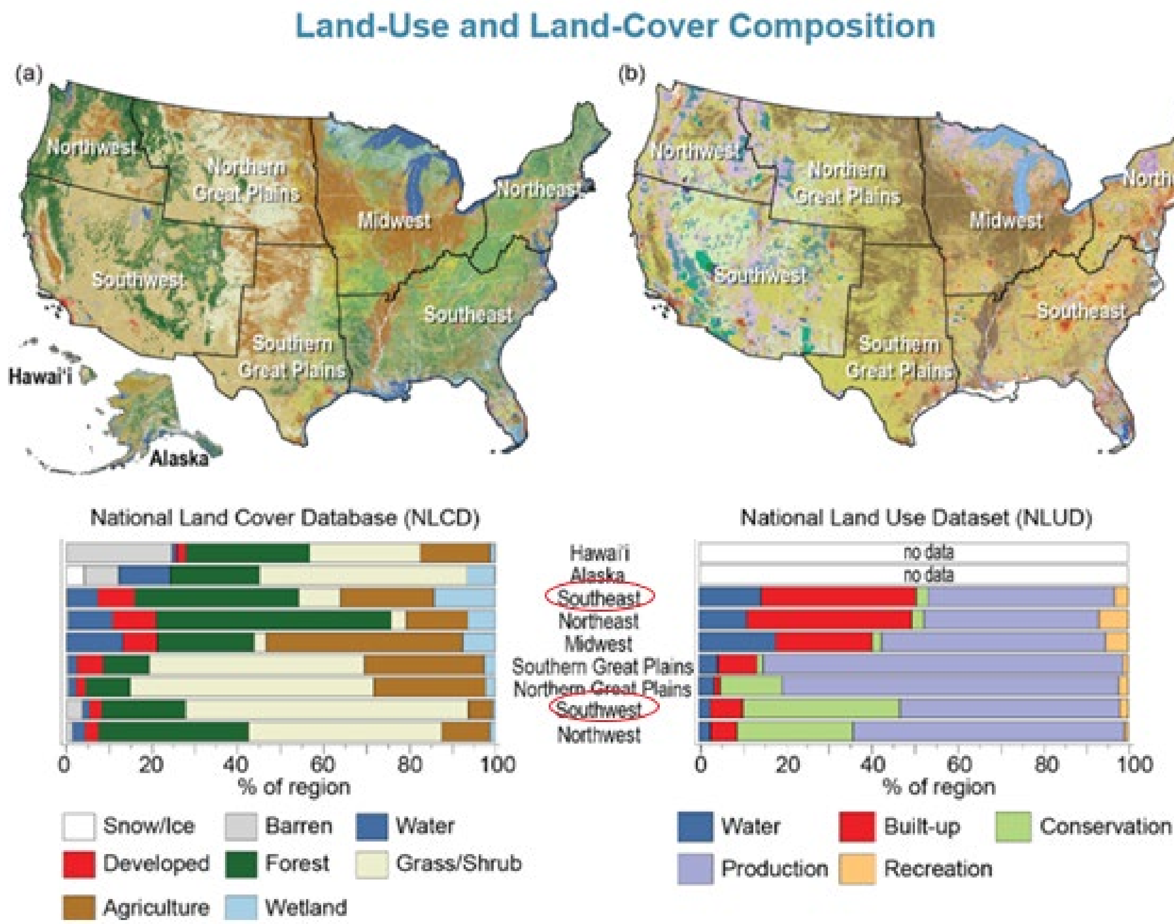

Figure 5 Land Use and Land Cover Composition Of The Contiguous US: Emphasis on the Southwest and Southeast land use and land cover (Sleeter et al., 2018).

There are twelve soil orders that group soils based on soil properties theorized to have been established through the same general genetic processes over millennia (Brady & Weil, 2008). Figure 6 depicts that the dominant soil orders in the Southwest are Alfisols and Aridisols while the Ultisols is the dominant order in the Southeast (Brady & Weil, 2008; Natural Resources Conservation Service [NRCS], n.d.). The following characteristics of the soil orders are from Brady & Weil, 2008 and Soil Survey Staff, 1999. Aridisols and Ultisols sit on opposite ends of the spectrum of weathering with Alfisols in the middle. The concept of Aridisols is based on the "limited availability of soil moisture for sustained plant growth," a slight degree of weathering, and formed under desert shrub vegetative conditions. The moderate characteristics of Alfisols include an intermediate degree of weathering with moist, mildly acid clay accumulation, and soils warm enough to grow plants over half the year. In California, Alfisols were formed under the savanna, a mix of trees and grass. Ultisols contain an intermediate-strong degree of weathering extensive in warm and humid environments, a wide variety of parent material, and formed under "mixed coniferous and hardwood forest vegetation at the time of settlement now used as cropland or pasture."

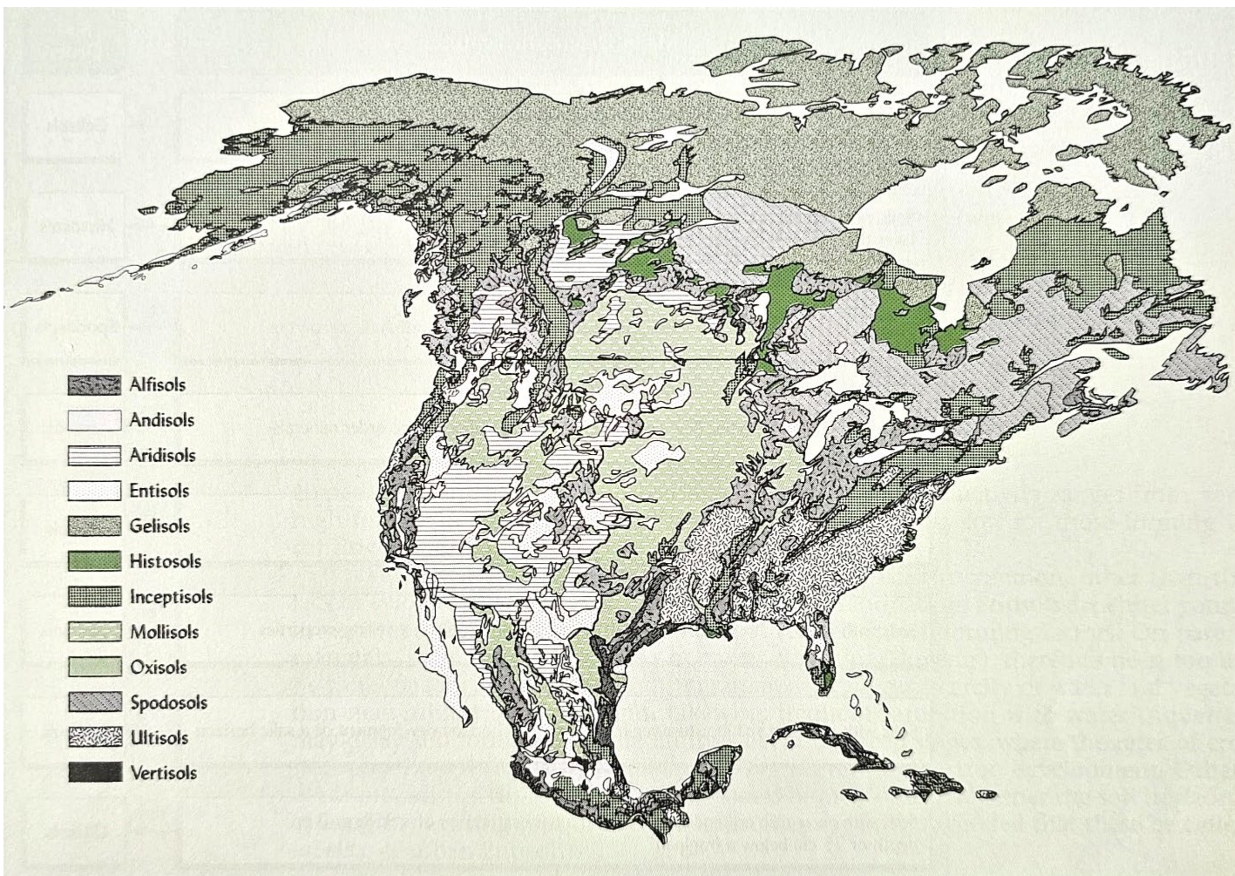

Figure 6 Simplified US Soil Order Map: A simplified map of the dominant soil orders of the contiguous US with dominant orders of Aridisols and Alfisols in the southwest and Ultisols in the southeast (Brady & Weil, 2008 adapted from NRCS, n.d.)

4.4 Overview of Ecological Impacts

Persevering ecological function is vital for maintaining ecosystem services as they provide essential infrastructure for human societies (Heal, 2001). Ecosystem services prioritized for preservation or management to align with the decarbonization goals of USSE development include 1) biodiversity and 2) carbon sequestration (Hastik et al., 2015; Heal, 2001; obz et al., 2015). The existing studies on the impacts of LULC conversion for USSE focused on arid or semi-arid grassland ecosystems. Preservation of these two ecosystem services is vital to maintaining the sustainable development objectives of the 2050 decarbonization.

4.5 Biodiversity

The studies on biodiversity impacts from LULC to USSE included analysis of avian mortality studies, soil sampling, global positioning service (GPS) tagged ungulate tracking, and desktop analysis of migration corridors. The avian study results were that a positive relationship was observed between facility size and avian mortality rate and the lake effect hypothesis was unsupported except in a narrow range of the desert bird corridors (Kosciuch et al., 2020; Kosciuch et al., 2021; Visser et al., 2017; Waltson et al., 2015). The field study with GPS-tagged ungulate tracking on pronghorn (*Antilocapra americana*) in Wyoming rangeland found that impenetrable USSE fencing disrupted ungulate biodiversity and migration (Sawyer et al., 2022). The desktop analysis for habitat fragmentation assessments did not leverage species GPS tracking but instead utilized existing published (Levin et al., 2023) or unpublished (Leskova et al., 2021) migration corridor models to predict impacts from LULC for USSE (Hernandez et al., 2014a; Lovich and Ennen 2011). Soil and plot sampling at USSE facilities indicated that the microclimate variation in sunlight and precipitation across the USSE footprint created an increase in the biodiversity of microbial and plant species (Bai et al., 2022; Li et al., 2023; Liu et al., 2023; Yuan et al., 2022). All studies supported that USSE siting upon previously disturbed or would have a lower impact on biodiversity, that LULC conversion to USSE is anticipated across migration corridors, and studies were concentrated in xeric habitats.

4.6 Carbon Sequestration

Carbon emissions from USSE plant operation are negligible (Bukhary, et al., 2018). The bulk of carbon loss associated with USSE LULC occurs within the construction phase of the USSE lifecycle due to the devegetation, removal of topsoil, and grading (Choi et al., 2018). Forests are vital carbon sinks (Heal, 2001) and the largest negative impact from above-ground disruptions to carbon sinks would be if USSE LULC primarily took place upon forestland (Redlin and Gries, 2021). However, global USSE analyses identified that major impacts on the carbon budget through deforestation were avoided as a preference for LULC conversion upon grassland or cropland habitats was observed (Kruitwagen, 2021) with a forecasted trend to continue a preference for non-forested land (Adeh et al., 2019). LULC conversion for USSE entails earth work and native vegetation removal which creates a change in the carbon sequestration of that ecosystem (Hernandez et la., 2014a; Zhao et al., 2024). Even more vital for balancing the carbon toward carbon sequestration is managing soil organic matter (SOM) as “more carbon is stored in the world’s soils than in the world’s plant biomass and atmosphere combined” (Brady and Weil, 2008). Several studies conducted soil or vegetation sampling for carbon content at USSE seven, eight, or an undisclosed number of years of operation in arid regions with all studies documenting carbon stores (SOC and vegetation) highest at the ‘outside facility areas’ undisturbed by USSE conversion, followed by the gap areas, with the lowest carbon stores at the non-gap under array samples which received the lowest sunlight and precipitation inputs as identified in Figure 3 above (Bai et al., 2022; Choi et al., 2020; Li et al., 2023; Moscatelli et al., 2022; Yuan et al., 2022; Yue et al., 2021; Zhao et al., 2024). The beneficial balance to the global carbon budget of the operational phase of USSE facilities in reduction of US emissions was valued at

$1 trillion in $2013 dollar for benefit from projected 2050 USSE generation (Jacobson et al., 2015). Carbon sampling in seven studies ranged from demonstrated that fire load reduction and anti-shading vegetation management did not negatively impact carbon sequestration as gap areas contained higher SOC than non-gap areas.

5.0 Discussion

5.1 Biodiversity Impacts from USSE LULC in the US Coastal Plain

Terrestrial mammal species richness is a biodiversity indicator with a higher number representing a higher biodiversity. The mammal species richness is low across the US compared to the rest of the rest of the western hemisphere (Olson et al., 2001). As depicted in Figure 5 and interpreted from Olson et al., 2001, the Southeast Coastal Plain contains a lower species richness (45-66) than the Southwest Western Mountains ecoregion (67-88) but the same score as the Southwest Xeric ecoregion. Therefore, the results of the biodiversity studies which fell within the Xeric ecoregion could translate well to the Coastal Plain in terms of assessing overall ecological impact to biodiversity. However, the Sawyer et al., 2022 study on ungulates within the Southern Plains would not translate well to the biodiversity impacts to the Coastal Plains.

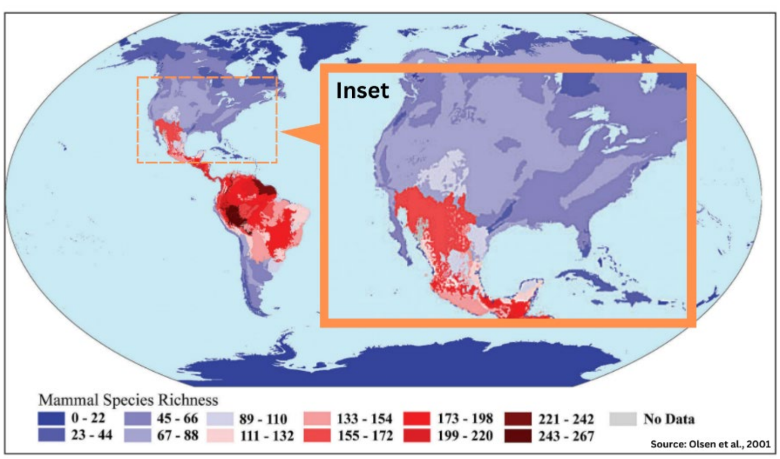

Figure 7 Biodiversity Indicator by Ecoregion: A map demonstrating biodiversity through the mammal species richness as refined by ecoregion (Olsen et al., 2001)

5.2 Carbon Cycle Impacts from USSE LULC in the US Coastal Plain

All seven documented field analyses on carbon sequestration in vegetation and soil were within arid or semi-arid regions upon formerly native grassland (Bai et al., 2022; Choi et al., 2020; Li et al., 2023; Moscatelli et al., 2022; Yuan et al., 2022; Yue et al., 2021; Zhao et al., 2024). As discussed in Sections 4.3 and 4.6 above, the Southeast is dominated by a LULC of forestland and production with an aversion to forestland habitats documented by USSE development (Kruitwagen, 2021). Therefore, cropland land use is assumed to dominate the LULC conversion to USSE within the Southeast which would entail a shift from rotational crop land use to a perennial cover grass and would increase carbon sequestration (Brady and Weil, 2008). Carbon sequestration is anticipated to be higher due to the increased weathering within Ultisols in the Coastal Plain compared to the field studies completed in the arid and semi-arid habitats. The studies were near one decade of USSE operation with soils observed as still demonstrating a statistically significant difference in SOC compared to the undisturbed soils (Bai et al., 2022; Choi et al., 2020; Li et al., 2023; Moscatelli et al., 2022; Yuan et al., 2022; Yue et al., 2021; Zhao et al., 2024). Within the Coastal Plain, accumulation of SOC to pre-construction levels is anticipated to occur at a faster rate, nearer two years as the USSE operation contains a perennial grass species, typically bahiagrass (*Paspalum notatum Fluegge*), which is documented to improve SOC in rotation crop land covers (Gamble et al., 2014). Carbon gains in the active faction of vegetation and soils and then the sequestered faction is anticipated to accumulate faster in the Coastal Plain (Brady and Weil, 2008). Due to increased weathering in the Ultisols of the Coastal Plain and impacted soils from rotation crops, carbon sequestration is forested to be an improved ecological impact from USSE LULC conversion.

6.0 conclusion

6.1 Summary of Findings

Assessing the ecological impacts from land use and land cover (LULC) conversion to Utility-Scale Solar Energy (USSE) required first a wide national lens view followed by narrowing the extent to the regional and facility level. The national results were that 11,000 to 40,000 km2 is forecasted for conversion to USSE which encompasses the photovoltaic (PV) footpring and ancillary structures but not transmission lines. Digging into the ecological shifts from LULC to USSE or USSE operation, required a narrow regional or facility scale assessment on biodiversity, carbon sequestration, and nutrient cycles. The studies regions included in these studies were xeric or arid habitats. Ecological impacts from LULC to USSE was mostly associated with corridor disruptions predominantly from roadways or transmission corridors than the USSE facility footprint (Lovich and Ennen, 2011). Spanning14,000 km^2 to 45,000 km^2, the proposed LULC encompasses a grand land area. However, the estimated LULC conversion is less than the 30,000 km^2 land area already converted by 2020 for oil and gas wells, ancillary roadways, and storage facilities, which did not include the area for oil and gas combustion facilities (Levin et al., 2023).

6.2 Limitations and Gaps

A complete picture of the ecological impacts of photovoltaic (PV) USSE energy production requires a cradle-to-grave approach spanning the phases of component manufacturing and material acquisition, construction, operation, and decommissioning. The advanced supply chain economics required to assess USSE component manufacturing of operational and future USSE was beyond the capabilities of this study. USSE facilities are forecasted for a 30-year operation lifetime and due to the recent deployment of USSE, no studies on decommissioning were identified (NREL et al., 2021). Not all phases of the USSE lifecycle were analyzed by this study but the LULC conversion during the construction phase and the 30-year operation phase would have the most impact on regional and global ecologies.

No studies of USSE in converted row crop or coastal plain ecoregions within the US or worldwide were identified with very few empirical studies conducted overall. Due to the gap in empirical ecological studies of USSE, the US Department of Energy (DoE) Solar Energy Technologies Office issued $15 million in funding in 2022 via the Solar with Wildlife and Ecosystem Services Benefits (SolWEB) Funding Program (US DoE, 2022). Until the results of these studies are published, the methodologies of the existing studies and this study were limited to extrapolating completed empirical studies to apply to USSE assessments.

6.3 Future Implications for Research, Policy, & Action

Society is in an energy transition with major transformations from USSE development forecasted not only within the US but globally. This transition brings opportunity for research. Studies that create economic and ecologically beneficial technologies and practices are vital for creating a sustainable transition. Since croplands contain the greatest USSE potential (Adeh et al., 2019), research opportunities are available that focus on the sustainable conversion of cropland land uses to USSE. Improvements in PV technology expanded the suitability of non-arid ecoregions for USSE and further studies in these habitats are necessary with a bias toward arid habitats identified across all studies. Policy and political action necessary to combat climate change and implement decarbonization strategies entails maintaining the progress from the Inflation Reduction Act (IRA) and expanding the research provided through SolWEB to fill the gap of empirical research on USSE. Public opposition through local pushback creates a large risk to USSE development and meeting 2050 decarbonization strategies (Jenkins et al., 2021). Actions that continue expanding research to address local environmental concerns and pairing the research with communication initiatives is vital to complete the sustainable energy transformation across the US and globally.

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