DISSERTATION

SHARING SUNLIGHT: ECOSYSTEM ECOLOGY OF MULTI-USE SOLAR ENERGY SYSTEMS IN THE SOUTHEASTERN U.S.

Submitted by

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ABSTRACT

SHARING SUNLIGHT: ECOSYSTEM ECOLOGY OF MULTI-USE SOLAR ENERGY SYSTEMS IN THE SOUTHEASTERN U.S.

Solar photovoltaic (PV) energy generation is one of the most impactful strategies for reducing global greenhouse gas emissions and mitigating climate change. However, compared to fossil-based energy sources, solar PV has a significantly higher spatial footprint and is often sited on agricultural lands, raising concerns about environmental impact and agricultural displacement. This has spurred the emergence of multi-use solar PV systems, where agriculture (agrivoltaics) or ecosystem services (ecovoltaics) are integrated with solar energy generation on the same piece of land. These systems have the potential to increase land-use efficiency, improve the environmental outcomes of large-scale solar deployment, and provide a range of co-benefits. This dissertation presents an evaluation of the ecological impacts of solar PV systems in the southeastern United States, a geographic and climatic region underrepresented in previous research. The results of three field studies at operational PV arrays across the southeastern U.S. highlight the potential for multi-use solar PV in this region. Data from these sites show minimal effects from low-impact array construction methods, including avoiding grading and retaining vegetation cover, the potential to maintain vegetation and agricultural productivity, despite the reduction in solar radiation and redistribution of precipitation from the PV modules, and no evidence of negative impacts on soil carbon stocks. This work emphasizes the influence of both climate region and site-specific variables, including array geometry, tracking algorithm, and soil texture, and the importance of considering these factors in both research and practice.

ACKNOWLEDGEMENTS

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To my advisor, Dr. Keith Paustian – thank you for taking a chance on an engineer who wanted to study soil science. I have learned so much from you, not just about soil biogeochemistry and ecosystem ecology, but about how to ask good questions and look at the world as a scientist. To my committee, Dr. Rich Conant, Dr. Alan Knapp, and Dr. Meagan Schipanski, thank you for your guidance and encouragement throughout this academic adventure. To my incredible team of CSU lab assistants – Brennan Curry, Kent Klevens, Nicole

Murray, Alex Schmett, Rebekah Ramirez, and Sara Powell, thank you for your endless hours of sieving soils and grinding biomass samples. Lab work is not always glamorous, but it is the backbone of research, and this work would not have been possible without you. Thank you to the InTERFEWS program and the SoGES Diana Wall Sustainability Fellowship for expanding my graduate school experience, for introducing me to the most incredible students across the university, and for helping me build the skills to scale the impacts of my research.

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CHAPTER 1: INTRODUCTION

1. Climate, Carbon & Clean Energy

The rapid increase in emissions of greenhouse gases (GHGs) since the Industrial Revolution has disrupted the planetary energy budget, raising global mean temperatures and resulting in a cascade of harmful effects (IPCC, 2023). From 2011 to 2020, the global mean temperature was 1.1 °C warmer than from 1850 to 1900 (IPCC, 2023). While the world is already experiencing the impacts of this warming, from increasingly destructive extreme weather events, to extended droughts, and dangerously high temperatures, the magnitude and severity of these impacts will only intensify under business-as-usual emission scenarios (IPCC, 2023).

Without a deep and rapid reduction in emissions, global temperatures could rise by as much as 4 °C by the end of the century, ushering in more extreme heat, droughts, and more intense precipitation and flooding events (IPCC, 2023). Together, these climate changes pose threats of species loss, severe challenges for food production, and serious harm to human health. Avoiding the most devastating impacts of climate change requires reaching net zero GHG emissions by the end of the century, with global carbon dioxide (CO_2) emissions reaching this point even earlier (IPCC, 2023).

At the heart of a rapid reduction in GHGs is decarbonized energy generation, which accounts for over a third of GHG emissions globally (Dhakal et al., 2023). Energy generation is not only one of the most technologically mature areas for decarbonization, but also facilitates the decarbonization of other sectors via electrification (Clarke et al., 2023). Transitioning away from a fossil fuel-based energy system will require a suite of renewable and low-carbon energy technologies, with a tailored mix of solutions for different climate regions and geographies (Clarke et al., 2023).

From a GHG mitigation perspective, solar energy is among the highest potential near-term strategies. The IPCC Sixth Assessment Report found that solar energy could reduce GHG emissions by up to 4.5 petagrams (Pg) CO_2 eq/year, most of which could be achieved at a cost below the reference case (IPCC, 2023). The cost of solar PV has plummeted over the last two decades, and installation has increased exponentially (Clarke et al., 2023), scaling from around 135 GW in 2013 to nearly 2,000 GW in 2024 (IRENA, 2025).

However, reducing GHG emissions alone is not sufficient to reach net zero – nearly all decarbonization scenarios include emission sinks that actively draw CO_2 out of the atmosphere (IPCC, 2023; Larson et al., 2021). While there will likely be technological solutions, such as carbon capture and storage from fossil-based power plants or direct air capture, one of the most powerful engines for drawing down CO_2 is leveraging the power of photosynthesis and nature-based climate solutions (Griscom et al., 2017; Paustian et al., 2016).

Globally, soils hold around 1500 Pg of carbon in the top meter – more than the atmosphere and all terrestrial biomass combined (Batjes, 1996; Lal, 2008; Scharlemann et al., 2014). Through conversion of native soils to agriculture and certain management practices, agricultural soils have lost an estimated 133 Pg C from the top two meters, mostly within the last 200 years (Sanderman et al., 2017). This means there is a significant opportunity for sequestering carbon in these depleted soils. Alongside solar and wind energy, the Sixth Assessment Report identifies reduced conversion of natural ecosystems, carbon sequestration in agriculture, and ecosystem restoration, afforestation, and reforestation as the next highest potential mitigation options in the near term, ranging from about 3-4 Pg CO_2-eq/yr mitigation potential (IPCC, 2023).

2. The Case for Multi-Use Solar Energy

Multi-use solar PV, or the practice of integrating solar energy generation alongside other land uses such as agriculture or ecosystem services, has emerged as a uniquely positioned climate solution at this intersection of CO_2 emissions reduction, nature-based climate solutions, and climate adaptation. While solar energy has many advantages as a renewable electricity source, including low water demand, modular deployment capability across a range of scales, and low costs compared to fossil generation sources (Solar Futures Study, 2021), it has a higher land footprint per unit of energy (van Zalk & Behrens, 2018). Because of the larger land footprint, the land management and potential land-use change emissions associated with the construction and presence of solar arrays could actually negate some of the climate mitigation benefits (van de Ven et al., 2021).

Additionally, and especially in the United States, a majority of solar arrays are sited on former crop or grazing lands (Maguire et al., 2024), raising concerns about the loss and displacement of agricultural production. Conventional solar PV development often has negative environmental impacts (Grodsky & Hernandez, 2020; Hernandez et al., 2014), usually tied to construction practices like vegetation scraping, grading, and topsoil removal, or management practices such as spraying herbicide and/or pesticide.

Spurred by both these challenges and potential synergies, the practice of integrating other land uses with solar energy generation has emerged and steadily grown over the last decade and a half. Agrivoltaics, or the integration of agriculture and solar photovoltaics, was first proposed in the 1980's by German solar energy researchers (Goetzberger & Zastrow, 1982). It wasn't for another several decades, however, that both research and practice in the field truly took off, with a 2011 paper often attributed with the origin of the term "agrivoltaics" (Dupraz et al., 2011). In the decade and a half since, research in the field has expanded rapidly, with over a 700% increase between 2013 and 2023 (Bacon et al., 2024). Much of this research has focused on characterizing the unique microclimatic conditions within PV arrays and evaluating the potential of different crops in these systems (Adeh et al., 2018; Armstrong et al., 2016; Barron-Gafford et al., 2019; Mamun et al., 2022; Vervloesem et al., 2022).

Ecovoltaics, or the integration of ecosystem services and solar PV, encompasses a wide range of multi-use systems where ecosystem function is co-prioritized alongside energy generation (Sturchio & Knapp, 2023). This can include planting pollinator habitat, managing for soil carbon sequestration, or supporting biodiversity (Randle-Boggis et al., 2020; Walston et al., 2018).

While the field is still quite young, research to date suggests strong potential synergies of multi-use solar PV systems, including increased water use efficiency, improved yield of certain crops, and greater drought resilience (Barron-Gafford et al., 2019; Merheb et al., 2025; Sturchio & Knapp, 2025). These synergies are particularly valuable in the context of climate adaptation, as we move into a hotter, drier world in many areas.

3. Multi-Use Solar PV in the Southeastern United States

Motivated by the expansion and potential of multi-use solar PV as a climate solution, but recognizing the associated complexities, this dissertation presents a systematic evaluation of multi-use solar PV systems in the southeastern U.S. I focus on grassland ecosystems, with research relevant to both agrivoltaic grazing systems and ecovoltaic systems more broadly.

This dissertation consists of four core chapters (Figure 1). The following chapter (Chapter 2) provides context for the subsequent empirical chapters, consisting of a literature review and gap analysis for agrivoltaic grazing systems. Since existing research on these systems is quite limited, the review draws on adjacent fields, covering research on the ecological impacts of PV infrastructure in grasslands, as well as the integration of livestock and solar PV.

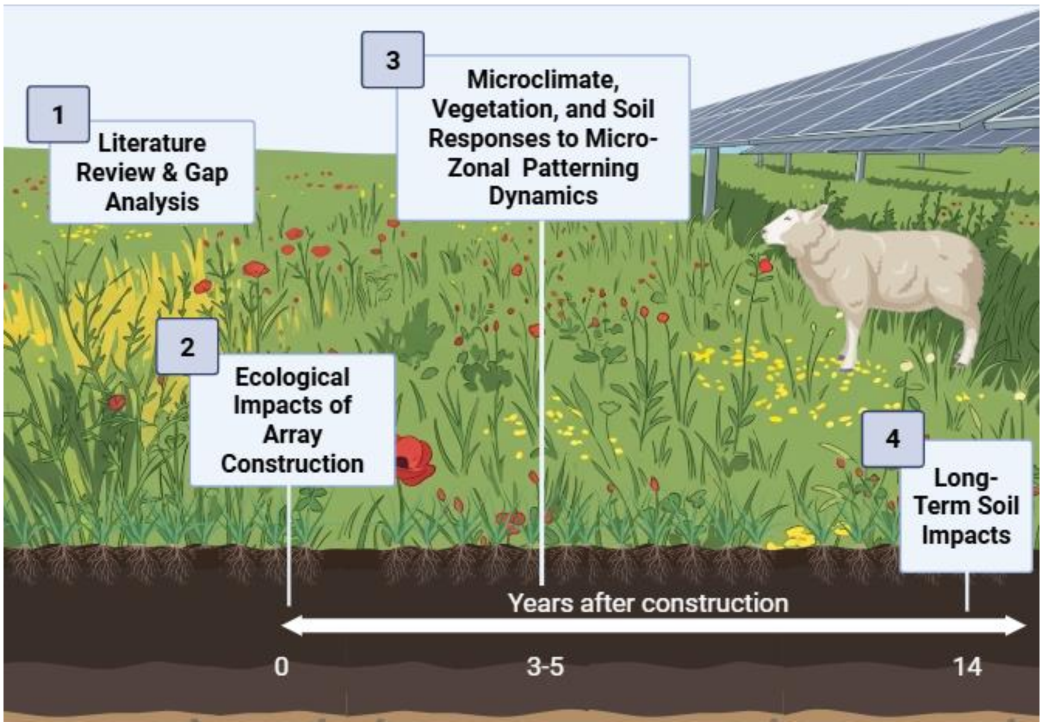
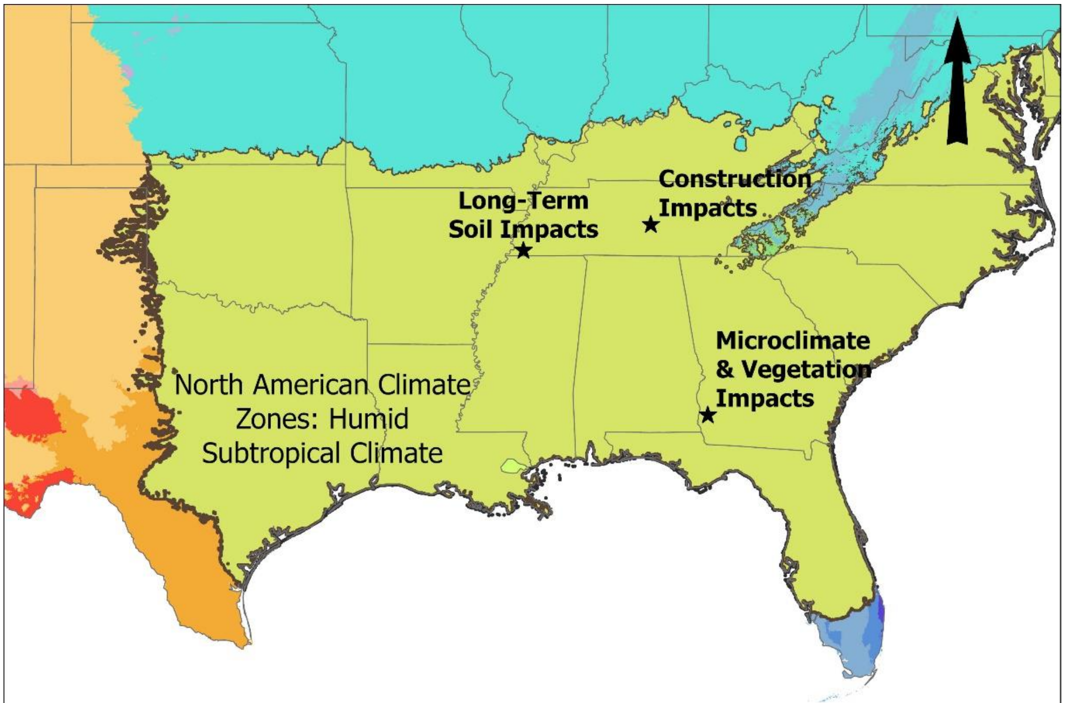


Figure 1. This dissertation consists of four core chapters. The first presents a literature and gap analysis on agrivoltaic grazing systems, providing the context for the following empirical chapters. The next three chapters present data from three different field sites in the southeastern U.S., presenting research across the lifespan of a multi-use solar PV array, from construction impacts on ecosystem variables, to the vegetation and soil responses to the microclimate created by PV modules, and how this interacts with land management, to the long-term impacts of PV arrays on soil properties. *Figure created with BioRender.*

The three field-based chapters present research from three different operational, single-axis tracking PV systems in the southeastern U.S (Figure 2), contributing to some of the key research gaps identified in Chapter 2. These site investigations ranged from the pre-construction phase to fourteen years post-construction, facilitating the evaluation of ecological impacts across the lifespan of a PV array. Together, these chapters explore the short- and long-term ecological impacts of solar PV infrastructure and multi-use solar in a humid subtropical climate to better understand the potential benefits, as well as the tradeoffs, of these systems.



Study	Construction Year	Capacity (MW)	Management
Long-Term Soil Impacts	2011	1	Mowed
Construction Impacts	2025	4.5	Cattle Grazing
Microclimate & Vegetation Impacts	2019	102.5	Sheep Grazing / Mowing

Figure 2. This dissertation includes data from three field sites across the southeastern United States. All field sites are located within the Humid Subtropical North American Climate Zone (green), with two sites in Tennessee and one site in Georgia. All field site arrays were single-axis tracking, with capacities ranging from 1 MW to over 100 MW.

Chapter 3 presents data on the ecological impacts of array construction. Chapter 4 presents data from an extensive field study on the microclimate alterations created by the PV modules within this climate region, impacts on soils and vegetation, and how these changes interact with management impacts. Chapter 5 presents data from a 14-year-old array, looking specifically at long-term soil impacts.

This dissertation addresses several key gaps in the field. First, research on multi-use solar PV systems within this climate region is limited, with much of the existing research concentrated in the arid west or temperate northeastern U.S or Europe. While abundant sunshine in more arid regions is more conducive to solar PV, we're seeing solar development across the entire country, with extensive buildout within the southeastern U.S. (SEIA, 2025). The extensive microclimate and vegetation data unique to this climate region fill a meaningful gap in the literature and body of knowledge. Next, paired pre- and post- construction sampling is very rare in the field, with only one other before/after control/impact study identified (Karban et al., 2025). Lastly, data on long-term (decade-plus) impacts on soils within PV arrays are very limited, and to my knowledge, the final chapter includes some of the oldest soil samples from within a single-axis tracking array. Together, this body of work provides valuable insights into the potential of multi-use solar PV in humid subtropical climates, with the goal of supporting the deployment of solar PV that is aligned with both climate and ecological sustainability.

REFERENCES

Adeh, E. H., Selker, J. S., & Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLOS ONE*, *13*(11), e0203256. https://doi.org/10.1371/journal.pone.0203256

Armstrong, A., Ostle, N. J., & Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*, *11*(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016

Bacon, T., Ohlert, T., Toy, C., Siggers, J. A., & Sturchio, M. A. (2024). Network science can improve the sustainable development of solar energy. *Environmental Research: Energy*, *1*(4), 043002. https://doi.org/10.1088/2753-3751/ad99dc

Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, *2*(9), Article 9. https://doi.org/10.1038/s41893-019-0364-5

Batjes, N. H. (1996). *Total carbon and nitrogen in the soils of the world*. https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/j.1365-2389.1996.tb01386.x

Clarke, L., Wei, Y.-M., De La Vega Navarro, A., Garg, A., Hahmann, A. N., Khennas, S., Azevedo, I. M. L., Loschel, A., Singh, A. K., Steg, L., Strbac, G., & Wada, K. (2023). 2022: Energy Systems. In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change* (1st ed., pp. 613–746). Cambridge University Press. https://doi.org/10.1017/9781009157926.008

Dhakal, S., Minx, J. C., Toth, F. L., Abdel-Aziz, A., Figueroa Meza, M. J., Hubacek, K., Jonchkheere, I. G. C., Yong-Gun, K., Nemet, S., Pachauri, S., Tan, X. C., & Wiedmann, T. (2023). Emissions Trends and Drivers. In *Climate Change 2022—Mitigation of Climate Change* (1st ed., pp. 215–294). Cambridge University Press. https://doi.org/10.1017/9781009157926.004

Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renewable Energy, Renewable Energy: Generation & Application*, *36*(10), 2725–2732. https://doi.org/10.1016/j.renene.2011.03.005

Goetzberger, A., & Zastrow, A. (1982). On the Coexistence of Solar-Energy Conversion and Plant Cultivation. *International Journal of Solar Energy*, *1*(1), 55–69. https://doi.org/10.1080/01425918208909875

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., … Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Grodsky, S. M., & Hernandez, R. R. (2020). Reduced ecosystem services of desert plants from ground-mounted solar energy development. *Nature Sustainability*, *3*(12), Article 12. https://doi.org/10.1038/s41893-020-0574-x

Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., Barrows, C. W., Belnap, J., Ochoa-Hueso, R., Ravi, S., & Allen, M. F. (2014). Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*, *29*, 766–779. https://doi.org/10.1016/j.rser.2013.08.041

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.

IRENA. (2025, July 10). *Solar energy*. https://www.irena.org/Energy-Transition/Technology/Solar-energy

Karban, C. C., Munson, S. M., Kobelt, L. A., & Lovich, J. E. (2025). Short-term ecological effects of solar energy development depend on plant community, soil type and disturbance intensity. *Journal of Applied Ecology*, *62*(4), 945–957. https://doi.org/10.1111/1365-2664.14882

Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 815–830. https://doi.org/10.1098/rstb.2007.2185

Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik, E., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K., & Swan, A. (2021). *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final report*. Princeton University. https://www.dropbox.com/s/ptp92f65lgds5n2/Princeton%20NZA%20FINAL%20REPORT%20%2829Oct2021%29.pdf?dl=0

Maguire, K., Tanner, S., & Winikoff, J. B. (2024, September 12). *Agricultural Land Near Solar and Wind Projects Usually Remained in Agriculture After Development*. USDA Economic Research Service. https://www.ers.usda.gov/amber-waves/2024/september/agricultural-land-near-solar-and-wind-projects-usually-remained-in-agriculture-after-development

Mamun, M. A. A., Dargusch, P., Wadley, D., Zulkarnain, N. A., & Aziz, A. A. (2022). A review of research on agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *161*, 112351. https://doi.org/10.1016/j.rser.2022.112351

Merheb, C., Macknick, J., Davatzes, N., & Ravi, S. (2025). Synergies and trade-offs of multi-use solar landscapes. *Nature Sustainability*, 1–14. https://doi.org/10.1038/s41893-025-01600-1

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174

Randle-Boggis, R. J., White, P. C. L., Cruz, J., Parker, G., Montag, H., Scurlock, J. M. O., & Armstrong, A. (2020). Realising co-benefits for natural capital and ecosystem services from solar parks: A co-developed, evidence-based approach. *Renewable and Sustainable Energy Reviews*, *125*, 109775. https://doi.org/10.1016/j.rser.2020.109775

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences*, *114*(36), 9575–9580. https://doi.org/10.1073/pnas.1706103114

Scharlemann, J. P., Tanner, E. V., Hiederer, R., & Kapos, V. (2014). Global soil carbon: Understanding and managing the largest terrestrial carbon pool. *Carbon Management*, *5*(1), 81–91. https://doi.org/10.4155/cmt.13.77

SEIA. (2025). Solar State By State. *SEIA*. https://seia.org/solar-state-by-state/

Solar Futures Study. (2021). U.S. Department of Energy. https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf
Sturchio, M. A., & Knapp, A. K. (2023). Ecovoltaic principles for a more sustainable, ecologically informed solar energy future. *Nature Ecology & Evolution*, 1–4. https://doi.org/10.1038/s41559-023-02174-x
Sturchio, M. A., & Knapp, A. K. (2025). Evidence of photovoltaic aridity mitigation in semi-arid grasslands. *Environmental Research Letters*, *20*(6), 064047. https://doi.org/10.1088/1748-9326/add94d
van de Ven, D.-J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., & Gonzalez-Eguino, M. (2021). The potential land requirements and related land use change emissions of solar energy. *Scientific Reports*, *11*(1), Article 1. https://doi.org/10.1038/s41598-021-82042-5
van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023
Vervloesem, J., Marcheggiani, E., Choudhury, M. A. M., & Muys, B. (2022). Effects of Photovoltaic Solar Farms on Microclimate and Vegetation Diversity. *Sustainability*, *14*(12), Article 12. https://doi.org/10.3390/su14127493
Walston, L. J., Mishra, S. K., Hartmann, H. M., Hlohowskyj, I., McCall, J., & Macknick, J. (2018). Examining the Potential for Agricultural Benefits from Pollinator Habitat at Solar Facilities in the United States. *Environmental Science & Technology*, *52*(13), 7566–7576. https://doi.org/10.1021/acs.est.8b00020

CHAPTER 2: AGRIVOLTAIC GRAZING SYSTEMS FOR A SUSTAINABLE FUTURE: A MULTI-DISCIPLINARY REVIEW & GAP ANALYSIS[1]

1. Introduction

A key strategy in reducing global greenhouse gas emissions and mitigating the impacts of climate change is a global transition towards zero-emission sources of energy generation (Larson et al., 2021). Solar photovoltaics (PV) are expected to play an important role in this energy transition, potentially accounting for up to half of total global electricity generation by 2050 (Nijsse et al., 2023), up from less than 5% in 2022 (Haegel & Kurtz, 2023). Solar energy is already the lowest-cost option for electricity in many regions of the world (including the U.S., Mexico, much of Europe, India, and Australia), can be deployed across a diverse range of scales, uses minimal water, and offers predictable energy generation patterns (Energy Transition Factbook, 2023; U.S. Department of Energy, 2021). However, solar PV has a higher land footprint than other energy sources (van Zalk & Behrens, 2018), and meeting the projected generation levels could require 0.5% to 1.5% of global land area by 2085, depending on climate and technology development (Saxena et al., 2024).

This magnitude of required land raises concerns about the displacement of agricultural land uses as well as degradation of pasture and rangeland ecosystems, including negative impacts to soil health, nutrient cycling, water cycling, and biodiversity (Adeh et al., 2019; Bessette et al., 2024; Gomez-Casanovas et al., 2023; Grodsky & Hernandez, 2020; Hernandez et al., 2014; Moscatelli et al., 2022; Sturchio et al., 2022). Co-locating solar PV and agriculture or ecosystem

[1] Bacon, T., A. C. Monlezun, M. Hong, et al. "Agrivoltaic Grazing Systems for a Sustainable Future: A Multi-Disciplinary Review & Gap Analysis." Earth's Future 13, no. 8 (2025): e2024EF005429. https://doi.org/10.1029/2024EF005429.

services, often referred to as agrivoltaics or ecovoltaics, respectively (Le Moigne et al., 2021; Macknick et al., 2022; McCall et al., 2023; Sturchio & Knapp, 2023; Tölgyesi et al., 2023), has been proposed as a solution for mitigating some of these impacts and has received increasing attention in the last decade. Research to date suggests that these multi-land-use systems can offer a range of benefits across the food-energy-water nexus, such as improved water use efficiency, increased yield, increased soil carbon and nutrients, and moderated soil and air temperatures (Barron-Gafford et al., 2019; Choi et al., 2023; Guerin, 2019; Hernandez et al., 2019; Rahmaniah & Tay, 2023; Randle-Boggis et al., 2020).

One of the most common forms of these multi-land-use systems today is the co-location of sheep grazing and solar PV, often called "solar grazing" (Figure 1). While global data on the prevalence of these systems is limited, regions with more comprehensive data on agrivoltaic systems highlight the relative dominance of solar grazing systems. In the U.S., almost three-quarters of cataloged agrivoltaic projects by land area employ grazing (*Agrivoltaics Map*, n.d.). In Europe, over 80% of cataloged agrivoltaics projects larger than 5 megawatts (MW) incorporate livestock ("Agrisolar Digital Map by SolarPower Europe," n.d.). Grazing is a popular option because it can reduce the operating costs of mowing while maintaining agricultural activity to produce both food and energy from the same piece of land (McCall et al., 2023).

Figure 1. Sheep within an agrivoltaic grazing system in Georgia, U.S. *Image courtesy of Silicon Ranch.*

Despite the prevalence of solar grazing systems, there is limited understanding of the impacts of agrivoltaic grazing on ecosystem and livestock outcomes. Research specific to agrivoltaic grazing systems is sparse, with few published studies. Challenges of studying these systems include added ecological heterogeneity introduced by grazing and PV modules, the need for scalable study areas, logistical challenges with replication and long-term studies, and a lack of resources and funding to support research.

Agrivoltaic grazing systems can be framed as the integration of three components: land, livestock, and solar PV (Figure 2). Here, “land” includes both biotic and abiotic ecosystem components, including vegetation, soil, hydrology, biogeochemical cycling, and microclimate. While research on the integration of all three components is limited, there is a range of existing research adjacent to these systems that considers the integration of two out of these three components. For example, research on the microclimate and vegetation impacts of PV modules (integration of land and solar PV) (Adeh et al., 2018; Armstrong et al., 2016; Sturchio et al., 2022) or the role of shade in livestock wellbeing (integration of solar PV and livestock) (Faria et al., 2023; Sharpe et al., 2021) can supplement research on agrivoltaic grazing systems to better inform key research directions and priorities.

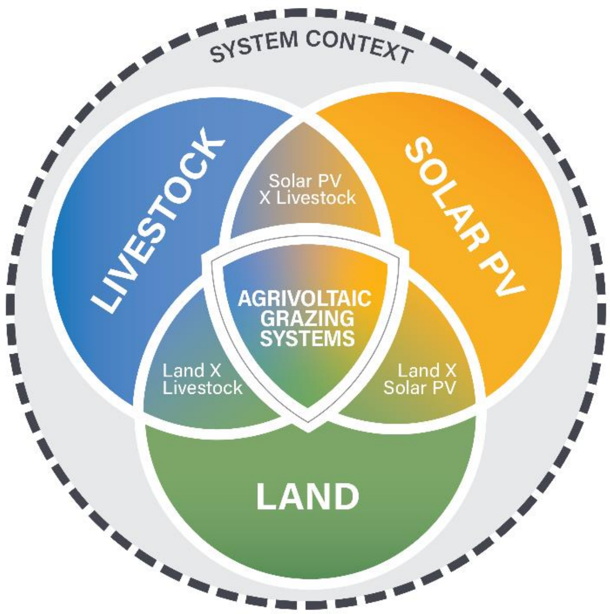


Figure 2. Agrivoltaic grazing systems can be viewed as the integration of livestock, solar PV, and land. Existing literature on interactions of two of these three components (Solar PV × Livestock, Land × Solar PV, and Land × Livestock where the "×" represents the integration of the two components) can supplement the limited existing research on agrivoltaic grazing systems while informing key research priorities. These physical components are situated within a broader system context, including policy, economics, life cycle outcomes, and community impact.

The interaction between the three physical components can then be situated within the broader system context, with considerations including policy, economics, life cycle outcomes, and community impact. While each of these components alone is highly complex, and the connections and integrations between components are nuanced, this conceptual mapping provides a preliminary framework for approaching literature synthesis.

The objective of this review is to provide a global synthesis of the existing research on agrivoltaic grazing systems and adjacent research on the integration of at least two of the three system components (land, livestock, and solar PV), as well as research on the broader system context for agrivoltaic grazing systems to identify key gaps in the literature and inform agrivoltaic grazing research moving forward.

2. Methods

A systematic search of peer-reviewed research on agrivoltaic grazing systems and adjacent fields (integration of two out of the three components shown in Figure 2: land, livestock, and solar PV) was conducted. The search was conducted using the National Renewable Energy Lab's InSPIRE database of agrivoltaic research, as well as Web of Science and Google Scholar. The initial search was conducted in Fall 2023 and updated in February 2025.

First, published agrivoltaic reviews and meta-analyses were identified and reviewed for their coverage of agrivoltaic grazing systems. This search focused on reviews of existing research in the field, excluding those studies focused exclusively on PV technologies, greenhouse agrivoltaic systems, or aquavoltaics. Case studies, conceptual design studies, and evaluations of geographically specific applications were also excluded. Thirty-four reviews that met these criteria were identified, most of which either did not discuss agrivoltaic grazing systems in detail or noted the lack of literature in this area (Gomez-Casanovas et al., 2023; Granit, 2021; Klokov et al., 2023; Mamun et al., 2022; Sarr et al., 2023; Weselek et al., 2021; Zainol Abidin et al., 2021, full list of reviews available in the Open Research section).

Two of the identified reviews focused specifically on sheep-based agrivoltaic grazing systems, both published since 2024. Vaughan & Brent (2024) reviewed solar PV technology considerations and agrivoltaic impacts on agricultural productivity and land, concluding that well-designed sheep grazing agrivoltaic systems can have positive environmental, economic, and social impacts. Stewart et al. (2025) discuss agro-ecological impacts, operational challenges, and industry potential of sheep agrivoltaic grazing systems, identifying gaps in our understanding of impacts on native plant communities and management decisions for balancing vegetation management and grazing goals.

Following the analysis of review papers, a more extensive search of research on agrivoltaic grazing systems was conducted (Figure 3). All the publications cataloged in the InSPIRE database under “animal grazing” were reviewed. An additional search was carried out using Web of Science and Google Scholar with key search terms including: “agrivoltaics”; “livestock agrivoltaics”; “solar grazing”; “animal agrivoltaics”; “agrophotovoltaics”; “pasture-based photovoltaic”; and “solar sharing”. Abstracts of peer-reviewed publications returned by this search were reviewed and included in our review contingent upon the publication providing novel experimental or modeling data on the integration of at least two of the three components of interest: land, livestock, and solar PV. For a publication to meet this criterion, it had to evaluate how the interaction between components affected outcomes, reflected in both data and discussion. Studies were also included if they provided novel experimental data or analysis relevant to the broader systems context of agrivoltaic grazing, including life-cycle assessment, policy analysis, economics, or social dimensions of agrivoltaic grazing systems. We also included a select number of government reports, conference presentations, and theses that provided important perspectives or data otherwise missing.

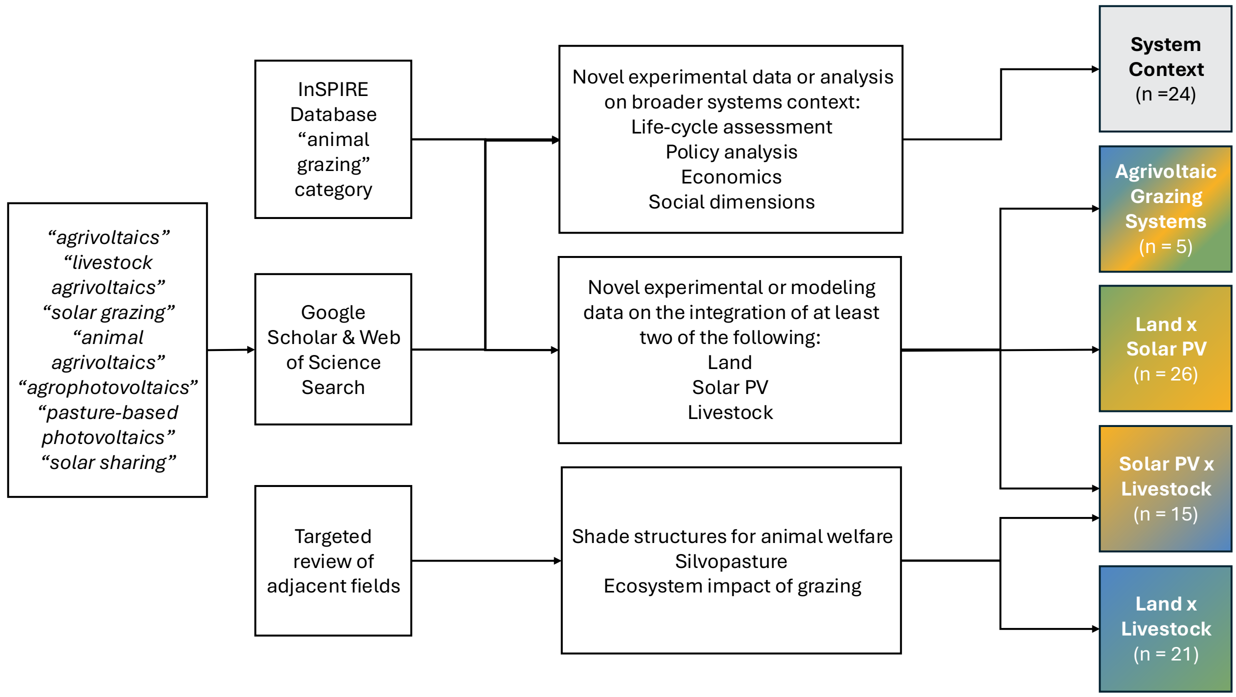


Figure 3. Illustrative flow-chart of methods for literature review.

Additionally, a more targeted review of literature from adjacent fields relevant to this review but not returned by the initial search, including shade structures for animal welfare, silvopasture, and ecosystem impacts of grazing, was conducted to supplement areas with less agrivoltaic-specific research. Since these fields are significantly larger, the review focused on influential studies and key meta-analyses. In total, 83 publications were identified for inclusion in this review.

These publications spanned three distinct categories, consistent with the conceptual framework illustrated in Figure 2:

- Studies that provided novel field data on agrivoltaic grazing systems, considering the integration of land, solar PV, and livestock. While an agrivoltaic grazing system study did not necessarily have to present data on each of the three components, all had to play a meaningful role in the experimental design and data collection. Five studies were identified within this category, motivating the need to consider literature from adjacent fields.

- Studies from adjacent fields that provided novel data on the integration of two out of the three components:
    - Land × Solar PV (26 studies)
    - Solar PV × Livestock (15 studies)
    - Land × Livestock (21 studies)
- Studies that provide economic, political, and social context for better understanding agrivoltaic grazing systems, as well as studies that consider the life cycle climate impacts of agrivoltaic grazing systems. Twenty-four studies that provided context for agrivoltaic grazing systems were identified.

Several publications were included in more than one category because they met multiple criteria; for example, an agrivoltaic grazing paper was also included in the land × solar PV category since it provided data on the impacts of solar modules on vegetation productivity.

3. Synthesis of Existing Research

3.1 Agrivoltaic Grazing Systems

Research specific to the integration of land, livestock, and solar PV that considers all three components in experimental design and data collection is limited. The search returned five publications that met these criteria, all published since 2021 (Table 1). Additional publications that are specific to agrivoltaic grazing systems but did not include field research are discussed in Section 5: System Context. All the identified field studies were conducted in sheep-grazed systems, were based in the U.S., and utilized a mix of single-axis tracking and fixed-angle solar PV systems.

Table 1. Existing Field Research on Agrivoltaic Grazing Systems

Study	Study site	Array size & tracking	Species	Objectives	Data collected	Key results
(Andrew et al., 2021)	Corvallis, OR, U.S.	1.4 MW, fixed angle	Sheep	Compare lamb production in an agrivoltaic system compared to a traditional pasture system	Herbage dry matter; liveweight gain; liveweight production; water intake; lamb foraging behavior; herbage mass; herbage quality	Pasture production was 9-33% lower in the agrivoltaics system, but forage quality was higher and lamb production did not differ. Lambs spent most of their time under modules
(Andrew et al., 2024)	Corvallis, OR, U.S.	1.4 MW, fixed angle	Sheep	Compare lamb production across simple, diverse, and legume pastures within an agrivoltaic system	Soil moisture; air temperature; herbage dry matter, including botanical fractions; liveweight gain, herbage on offer	Pasture diversification resulted in higher pasture productivity and animal production. Pasture production is significantly
(Kochendoerfer et al., 2025)	Dryden, NY, U.S.	18 MW, fixed angle	Sheep	Investigate the impact of stocking rates, site preparation, and microclimate on vegetation and livestock outcomes.	Herbage production; herbage nutritional quality; sheep flock health; vegetation height	Identified an optimal stocking rate of 8 sheep per hectare for optimizing management goals. Herbage yield was lowest underneath panels (up to 56%).
(Kampherbeek et al., 2023)	San Luis Obispo County, CA, U.S.	4.5 MW, single-axis tracking	Sheep	Fill a noted gap in research on sheep behavior within an agrivoltaic system	Grazing behavior; forage mass; forage quality	Sheep spent more time grazing in the solar treatment and spent most of their time under the modules. Total forage production was lower in the solar treatment, but forage quality higher
(Towner et al., 2022)	MN, U.S.	6 "commercial solar PV sites"	Sheep	Evaluate the impacts of solar grazing on soil carbon and nutrients	Forage productivity by species; soils (TOC, TC, TN, pH, OM, nutrients, particle size, compressive strength)	Strategic managed grazing can improve carbon sequestration and soil properties

Andrew et al. (2021) and Kampherbeek et al. (2023) both found an increase in forage quality under the solar modules relative to the control. This difference could be attributed to the micro-climate created by the modules and the redistribution of moisture, leading to growing conditions that favor vegetation with higher nitrogen (Kampherbeek et al., 2023). Studies consistently observed a decrease in forage production within the solar array, likely due to the reduction in solar radiation reaching the canopy (Andrew et al., 2021; Andrew et al., 2024; Kochendoerfer et al., 2025; Kampherbeek et al., 2023). The lower forage production within the array did not appear to impact liveweight production, which was comparable between the solar and open pasture treatments (Andrew et al., 2021). This could be attributed to the higher forage quality and/or the fact that sheep spent more time grazing in the solar treatment than in native rangeland (Kampherbeek et al., 2023). Andrew et al. (2024) found that pasture diversification is a potential strategy for increasing forage production and lamb growth rates; however, both Andrew and Kochendoerfer (2025) found that seeding legumes does not offer any additional benefits.

Sheep and lambs spent a large portion of time under the modules, potentially showing a preference for the microclimate created by the modules (Andrew et al., 2021; Kampherbeek, 2023). Management parameters, including rotation frequency and stocking density, also impacted animal behavior and well-being. Kampherbeek (2023) found that sheep spent more time grazing when rotated every four days compared to daily rotation. Stocking density impacted both herbage yield and flock health, with an optimum (for the specific study system and climate) identified at 8 sheep per ha, after which Body Condition Score declined (Kochendoerfer et al., 2025).

Towner et al. is the only agrivoltaic grazing study identified that evaluated soils within an agrivoltaic grazing system and found an increase in soil carbon and nitrogen in grazed systems compared to systems that were not grazed (Towner et al., 2022).

Key Takeaways – Agrivoltaic Grazing Systems:

- Decrease in forage production within the array relative to control.
- Evidence of potentially higher forage quality within the array.
- Livestock seem to display a preference for grazing under PV modules.
- Potential increase in soil carbon and nitrogen in grazed systems compared to systems that were not grazed.

3.2 Land × Solar PV

A total of 26 studies were identified that considered the integration of solar PV and land, relevant to agrivoltaic grazing systems. Within the fields of agrivoltaics and ecovoltaics, much of the existing research has focused on characterizing the microclimate, ecological, and biogeochemical impacts of adding solar PV modules to a landscape. Particularly relevant to agrivoltaic grazing systems are changes to vegetation productivity, as well as microclimate alterations that could impact grazing outcomes.

One of the most relevant environmental factors to agrivoltaic grazing systems is the impact on vegetation productivity. Supporting sufficient forage is central to successful livestock integration, and several studies have evaluated grassland vegetation dynamics within a solar array (Adeh et al., 2018; Al Mamun et al., 2023; Andrew et al., 2021; Armstrong et al., 2016; Kampherbeek, 2023; Loan & Picon-Cochard, 2022; Moscatelli et al., 2022; Sturchio et al., 2022, 2024; Weselek et al., 2021). Research suggests that vegetation productivity is influenced not only by total solar radiation but also by solar radiation timing (i.e. morning vs afternoon sun) and soil moisture, which are both affected by climate and PV array geometry (Sturchio et al., 2022).

Figure 4. "Zones" relative to PV modules in which vegetation productivity is measured and reported across studies (Table 2). This image illustrates these zones in a single-axis tracking system, however the same concepts are commonly applied in fixed-angle systems as well. Several studies included in Table 2 present array-level biomass data, which in some cases is an average of zones within the array (Andrew et al., 2024; Sturchio et al., 2024) but in other cases, sampling locations relative to the PV modules are not specified (Kampherbeek et al., 2023; Weselek et al., 2021).

Field-scale experimental studies have observed a large range of module impacts on vegetation productivity. A majority of studies that provide data on total array productivity compared to a control site observe a decrease in biomass ranging from 6% to 48% (Andrew et al., 2021, 2024; Kampherbeek et al., 2023; Sturchio et al., 2024; Weselek et al., 2021). However, there are typically significant differences in biomass observed under the modules compared to the area between module rows (Figure 4, Table 2). Reported biomass under modules compared to a control site ranges from a 77% decrease to a 90% increase. In the area between rows of modules, observed biomass ranged from 37% lower to 18% higher than the control (Adeh et al., 2018; Andrew et al., 2024; Armstrong et al., 2016; Loan & Picon-Cochard, 2022; Sturchio et al., 2024). There is a wide range of confounding variables that can influence vegetation data and make comparison across these studies difficult, including climate, elevation, ecological zone, plant species communities, array geometry (e.g. module height, row spacing, tracking vs fixed, etc.), sampling points relative to the modules, sampling methods, previous land use and construction practices, and time of sampling. Vegetation data across four growing seasons within an agrivoltaic grazing system in Corvallis, OR, U.S. further highlights the impact of interannual climate variability on these results (Andrew et al., 2021, 2024).

Table 2. Effects of Solar PV on Above-Ground Grassland Biomass.

Study	**Study site**	**Ann. precip (mm)**	**Array size & tracking (MW)**	**Change in biomass, relative to control**			**Biomass under modules relative to between rows**
				Within array	Between modules	Under modules	
(Adeh et al., 2018)	Corvallis, OR, U.S.	1086	1.435 MW, fixed angle		-16%	90%	126%
(Andrew et al., 2021)	Corvallis, OR, U.S.	1086	1.4 MW, fixed angle	-9 to -33%			-1% to 3%
Andrew et al., 2024)	Corvallis, OR, U.S.	1086	1.4 MW, fixed angle	-26% to -48%	-6% to -37%	-49% to -77%	-46% to -64%
(Armstrong et al., 2016)	Watchfield, UK	680	5 MW, fixed		17%	-74%	-78%
(Kochendoerfer et al., 2025)	Dryden, NY, U.S.	1036	18 MW, fixed angle				-42%
(Kampherbeek et al., 2023)	San Luis Obispo County, CA, U.S.	584	4.5 MW, single-axis tracking	-32%			
(Loan & Picon-Cochard, 2022)	Braize, France	800	NA, fixed angle		-26%	15%	54%
(Loan & Picon-Cochard, 2022)	Marmanhac, France	1200	NA, fixed angle		18%	-10%	-24%
(Moscatelli et al., 2022)	Montalto di Castro, Viterbo, Italy	800	0.099 MW, fixed angle				-58%
(Sturchio et al., 2022)	Longmont, CO, U.S.	365	1.2 MW, single-axis tracking				-20%
(Sturchio et al., 2024)	Longmont, CO, U.S.	365	1.2 MW, single-axis tracking	-9%	-17%	-26%	-11%
(Weselek et al., 2021)	Herdwangen -Schonach, Germany	900	0.194 MW, fixed angle	-6 to -8%			

Echoing the findings of Kampherbeek et al. (2023) discussed in the prior section, Loan & Picon-Cochard (2022) found that vegetation nitrogen content was higher in the array across treatments with opposite total biomass responses. However, Sturchio et al. (2024) observed lower crude protein content across zones within the array compared to control plants. In addition to altering forage quantity and quality, there is data suggesting that plant species composition may vary between an array and a control site, and between zones within an array (Randle-Boggis et al., 2020; Uldrijan et al., 2021).

The presence of PV modules is also hypothesized to impact soil characteristics and nutrient cycling, however, research in this area is more limited and with inconclusive results (Choi et al., 2020; Lambert et al., 2021; Moscatelli et al., 2022; Towner et al., 2022). Many soil properties (and particularly soil carbon) are slow to show measurable responses to management changes (Smith, 2004), making prior land use and solar array construction practices particularly influential, especially since many of the study systems are relatively young. Across a multi-year study, Choi et al. (2024) found inconsistent impacts on soil nutrient status and characteristics across study sites, and emphasized the influence of original soil texture and construction history on soil outcomes.

A study in France found no significant difference in soil chemical properties and soil carbon between a solar park and a neighboring abandoned vineyard, but the soil carbon in these “anthropogenic land cover types” was 2.5 times lower than in semi-natural systems, emphasizing the importance of site history and management (Lambert et al., 2021). One of the few studies to measure total soil carbon and nitrogen found a significant decrease in carbon and nitrogen within the array compared to the control, however, this is likely attributed to the removal of topsoil during array construction (Choi et al., 2020). This study also did not observe any difference in soil characteristics between micro-climate zones relative to the PV modules, potentially due to construction disturbance and slow soil response. However, within a vegetated solar area, soil carbon and nitrogen levels similar to the control site were observed, both higher when compared to a bare solar area (Choi et al., 2023). One of the most mature study sites (sampled after seven years) found higher soil pH and salinity within the solar array compared to the control (Moscatelli et al., 2022). They also observed higher total organic carbon and nitrogen in the gap between modules compared to the control, but lower values directly under the modules (Moscatelli et al., 2022). However, the control in this study was agricultural land, while the array area was planted in grassland species, potentially confounding this comparison.

Microclimate alterations from PV modules have been well-documented (Adeh et al., 2018; Armstrong et al., 2016; Barron-Gafford et al., 2019; Choi et al., 2020) and are relevant to agrivoltaic grazing systems, particularly as they affect animal welfare (discussed in the following section). Research to date suggests that PV modules can have a buffering effect on air temperature, decreasing temperatures during the day and increasing them at night relative to an open-air control (Armstrong et al., 2016; Barron-Gafford et al., 2019; Marrou, Guilioni, et al., 2013). However, other studies have shown insignificant variations in air temperature (Choi et al., 2023; Vervloesem et al., 2022). There is a similar effect on soil temperature over a seasonal scale, with cooler temperatures in the summer, in some cases by up to 10 °C, and in some studies, slightly warmer temperatures in the winter relative to a control (Armstrong et al., 2016; Choi et al., 2023; Gill et al., 2024; Lambert et al., 2021; Liu et al., 2019; Loan & Picon-Cochard, 2022; Marrou, Guilioni, et al., 2013; Moscatelli et al., 2022; Tanner et al., 2020).

PV modules have also been found to impact water dynamics, altering soil moisture by redistributing precipitation and modifying patterns of evapotranspiration (ET), maintaining higher soil moisture within the array relative to the control (Adeh et al., 2018; Barron-Gafford et al., 2019; Moscatelli et al., 2022; Sturchio et al., 2022). While not directly applicable to grazing systems, one study observed a 10-30% reduction in lettuce and cucumber ET (Marrou, Dufour, et al., 2013). Simulated ET based on field data found variable ET across array zones with higher values on the eastern edge and lower values under the modules, compared to the control (Kannenberg et al., 2023). Some studies, however, have found no difference in soil moisture between the array and control (Choi et al., 2023; Lambert et al., 2021; Loan & Picon-Cochard, 2022) and have even observed higher soil moisture in the control relative to directly under the module in certain desert environments (Tanner et al., 2020).

Key Takeaways – Land × Solar PV:

- PV modules in a grassland may decrease overall vegetation productivity, depending on ecological context, but could increase forage quality, with spatial variability in vegetation productivity relative to modules, and strong influence from climate & site history.
- PV modules alter water dynamics, modifying evapotranspiration, and potentially increasing soil moisture.
- Air and soil temperature below modules tend to be lower relative to the control in the summer but can remain higher than the control in the winter, depending on the climate.

3.3 Solar PV × Livestock

The potential of solar PV as a shading resource for livestock has dominated the research on livestock in solar PV systems. This emphasis is understandable given the critical role shade access plays in animal welfare. Access to shading resources reduces livestock heat stress, which can negatively impact animal well-being and performance and even result in death (Edwards-Callaway et al., 2021). Concern about heat stress and the importance of shade resources is only increasing with increasing global temperatures (Edwards-Callaway et al., 2021). Cattle exposure to conditions exceeding their thermoneutral zone can lead to decreased immune function, increased stress and frustration, and altered behavior patterns. Ultimately, this leads to reduced biological function, mental state or affect, and ability to display natural behaviors (Edwards-Callaway et al., 2021).

Our review identified seven studies on the impact of PV modules on animal behavior and animal welfare outcomes (Table 3), two of which were discussed in the first section of this review. This research can be supplemented with animal science literature on shading resources and lessons from silvopasture studies and other animal behavior literature.

Table 3. Field studies on livestock welfare and behavior within PV systems.

Study	Study site	Species	Array size & tracking	Data collected
(Carvalho Fonsêca et al., 2023)	Sao Paulo, Brazil	Sheep	335 W, fixed angle	Wool-surface, skin, and vaginal temperature; shade-use behavior; solar radiation
(Maia et al., 2020)	Sao Paulo, Brazil	Sheep	335 W, fixed angle	Behavior and shade use; solar radiation
(Sharpe et al., 2021)	Morris, MN, USA	Dairy cows	30 kW, fixed angle	Animal behavior, hygiene, milk production, body temperature
(Heins et al., 2022)	Morris, MN, USA	Dairy cows	30 kW, fixed angle	Internal body temperature; activity; rumination; hygiene, milk production.
(Faria et al., 2023)	Sao Paulo, Brazil	Heifers	335 W, fixed angle	Meteorological data; behavior response; enteric methane emissions
(Kochendoerfer et al., 2025)	Dryden, NY, U.S.	Sheep	18 MW, fixed angle	Weight; body condition score; gastrointestinal nematode load
(Kampherbeek et al., 2023)	San Luis Obispo, CA, USA	Sheep	4.5 MW, single-axis tracking	Grazing behavior; forage mass and quality
(Andrew et al., 2021)	Corvallis, OR, USA	Sheep	1.4 MW, fixed angle	Liveweight gain; liveweight production; water intake; lamb foraging behavior; herbage mass and quality

Of the studies identified, five focused on sheep (Andrew et al., 2021; Carvalho Fonsêca et al., 2023; Kampherbeek et al., 2023; Kochendoerfer et al., 2025; Maia et al., 2020) and three focused on dairy cows or heifers (Faria et al., 2023; Heins et al., 2022; Sharpe et al., 2021). Aside from the Andrew et al. (2021), Kochendoerfer et al. (2025), and Kampherbeek et al. (2023) studies, which were conducted on larger scales, these studies were conducted with a relatively small number of modules added to a pasture, and data were collected over a few weeks, measuring livestock body temperature, shade preference, behavior, and respiratory rate. Results consistently illustrate that the addition of solar modules to a pasture reduced livestock radiant heat load and livestock body temperature, particularly at times of day with higher solar radiation. Biophysical modelling data also suggests that microclimate alterations measured within an array (wind speed, rainfall, and temperature) could improve lamb survival (Gill et al., 2024), but further empirical data will be needed to confirm this finding.

In addition to finding that solar modules can reduce radiant heat stress when available as a shading resource for animals, research suggests that livestock may prefer the shade provided by solar PV to traditional shade cloths (Maia et al., 2020). When given the choice, sheep spent 38% of their time under modules, compared to just 1% under the shade cloth, potentially due to the greater reduction in radiant heat load under PV modules (Maia et al., 2020).

Agrivoltaic grazing systems can also be expected to change animal behavior within a pasture or rangeland. Initial research has found that sheep spent more time grazing within the solar array treatment compared to native rangeland. Within the array, sheep also spent the majority of their time directly under the modules (Kampherbeek et al., 2023).

Another dimension of solar PV x livestock is the impact of these systems on livestock production. Initial research in agrivoltaic grazing systems found no decrease in lamb liveweight

(Andrew et al., 2021) or dairy cow milk production (Heins et al., 2022). However, Kochendoerfer et al. (2025) identified an optimum stocking density of 8 sheep per ha, which is lower than the 12 sheep per ha estimated for the site by the USDA Web Soil Survey. Additional studies across a range of climates, vegetation types, and livestock management systems will be needed to better characterize these impacts.

Silvopasture research reiterates some of these conclusions and provides a proxy for thinking about grazing within a solar array due to the similar microclimate alterations from the inclusion of a canopy (either biological or synthetic) in a grazing system. Much of existing silvopasture research was carried out in tropical climates but shows similar improvements in thermoregulation and animal welfare from the presence of shade on a grazing landscape (de Oliveira et al., 2022; De-Sousa et al., 2023; Galloso-Hernández et al., 2020; Giro et al., 2019). In addition to improving thermoregulation, there is evidence that the microclimate created in silvopasture systems can impact livestock behavior and performance, including longer rumination, shorter resting time, and less time spent searching for water (Giro et al., 2019). A review and meta-analysis of silvopasture research identified a "sweet spot" of tree density and spacing with which there is greater forage mass, increased crude protein, and improved animal weight gain, compared to a grass monoculture system (de Oliveira et al., 2022).

<u>Key Takeaways – Solar PV × Livestock:</u>

- The addition of solar PV to pasture provides valuable shade for livestock that reduces radiant heat load and is preferred by livestock, particularly when solar radiation is high.
- Limited early research suggests no decrease in livestock outputs from the presence of PV modules.

3.4 Land × Livestock

Central to agrivoltaic grazing systems are the layered ecological impacts of solar PV and livestock. The immense body of research on the relationship between livestock, plants, and soil can provide a foundation and direct future research toward key questions, methods, and indicators for agrivoltaic-specific studies. The impacts of livestock grazing on ecosystem outcomes have been studied extensively since the 1800s and the birth of rangeland science and will not be covered exhaustively in this review. Rather this section will highlight key publications from this body of literature, examined through the lens of agrivoltaic grazing system relevance.

Large ruminants play a central role in grassland ecosystem maintenance, from symbiotic relationships with grassland plant communities and other grazers to important impacts on nutrient and water cycling (Bell, 1971; Knapp et al., 1999). However, studying ecological outcomes as a result of livestock grazing is highly complex, in large part due to the variable influences of climate, plant communities, grazing management (the human dimension), and site characteristics like soil texture (Abdalla et al., 2018; Briske et al., 2011; Teague et al., 2013). In grazing research to date there is inconsistency in methodologically defining the type or intensity of grazing, resulting in a large spectrum of approaches and strategies (Stanley et al., 2024). Therefore, results are highly context-dependent and can have different or even paradoxical implications. For example, while some studies have observed grazing benefits of biomass productivity, soil health, and biodiversity, others have observed negative impacts of biomass removal and loss of soil organic carbon (Monlezun, 2022).

The primary interface between livestock and the land is vegetation. This is also key from an agrivoltaics grazing perspective because solar array operators often utilize vegetation cover to manage erosion and storm water runoff and sustaining adequate forage is essential for successful livestock integration. By selectively defoliating grasses, exposing different plants to sunlight, and accelerating decomposition of litter and other organic matter, grazing can increase both plant community diversity and forage quality (Augustine et al., 2017; Derner et al., 2009; Frank et al., 1998; Knapp et al., 1999; Porensky et al., 2020). However, these outcomes are shown to be highly dependent on both climate and the specifics of the grazing management, including stocking density, duration, frequency, and season of use.

Mediated through primary defoliation impacts and secondary impacts of trampling and manure and urine deposition, grazing strongly influences soil nutrient cycling, which contributes to overall ecosystem health and function. Some research suggests that with the appropriate management for a specific site and climate, grazing can increase soil carbon and nitrogen content (Machmuller et al., 2015; Mosier et al., 2021; Reeder & Schuman, 2002; Teague et al., 2011, 2016), while other studies have found no significant change to soil nutrients as a result of livestock grazing (Abdalla et al., 2018; Derner et al., 2019).

Discrepancies across the scientific literature lead us to conclude that the land x livestock interface is incredibly nuanced and context-dependent (Briske et al., 2013; Sanderson et al., 2020), which will only be exacerbated by the integration of solar PV. Therefore, when examining this research adjacent to agrivoltaic grazing systems, it is important to acknowledge the social-ecological context when extrapolating results and conclusions.

<u>Key Takeaways – Land × Livestock:</u>

- Appropriate grazing can fill an important ecosystem niche and provide beneficial outcomes to biodiversity, forage quality, and soil quality.

- However, grazing outcomes can be highly variable and are strongly dependent on climate, grazing management, and site characteristics.

3.5 System Context

In addition to the field research discussed above, there is emerging research on the social, economic, and political context of grazing agrivoltaic systems, as well as studies on the life cycle outcomes of dual-use systems (together referred to as system context). While field research is essential for addressing research questions about the biotic and abiotic dynamics of these systems, broader system analysis and consideration of the complex context of solar grazing will be essential for successful design and deployment.

3.5.1 Economics

Economics plays a major role in dictating which kind of solar PV systems are developed and how they are constructed and managed. Agrivoltaic grazing systems will potentially differ in capital costs, due to design alterations to co-prioritize grazing, and operations and maintenance (O&M) from conventional solar arrays. However, there is limited research on the capital cost impacts of different solar grazing systems since most of the existing systems are based on sheep grazing within standard array designs (*Agrivoltaics Map*, n.d.). In terms of O&M, solar grazing systems can impact both vegetation establishment costs and vegetation maintenance costs. While one survey of O&M costs found that mowed vegetation is the most cost-effective option in the early years of a solar project, sheep grazing is close to cost parity on a per kilowatt basis, and could potentially become more economically favorable as the project matures, since many of the higher costs are in the first few years (McCall et al., 2023). A study of rabbit-based agrivoltaic grazing systems found that co-locating rabbits in solar arrays for vegetation management and the production of agricultural products could improve site revenue by up to 24% (Lytle et al., 2021).

The financial feasibility of agrivoltaic grazing systems will likely depend on site-specific variables including leasing rate, acreage, flock size, and capital investments (Louk, 2023). However, in interviews with solar developers, performance engineers, and policy experts, participants generally considered grazing integration to be a potential cost-saver (Pascaris, Schelly, et al., 2021). Preliminary research is beginning to confirm these findings. A Canadian financial analysis found that across a range of scales (200 kW to 465 MW) and business models (breeding ewes on-farm or purchasing lambs at auction), sheep grazing agrivoltaic system earning margins and return on investment were both higher than the agricultural industry average (Gasch et al., 2025). A cost-benefit analysis of agrivoltaics on dairy farmland in New Zealand found that while substantial initial investment is required, the overall benefit for the economy is an order of magnitude larger (Brent, 2024). Preliminary work on economic tools analyzing the adoption of dual-use systems shows potential for evaluating these tradeoffs and considering designs, however will need additional refinements specific to grazing systems (Feuerbacher et al., 2021).

3.5.2 Policy

The complex policy and regulatory landscape created by the intersection of energy and agricultural land uses will continue to play a major role in the deployment of solar grazing systems. A comparative analysis of legal and policy frameworks for agrivoltaics across a selection of countries leading in the field identified common themes, particularly the limiting nature of existing legal frameworks, especially related to agriculture. However, positive changes that supported agrivoltaics were noted in several countries, including Japan, South Korea, Taiwan and Germany (Tajima et al., 2022).

Analysis specifically to agrivoltaic grazing systems, however, is very limited. Existing policies in Japan and Taiwan set maximum yield requirements, suggesting a greater focus on crop-based systems (Tajima et al., 2022). French legislation sets a similar yield requirement, however, specifies that this does not apply to livestock systems, although a maximum module coverage criterion still holds (Decree No. 2024-318, 2024).

A 2022 review of U. S. policy, zoning, and taxation laws relevant to grazing agrivoltaics found a very inconsistent landscape and considerable legal barriers (Guarino & Swanson, 2022). Researchers identified the need for a comprehensive legislative framework, consistent across local, state, and federal levels to support the deployment of agrivoltaics (Guarino & Swanson, 2022; Pascaris, 2021a). A 2024 report specific to land-use regulations for solar PV development in Colorado, U.S. reiterated the variability of permitting requirements and also highlighted the potential of some county-level policies to limit agrivoltaic deployment (Jackson et al., 2024).

Information like this offers insight into the geographical, social, and political barriers and complexities of agrivoltaics as a land-use opportunity. Additionally, existing policy frameworks highlight the importance of clear definitions and parameters that consider key differences between agrivoltaic grazing systems and crop-based systems.

3.5.3 Society

To understand agrivoltaic grazing systems and their potential as a climate and land use solution, we must also understand their human dimensions. Collaboration between land managers, utility companies, ranchers, and solar developers is essential to the implementation of agrivoltaics. Additionally, local community members and their perspectives can have a strong gateway impact on project approval and permitting. The field has drawn criticism for a mono-focus on the technical aspects of these systems without consideration for the complex local stakeholder interactions and relationships (Moore et al., 2022). Literature on this topic, especially specific to agrivoltaic grazing systems rather than agrivoltaics more broadly, is very limited. However, early research provides valuable insights and directions for additional work.

In interviews with agricultural sector experts in the U.S., Pascaris et al. (2020) found that participants perceived potential benefits from dual-use solar, yet there were significant barriers to adoption, including the importance of just compensation, systems designed to facilitate agricultural flexibility, and the need for confidence in the long-term productivity of the land. Interviews conducted by Torma & Aschmann-Witzel (2023) found a broad range of perceptions on agrivoltaics, emphasizing similar themes of opportunity and barriers. Multiple interview-based studies have emphasized the deep-rooted importance of agriculture and place-based identity tied to the land, which has significant relevance to dual-use solar development (Moore et al., 2022; Nicholls, 2020; Pascaris et al., 2020). Local communities have a substantial bearing on the development of solar energy, as many siting decisions are made at the local level and community opposition can halt projects.

Case studies from the United Kingdom emphasize the importance of “community-oriented development” of solar energy (Nicholls, 2020), and another study suggests that incorporating agricultural components into solar development can substantially increase public support (Pascaris et al., 2022). Taylor et al. (2023) apply an energy-justice framework to agrivoltaics and further echo the importance of centering justice to the adoption of agrivoltaic systems (Taylor et al., 2023). Additionally, Pascaris et al. (2023) found that socio-political aspects are key to agrivoltaic expansion, especially the demonstration of co-benefits and public opposition to the conversion of farmland (Pascaris et al., 2023). However, some stakeholders view solar grazing as disingenuous or a façade for pushing solar development in general (Nicholls, 2020). An eye-tracking analysis of perception and acceptance of agrivoltaics in Germany found that the addition of cattle to an image of a solar PV system did not influence acceptance of agrivoltaics; however, available data limits fully understanding potential underlying causes of this result (Schröter et al., 2024). The willingness for adoption by ranchers and agricultural land managers will be central to the deployment of agrivoltaic grazing systems.

3.5.4 Life Cycle Assessment

In making land use and energy decisions related to agrivoltaic grazing systems, it is crucial to understand the lifecycle impacts of dual-use systems compared to single-use alternatives. Two life cycle assessments of agrivoltaic grazing systems were identified in the literature review, one in a sheep-based system (Handler & Pearce, 2022) and one in a rabbit-based system (Pascaris, et al., 2021b). Both analyses concluded that the integration of livestock and solar PV offers greenhouse gas emission benefits compared to keeping the two systems separate. (Handler & Pearce, 2022; Pascaris et al., 2021b). However, both studies found that the lifecycle environmental impacts of these systems were dominated by the difference between solar energy and conventionally generated electricity. While the dual-use systems offered some lifecycle advantages over single-use solar PV and single-use grazing, the magnitude of this benefit was dwarfed by the benefits of PV over conventional fossil-based electricity, emphasizing the potential of agrivoltaics in facilitating solar PV projects that might not have been developed otherwise (Handler & Pearce, 2022; Pascaris et al., 2021b).

3.5.5 Conceptual Design & Management

A final subset of identified literature on agrivoltaic grazing pertained to the conceptual design and management of these systems. Lytle et al. (2021) proposed a conceptual design for rabbit-based agrivoltaic grazing systems and established the viability of such systems through technical, environmental, and economic analyses. Zhang et al. (2023) proposed integrating pasture-based PV at data centers with high energy demands to reduce the environmental burden of these centers and concluded that if implemented at the appropriate site type, this integration could provide environmental and economic benefits.

Al Mamun et al. (2023) published a hybrid modeling/field research study. The study used the APSIM model to simulate sub-tropical grass production under various solar PV configurations (fixed angle, single-axis tracking, and dual-axis tracking) and then applied different grazing practices. The model was validated against field measurements of grass production taken in a reference location.

<u>Key Takeaways – System Context:</u>

- Grazing agrivoltaics can offer potential operation and maintenance savings compared to conventional solar.
- The current policy and regulatory landscape is variable and could create barriers for the deployment of agrivoltaic grazing systems.
- Agrivoltaic grazing systems exist in a complex network of stakeholders, and it is essential to better understand the human dimension of these systems.
- Initial life cycle assessments suggest potential emissions savings of dual-use agrivoltaic grazing systems compared to single-use systems.

- The development of agrivoltaic design templates and of best management practices could assist the industry in moving forward from concept to deployment with reduced uncertainty.

This synthesis of existing literature on agrivoltaic grazing systems and adjacent fields allows for the development of a more comprehensive version of the framework for conceptualizing agrivoltaic grazing and research on these systems proposed in Figure 2. Existing research helps us identify key components within each of the broader categories (land, livestock, solar PV) as well as begin to map connections between these components (Figure 5). This provides insight into the complexity of understanding and studying these systems, as well as key relations that expose gaps for further research. Robust agrivoltaics grazing research exists within the center of this web, meaningfully considering connections between the three components in experimental design and data collection.

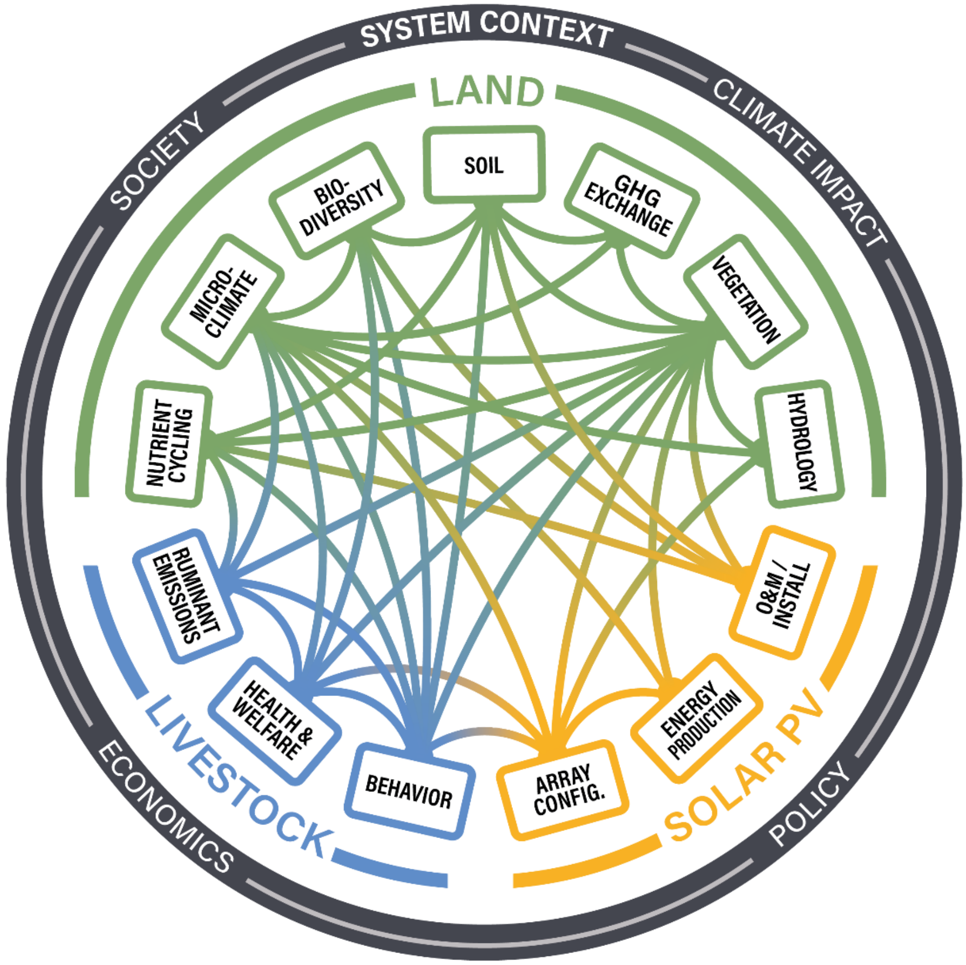


Figure 5. Agrivoltaic grazing systems reflect complex interactions between livestock, land, and solar PV, situated within broader contexts including economics, social dynamics, policy, and climate.

4. Gap Analysis

Based on this literature synthesis, we identified gaps in agrivoltaic grazing research. These gaps emphasize the information from existing adjacent research that is not generalizable or extrapolative to agrivoltaic grazing systems. We identified six key areas of inquiry where we believe additional research is needed to advance sustainable agrivoltaic grazing systems:

1. **PV-livestock integration.** The success of agrivoltaic grazing systems rests on the synergistic co-production of energy and livestock, and additional research is needed to better understand

the impacts of these systems on livestock behavior, health, production, and agricultural outcomes. This is particularly important as these systems expand to other species, including beef and dairy cattle. Like solar PV, the grass-fed beef and dairy industries require large swaths of land, and potential synergies have been illuminated by a very small number of scientific studies. The introduction of new species raises questions about animal behavior in a novel solar PV environment, specifically in terms of animal welfare standards and the safety of the animals, the solar infrastructure, and the managers and operators who work on the site. Continued research related to livestock interactions with solar infrastructure, breed-specific differences, and animal welfare assessment will help highlight compatibilities and minimize risk at the livestock/PV interface. Many questions also remain regarding impacts on variables like animal fertility, pregnancy rates, weaning rates, stress, feed-to-carcass efficiency, harvest yield, and meat quality. Research addressing these variables in agrivoltaic grazing systems compared to control or reference scenarios over longer experimental time horizons will inform ranchers and farmers regarding the potential benefits and risks of engaging in agrivoltaic grazing projects. Key research questions include:

- What are the optimal system design parameters for ensuring livestock well-being within an agrivoltaic grazing system?
- How do livestock production parameters, including fertility, pregnancy rates, weaning rates, harvest yield, and feed-to-carcass efficiency, differ in an agrivoltaic grazing system when compared to a conventional grazing system?
- What livestock breeds and species are best suited to agrivoltaic grazing systems?
- How does module design (including panel transparency, size, spacing, etc.) impact livestock interaction with infrastructure, behavior, and well-being?

2. **Layered ecological impacts**. Both solar PV and livestock grazing interact with biogeochemical cycling and ecological function. Understanding the layered impacts and interactions of these systems when integrated is central to agrivoltaic grazing research. Both solar PV design (e.g., fixed angle versus tracking modules) and livestock grazing introduce spatial heterogeneity into a landscape. Characterizing and quantifying overlapping spatial variability will inform our understanding of outcomes, such as net carbon balance, soil impacts, and vegetation productivity. This characterization is important for evaluating ecosystem services, including soil carbon sequestration and biodiversity, potentially facilitated by these systems. Understanding these layered ecological impacts will require large amounts of high-quality experimental data that will allow us to generalize outcomes. This must include large treatment areas with controls, replicated samples, and consistent methods and sampling design to allow for comparison across studies. As ecological outcomes will be impacted by previous land use, site age, construction practices, and management practices, consistency and transparency in reporting these confounding factors will be essential. It will also be essential to have studies span a wide variety of climate zones, soil types, and array designs to understand how these variables influence system outcomes. Key research questions to make progress towards addressing this gap include:
    - How do ecological outcomes, including vegetation productivity, soil characteristics, including microbiology, and hydrologic conditions, in a grazed solar array differ from a traditionally managed mowed array?
    - How does grazing impact carbon cycling and soil carbon sequestration within a solar array?

- Are there generalizable ecological impacts from solar grazing systems across climate zones?

3. **Biogeochemical and economic modeling.** Datasets from the above-mentioned ecological research can contribute to the foundation for building or improving biogeochemical models. This kind of modeling should incorporate the influence of both solar PV and grazing on the ecosystem, as well as validate outcomes with measurements across varying climatic or ecological contexts. Validated biogeochemical models and data continuously updated in the life cycle of these systems would also improve economic analysis. Since economics plays such a large role in dictating how, where, and when solar arrays are constructed, representative economic and financial models specific to agrivoltaic grazing systems will be essential to the deployment of these systems. The development of these economic models will rely on additional data on capital and O&M costs. The use of predictive models will allow us to generalize knowledge and identify knowledge gaps, compare management plans, and forecast potential impacts. Well-validated, integrated ecological and economic models for agrivoltaic grazing systems will be essential for conceiving and testing new system designs and planning projects with increased confidence that they will achieve the desired outcomes. Key research questions include:
    - Can a biogeochemical model successfully predict ecological outcomes and forecast impacts across different climate zones, array designs, and management practices, as validated against robust field data?
    - What are the long-term ecological and economic impacts of applying different management practices and array designs in various climate zones?

- What are the most important considerations for the economic feasibility of a sustainable agrivoltaic grazing project?

4. **Management best practices**. Effective on-the-ground management following installation is necessary for successful agrivoltaic longevity. More research is needed to evaluate the best tools and practices for managing livestock within a solar array, specifically methods for using Adaptive Multi-paddock Grazing (Teague et al., 2013) or rotational grazing. Logistics such as fencing, livestock water placement, loading pens, and predation are areas of concern for livestock managers, and research will help clarify best practices. Additionally, successful livestock management may hinge on pre- and post-solar installation methods and practices. Techniques such as avoided topsoil removal by grading, revegetation seed mixes, timing of planting and grazing, soil amendments, cable management, and electrical combining, inverting, and transmitting designs should all be studied and optimized for dual-use systems. Key research questions include:
    - What are the impacts of specific grazing practices (continuous vs rotational, grazing intensity, duration, etc.) on ecological outcomes?
    - What are the optimal solar installation methods for supporting successful agrivoltaic grazing systems?
5. **Social Dimensions.** While research on the social dimensions of general agrivoltaics is limited, social research specific to grazing agrivoltaic systems is practically non-existent. Stakeholder and community perspectives are highly influential in solar PV development and permitting success, and better understanding drivers of acceptance and resistance is critical (Pascaris, 2022). This is also true for ranchers, farmers, and graziers who may be candidates for agrivoltaic grazing partnerships. Notably, in addition to inventorying the scope and scale

of grazing agrivoltaics deployment nationwide, a 2024 U.S. Census of Solar Grazing also surveyed grazier motivations for and perceived benefits of engaging in agrivoltaic partnerships (*ASGA Call 85*, 2025). Likewise, a Colorado-based survey broadly investigated agricultural sector interests and concerns with agrivoltaics (Goncharova et al., 2024). In the U.S., progress has been made to understand the social dimensions of grazing agrivoltaics, but broadly, there are large gaps and much more to learn, especially on a global scale. Key research questions include:

- What are the drivers and barriers to acceptance of grazing agrivoltaics?
- What are best practices for grazing agrivoltaics deployment?
- What are the most trusted information sources for agrivoltaics education and knowledge-building?
- What are the mechanisms for new knowledge adoption and opinion change?
- What are perceived benefits and risks of grazing agrivoltaics partnerships?

6. **Collaborative science**. Lastly, we identify a gap not just in research topics but in how research is conducted. Agrivoltaic grazing systems bring together diverse stakeholders and consequently rely on strong collaboration between ranchers, landowners and land stewards, solar developers, utility companies, and researchers to develop successful systems with mutual benefits across all three components (ecosystem, livestock, and solar PV). The co-production of knowledge via collaborative science can have greater relevance to stakeholders because researchers will address a wider range of perspectives and translate real-world challenges into research questions (Porensky, 2021). This should include on-farm research incorporating partnerships with solar PV experts, ranchers, and cross-disciplinary scientists to ensure the research is relevant and applicable.

5. Conclusions

This literature synthesis and gap analysis highlights several overarching themes and key takeaways central to agrivoltaic grazing systems. We emphasize first and foremost a systems perspective, where agrivoltaic grazing systems are embedded in a complex social-ecological context. The impact of grazing on an ecosystem can be incredibly variable with influence from a wide range of local factors. When introducing additional spatial heterogeneity through the integration of PV modules, this variability will only increase. Research on these systems must therefore be cognizant of this complexity throughout the experiment. The relationship between microclimate, animal behavior, and ecosystem outcomes are all heavily interrelated, making a holistic, systems perspective critical for the field.

An additional key takeaway that spans all the components and gaps discussed is the importance of coordinated research efforts. Compounding the challenges of limited studies is a lack of standardization across studies making it difficult to draw generalized conclusions. In addition to the need for additional research, there is a need for consistent data collection and inclusion of key variables across agrivoltaic grazing systems to facilitate greater synthesis.

Grazing agrivoltaics is a rapidly expanding field that has strong potential for increasing land-use efficiency, minimizing land-use tradeoffs, and improving the ecological outcomes of renewable energy buildout. Despite the prevalence of solar grazing, there is very limited research on the sustainability impacts of these systems and best practices for successful management. This review synthesizes existing research specific to agrivoltaic grazing systems and relevant research from adjacent fields to identify key knowledge gaps and recommendations for future research directions. We propose a conceptual framework for understanding agrivoltaic grazing systems centered on the integration of three fundamental components: land, livestock, and solar PV.

Existing research that studies the integration of two out of these three components can aid in filling some research gaps as well as informing our understanding of what new research specific to agrivoltaic grazing systems is needed. Based on the literature synthesis and this framework, we identify six key research gaps that should be priority directions for new research on agrivoltaic grazing systems. These gaps include foundational research on the integration of livestock with solar infrastructure and characterizing the layered ecological impacts of co-locating grazing and solar PV, which will improve our capacity for modeling these systems, facilitating improved long-term and predictive abilities to inform design as well as management best practices. These technical research gaps are situated within the broader need to understand the social dimensions of these systems and centralize collaborative research. Filling these gaps is essential to realizing the potential of these multi-land-use systems.

REFERENCES

Abdalla, M., Hastings, A., Chadwick, D. R., Jones, D. L., Evans, C. D., Jones, M. B., Rees, R. M., & Smith, P. (2018). Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. *Agriculture, Ecosystems & Environment*, *253*, 62–81. https://doi.org/10.1016/j.agee.2017.10.023

Adeh, E. H., Good, S. P., Calaf, M., & Higgins, C. W. (2019). Solar PV Power Potential is Greatest Over Croplands. *Scientific Reports*, *9*(1), Article 1. https://doi.org/10.1038/s41598-019-47803-3

Adeh, E. H., Selker, J. S., & Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLOS ONE*, *13*(11), e0203256. https://doi.org/10.1371/journal.pone.0203256

Agrisolar Digital Map by SolarPower Europe. (n.d.). *Agrisolar Europe*. Retrieved February 27, 2025, from https://agrisolareurope.org/map/

Agrivoltaics Map. (n.d.). InSPIRE, National Renewable Energy Lab. Retrieved November 30, 2023, from https://openei.org/wiki/InSPIRE/Agrivoltaics_Map

Al Mamun, M. A., Garba, I. I., Campbell, S., Dargusch, P., deVoil, P., & Aziz, A. A. (2023). Biomass production of a sub-tropical grass under different photovoltaic installations using different grazing strategies. *Agricultural Systems*, *208*, 103662. https://doi.org/10.1016/j.agsy.2023.103662

Andrew, A. C., Higgins, C. W., Smallman, M. A., Graham, M., & Ates, S. (2021). Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System. *Frontiers in Sustainable Food Systems*, *5*. https://www.frontiersin.org/articles/10.3389/fsufs.2021.659175

Andrew, A. C., Higgins, C. W., Smallman, M. A., Prado-Tarango, D. E., Rosati, A., Ghajar, S., Graham, M., & Ates, S. (2024). Herbage and sheep production from simple, diverse, and legume pastures established in an agrivoltaic production system. *Grass and Forage Science*, *79*(2), 294–307. https://doi.org/10.1111/gfs.12653

Armstrong, A., Ostle, N. J., & Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*, *11*(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016

Augustine, D. J., Derner, J. D., Milchunas, D., Blumenthal, D., & Porensky, L. M. (2017). Grazing moderates increases in C_3 grass abundance over seven decades across a soil texture gradient in shortgrass steppe. *Journal of Vegetation Science*, *28*(3), 562–572. https://doi.org/10.1111/jvs.12508

Bacon, Taylor; Monlezun, Anna Clare; Hong, Mu et al. (2025). Agrivoltaic grazing systems for a sustainable future: Citation database for a multi-disciplinary review & gap analysis [Dataset]. Dryad. https://doi.org/10.5061/dryad.cvdncjtf6

Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, *2*(9), Article 9. https://doi.org/10.1038/s41893-019-0364-5

Bell, R. H. V. (1971). A Grazing Ecosystem in the Serengeti. *Scientific American*, *225*(1), 86. https://doi.org/doi:10.1038/scientificamerican0771-86
Bessette, D. L., Hoen, B., Rand, J., Hoesch, K., White, J., Mills, S. B., & Nilson, R. (2024). Good fences make good neighbors: Stakeholder perspectives on the local benefits and burdens of large-scale solar energy development in the United States. *Energy Research & Social Science*, *108*, 103375. https://doi.org/10.1016/j.erss.2023.103375
Briske, D. D., Bestelmeyer, B. T., Brown, J. R., Fuhlendorf, S. D., & Wayne Polley, H. (2013). The Savory Method Can Not Green Deserts or Reverse Climate Change. *Rangelands*, *35*(5), 72–74. https://doi.org/10.2111/RANGELANDS-D-13-00044.1
Briske, D. D., Sayre, N. F., Huntsinger, L., Fernandez-Gimenez, M., Budd, B., & Derner, J. D. (2011). Origin, Persistence, and Resolution of the Rotational Grazing Debate: Integrating Human Dimensions Into Rangeland Research. *Rangeland Ecology & Management*, *64*(4), 325–334. https://doi.org/10.2111/REM-D-10-00084.1
Carvalho Fonsêca, V. de F., de Andrade Culhari, E., Moura, G. A. B., Nascimento, S. T., Milan, H. M., Neto, M. C., & Maia, A. S. C. (2023). Shade of solar panels relieves heat load of sheep. *Applied Animal Behaviour Science*, *265*, 105998. https://doi.org/10.1016/j.applanim.2023.105998
Choi, C. S., Cagle, A. E., Macknick, J., Bloom, D. E., Caplan, J. S., & Ravi, S. (2020). Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure. *Frontiers in Environmental Science*, *8*. https://www.frontiersin.org/articles/10.3389/fenvs.2020.00140
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. *Earth's Future*, *11*(6), e2023EF003542. https://doi.org/10.1029/2023EF003542
de Oliveira, A. F., Menezes, G. L., Gonçalves, L. C., de Araújo, V. E., Ramirez, M. A., Guimarães Júnior, R., Jayme, D. G., & Lana, Â. M. Q. (2022). Pasture traits and cattle performance in silvopastoral systems with *Eucalyptus* and *Urochloa*: Systematic review and meta-analysis. *Livestock Science*, *262*, 104973. https://doi.org/10.1016/j.livsci.2022.104973
Derner, J. D., Augustine, D. J., & Frank, D. A. (2019). Does Grazing Matter for Soil Organic Carbon Sequestration in the Western North American Great Plains? *Ecosystems*, *22*(5), 1088–1094. https://doi.org/10.1007/s10021-018-0324-3
Derner, J. D., Lauenroth, W. K., Stapp, P., & Augustine, D. J. (2009). Livestock as Ecosystem Engineers for Grassland Bird Habitat in the Western Great Plains of North America. *Rangeland Ecology & Management*, *62*(2), 111–118. https://doi.org/10.2111/08-008.1
De-Sousa, K. T., Deniz, M., Dittrich, J. R., & Hötzel, M. J. (2023). Effects of tree arrangements of silvopasture system on behaviour and performance of cattle – a systematic review. *Annals of Animal Science*, *23*(3), 629–639.
Edwards-Callaway, L. N., Cramer, M. C., Cadaret, C. N., Bigler, E. J., Engle, T. E., Wagner, J. J., & Clark, D. L. (2021). Impacts of shade on cattle well-being in the beef supply chain. *Journal of Animal Science*, *99*(2), skaa375. https://doi.org/10.1093/jas/skaa375
Energy Transition Factbook. (2023). Bloomberg NEF. https://assets.bbhub.io/professional/sites/24/BloombergNEF-CEM-2022-Factbook.pdf
Faria, A. F. P. A., Maia, A. S. C., Moura, G. A. B., Fonsêca, V. F. C., Nascimento, S. T., Milan, H. F. M., & Gebremedhin, K. G. (2023). Use of Solar Panels for Shade for Holstein Heifers. *Animals*, *13*(3), Article 3. https://doi.org/10.3390/ani13030329

Feuerbacher, A., Laub, M., Högy, P., Lippert, C., Pataczek, L., Schindele, S., Wieck, C., & Zikeli, S. (2021). An analytical framework to estimate the economics and adoption potential of dual land-use systems: The case of agrivoltaics. *Agricultural Systems*, *192*, 103193. https://doi.org/10.1016/j.agsy.2021.103193

Frank, D. A., McNaughton, S. J., & Tracy, B. F. (1998). The Ecology of the Earth's Grazing Ecosystems: Profound functional similarities exist between the Serengeti and Yellowstone. *BioScience*, *48*(7), 513–521. https://doi.org/10.2307/1313313

Galloso-Hernández, M. A., Rodríguez-Estévez, V., Alvarez-Díaz, C. A., Soca-Pérez, M., Dublin, D., Iglesias-Gómez, J., & Guelmes, L. S. (2020). Effect of Silvopastoral Systems in the Thermoregulatory and Feeding Behaviors of Water Buffaloes Under Different Conditions of Heat Stress. *Frontiers in Veterinary Science*, *7*. https://doi.org/10.3389/fvets.2020.00393

Giro, A., Pezzopane, J. R. M., Barioni Junior, W., Pedroso, A. de F., Lemes, A. P., Botta, D., Romanello, N., Barreto, A. do N., & Garcia, A. R. (2019). Behavior and body surface temperature of beef cattle in integrated crop-livestock systems with or without tree shading. *Science of The Total Environment*, *684*, 587–596. https://doi.org/10.1016/j.scitotenv.2019.05.377

Gomez-Casanovas, N., Mwebaze, P., Khanna, M., Branham, B., Time, A., DeLucia, E. H., Bernacchi, C. J., Knapp, A. K., Hoque, M. J., Du, X., Blanc-Betes, E., Barron-Gafford, G. A., Peng, B., Guan, K., Macknick, J., Miao, R., & Miljkovic, N. (2023). Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production. *Cell Reports Physical Science*, *4*(8), 101518. https://doi.org/10.1016/j.xcrp.2023.101518

Granit, I. (2021). *Solar Energy Within the Water-Energy-Food Security Nexus: A Systematic Review*. *1*, 35.

Grodsky, S. M., & Hernandez, R. R. (2020). Reduced ecosystem services of desert plants from ground-mounted solar energy development. *Nature Sustainability*, *3*(12), Article 12. https://doi.org/10.1038/s41893-020-0574-x

Guarino, J., & Swanson, T. (2022). Emerging Agrivoltaic Regulatory Systems: A Review of Solar Grazing. *Chicago-Kent Journal of Environmental and Energy Law*, *12*(1), 1–30.

Guerin, T. F. (2019). Impacts and opportunities from large-scale solar photovoltaic (PV) electricity generation on agricultural production. *Environmental Quality Management*, *28*(4), 7–14. https://doi.org/10.1002/tqem.21629

Haegel, N. M., & Kurtz, S. R. (2023). Global Progress Toward Renewable Electricity: Tracking the Role of Solar (Version 3). *IEEE Journal of Photovoltaics*, *13*(6), 768–776. IEEE Journal of Photovoltaics. https://doi.org/10.1109/JPHOTOV.2023.3309922

Handler, R., & Pearce, J. M. (2022). Greener sheep: Life cycle analysis of integrated sheep agrivoltaic systems. *Cleaner Energy Systems*, *3*, 100036. https://doi.org/10.1016/j.cles.2022.100036

Heins, B. J., Sharpe, K. T., Buchanan, E. S., & Reese, M. H. (2022). Agrivoltaics to shade cows in a pasture-based dairy system. *AIP Conference Proceedings*, *2635*(1), 060001. https://doi.org/10.1063/5.0103148

Hernandez, R. R., Armstrong, A., Burney, J., Ryan, G., Moore-O'Leary, K., Diédhiou, I., Grodsky, S. M., Saul-Gershenz, L., Davis, R., Macknick, J., Mulvaney, D., Heath, G. A., Easter, S. B., Hoffacker, M. K., Allen, M. F., & Kammen, D. M. (2019). Techno–

ecological synergies of solar energy for global sustainability. *Nature Sustainability*, *2*(7), Article 7. https://doi.org/10.1038/s41893-019-0309-z
Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., Barrows, C. W., Belnap, J., Ochoa-Hueso, R., Ravi, S., & Allen, M. F. (2014). Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*, *29*, 766–779. https://doi.org/10.1016/j.rser.2013.08.041
Jackson, A., Doubleday, K., Staie, B., Perna, A., Sabraw, M., Voss, L., Alvarez, A., Kominek, B., & Macknick, J. (2024). *County Land-Use Regulations for Solar Energy Development in Colorado* (NREL/TP--6A20-88556, 2339555, MainId:89335; p. NREL/TP--6A20-88556, 2339555, MainId:89335). https://doi.org/10.2172/2339555
Kampherbeek, E. W. (2023). A preliminary investigation of the effect of solar panels and rotation frequency on the grazing behavior of sheep (Ovis aries) grazing dormant pasture. *Applied Animal Behaviour Science*, *258*, 105799. https://doi.org/10.1016/j.applanim.2022.105799
Kampherbeek, E. W., Webb, L. E., Reynolds, B. J., Sistla, S. A., Horney, M. R., Ripoll-Bosch, R., Dubowsky, J. P., & McFarlane, Z. D. (2023). A preliminary investigation of the effect of solar panels and rotation frequency on the grazing behavior of sheep (Ovis aries) grazing dormant pasture. *Applied Animal Behaviour Science*, *258*, 105799. https://doi.org/10.1016/j.applanim.2022.105799
Kannenberg, S. A., Sturchio, M. A., Venturas, M. D., & Knapp, A. K. (2023). Grassland carbon-water cycling is minimally impacted by a photovoltaic array. *Communications Earth & Environment*, *4*(1), Article 1. https://doi.org/10.1038/s43247-023-00904-4
Kochendoerfer, N., Westbrook, A. S., McMillan, C. E., Lapierre, P. A., Zaman, M. A., Morris, S. H., DiTommaso, A., & Grodsky, S. (2025). Co-Location of Sheep Grazing and Solar Energy Production Yields Agrotechnological Synergies. *Agricultural Systems*, *229*(104403). https://doi.org/https://doi.org/10.1016/j.agsy.2025.104403
Klokov, A. V., Loktionov, E. Y., Loktionov, Y. V., Panchenko, V. A., & Sharaborova, E. S. (2023). A Mini-Review of Current Activities and Future Trends in Agrivoltaics. *Energies*, *16*(7), Article 7. https://doi.org/10.3390/en16073009
Knapp, A. K., Blair, J. M., Briggs, J. M., Collins, S. L., Hartnett, D. C., Johnson, L. C., & Towne, E. G. (1999). The Keystone Role of Bison in North American Tallgrass Prairie: Bison increase habitat heterogeneity and alter a broad array of plant, community, and ecosystem processes. *BioScience*, *49*(1), 39–50. https://doi.org/10.1525/bisi.1999.49.1.39
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*(18), 5190–5202. https://doi.org/10.1002/ldr.4101
Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik, E., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K., & Swan, A. (2021). *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final report*. Princeton University. https://www.dropbox.com/s/ptp92f65lgds5n2/Princeton%20NZA%20FINAL%20REPORT%20%2829Oct2021%29.pdf?dl=0
Le Moigne, M., Grison, C., Cases, L., & Hossaert-McKey, M. (2021). *Photovoltaism, Agriculture and Ecology: From Agrivoltaism to Ecovoltaism*. Wiley-ISTE. https://www.wiley.com/en-

us/Photovoltaism%2C+Agriculture+and+Ecology%3A+From+Agrivoltaism+to+Ecovoltaism-p-9781119887713
Liu, Y., Zhang, R.-Q., Huang, Z., Cheng, Z., López-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*(18), 2177–2186. https://doi.org/10.1002/ldr.3408
Loan, M., & Picon-Cochard, C. (2022). *One Year of Grassland Vegetation Dynamics in two Sheep-Grazed Agrivoltaic Systems*.
Louk, B. (2023). Solar Grazing as a Possible Vegetation Management Solution: A Budget Analysis. *Agricultural Economics and Agribusiness Undergraduate Honors Theses*. https://scholarworks.uark.edu/aeabuht/26
Lytle, W., Meyer, T. K., Tanikella, N. G., Burnham, L., Engel, J., Schelly, C., & Pearce, J. M. (2021). Conceptual Design and Rationale for a New Agrivoltaics Concept: Pasture-Raised Rabbits and Solar Farming. *Journal of Cleaner Production*, *282*, 124476. https://doi.org/10.1016/j.jclepro.2020.124476
Machmuller, M. B., Kramer, M. G., Cyle, T. K., Hill, N., Hancock, D., & Thompson, A. (2015). Emerging land use practices rapidly increase soil organic matter. *Nature Communications*, *6*, 6995. https://doi.org/10.1038/ncomms7995
Macknick, J., Hartmann, H., Barron-Gafford, G., Beatty, B., Burton, R., Seok-Choi, C., Davis, M., Davis, R., Figueroa, J., Garrett, A., Hain, L., Herbert, S., Janski, J., Kinzer, A., Knapp, A., Lehan, M., Losey, J., Marley, J., MacDonald, J., … Walston, L. (2022). *The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons from the InSPIRE Research Study* (NREL/TP-6A20-83566, 1882930, MainId:84339; p. NREL/TP-6A20-83566, 1882930, MainId:84339). https://doi.org/10.2172/1882930
Maia, A. S. C., Culhari, E. de A., Fonsêca, V. de F. C., Milan, H. F. M., & Gebremedhin, K. G. (2020). Photovoltaic panels as shading resources for livestock. *Journal of Cleaner Production*, *258*, 120551. https://doi.org/10.1016/j.jclepro.2020.120551
Mamun, M. A. A., Dargusch, P., Wadley, D., Zulkarnain, N. A., & Aziz, A. A. (2022). A review of research on agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *161*, 112351. https://doi.org/10.1016/j.rser.2022.112351
Marrou, H., Dufour, L., & Wery, J. (2013). How does a shelter of solar panels influence water flows in a soil–crop system? *European Journal of Agronomy*, *50*, 38–51. https://doi.org/10.1016/j.eja.2013.05.004
Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., & Wery, J. (2013). Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? *Agricultural and Forest Meteorology*, *177*, 117–132. https://doi.org/10.1016/j.agrformet.2013.04.012
McCall, J., Macdonald, J., Burton, R., & Macknick, J. (2023). Vegetation Management Cost and Maintenance Implications of Different Ground Covers at Utility-Scale Solar Sites. *Sustainability*, *15*(7), Article 7. https://doi.org/10.3390/su15075895
Monlezun, A. C. (2022). *Partnerships on Colorado Conservation Lands: Social-Ecological Outcomes of Collaborative Grazing Management* [Ph.D., Colorado State University]. https://www.proquest.com/docview/2766456822/abstract/7E96FE1273E8428DPQ/1
Moore, S., Graff, H., Ouellet, C., Leslie, S., & Olweean, D. (2022). Can we have clean energy and grow our crops too? Solar siting on agricultural land in the United States. *Energy Research & Social Science*, *91*, 102731. https://doi.org/10.1016/j.erss.2022.102731

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*, e00500. https://doi.org/10.1016/j.geodrs.2022.e00500
Mosier, S., Apfelbaum, S., Byck, P., Calderon, F., Teague, R., Thompson, R., & Cotrufo, M. F. (2021). Adaptive multi-paddock grazing enhances soil carbon and nitrogen stocks and stabilization through mineral association in southeastern U.S. grazing lands. *Journal of Environmental Management*, *288*, 112409. https://doi.org/10.1016/j.jenvman.2021.112409
Nicholls, J. (2020). Technological intrusion and communicative renewal: The case of two rural solar farm developments in the UK. *Energy Policy*, *139*, 111287. https://doi.org/10.1016/j.enpol.2020.111287
Nijsse, F. J. M. M., Mercure, J.-F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., Vercoulen, P., & Pollitt, H. (2023). The momentum of the solar energy transition. *Nature Communications*, *14*(1), Article 1. https://doi.org/10.1038/s41467-023-41971-7
Pascaris, A. S. (2021). Examining existing policy to inform a comprehensive legal framework for agrivoltaics in the U.S. *Energy Policy*, *159*, 112620. https://doi.org/10.1016/j.enpol.2021.112620
Pascaris, A. S., Gerlak, A. K., & Barron-Gafford, G. A. (2023). From niche-innovation to mainstream markets: Drivers and challenges of industry adoption of agrivoltaics in the U.S. *Energy Policy*, *181*, 113694. https://doi.org/10.1016/j.enpol.2023.113694
Pascaris, A. S., Handler, R., Schelly, C., & Pearce, J. M. (2021). Life cycle assessment of pasture-based agrivoltaic systems: Emissions and energy use of integrated rabbit production. *Cleaner and Responsible Consumption*, *3*, 100030. https://doi.org/10.1016/j.clrc.2021.100030
Pascaris, A. S., Schelly, C., Burnham, L., & Pearce, J. M. (2021). Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics. *Energy Research & Social Science*, *75*, 102023. https://doi.org/10.1016/j.erss.2021.102023
Pascaris, A. S., Schelly, C., & Pearce, J. M. (2020). A First Investigation of Agriculture Sector Perspectives on the Opportunities and Barriers for Agrivoltaics. *Agronomy*, *10*(12), Article 12. https://doi.org/10.3390/agronomy10121885
Pascaris, A. S., Schelly, C., Rouleau, M., & Pearce, J. M. (2022). Do agrivoltaics improve public support for solar? A survey on perceptions, preferences, and priorities. *Green Technology, Resilience, and Sustainability*, *2*(1), 8. https://doi.org/10.1007/s44173-022-00007-x
Porensky, L. M. (2021). Embracing complexity and humility in rangeland science. *Rangelands*, *43*(4), 142–150. https://doi.org/10.1016/j.rala.2021.03.007
Porensky, L. M., McGee, R., & Pellatz, D. W. (2020). Long-term grazing removal increased invasion and reduced native plant abundance and diversity in a sagebrush grassland. *Global Ecology and Conservation*, *24*, e01267. https://doi.org/10.1016/j.gecco.2020.e01267
Rahmaniah, F., & Tay, S. E. R. (2023). Environmental benefits of co-located photovoltaic and greenery systems: A review on the operational performance and assessment framework across climate zones. *Sustainable Energy Technologies and Assessments*, *58*, 103301. https://doi.org/10.1016/j.seta.2023.103301

Randle-Boggis, R. J., White, P. C. L., Cruz, J., Parker, G., Montag, H., Scurlock, J. M. O., & Armstrong, A. (2020). Realising co-benefits for natural capital and ecosystem services from solar parks: A co-developed, evidence-based approach. *Renewable and Sustainable Energy Reviews*, *125*, 109775. https://doi.org/10.1016/j.rser.2020.109775

Reeder, J. D., & Schuman, G. E. (2002). Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. *Environmental Pollution*, *116*(3), 457–463. https://doi.org/10.1016/S0269-7491(01)00223-8

Sanderson, J. S., Beutler, C., Brown, J. R., Burke, I., Chapman, T., Conant, R. T., Derner, J. D., Easter, M., Fuhlendorf, S. D., Grissom, G., Herrick, J. E., Liptzin, D., Morgan, J. A., Murph, R., Pague, C., Rangwala, I., Ray, D., Rondeau, R., Schulz, T., & Sullivan, T. (2020). Cattle, conservation, and carbon in the western Great Plains. *Journal of Soil and Water Conservation*, *75*(1), 5A-12A. https://doi.org/10.2489/jswc.75.1.5A

Sarr, A., Soro, Y. M., Tossa, A. K., & Diop, L. (2023). Agrivoltaic, a Synergistic Co-Location of Agricultural and Energy Production in Perpetual Mutation: A Comprehensive Review. *Processes*, *11*(3), Article 3. https://doi.org/10.3390/pr11030948

Saxena, A., Brown, C., Arneth, A., & Rounsevell, M. (2024). Advanced photovoltaic technology can reduce land requirements and climate impact on energy generation. *Communications Earth & Environment*, *5*(1), 1–11. https://doi.org/10.1038/s43247-024-01754-4

Sharpe, K. T., Heins, B. J., Buchanan, E. S., & Reese, M. H. (2021). Evaluation of solar photovoltaic systems to shade cows in a pasture-based dairy herd. *Journal of Dairy Science*, *104*(3), 2794–2806. https://doi.org/10.3168/jds.2020-18821

Smith, P. (2004). How long before a change in soil organic carbon can be detected? *Global Change Biology*, *10*(11), 1878–1883. https://doi.org/10.1111/j.1365-2486.2004.00854.x

Solar Futures Study. (2021). U.S. Department of Energy. https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf

Stanley, P. L., Wilson, C., Patterson, E., Machmuller, M. B., & Cotrufo, M. F. (2024). Ruminating on soil carbon: Applying current understanding to inform grazing management. *Global Change Biology*, *30*(3), e17223. https://doi.org/10.1111/gcb.17223

Sturchio, M. A., Kannenberg, S. A., & Knapp, A. K. (2024). Agrivoltaic arrays can maintain semi-arid grassland productivity and extend the seasonality of forage quality. *Applied Energy*, *356*, 122418. https://doi.org/10.1016/j.apenergy.2023.122418

Sturchio, M. A., & Knapp, A. K. (2023). Ecovoltaic principles for a more sustainable, ecologically informed solar energy future. *Nature Ecology & Evolution*, 1–4. https://doi.org/10.1038/s41559-023-02174-x

Sturchio, M. A., Macknick, J. E., Barron-Gafford, G. A., Chen, A., Alderfer, C., Condon, K., Hajek, O. L., Miller, B., Pauletto, B., Siggers, J. A., Slette, I. J., & Knapp, A. K. (2022). Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. *Ecosphere*, *13*(12), e4334. https://doi.org/10.1002/ecs2.4334

Tajima, M., Doedt, C., & Iida, T. (2022). Comparative study on the land-use policy reforms to promote agrivoltaics. *AIP Conference Proceedings*, *2635*(1), 050003. https://doi.org/10.1063/5.0115906

Tanner, K. E., Moore-O'Leary, K. A., Parker, I. M., Pavlik, B. M., & Hernandez, R. R. (2020). Simulated solar panels create altered microhabitats in desert landforms. *Ecosphere*, *11*(4), e03089. https://doi.org/10.1002/ecs2.3089

Taylor, M., Pettit, J., Sekiyama, T., & Sokołowski, M. M. (2023). Justice-driven agrivoltaics: Facilitating agrivoltaics embedded in energy justice. *Renewable and Sustainable Energy Reviews*, *188*, 113815. https://doi.org/10.1016/j.rser.2023.113815

Teague, R., Provenza, F., Kreuter, U., Steffens, T., & Barnes, M. (2013). Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience? *Journal of Environmental Management*, *128*, 699–717. https://doi.org/10.1016/j.jenvman.2013.05.064

Teague, W. R., Apfelbaum, S., Lal, R., Kreuter, U. P., Rowntree, J., Davies, C. A., Conser, R., Rasmussen, M., Hatfield, J., Wang, T., Wang, F., & Byck, P. (2016). The role of ruminants in reducing agriculture's carbon footprint in North America. *Journal of Soil and Water Conservation*, *71*(2), 156–164. https://doi.org/10.2489/jswc.71.2.156

Teague, W. R., Dowhower, S. L., Baker, S. A., Haile, N., DeLaune, P. B., & Conover, D. M. (2011). Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. *Agriculture, Ecosystems & Environment*, *141*(3), 310–322. https://doi.org/10.1016/j.agee.2011.03.009

Tölgyesi, C., Bátori, Z., Pascarella, J., Erdős, L., Török, P., Batáry, P., Birkhofer, K., Scherer, L., Michalko, R., Košulič, O., Zaller, J. G., & Gallé, R. (2023). Ecovoltaics: Framework and future research directions to reconcile land-based solar power development with ecosystem conservation. *Biological Conservation*, *285*, 110242. https://doi.org/10.1016/j.biocon.2023.110242

Torma, G., & Aschemann-Witzel, J. (2023). Social acceptance of dual land use approaches: Stakeholders' perceptions of the drivers and barriers confronting agrivoltaics diffusion. *Journal of Rural Studies*, *97*, 610–625. https://doi.org/10.1016/j.jrurstud.2023.01.014

Towner, E., Karas, T., Janski, J., Macknick, J., & Ravi, S. (2022). *Managed sheep grazing can improve soil quality and carbon sequestration at solar photovoltaic sites* [Other]. Soil Science. https://doi.org/10.1002/essoar.10510141.1

Uldrijan, D., Kováčiková, M., Jakimiuk, A., Vaverková, M. D., & Winkler, J. (2021). Ecological effects of preferential vegetation composition developed on sites with photovoltaic power plants. *Ecological Engineering*, *168*, 106274. https://doi.org/10.1016/j.ecoleng.2021.106274

van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

Vervloesem, J., Marcheggiani, E., Choudhury, M. A. M., & Muys, B. (2022). Effects of Photovoltaic Solar Farms on Microclimate and Vegetation Diversity. *Sustainability*, *14*(12), Article 12. https://doi.org/10.3390/su14127493

Weselek, A., Bauerle, A., Hartung, J., Zikeli, S., Lewandowski, I., & Högy, P. (2021). Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agronomy for Sustainable Development*, *41*(5), 59. https://doi.org/10.1007/s13593-021-00714-y

Zainol Abidin, M. A., Mahyuddin, M. N., & Mohd Zainuri, M. A. A. (2021). Solar Photovoltaic Architecture and Agronomic Management in Agrivoltaic System: A Review. *Sustainability*, *13*(14), Article 14. https://doi.org/10.3390/su13147846

Zhang, J., Wang, T., Chang, Y., & Liu, B. (2023). A sustainable development pattern integrating data centers and pasture-based agrivoltaic systems for ecologically fragile areas.

Resources, Conservation and Recycling, *188*, 106684. https://doi.org/10.1016/j.resconrec.2022.106684

CHAPTER 3: ECOLOGICAL IMPACTS OF SOLAR ARRAY CONSTRUCTION IN A HUMID SUBTROPICAL GRASSLAND: NATURAL VARIATION AND CONSERVATION MANAGEMENT OUTWEIGHED DISTURBANCE[2]

1. Introduction

Solar photovoltaic (PV) energy generation can significantly reduce greenhouse gas emissions and is a key tool for mitigating climate change (IPCC, 2023). Over the last decade, solar PV capacity globally has increased from around 135 GW in 2013 to almost 2,000 GW in 2024 (IRENA, 2025). These trends are expected to continue, with costs dropping and deployment increasing (IPCC, 2023). However, compared to other forms of energy generation, solar PV has a higher land footprint (van Zalk & Behrens, 2018), which has raised concerns, particularly because in the United States, a majority of solar arrays are installed on agricultural land (Maguire et al., 2024; Stid et al., 2025). Understanding the impacts of these energy systems on the land, as well as the potential to integrate multiple land uses (agrivoltaics and ecovoltaics), is therefore essential for the sustainable deployment of solar energy.

Much of the research on these questions has been conducted within existing PV arrays, with comparisons drawn to neighboring areas without PV modules as a control (Adeh et al., 2018; Armstrong et al., 2016; Bacon et al., 2026 *in prep*; Choi et al., 2020; Grodsky & Hernandez, 2020; Lambert et al., 2021). However, in cases like these, it's difficult to differentiate between the impacts of PV array installation and the impacts of the presence of the PV array itself. Few studies have been able to isolate the effects of array installation on key ecological indicators. This is likely due, at least in part, to the challenges of accessing sites for sampling

[2] Bacon, Taylor, A. C. Monlezun, N. de Vries, A. Banuelos, M. Hong, and K. Paustian. "Ecological Impacts of Solar Array Construction in a Humid Subtropical Grassland: Natural Variation and Conservation Management Outweighed Disturbance." 2026 [In prep]

before and after PV installation. This has been identified as a significant gap in the field (Krasner et al., 2025; Stid et al., 2025).

There is a wide range of installation methods and practices, and environmental outcomes will vary accordingly. Installation practices can be viewed along a spectrum from high-impact to low-impact. High-impact practices include vegetation removal, extensive grading, and topsoil removal (Stid et al., 2025), and evidence suggests these practices can leave a legacy effect for decades to come. At a PV site that was intensively graded, even with revegetation, soil nutrient and physical properties were still degraded relative to a comparative grassland after nearly a decade of recovery (Choi et al., 2020). Low-impact practices include using a racking system that can accommodate uneven terrain and reduce the need for grading, retaining existing vegetation and maintaining living roots, and limiting heavy machinery traffic, particularly when the soil is wet (Bureau of Land Management, 2024; NREL, 2026; Stid et al., 2025). Karban et al. (2025) found a direct relationship between disturbance intensity and ecological impacts during PV array construction at the Gemini Solar Array in Nevada. Low-impact construction practices offer better alignment with the goals of multi-use solar energy systems, however ecological outcomes remain poorly characterized.

In addition to variation in construction practices, ecosystem response to PV array installation will also vary across climate regions. One of the only existing before-after control-impact (BACI) studies on PV installation was conducted in a desert ecosystem in the Southwestern U.S. (Karban et al., 2025). While these results are valuable, they are unlikely to transfer directly to other diverse geographies (Bureau of Land Management, 2024).

This study aims to address this research gap by investigating the impacts of PV array installation on ecological conditions in the southeastern United States. Using a BACI research design, we ask: how does the installation of a PV array following low-impact construction practices impact soil compaction, water infiltration, and vegetation cover? We hypothesized that even with low-impact construction practices, array installation would increase soil compaction and cause a corresponding decrease in water infiltration, with more limited impacts on vegetation cover due to the site's location in a region with high vegetation productivity.

2. Methods

2.1 Site Description

Research was conducted at the Silicon Ranch 'CattleTracker' Outdoor Test Lab Site, southeast of Nashville, TN. This site is a 4.5 MWp single-axis tracking utility distribution-tied, solar PV array mounted at a height of 2.25 m to accommodate cattle grazing. There are two primary soil types present at the site: Eagleville silty clay loam and Talbott silt loam (Soil Survey Staff, n.d.). The site was populated with predominantly cool-season grasses (Kentucky bluegrass (*Poa pratensis*), red fescue (*Festuca rubra*), and tall fescue (*Schedonorus arundinaceus*). A full list of plant species identified at the site is available in Supplemental Materials, Table S1.

The land was purchased by Silicon Ranch in 2023. The previous landowner had owned the property since 2010, and it was utilized for cattle pasture and hay fields. In November 2023, soil amendments (fertilizer and lime) were applied across the entire site in response to soil nutrient testing commissioned by Silicon Ranch. Construction began in December 2024. The eastern edge of the site (outside of the study area) required more intensive land work due to an extensive rock outcropping. The western edge of the array, where data was collected, was not graded. After all necessary earthwork was complete (early 2025), soil amendments (fertilizer and lime) were added across the array footprint, and the array footprint was broadcast-seeded with a temporary seed mix (Table S2), with a focus on the areas where vegetation had been most disrupted by construction.

The array was installed utilizing low-impact practices, where established vegetation was left intact during construction, and vehicles traveled over existing vegetation. A terrain-following tracking system was also used, reducing the need to grade or re-contour the site. Due to the underlying rock, a rock drill was used to install steel piles. Once the piles were installed, modules were racked using a truck with a modified trailer to accommodate the taller racking height. After the array was completed in September 2025, additional seed was drilled with a sod driller or broadcast within the array. Vegetation was mowed once in early May 2025 and again in late August 2025.

Our study of construction impacts on key ecological indicators was designed following a BACI framework. Data were collected in two treatment areas: a control area and an array area at two time points: before construction (December 3-4, 2024) and after construction (November 19-20, 2025). Pre- and post-construction sampling points were within 1 year +/- 2 weeks to control for consistent ambient environmental conditions to the greatest extent possible. The control treatment was a pasture directly adjacent to where the array was installed and was not impacted by construction. The array treatment was the furthest west portion of the array area, where the soil type was most compatible with the control, based on the USDA Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) soil textures (Figure 1).

Within each treatment, eight transects, each 50m long, running East-West (perpendicular to rows of PV modules) were established using randomly generated points within the bounds of each treatment area. The location of the start and end of each transect was recorded and marked in the field to enable resampling along the same transects. Post-construction, the location of the transect start, relative to the rows of PV modules, was recorded. This allowed us to retroactively determine the micro-zone, or spatial position relative to the PV modules, for each sampling point along the transect, consistent with ecological research practice within PV arrays (Bacon et al., 2026 *in prep*; Sturchio et al., 2022; Toy et al., 2025). We categorized points into one of four micro-zones: directly under the modules (U), on the eastern (E) and western (W) drip edges of the modules, and in the space between rows of modules (B) – a schematic of these micro-zones, along with the exact dimensions, is available in Supplemental Materials Figure S1.

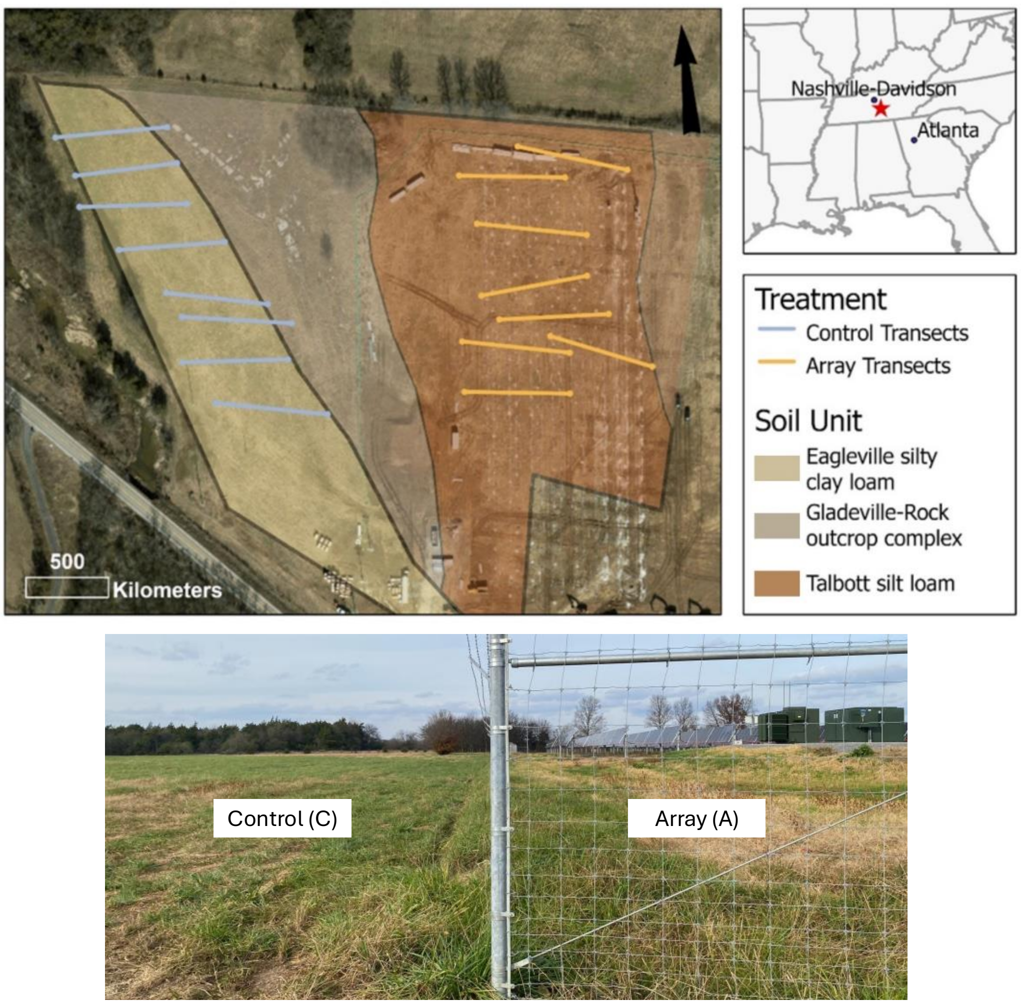


Figure 1. Experimental design for BACI study of solar PV array construction impacts. a) Transect location and soil units (Soil Survey Staff, n.d.) for control and array treatments. b) Photograph taken November 19, 2025, showing the control treatment and adjacent array treatment following completion of array installation.

2.2 Field Data Collection

Three ecological indicators were sampled before and after construction: soil penetration resistance (PR), unsaturated hydraulic conductivity (K_{unsat}), and vegetation cover. These indicators were selected to quantify the site's physical, hydrological, and ecological characteristics, which we anticipated would be impacted by construction. These indicators could also feasibly be replicated year-to-year to track the ecosystem response and recovery.

PR was measured using a static cone penetrometer (AMS, SKU 59010). PR is commonly used as an indicator of soil compaction, and penetrometers are a well-established method for evaluating the impacts of disturbances (vehicle traffic, tillage, construction, grazing, etc.) (Kuhwald et al., 2020; Mulholland & Fullen, 1991; Steyn et al., 1995; Tollner et al., 1990). In the context of solar array construction, Karban et al. (2025) employed similar methodologies, and the New York State Department of Agriculture and Markets includes penetrometer measurements in their guidance for monitoring and mitigating environmental impacts of solar development (NYSDAM, 2019).

PR measurements were taken at 15 cm depth every 5 m along each transect (n = 160), with the same observer for all samples, both pre- and post-construction. Samples along each transect were treated as subsamples and aggregated to the transect level to avoid spatial autocorrelation. A significant limitation of penetrometers is their sensitivity to soil moisture (Raper, 2005; To & Kay, 2005). To account for the influence of soil moisture, we sampled during the same time of year when we would anticipate more consistent hydrological patterns and avoided sampling immediately following a precipitation event. While we could not take core samples and directly measure soil moisture, we used a process-based biogeochemical model to estimate soil moisture on the sampling days with the site's specific soil properties and land-use history, and consulted soil moisture data from a nearby weather station (USDA Natural Resources Conservation Service, SCAN site 2077) to better understand potential variability between sampling dates.

Unsaturated hydraulic conductivity was measured using a mini disk infiltrometer, which infiltrates water into the soil at a slight tension through a porous disk, offering a faster alternative to ponding-ring methods and facilitating improved capture of spatial variability (METER Group, 2021). Measurements were taken every 10m along each transect (n = 80). Instrument suction was set to 2 cm in accordance with guidance provided by the manufacturer. Volume readings were taken every 30-seconds for 15 minutes or until 30 mL of water had infiltrated the soil, whichever came first. Unsaturated hydraulic conductivity was calculated from this time series and Van Genuchten parameters, which were estimated based on SSURGO soil texture for each treatment area (METER Group, 2021; Soil Survey Staff, n.d.).

To evaluate vegetation cover, 0.5m x 0.5m quadrants were established every 10 m along every transect (n = 80). Overhead photographs were taken of each quadrant with a digital camera, utilizing a step stool to ensure the entire quadrant was captured with the camera perpendicular to the ground. These photographs were analyzed using SamplePoint image analysis software to estimate the ground cover by plant functional group (Booth et al., 2006). The images were resized in ArcGIS Pro to meet SamplePoint's PictureBox requirements, and then 100 systematic points were created per image in a grid. The single pixel at the center of each point was then manually classified by category (grasses, forbs, legumes, bare ground, litter, and rock).

2.3 Evaluation of Data Consistency

After field data collection and analysis, an additional analysis was conducted to evaluate the consistency of the changes in PR and K_{unsat}. Both PR and K_{unsat} reflect features of soil structure, and can both be related to soil bulk density (Schaap et al., 2001; Whalley et al., 2007). Therefore, to evaluate the consistency of the changes in these two indicators, we used mathematical models to relate the changes in K_{unsat} and PR to an implied change in bulk density (ΔBD).

First, we used the process-based biogeochemical model DayCent® (Parton et al., 1998) to estimate volumetric water content (VWC) at 0-15cm depth in each treatment during the sampling days. The model inputs included PRISM weather data (PRISM Group, n.d.), soil texture and pH from SSURGO, alongside land-use history and vegetation type from the site. Other soil inputs to the DayCent® model, including saturated conductivity, bulk density, field capacity, and wilting point, were estimated by soil texture and pedotransfer functions (Saxton et al., 1986). Following the spin-up period, the model was run for all of 2024 and 2025.

To estimate the implied change in bulk density from the change in K_{unsat}, we employed the Rosetta pedotransfer function (Schaap et al., 2001), which predicts saturated hydraulic conductivity and Van Genuchten retention curve parameters from soil texture and bulk density. Using the ROSETTA function in R (Beaudette et al., n.d.), we ran the model across a range of bulk densities with the SSURGO texture for each treatment. This allowed us to estimate a treatment-specific slope relating log-transformed saturated hydraulic conductivity to bulk density ($d\log_{10}(K_s)/dBD$). This slope was then used to calculate an implied change in bulk density from the measured change in hydraulic conductivity. This method assumes that the change in measured unsaturated hydraulic conductivity reflects a change in saturated hydraulic conductivity (i.e., that the relationship between these values is stable), which introduces some additional uncertainty into this validation (Ankeny et al., 1991; Reynolds & Elrick, 1991).

We also used the Whalley et al. (2007) pedotransfer function to estimate the implied change in bulk density from the change in PR (Supplemental Materials Eq. S1). This equation relates PR to bulk density, accounting for matric potential, derived through the Van Genuchten inversion using DayCent® estimated VWC. While pedotransfer functions are often soil-specific, Whalley et al. (2007) validated this relationship on a broad range of soils and found that the three coefficients were relatively generalizable. However, the function is not truly universal, so to mitigate imperfect transferability, we used only the slope coefficients as sensitivity parameters rather than using the full equation for absolute prediction. The implied ΔBD was calculated, first using just the bulk density slope term (not accounting for changes in soil moisture), and then adding an explicit moisture correction using the matric potential term.

2.4 Remote Sensing Satellite Data Analysis

To supplement the pre- and post-construction field data and better understand land-use history at the site, remote sensing data were used to characterize historic trends in ecosystem productivity and site characteristics prior to the acquisition of the site for solar power generation. Data were obtained and analyzed through Google Earth Engine, using the centroid of each treatment area. Net primary productivity (NPP) data from 1986-2024 were acquired from the Rangeland Analysis Platform (RAP), which utilizes data from Landsat 5 TM, Landsat 7 EMT+, and Landsat 8 OLI at a 30 m spatial resolution (Jones et al., 2021). RAP estimates NPP using a process-based model that integrates vegetation cover by plant functional type (PFT), absorbed solar radiation, and meteorology. Plant functional types (annual forb and grass, perennial forb and grass, shrub, and tree) were determined at the sub-pixel level utilizing a model trained on tens of thousands of paired field plots and satellite observations, then applied across the full Landsat archive to predict fractional cover. NPP values for each PFT were summed to calculate total NPP, which was then averaged annually within each treatment area. NPP data were supplemented with two additional remote sensing indices: bare soil index (BSI) and normalized difference vegetation index (NDVI). Both indices were calculated from spectral bands from Landsat 8 OLI for 2013-2024. BSI reflects the exposed mineral soil, on a normalized scale of -1 to +1, with negative values indicating surfaces dominated by vegetation or water (Rikimaru et al., 2002). NDVI is an indicator of vegetation presence and greenness (-1 to +1) with values around 0 indicating bare soil, rock, or sand, and high values indicative of dense vegetative cover (Deering & Eck, 1987). Full details on the remote sensing data sources and indices are available in Supplemental Materials Table S4.

2.5 Statistical Methods

Statistical analysis was carried out in R (R Core Team, 2025). All field measurements were analyzed using linear mixed-effects models with the R package *lme4* (Bates et al., 2015). Treatment (array/control), sampling time (pre/post), and the interaction between the two were modeled as fixed effects, and transect ID was included as a random effect. Transect-level means were treated as statistically independent values. Each model was evaluated using diagnostic plots to ensure assumptions were met, and pairwise interactions were analyzed using the *emmeans* package (Lenth et al., 2025). K_{unsat} was log-transformed for the linear mixed-effects model, and individual models were also run for the coverage changes of each vegetation cover category. Satterthwaite's method was used for degrees of freedom approximation (Satterthwaite, 1946).

Additional statistical analysis was conducted to evaluate changes within the array treatment against background changes in the control treatment. For each transect in the array treatment, the mean change in log-transformed K_{unsat} and PR in the control treatment was subtracted to represent the change in the array relative to the background changes at the site, as represented by the change in the control treatment. A one-sample t-test was used to test if this difference was significantly different from 0 (i.e., the array and the control changed consistently).

3. Results

3.1 Field Data

Between pre-construction sampling in December 2024 and post-construction sampling in November 2025, we observed a significant increase in K_{unsat} and a significant decrease in PR in both the array and control treatment (Figure 2).

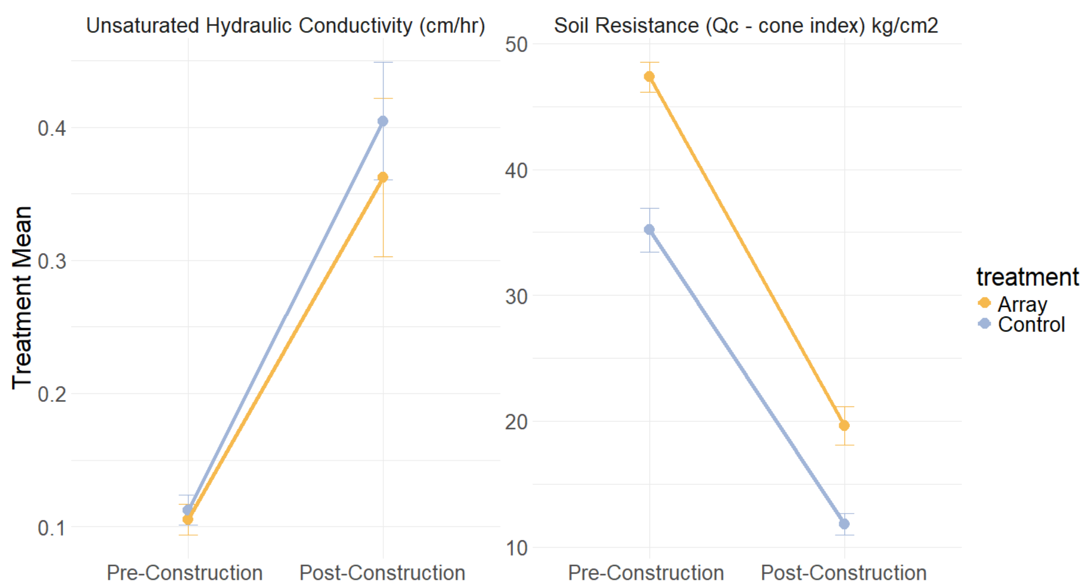


Figure 2. Change in treatment-level mean unsaturated hydraulic conductivity (left) and soil penetration resistance (right) from pre-construction to post-construction sampling. The error bars show +/- standard error.

K_{unsat} was consistent across both treatments, with no significant differences between the array and control areas, either before or after construction. The array treatment had significantly higher PR than the control, both before and after construction. PR was the only field measurement with a marginal treatment × time interaction effect ($p = 0.065$, Table 1). When accounting for the change in PR in the control as a background change, the mean change in PR in the array was significantly greater than 0 ($p = 0.032$), suggesting that there were construction impacts on PR within the array. This was not the case for K_{unsat}.

Table 1. Results from linear-mixed effect models for field measurements.[1]

Response Variable	Predictor Variable	F	df	*p*	sig.
	Treatment	0.68	14	0.423	
$\log(K_{unsat})$	Time	139.02	14	< 0.001	***
	Treatment x Time	0.16	14	0.697	
	Treatment	38.71	14	<0.001	***
PR	Time	556.11	14	<0.001	***
	Treatment x Time	4.02	14	0.065	.

Grass %	Treatment	0.25	14	0.627	
	Time	3.01	14	0.105	
	Treatment x Time	2.30	14	0.151	
Forbs %	Treatment	0.40	14	0.539	
	Time	17.22	14	<0.001	***
	Treatment x Time	0.18	14	0.672	
Litter %	Treatment	0.63	14	0.442	
	Time	7.13	14	0.018	*
	Treatment x Time	0.36	14	0.559	
Bare ground %	Treatment	0.30	14	0.586	
	Time	2.74	14	0.109	
	Treatment x Time	0.30	14	0.585	
Rock %	Treatment	1.47	14	0.234	
	Time	0.53	14	0.473	
	Treatment x Time	0.53	14	0.473	

[1] *Singular fit detected for legume linear mixed effect model, so it was excluded from this table; random effect (i.e., transect) variance estimated at 0.*

Post-construction, individual sampling points along each transect were assigned to a micro-zone relative to the PV modules (Supplemental Materials Figure S1). We found no significant differences in K_{unsat} between zones (p = 0.88); however, micro-zone patterning emerged in PR (p < 0.001). Within the array treatment, PR in the micro-zone directly below the modules (under) and in the rows between modules (between) was significantly higher than in the control (p = 0.010, 0.007, respectively). It's important to note this was a post-hoc analysis, and subsample points were not evenly distributed across zones, leading to unequal sample sizes.

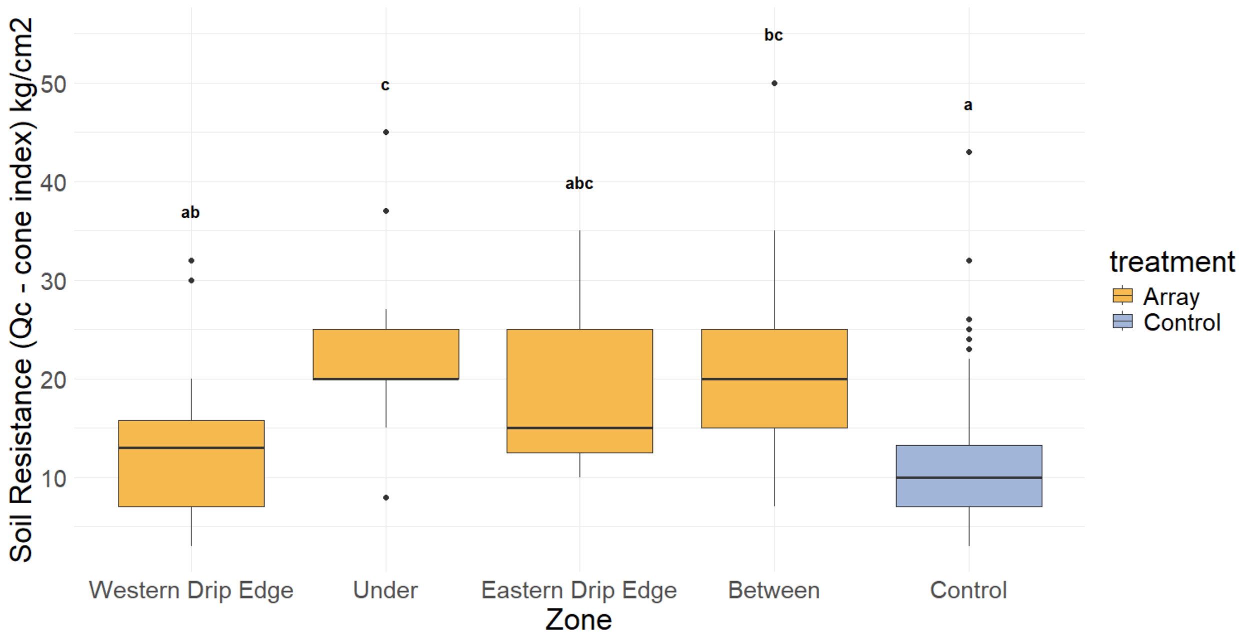


Figure 3. Micro zone-level soil penetration resistance (PR) at post-construction sampling. Boxplots show the mean (center line), interquartile range (box), +/- 1.5 times the interquartile range (whiskers), and outliers (points). Micro zones (i.e., position relative to PV modules) were retroactively assigned to each sampling point along a transect based on the start-point of the transect and the array dimensions (Supplemental Materials Figure S1).

In pre- and post-construction sampling, both treatments were dominated by grass species (> 86% for all time points and treatments), with a smaller presence of legumes, forbs, and litter. Rock and bare ground were very limited in both treatments, both pre- and post-construction (< 0.5%). Looking at pairwise comparisons of before and after construction, in the array treatment, we observed a significant decrease in grass cover and an increase in forb and litter cover (Table 2). In the control, we also observed a significant increase in forbs, as well as a decrease in legumes. The treatment × time interaction was not statistically significant for any vegetation cover categories (Table 1).

Table 2. Pairwise *emmeans* results for vegetation cover changes pre- to post-construction by treatment. Bolded entries indicate $p < 0.05$.

	Grass	Forbs	Legumes	Litter
Array	**$p = 0.0373$**	**$p = 0.0059$**	$p = 0.3465$	**$p = 0.0365$**
Control	$p = 0.8799$	**$p = 0.0198$**	**$p = 0.0197$**	$p = 0.1653$

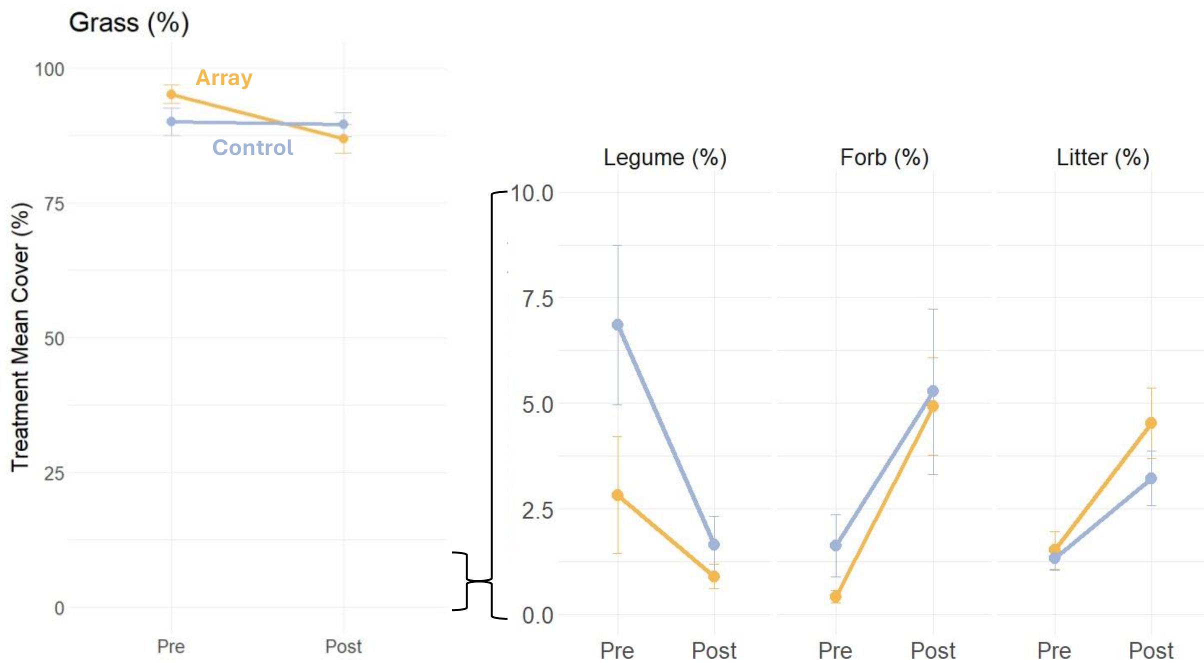


Figure 4. Treatment level change in vegetation cover before and after construction by cover class. Bare ground and rock each accounted for less than 0.2% of cover, both before and after construction. Error bars show +/- standard error.

3.2 Evaluation of Data Consistency

The DayCent biogeochemical model, with soil texture and weather inputs of our field site, estimated VWC to be 22.5%-30.6% pre-construction, and 23.5%-31.5% post-construction, averaged over a depth of 0-15cm (the same depth interval at which PR was measured) (Table 3). We also consulted measured soil moisture data from the nearest available weather station (approximately 100 km from the field site), which showed a similar pattern of slightly elevated soil moisture at the time of post-construction sampling, but on the whole quite similar soil moisture levels. In the array, VWC was estimated to be about 4.4% higher during post-construction sampling compared to pre-construction sampling, and in the control, this difference dropped to 2.9%.

Table 3. Modeled volumetric water content from DayCent® in each treatment on pre- and post-construction sampling dates. Supplemented with 4-in soil moisture data from the nearest USDA NRCS weather station (USDA).

	Array (0-15cm)	Control (0-15cm)	*Eastview Farm SCAN Site 2077 (4-in)*
Pre-construction (Dec 3, 2024)	22.5%	30.6%	*34.0%*
Post-construction (Nov 19, 2025)	23.5%	31.5%	*35.3%*

Figure 5 plots the implied ΔBD from the measured change in PR against the implied ΔBD from the measured change in K_{unsat}. Consistent with the measured direction of change in PR and K_{unsat}, all the implied ΔBD are negative, ranging from -0.26 to -0.61 g/cm^3 for the PR implied ΔBD (moisture corrected), and -0.06 to -0.37 g/cm^3 for the K_{unsat} implied ΔBD. The measured K_{unsat} values predicted a mean ΔBD of -0.24 in both the array and the control. The measured PR values predicted a greater magnitude of change in BD, with a mean ΔBD of -0.38 g/cm^3 in the array and -0.48 g/cm^3 in the control (moisture corrected). In the array, there was more variability between transects, but the mean predicted ΔBD from K_{unsat} and PR had greater alignment, with a difference of 0.14 g/cm^3. In the control, there was tighter clustering of the transects, but greater differences between the mean estimated ΔBD from each data set, 0.24 g/cm^3. The moisture correction in the PR implied ΔBD improves the consistency with the implied ΔBD from K_{unsat}. In both treatments, the transects with the greatest disagreement between implied ΔBD from K_{unsat} and PR were those with the largest PR implied ΔBD.

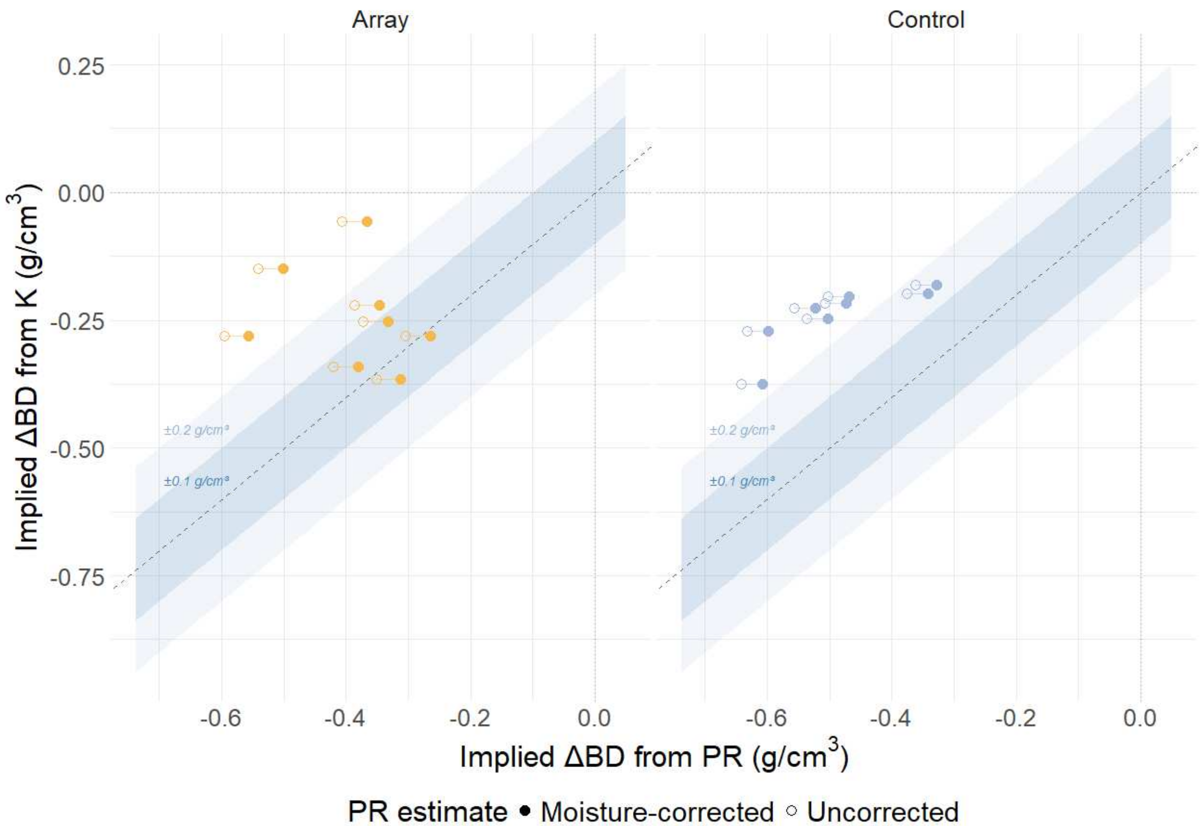


Figure 5. Implied change in bulk density from change in PR (x-axis) and from change in K_{unsat} (y-axis). The dashed line shows y = x and represents perfect agreement between the two estimates. Points that fall within the darker band have implied bulk densities within +/- 0.1g/cm^3 of each other, and points that fall within the lighter band are within +/- 0.2 g/cm^3. The unshaded circles show the implied change in bulk density from PR when just the slope of the Whalley pedotransfer function is used. The solid circles show the implied change in bulk density from PR when differences in soil moisture between the two sampling points are explicitly accounted for.

3.3 Remote Sensing Data & Longer-Term Trends

Remote sensing data allowed us to examine trends in the productivity and characteristics of the field site in the decades leading up to the field sampling discussed here. We observed a consistent upward trend in NPP at the site since the late 1980’s with some notable anomalies in the early 2000’s and around 2008, particularly in the portion of the site where the array was constructed (Figure 6a). Since 2012, other remote sensing indices demonstrate similar trends at the site, with a downward trend in the BSI and an upward trend in the NDVI (Figure 6b).

Between 2013 and 2024, BSI ranged from -0.12 to 0.00, values consistent with limited bare soil. NDVI ranged from 0.56 to 0.67, consistent with moderate to dense vegetation coverage.

In the decade leading up to the array installation, two years stand out against the broader trends – 2016 and 2023. In both years, the data showed an increase in BSI and a notable drop in NDVI and NPP. Precipitation was below average in both years (11% and 14% below the 1986-2024 average, respectively). Without detailed land-use history data, it's difficult to identify specific causes for these events, however satellite imagery from December 2016 suggests some form of disturbance occurred, leaving patches of bare soil across the site (Supplemental Materials, Figure S2). Historic satellite imagery from November 2023 shows reduced greenness relative to the same period in prior years, potentially tied to the lower annual precipitation that year.

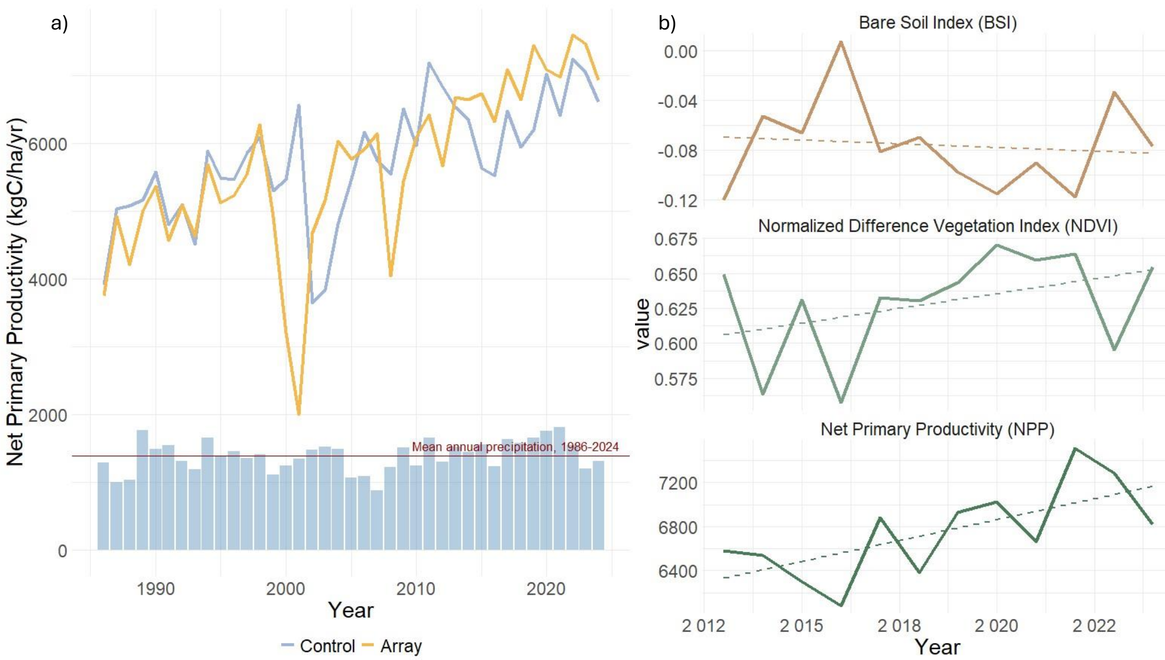


Figure 6. Results from remote sensing analysis: a) Net primary productivity data (NPP) by year for the areas of the pasture that became the control (blue line) and array (yellow line) sites. Blue bars show annual precipitation (mm) on the same y-axis scale, and the red line shows the mean annual precipitation over the period shown (1986 to 2024). b) Trends between 2012 and 2024 in two dimensionless remote sensing indices (bare soil index and normalized difference vegetation index) and NPP, averaged over both treatments. Dashed lines show linear regression fits (OLS) for each index.

4. Discussion

Contrary to our hypothesis, we observed changes in K_{unsat} and PR consistent with the loosening of soil structure between pre-construction and post-construction sampling in both the array and control treatments, rather than the isolated compaction with the array that we had anticipated. The change over time of both of these soil variables would be interpreted as an improvement in soil structure from an ecological and agronomic perspective. We observed consistent changes in both the array and the control treatment, suggesting that other factors were more influential on these indicators than construction. When compared to the change over time in the control treatment, we found evidence of a significantly smaller decrease in PR in the array, potentially indicating some impact from construction (i.e., less of an improvement in soil structure at the array site compared to the control site).

We incorporated additional analyses to increase our confidence in and understanding of these unexpected results. The evaluation of data consistency using pedotransfer functions showed general agreement between the K_{unsat} and PR measurements. In the array, the implied ΔBD from measured K_{unsat} and PR values were, on average, within 0.14 g/cm^3 of each other. In the control, this increased to 0.24 g/cm^3. In both treatments, the change in PR values suggested a greater reduction over time in BD compared to the BD change inferred from differences in K_{unsat} between pre- and post-construction sampling. While there are limitations in applying these functions in this context, these additional analyses increased our confidence that these two datasets detected consistent changes in the soil structure.

With greater confidence in the consistency of the measured field data, we explored several different potential drivers that could have impacted both treatments and could help explain the observed changes at the site. These potential drivers include: background abiotic conditions, long-term trends, and construction-related management activities.

4.1 Background Abiotic Conditions

In considering possible explanations for the observed trend in our soil observations, we first considered differences in environmental conditions between the two sampling dates. The most relevant abiotic condition for the indicators measured was soil moisture. Penetrometers, in particular, are quite sensitive to soil moisture (Raper, 2005; To & Kay, 2005), and without direct measurements of VWC across both treatments on both sampling days, it would be difficult to fully elucidate the role that a difference in soil moisture might have played in the pre- to post-construction changes we observed. DayCent® model results alongside weather data from the site and soil moisture data from a weather station in the area increased our confidence that VWC was not dramatically different between pre- and post-construction sampling, but also confirmed that it was likely slightly higher during post-construction sampling. Higher soil moisture would be consistent with the directional trends observed for PR and K_{unsat}. Based on the Whalley et al. (2007) pedotransfer function, the estimated difference in VWC would account for only 9-28% of the difference in measured PR. This suggests that differences in soil moisture alone cannot fully explain the observed changes.

Another key consideration was the role of soil freeze/thaw cycles, which can have a significant influence on soil structure (Jabro et al., 2014; Leuther & Schlüter, 2021). Between pre- and post-construction sampling, there were several extended cold periods. In both January and February 2025, there were extended periods (20 and 9 consecutive days, respectively) with air temperature below freezing, including several days with the maximum air temperature below freezing, followed immediately by periods where the air temperature exceeded 20 °C. While air temperature does not translate directly to soil temperature, the duration of these periods, including several consecutive days where air temperature did not exceed freezing, would likely result in soil freeze/thaw cycles, especially in upper soil layers.

4.2 Trends in land use and management and vegetation productivity

Another possible influence involved longer-term land management trends at the site. Remote sensing data from the site over the last several decades, in tandem with historical satellite imagery, painted a picture of some significant disturbances in the early 2000's, followed by a period of recovery. In 2007, which was the lowest precipitation year in the period examined (1986-2024), there appeared to be a complete removal of vegetation from the site based on imagery from September of that year (Supplemental Materials Figure S2). Remote sensing indices used to provide insights into vegetative health showed an overall positive trend at the site from 2013-2024, and we observed a consistent upward trend in NPP, with some year-to-year variability, potentially suggesting an extended period of vegetation recovery from the hypothesized disturbance events.

Looking more closely at the decade leading up to this experiment, there were two notable anomalies in the overall trends in 2016 and 2023. While these years did not have as dramatic a drop in NPP as observed in the early 2000's, they may still be evidence of an ecosystem perturbation that influenced field data – particularly the 2023 event. Additionally, 2023 and 2024 were below-average precipitation years, followed by an average precipitation year in 2025. The two consecutive drier years preceding pre-construction data collection at the end of 2024, could have negatively impacted soil structure, which then rebounded and was improved by an average precipitation year in 2025, when post-construction sampling was conducted near the end of the year.

4.3 Construction-Related Management Activities

It's also possible that impacts from management activities related to the establishment of the solar facility contributed to the observed changes in PR and K_{unsat}. Between the purchase of the land and the start of construction, there was nearly a 2-year period in which the land was minimally disturbed. While we don't have access to detailed land management and grazing records, if the land had been previously over-grazed or heavily trafficked for haying, this could have been a period of recovery. During this period, fertilizer was applied to the site, but otherwise, there was minimal soil and vegetation disturbance.

One of the major controls on the impacts of PV array construction on the physical landscape is ground cover conditions before and during construction (Stid et al., 2025). There was robust vegetation cover just before construction began at the end of 2024, quantified during pre-construction sampling (abundant, well-established perennial grass cover with minimal bare ground). Between pre- and post-construction sampling, the array site (but not the control site) was re-seeded and fertilized a second time, and by the time we returned to the site for post-construction sampling, there was essentially no remaining bare ground. The vegetation recovery was quite rapid, and the array site had to be mowed several times during and after construction during the summer of 2025 (the control site was mowed as well).

From pre- to post-construction periods, we also observed an increase in annual species, especially in the array, which is a well-established disturbance response in grasslands (Belsky, 1992; Grime, 1977). Additionally, many of the forbs identified at the site were plants with large taproots (Supplemental Materials Table S1), which could have contributed to the observed change in soil structure (Burr-Hersey et al., 2020).

4.4 Limitations & Directions for Future Work

As discussed throughout this work, variability in environmental conditions is a major limitation of sampling at two different time points, especially when working with indicators that are sensitive to these background conditions. While we attempted to control this by sampling within the same two-week period, one year apart, there was still confounding variability in sampling conditions. Here, the importance of having a control treatment is made clear, as it improved our ability to distinguish between factors influencing the whole field site and the impacts of PV array construction.

Working within the context of solar PV array construction presented other limitations in our experimental conditions. The treatments were pre-assigned in the engineered design and layout of the site, and while the control and array areas had similar plant species communities and consistent management, there were some underlying differences in soil texture and topography, with the control located in a slightly more low-lying area with higher clay content. Typically, it is recommended that penetrometer data is collected in the spring for the most consistent soil moisture conditions, however we were constrained to sample in the late fall to align with the construction timing. We were also unable to take soil cores for a direct measurement of soil texture and VWC. Because of this, we had to rely on SSURGO data and modeled VWC, which introduced uncertainty into our analysis, especially the data validation.

Moving forward, replicating these methods annually and tracking ecosystem response to construction in a multiyear time series would improve our understanding of the interaction among background abiotic conditions and these ecological indicators.

5. Conclusion

Understanding the ecological impacts of construction is essential for the sustainable development and management of solar PV, especially in the context of agrivoltaic and ecovoltaic systems. We used a BACI design to measure the impact of array construction on PR, K_{unsat}, and vegetative cover. A year after construction started, vegetative cover had fully recovered from the disturbance, with very minimal rock or bare ground. Contrary to what we hypothesized, we observed a decrease in PR and an increase in K_{unsat}; in other words, an improvement in soil structure in the constructed solar facility relative to conditions at the site prior to array construction. Taken together, variation in background abiotic conditions, long-term trends, and construction-related management impacts offer some possible explanations for these unexpected results. Our results suggest that in this climate region and with the use of low-impact construction practices, other factors, including land-use history, long-term environmental trends, and management events surrounding construction, can have a greater impact on the ecosystem conditions we measured than construction itself. This work emphasizes the challenges of isolating the ecological impacts of construction and replicating BACI studies across a wider range of climates and construction practices.

REFERENCES

Adeh, E. H., Selker, J. S., & Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLOS ONE*, *13*(11), e0203256. https://doi.org/10.1371/journal.pone.0203256

Ankeny, M. D., Ahmed, M., Kaspar, T. C., & Horton, R. (1991). Simple Field Method for Determining Unsaturated Hydraulic Conductivity. *Soil Science Society of America Journal*, *55*(2), 467–470. https://doi.org/10.2136/sssaj1991.03615995005500020028x

Armstrong, A., Ostle, N. J., & Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*, *11*(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016

Bacon, T., Monlezun, A. C., Hong, M., de Vries, N., & Paustian, K. (2026). *Microclimate, vegetation and soil responses to micro-zonal solar photovoltaic patterning in a humid sub-tropical agrivoltaic grazing system* [In prep].

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using **lme4**. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Beaudette, D. E., Skaggs, T., & Reid, R. (n.d.). *Query USDA-ARS ROSETTA Model API — ROSETTA*. Retrieved March 30, 2026, from https://ncss-tech.github.io/soilDB/reference/ROSETTA.html

Belsky, A. J. (1992). Effects of Grazing, Competition, Disturbance and Fire on Species Composition and Diversity in Grassland Communities. *Journal of Vegetation Science*, *3*(2), 187–200. https://doi.org/10.2307/3235679

Booth, D. T., Cox, S. E., & Berryman, R. D. (2006). Point Sampling Digital Imagery with 'Samplepoint.' *Environmental Monitoring and Assessment*, *123*(1), 97–108. https://doi.org/10.1007/s10661-005-9164-7

Bureau of Land Management. (2024). *Appendix I: Solar Energy Technology Overview* (Final Programmatic Environmental Impact Statement / Resource Management Plan Amendment (Appendix) DOI-BLM-HQ-3000-2023-0001-RMP-EIS; Final PEIS and Proposed RMPA for Utility-Scale Solar Energy Development, Volume 2 — Appendices). Bureau of Land Management. https://eplanning.blm.gov/Documents/?id=adb73ad7-a7f2-f011-8407-001dd803d067&spid=7a017286-a8f2-f011-8406-001dd8008d46

Burr-Hersey, J. E., Ritz, K., Bengough, G. A., & Mooney, S. J. (2020). Reorganisation of rhizosphere soil pore structure by wild plant species in compacted soils. *Journal of Experimental Botany*, *71*(19), 6107–6115. https://doi.org/10.1093/jxb/eraa323

Choi, C. S., Cagle, A. E., Macknick, J., Bloom, D. E., Caplan, J. S., & Ravi, S. (2020). Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure. *Frontiers in Environmental Science*, *8*. https://www.frontiersin.org/articles/10.3389/fenvs.2020.00140

Deering, D. W., & Eck, T. F. (1987). Atmospheric optical depth effects on angular anisotropy of plant canopy reflectance. *International Journal of Remote Sensing*, *8*(6), 893–916. https://doi.org/10.1080/01431168708948697

Grime, J. P. (1977). Evidence for the Existence of Three Primary Strategies in Plants and Its Relevance to Ecological and Evolutionary Theory. *The American Naturalist*, *111*(982), 1169–1194. https://doi.org/10.1086/283244

Grodsky, S. M., & Hernandez, R. R. (2020). Reduced ecosystem services of desert plants from ground-mounted solar energy development. *Nature Sustainability*, *3*(12), Article 12. https://doi.org/10.1038/s41893-020-0574-x

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.

IRENA. (2025, July 10). *Solar energy*. https://www.irena.org/Energy-Transition/Technology/Solar-energy

Jabro, J. D., Iversen, W. M., Evans, R. G., Allen, B. L., & Stevens, W. B. (2014). Repeated Freeze-Thaw Cycle Effects on Soil Compaction in a Clay Loam in Northeastern Montana. *Soil Science Society of America Journal*, *78*(3), 737–744. https://doi.org/10.2136/sssaj2013.07.0280

Jones, M. O., Robinson, N. P., Naugle, D. E., Maestas, J. D., Reeves, M. C., Lankston, R. W., & Allred, B. W. (2021). Annual and 16-Day Rangeland Production Estimates for the Western United States. *Rangeland Ecology & Management*, *77*, 112–117. https://doi.org/10.1016/j.rama.2021.04.003

Karban, C. C., Munson, S. M., Kobelt, L. A., & Lovich, J. E. (2025). Short-term ecological effects of solar energy development depend on plant community, soil type and disturbance intensity. *Journal of Applied Ecology*, *62*(4), 945–957. https://doi.org/10.1111/1365-2664.14882

Krasner, N. Z., Fox, J., Armstrong, A., Ave, K., Carvalho, F., Li, Y., Walston, L. J., Ricketts, M. P., Jordaan, S. M., Abou Najm, M., Hartmann, H. M., Lybrand, R., & Hernandez, R. R. (2025). Impacts of photovoltaic solar energy on soil carbon: A global systematic review and framework. *Renewable and Sustainable Energy Reviews*, *208*, 115032. https://doi.org/10.1016/j.rser.2024.115032

Kuhwald, M., Hamer, W. B., Brunotte, J., & Duttmann, R. (2020). Soil Penetration Resistance after One-Time Inversion Tillage: A Spatio-Temporal Analysis at the Field Scale. *Land*, *9*(12). https://doi.org/10.3390/land9120482

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*(18), 5190–5202. https://doi.org/10.1002/ldr.4101

Lenth, R. V., Banfai, B., Bolker, B., Buerkner, P., Giné-Vázquez, I., Hervé, M., Jung, M., Love, J., Miguez, F., Piaskowski, J., Riebl, H., & Singmann, H. (2025). *emmeans: Estimated Marginal Means, aka Least-Squares Means* (Version 1.11.2-8) [Computer software]. https://cran.r-project.org/web/packages/emmeans/index.html

Leuther, F., & Schlüter, S. (2021). Impact of freeze–thaw cycles on soil structure and soil hydraulic properties. *SOIL*, *7*(1), 179–191. https://doi.org/10.5194/soil-7-179-2021

Maguire, K., Tanner, S., & Winikoff, J. B. (2024, September 12). *Agricultural Land Near Solar and Wind Projects Usually Remained in Agriculture After Development*. USDA Economic Research Service. https://www.ers.usda.gov/amber-waves/2024/september/agricultural-land-near-solar-and-wind-projects-usually-remained-in-agriculture-after-development

METER Group. (2021). *Mini Disk Infiltrometer*. METER Group. https://publications.metergroup.com/Manuals/20421_Mini_Disk_Manual_Web.pdf

Mulholland, B., & Fullen, M. A. (1991). Cattle trampling and soil compaction on loamy sands. *Soil Use and Management*, *7*(4), 189–193. https://doi.org/10.1111/j.1475-2743.1991.tb00873.x

NREL. (2026). *Low-Impact Solar Development Strategies Guidebook* [Project Guidebook / Wiki]. InSPIRE (Innovative Site Preparation and Impact Reduction on the Environment) — Open Energy Information (OpenEI). https://openei.org/wiki/InSPIRE/Guidebook

NYSDAM. (2019). *Guidelines for Solar Energy Projects—Construction Mitigation for Agricultural Lands*. New York State Department of Agriculture and Markets. https://agriculture.ny.gov/system/files/documents/2019/10/solar_energy_guidelines.pdf

Parton, W. J., Hartman, M., Ojima, D., & Schimel, D. (1998). DAYCENT and its land surface submodel: Description and testing. *Global and Planetary Change*, *19*(1), 35–48. https://doi.org/10.1016/S0921-8181(98)00040-X

PRISM Group. (n.d.). *Time Series Weather Data for Individual Locations* (Oregon State University) [Dataset]. Retrieved https://prism.oregonstate.edu

R Core Team. (2025). *R: A language and environment for statistical computing* [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org/

Raper, R. L. (2005). Agricultural traffic impacts on soil. *Journal of Terramechanics*, *42*(3–4), 259–280. https://doi.org/10.1016/j.jterra.2004.10.010

Reynolds, W. D., & Elrick, D. E. (1991). Determination of Hydraulic Conductivity Using a Tension Infiltrometer. *Soil Science Society of America Journal*, *55*(3), 633–639. https://doi.org/10.2136/sssaj1991.03615995005500030001x

Rikimaru, A., Roy, P., & Miyatake, S. (2002). Tropical forest cover density mapping. *Tropical Ecology*, *Vol 43*, 39–47.

Satterthwaite, F. E. (1946). An Approximate Distribution of Estimates of Variance Components. *Biometrics Bulletin*, *2*(6), 110–114. https://doi.org/10.2307/3002019

Saxton, K. E., Rawls, W. J., Romberger, J. S., & Papendick, R. I. (1986). Estimating Generalized Soil-water Characteristics from Texture. *Soil Science Society of America Journal*, *50*(4), 1031–1036. https://doi.org/10.2136/sssaj1986.03615995005000040039x

Schaap, M. G., Leij, F. J., & Van Genuchten, M. Th. (2001). rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology*, *251*(3–4), 163–176. https://doi.org/10.1016/S0022-1694(01)00466-8

Soil Survey Staff. (n.d.). *Soil Survey Geographic (SSURGO) Database for Christiana, TN.* (Natural Resources Conservation Service, United States Department of Agriculture) [Dataset]. Retrieved September 16, 2024, from https://websoilsurvey.nrcs.usda.gov/app/

Steyn, J. T., Tolmay, J. P. C., Human, J. J., & Kilian, W. H. (1995). The effects of tillage systems on soil bulk density and penetrometer resistance of a sandy clay loam soil. *South African Journal of Plant and Soil*, *12*(2), 86–90. https://doi.org/10.1080/02571862.1995.10634342

Stid, J. T., Zipper, S., Szydlowski, H. V., Bingaman, J., Anctil, A., & Kendall, A. D. (2025). *Current Knowledge on Low-Impact Ground-Mounted Solar Siting, Construction, and Installation Practices* [Kansas Geological Survey Open-File Report 2025-20]. Kansas Geological Survey. https://www.kgs.ku.edu/Publications/OFR/2025/OFR2025-20.pdf

Sturchio, M. A., Macknick, J. E., Barron-Gafford, G. A., Chen, A., Alderfer, C., Condon, K., Hajek, O. L., Miller, B., Pauletto, B., Siggers, J. A., Slette, I. J., & Knapp, A. K. (2022). Grassland productivity responds unexpectedly to dynamic light and soil water

environments induced by photovoltaic arrays. *Ecosphere*, *13*(12), e4334. https://doi.org/10.1002/ecs2.4334
To, J., & Kay, B. D. (2005). Variation in penetrometer resistance with soil properties: The contribution of effective stress and implications for pedotransfer functions. *Geoderma*, *126*(3–4), 261–276. https://doi.org/10.1016/j.geoderma.2004.08.006
Tollner, E. W., Calvert, G. V., & Langdale, G. (1990). Animal trampling effects on soil physical properties of two Southeastern U.S. ultisols. *Agriculture, Ecosystems & Environment*, *33*(1), 75–87. https://doi.org/10.1016/0167-8809(90)90145-4
Toy, C., Heider-Kuhn, N., & Schipanski, M. (2025). Impact of solar energy infrastructure and ecovoltaic management on semi-arid grassland carbon cycling. *Environmental Research Communications*, *7*(10), 105005. https://doi.org/10.1088/2515-7620/ae0b1d
USDA Natural Resources Conservation Service. (n.d.). *Eastview Farm SCAN site 2077* [Soil moisture data]. National Water and Climate Center. Retrieved February 2026, from https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=2077&state=tn
van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023
Whalley, W. R., To, J., Kay, B. D., & Whitmore, A. P. (2007). Prediction of the penetrometer resistance of soils with models with few parameters. *Geoderma*, *137*(3), 370–377. https://doi.org/10.1016/j.geoderma.2006.08.029

CHAPTER 4: MICROCLIMATE, VEGETATION, AND SOIL RESPONSES TO MICRO-ZONAL SOLAR PHOTOVOLTAIC PATTERNING IN A HUMID SUB-TROPICAL AGRIVOLTAIC GRAZING SYSTEM[3]

1. Introduction

As the world transitions towards a decarbonized energy system, renewable energy deployment must increase dramatically (Solar Futures Study, 2021). Solar photovoltaic (PV) accounts for a large portion of new generation capacity and is anticipated to supply up to 45% of total electricity generation in the United States (U.S.) by 2050 (Solar Futures Study, 2021). Solar PV has many advantages, including low cost, predictable generation patterns, and low water demands (Solar Futures Study, 2021). However, in contrast to other forms of energy generation, solar PV has a large land footprint (van Zalk & Behrens, 2018) and meeting projected energy generation levels could require up to 4.2 million hectares of land in the U.S. (Solar Futures Study, 2021). Since land well-suited to solar power plants shares many characteristics with agricultural land, this is likely to spur increased land-use tension.

Agrivoltaic systems that integrate agriculture and solar PV on the same land have been proposed as a strategy for increasing land-use efficiency and reducing land-use tension while often providing additional benefits across the food-energy-water nexus (Barron-Gafford et al., 2019; Choi et al., 2023; Guerin, 2019; Hernandez et al., 2019; Rahmaniah & Tay, 2023; Randle-Boggis et al., 2020). One of the most common forms of agrivoltaic systems, especially in the U.S., is the integration of livestock grazing with solar PV (*Agrivoltaics Map*, n.d.). Agrivoltaic grazing systems account for nearly three-quarters of cataloged agrivoltaic projects in the U.S. by

[3] Bacon, T., A. C. Monlezun, M. Hong, N. de Vries, and K. Paustian. "Microclimate, Vegetation and Soil Responses to Micro-Zonal Solar Photovoltaic Patterning in a Humid Sub-Tropical Agrivoltaic Grazing System." 2026. [Under review]

land area (*Agrivoltaics Map*, n.d.), with a recent census estimating 40,469 hectares of existing agrivoltaic grazing projects (Andrew et al., 2025), primarily grazed by sheep. Despite the prominence of grazing systems within the agrivoltaics industry, research on these systems is quite limited (Bacon et al., 2025). A major knowledge gap stems from the lack of field data on the layered ecological impacts of solar PV and grazing (Bacon et al., 2025). Filling this gap is essential to robustly characterizing dynamics within these systems and understanding their potential to ameliorate the ecological impacts of renewable energy deployment.

PV modules create spatial patterning of key ecosystem drivers. The modules alter canopy-level solar radiation and precipitation inputs in predictable and consistent ways due to solar array geometry and the tracking algorithms of the modules, creating highly variable but patterned microclimate conditions (Adeh et al., 2019; Armstrong et al., 2016; Sturchio et al., 2022; Vervloesem et al., 2022). Understanding the ecosystem dynamics of agrivoltaic grazing systems, therefore, requires studying how grazing impacts interact with ecological alterations caused by the installation and presence of modules.

This paper discusses results from the first two years of an agrivoltaic grazing study in the southeastern U.S. designed to address this knowledge gap and better understand the integration of grazing and solar PV. We studied ecosystem dynamics within a utility-scale agrivoltaic grazing system to characterize microclimate patterning and understand the impacts of altered ecosystem drivers at the plant and soil level. This research lays the foundation for understanding how land management practices within a solar array influence ecosystem outcomes. By quantifying microclimate conditions, forage productivity, and soil carbon under different land management systems (mowed solar PV array, integrated agrivoltaic sheep grazing system, and traditional grazed pasture), we evaluated the impacts of agrivoltaic grazing systems on ecosystem dynamics and carbon cycling.

We hypothesized that alterations to microclimate caused by the PV modules and array geometry would lead to patterned variability in biomass productivity, ultimately translating to micro-zonal differences in soil carbon stocks.

This study is unique for several reasons. Each treatment area is approximately 12 hectares, which is larger than many field sites and allows for better representation of variability within the treatment areas. This is also the first study of its kind located in the humid subtropical climate of the southeastern U.S., providing valuable information on the impacts of agrivoltaic grazing systems in different climate zones.

Our results provide valuable insights into the novel ecosystem created by the presence of PV modules, including interactions with different land management strategies. These insights are actionable and can be used to assist solar developers, ranchers, and land stewards in making better-informed decisions for agrivoltaics projects, moving towards reduced land-use tension and improved ecological outcomes.

2. Methods

Our study was conducted in Early County, GA, in the southeastern U.S. from April 2023 to April 2025. The region is humid sub-tropical with a mean annual temperature of 20.2 °C and a mean annual precipitation of 1152 mm (*NOAA NCEI U.S. Climate Normals Quick Access*, n.d.).

2.1 Experimental Design

To study the ecological outcomes of an agrivoltaic grazing system, we established two land management treatments: Agrivoltaics (AV – sheep grazing integrated with solar PV) and Solar PV (PV – standalone solar PV with conventional mowing management), alongside a comparative no-PV grazed pasture (Figure 1).

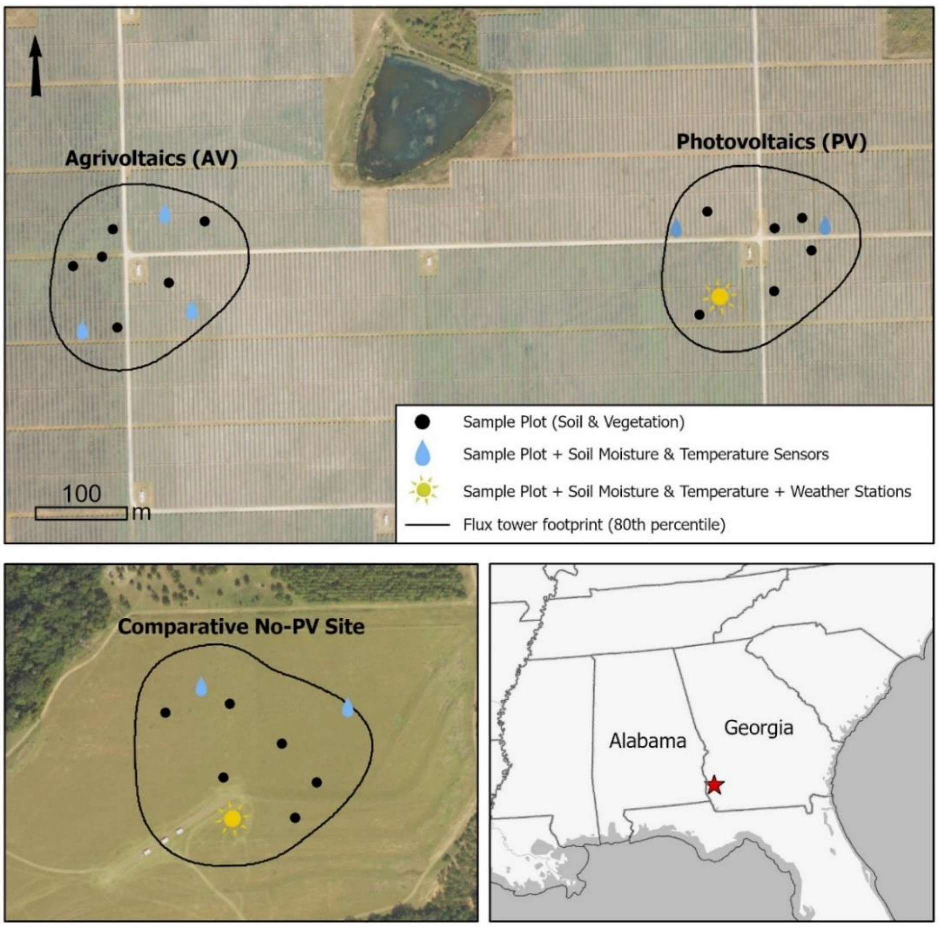


Figure 1. Treatment-level experimental design. The field site was in southwestern Georgia, U.S. Agrivoltaics (AV) and Photovoltaics (PV) treatments were located at Silicon Ranch's Bancroft Station. A comparative no-PV site was located on White Oak Pastures property in Bluffton, GA, 87pprox.. 11 km from Bancroft Station. Each treatment area was approximately 12 hectares, centered around an eddy-covariance flux tower and bounded by the 80th percentile of the flux footprint. Within each treatment, there were nine research plots where soil and vegetation samples were collected. Three plots per treatment included TEROS 11 soil moisture and temperature sensors, and one plot in the PV and no-PV sites also included ATMOS 41 weather stations. *Basemap imagery: Esri. Sources: TomTom, Garmin, FAO, NOAA, USGS, EPA, USFWS, USDA.*

The two solar PV treatments (AV and PV) were established at Bancroft Station, a 102.5 MW, single-axis tracking, utility-tied solar array. The array was constructed in 2019, and prior to construction, the land was in a corn-peanut-cotton farming rotation. During construction, topographic undulations were leveled, some trees were cut (outside of study areas), and wood was mulched and spread across the site. The site was revegetated with post-construction drill seeding; however, most early species appeared voluntarily from the seed bank. The site was first seeded at the outset of construction in fall 2019 and last seeded in spring 2020. Since then, sheep have grazed the site as the primary form of vegetation management, with minimal mowing when the grazing impact was insufficient. No chemical fertilizer, herbicide, or pesticide was used during the development of the site. Between 2020 and 2022 (pre-experimental period), the sheep were strategically fed hay with some broadcast seeding over hay bales to aid revegetation. No residual hay was observed when sampling commenced in 2023.

Within the array, we identified two areas with similar soil texture and vegetation composition, and the requisite size for deploying eddy covariance flux towers. The array treatments (AV and PV) were randomly assigned to these two areas. Beginning in April 2023, sheep were excluded from the PV treatment area.

A comparative no-PV site was established approximately 11 km northwest of Bancroft Station on the property of White Oak Pastures. The land was purchased by White Oak Pastures in 2020 and shares a similar land-use history to the AV and PV treatments, primarily monoculture crop rotation with some irrigation until seeded to grassland in 2020, with no use of chemical fertilizer, herbicide, or pesticide after being taken out of row crop production.

While the land-use history was similar between the array sites and the comparative no-PV site, there were significant limitations of the site as a true control. Conducting research at an existing utility-scale solar PV array, options for a control site that could accommodate a flux tower, had a similar land-use history, was ecologically similar to the array sites, and could be managed similarly were incredibly limited. This site offered the best option for collecting data in a pasture without PV infrastructure; however, differences in plant species composition (Supplemental Materials Figure S1) and management (Table 1) complicated the use of the site as a statistical control. For that reason, we refer to this site here as a comparative site and take this into account in our interpretation of results.

These treatments were designed to study outcomes from land management on a working farm. The treatments did not prescribe the specific grazing or mowing frequencies or durations, but rather, data were collected in response to the typical practices employed at this operational solar grazing facility and farm.

Table 1. Description of experimental site land management

Agrivoltaics (AV)	The AV treatment was managed using rotational sheep grazing. Between 600 and 1,000 head of ewes (not including the annual lamb crop) were rotated throughout the treatment area, grazing smaller areas for one to three days before being rotated off. Sheep were grazed within the array from March through October. Supplementary mowing was used in the spring and fall.
Solar Photovoltaics (PV)	The PV treatment was managed exclusively by vegetation mowing. The site was mowed to ensure vegetation did not interfere with PV modules. This typically translated to two to three mowing events each growing season.
Comparative No-PV (No-PV)	This site was managed primarily through cattle grazing, following similar ranch-wide rotational grazing strategies as those used within the array treatment. Grazing at the site was less consistent than at the array sites, with longer periods between grazing events.

Each treatment comprised approximately 12 hectares, centered around an eddy-covariance flux tower and bounded by the 80th percentile of the predicted flux footprint (fetch), based on historical seasonal wind patterns. Nine randomly located sampling plots (Figure 1) were established within each treatment area in April 2023. Each plot was 5.5m x 14m. Within the AV and PV treatments, the plots spanned two rows of modules to capture the unique micro-zones created by the modules (Figure 2). Field data were collected along 5.5m transects that ran perpendicular to the rows of modules. These transects passed through four distinct micro-zones established based on the work of Sturchio et al. (2022, 2024): directly under the module (U), in the inter-row space between modules (B), on the east "drip-edge" (E), and on the west "drip-edge" (W) of a solar module (Figure 2). The drip edges were defined by the extremes of the module positions. The boundary between the drip edges and under was defined by the module position at maximum tilt (60 degrees). The boundary on the other side of the drip edges, with micro-zone B, fell below the module edge when the modules were horizontal (Figure 2).

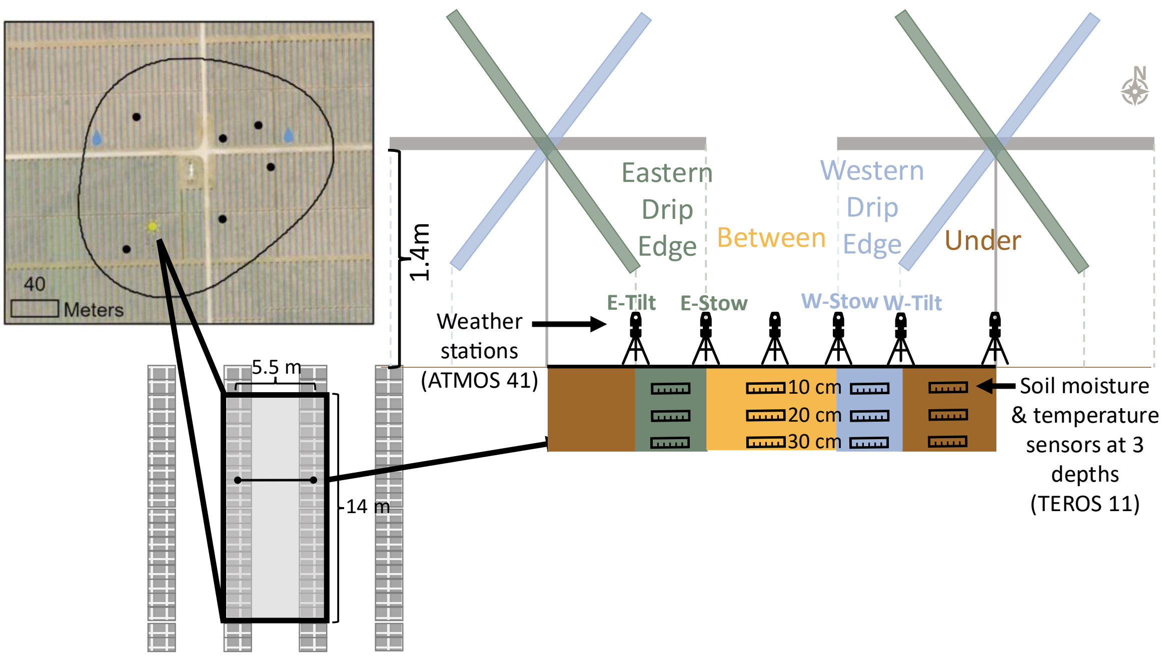


Figure 2. Plot design in the AV and PV treatments captures micro-zonal heterogeneity. Each plot was 5.5m by 14m, spanning two bays of modules. Data were collected along transects running perpendicular to module rows that intersected four distinct micro-zones: Eastern Drip Edge €; Between (B); Western Drip Edge (W), and Under (U). The cross-sectional view of a transect on the right shows the positions of the above-ground and below-ground microclimate sensors.

2.2 Data Collection

2.2.1 Microclimate

To characterize the variation in microclimate across micro-zones, key microclimate variables were sampled every three to ten seconds and reported at 15-minute output intervals between April 2023 and April 2025. These included solar radiation, precipitation, air temperature, soil temperature, and soil moisture.

Soil moisture (cm/cm) and soil temperature (ºC) were measured in three plots per treatment (Figure 1). METER Group TEROS 11 sensors were installed in each of the four micro-zones per plot, at three depths below the soil surface (10cm, 20cm, and 30cm) for a total of 81 soil moisture and temperature sensors across all three treatments (Figure 2).

The remaining microclimate variables were measured using METER Group ATMOS 41 weather stations, installed in a single representative plot in the PV treatment to avoid sheep interference with the instruments (Figure 1). One sensor was installed in the center of the U and B micro-zones, while two sensors were installed in each drip edge micro-zone (on either edge) to capture the variability within this micro-zone due to the movement (tracking) of the modules throughout the day (Figure 2) from fully tilted (e.g. Western Drip Edge – Tilt) to stowed at approximately horizontal (e.g. Western Drip Edge – Stow).

2.2.2 Vegetation

Vegetation samples were collected before and after every vegetation management event (i.e., grazing or mowing). Plots were typically mowed twice a year and grazed two to four times a year. For each sampling event, a random transect was established within the plot, perpendicular to the module rows (Figure 2). A sample was taken in each micro-zone along the transect using a 0.25 m^2 quadrat centered in the micro-zone. Standing plant material (biomass + standing dead) was clipped to the soil surface and collected, and then all plant litter was collected from the soil surface. Samples were oven-dried at 60 °C before being weighed and milled. A subsample of both live biomass and litter samples was dried at 105 °C and combusted in a muffle furnace (Thermolyne CPS-4022P; Dubuque, Iowa, U.S.) to measure ash-free dry matter.

2.2.3 Soil

Soil samples were collected in April 2023, just prior to treatment establishment. In each plot, two soil samples were collected per micro-zone along randomized transects using a hand core (5.25 cm diameter). Cores were divided into two depth segments: 0-10cm and 10-30cm, and then aggregated by micro-zone. This resulted in a total of n = 192 samples. Deep soil samples (30-50cm) were collected the following spring (April 2024) in three plots per treatment using a bucket auger. Sample volume was measured via water displacement. All soil samples were 12 mm sieved to separate roots and rocks, and then air-dried on site before being shipped to Colorado State University, where they were de-quarantined by oven-drying at 110 °C for 24 hours. A subsample was then 2 mm sieved, separating out roots and rocks. Fine and coarse roots were combined and measured for root biomass before being combusted in a muffle furnace (Thermolyne CPS-4022P; Dubuque, Iowa, U.S.) to compute ash-free dry matter content via loss on ignition. Total soil carbon and nitrogen (%) were measured using an Elemental Analyzer (Costech ECS 4010; Valencia, CA, USA).

2.3 Statistical Analysis

Statistical analysis was conducted in R (R Core Team, 2025). Linear mixed-effect models were used to evaluate soil moisture, soil temperature, vegetation, and soil carbon and nitrogen responses to micro-zone and treatment effects. The models were fit using the *lme4* package

(Bates et al., 2015), and post hoc comparisons were performed using the *emmeans* package (Lenth et al., 2025).

For soil moisture and temperature, 15-minute values were averaged to seasonal (growing season – April to October; winter – November to March) means for each sensor. First, treatment-level differences were modeled with treatment, season, and depth as fixed effects and plot and study year as random effects. If there were no significant differences between the array treatments (PV and AV), data from these two treatments were pooled for a micro-zone-level model with micro-zone, season, and depth as fixed effects and plot and study year as random effects. If treatment-level differences were detected, a combined treatment & micro-zone ID was used as a fixed effect to account for the nesting of micro-zones within treatments and the asymmetric micro-zone-levels between the AV and PV treatments and the no-PV.

For above-ground primary productivity responses to micro-zone and treatment effects within the AV and PV treatments, fixed effects included treatment, micro-zone, and year, while random effects included replicated plots and micro-zones nested within plots. To compare treatment-level differences, biomass and litter data were summarized to a treatment level, area weighted by zone, and then analyzed.

For soil carbon and nitrogen stocks, data from the AV and PV treatments were pooled to focus on differences across micro-zones, as the samples were taken prior to management differentiation by treatment. Fixed effects included micro-zone and depth, and random effects included replicated plots and micro-zones nested within plots. Residuals from all models were checked for normality and homoscedasticity. When necessary, values were log-transformed to ensure models complied with assumptions.

3. Ecosystem patterning across PV micro-zones

3.1 Microclimate

PV modules dramatically modified solar radiation and precipitation relative to a conventional pasture, and these modifications were key drivers of canopy-level microclimate alterations in soil moisture, soil temperature, and relative humidity.

Consistent with existing agrivoltaics and ecovoltaics research, solar radiation was reduced across all micro-zones relative to full sun conditions (Graham et al., 2021; Marrou et al., 2013; Sturchio et al., 2022). As shown in Figure 3, solar radiation levels and timing across micro-zones followed consistent patterns in response to the module tracking. Micro-zone E received sun in the morning and shade in the afternoon, while W received the converse. Micro-zone B received the most direct solar radiation, reaching a maximum of 67% of full sun in the summer. This micro-zone was shaded in the morning and evenings, while receiving close to full sun throughout the midday. Micro-zone U consistently received the least solar radiation, ranging from 17% to 22% of full sun. Zonal solar radiation patterns also varied seasonally. In the winter, cumulative solar energy was more similar across all array micro-zones, and in the 2023-2024 winter months, the drip edges received more solar energy than B (Supplemental Materials Figure S2).

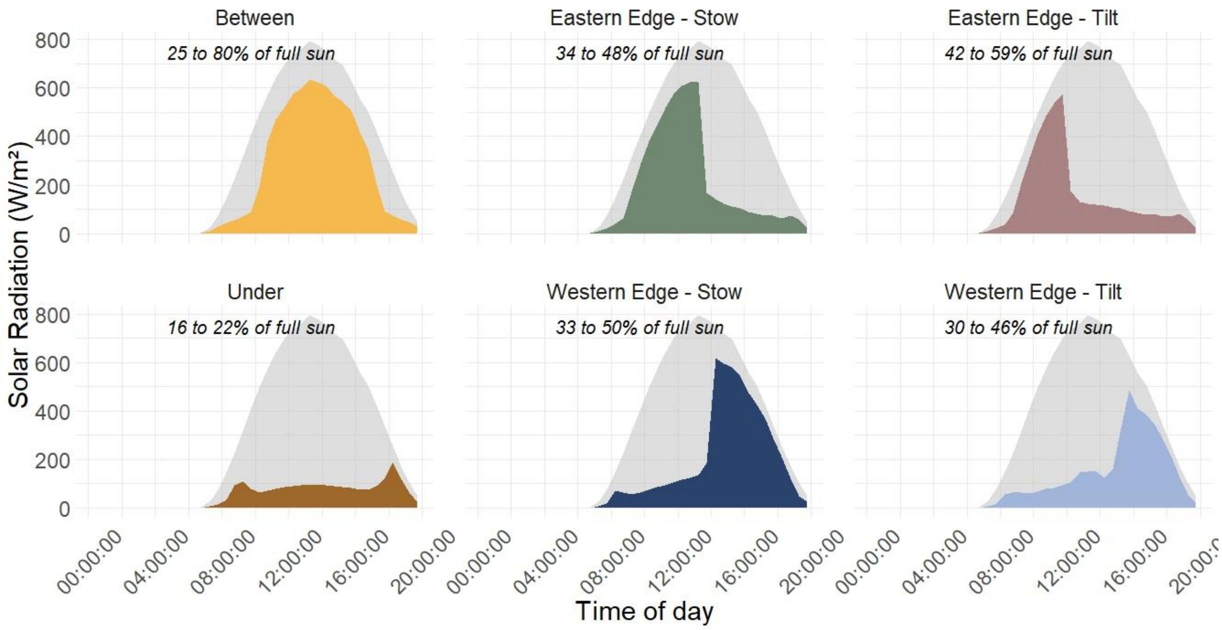


Figure 3. Average 15-minute solar radiation over the 2023 & 2024 growing season (April to October) by micro-zone. Percentage values show the min/max of monthly cumulative solar energy compared to full sun (grey shade). Within the drip edges, data are shown from the edge of the drip edge closest to micro-zone U (i.e. under the module edge when the modules are at the maximum tilt) as well as from the edge of the drip edge closest to micro-zone B (i.e. under the module edge when modules are parallel to ground) – see Figure 2.

PV modules intercepted precipitation, redistributing water across micro-zones. This resulted in greater effective precipitation (i.e., precipitation reaching the ground) in the drip edges (E and W) relative to the area between modules (B). Conversely, the modules largely prevented precipitation from reaching the under micro-zone. From April 2023 to April 2024, total annual effective precipitation in the outside (i.e., furthest from I-beam) edge of micro-zone E (E Stow) was 1736 mm, compared to approximately 1131 mm measured in B, which received no additional water redistribution – i.e., ca. 50% more in E than in B. Conversely, the microclimate sensors directly under the modules received only 142 mm of effective precipitation, nearly 90% less than in B.

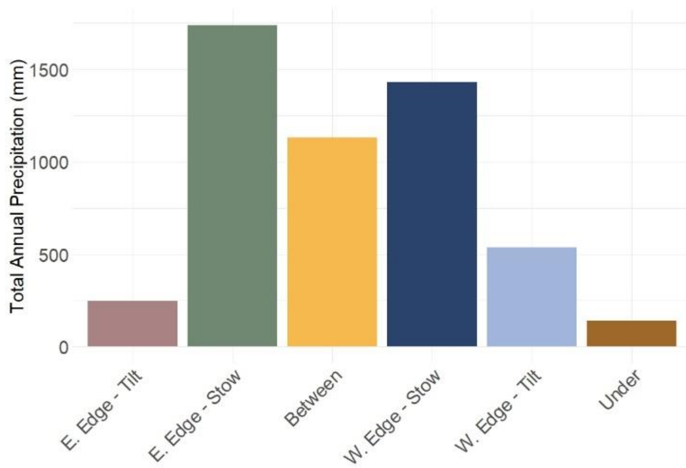


Figure 4. Total annual precipitation measured at the canopy level by micro-zone, April 2023 to April 2024.

The distribution of precipitation between the eastern and western drip edges was determined largely by the timing of precipitation events. The modules were programmed to stow approximately horizontal when overcast to maximize the absorption of diffuse radiation. In the morning, modules stowed with a slight eastern tilt, while in the afternoon, modules stowed with a slight western tilt. Overnight, modules were stowed with a 30-degree eastern tilt. Precipitation that fell overnight or in the morning, therefore, favored the eastern drip edge, while afternoon precipitation favored the western drip edge (Supplemental Materials Figure S3).

The patterning of solar radiation and precipitation caused by the modules translated into heterogeneity in other key ecosystem drivers, including soil temperature and soil moisture. The linear mixed effects models for soil moisture and soil temperature showed no significant treatment effects within the array (i.e., PV vs AV) (p = 0.28 & 0.36, respectively), so the array data were pooled to focus on within-array vs no-PV effects.

The PV modules had a cooling effect on soil temperatures in the micro-zones that experienced longer shaded periods. Mean growing season (April to October) soil temperatures in micro-zone U and drip-edge micro-zones were significantly lower ($p < 0.05$) than both B and the no-PV site, down to 30cm. There was no cooling effect observed in B relative to the no-PV site, and in the second study year, B had slightly higher soil temperature than no-PV (n.s.) (Figure 5). Micro-zone U experienced the lowest growing season soil temperatures, significantly lower than even the neighboring drip edges in some cases. Conversely, in winter, the PV modules had a slight insulating effect with warmer daily mean soil temperatures within the array compared to the no-PV site; however, this difference was not statistically significant.

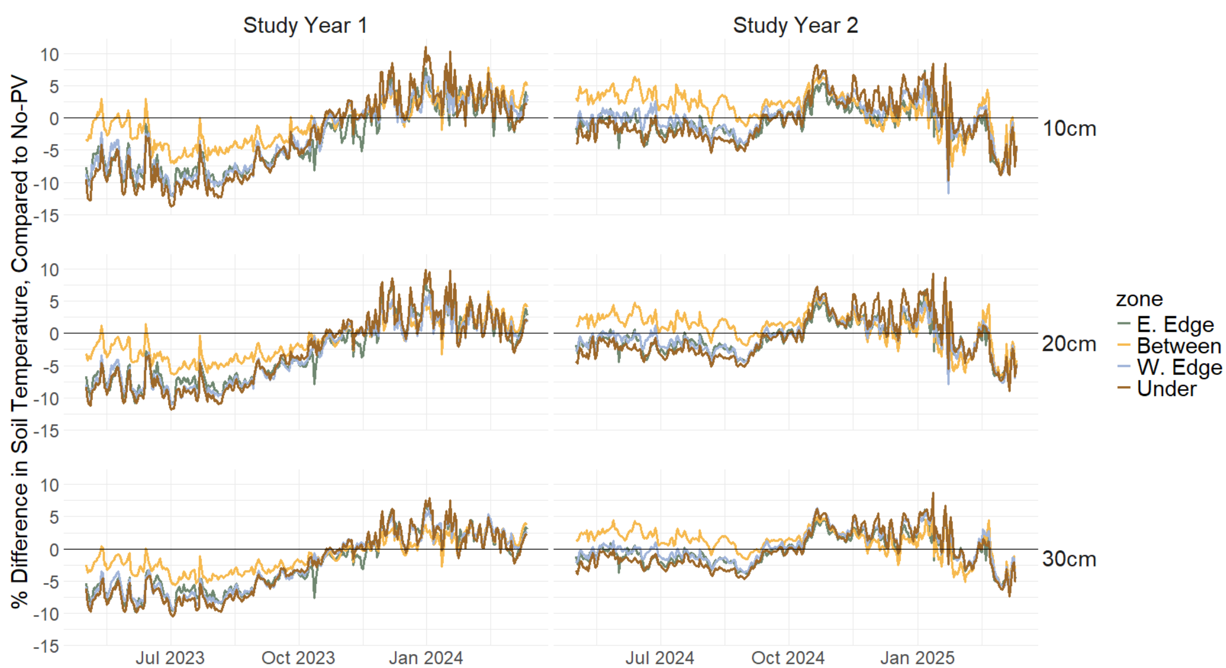


Figure 5. Percent difference in daily average soil temperature between array micro-zones and no-PV by depth and study year. During the growing season (Apr to Oct) soil temperature in micro-zones B and O was significantly higher than other micro-zones across all depths. Micro-zone U consistently had the lowest soil temperature. During the winter, there was no statistically significant difference in soil temperature between micro-zones.

We observed consistently higher soil moisture in micro-zone E compared to all other micro-zones across nearly all seasons and depths. Micro-zone E had significantly higher soil moisture ($p < 0.05$) than micro-zone U (with the array) and no-PV at all depths. The other micro-zones within the array consistently maintained higher (although not always statistically significant) soil moisture than the no-PV site. Differences were larger deeper in the soil profile, with smaller differences closer to the surface. We also observed larger effect sizes during the growing season, compared to the winter months. Differences in soil moisture were most extreme during drier periods (10cm no-PV soil moisture < 20%), when soil moisture in no-PV was 31-34% lower than E and 20-27% lower than U. When water was more abundant (10cm no-PV soil moisture > 20%), soil water content in no-PV was 13-15% lower than E and 6-8% lower than micro-zone U (Figure 6).

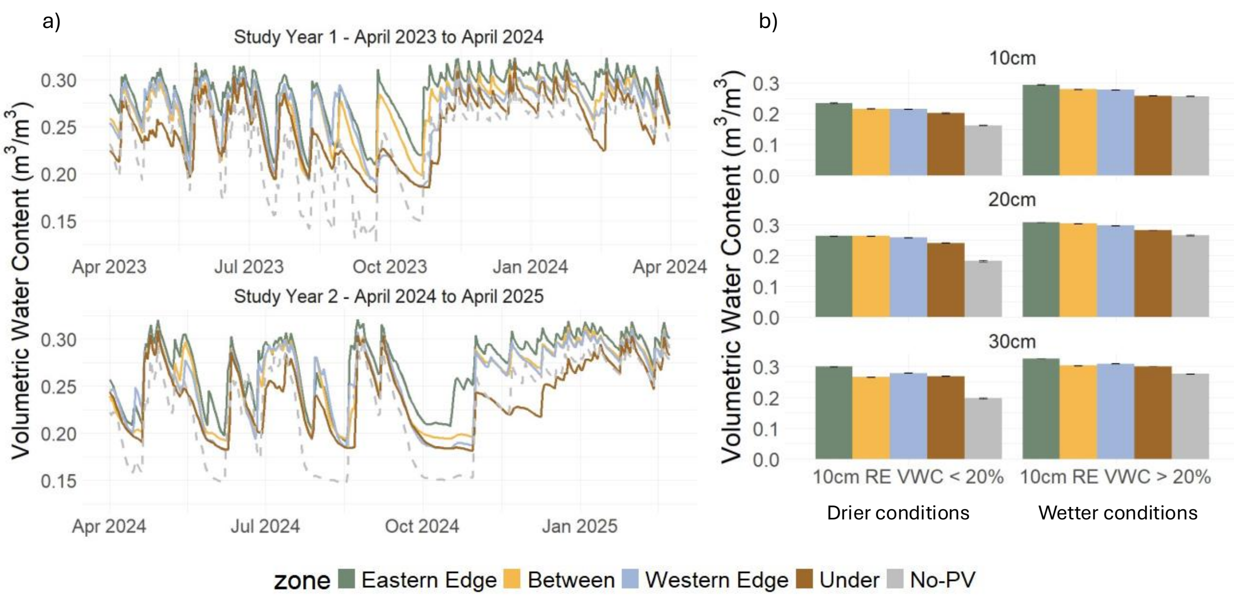


Figure 6. (a) Mean 10-cm volumetric water content by micro-zone across study years 1 and 2. (b) Mean daily soil moisture in drier conditions (no-PV 10cm soil moisture < 20%) (left) and wetter conditions (no-PV 10cm soil moisture > 20%) (right) across micro-zones. Every day between May 1, 2023 and April 30, 2025 was categorized as either wet or dry based on the mean daily soil moisture from the three 10cm sensors at the no-PV site using a 20% threshold.

3.2 Vegetation

Aboveground net primary productivity (ANPP) over the growing season was calculated by summing the first sampling point of the season with biomass regrowth between grazing or mowing events (e.g., the pre-grazing biomass sample minus the prior post-grazing biomass sample) for each micro-zone within every plot. In the AV treatment, micro-zone B had the highest ANPP both years (Figure 7). The drip edges were slightly reduced relative to B, while micro-zone U had the lowest ANPP. In the PV treatment, there was no consistent ANPP pattern year-to-year. In 2023, micro-zone B had the highest ANPP, similar to the AV treatment. However, in 2024, micro-zone E had the highest ANPP, with B and W slightly lower. Micro-zone did not have a statistically significant effect on ANPP in either year when accounting for treatment (p = 0.224). ANPP in the PV treatment was slightly reduced compared to AV, but the difference was not significant (p = 0.152). ANPP was significantly higher in 2024 (p = 0.048). Treatment and micro-zone level differences were small relative to high natural variability, which accounted for approximately 70% of the variance in ANPP.

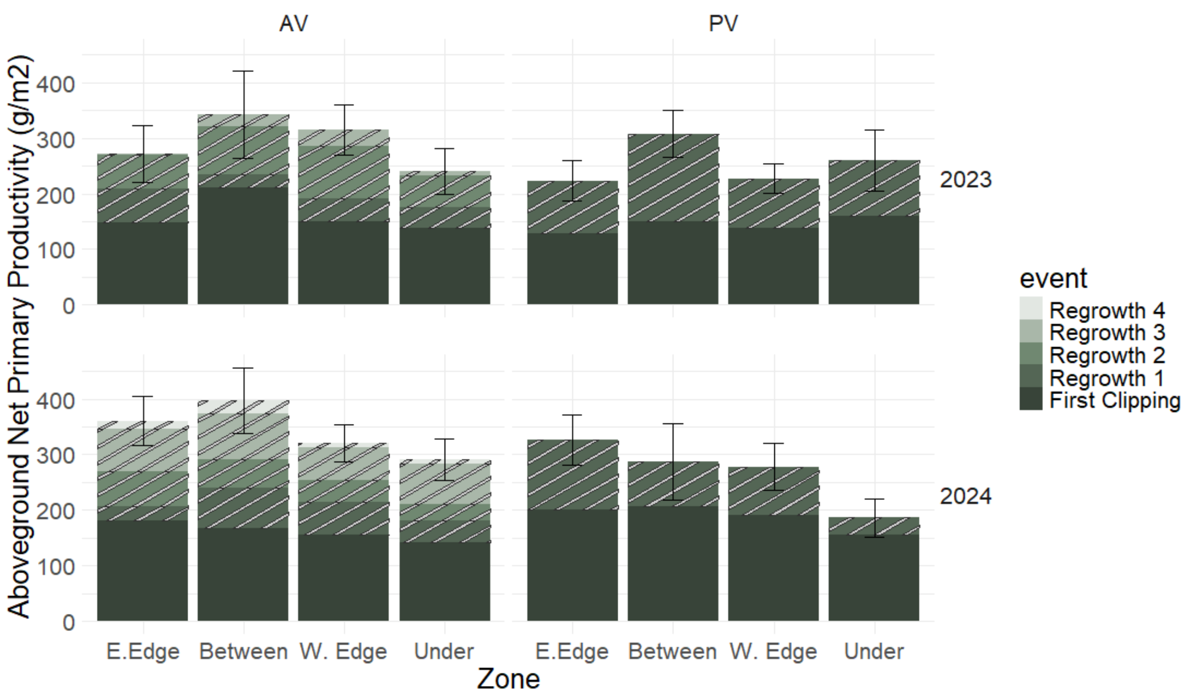


Figure 7. Mean aboveground net primary productivity (ANPP) by micro-zone and treatment for the 2023 and 2024 growing seasons. ANPP is calculated for each plot as the sum of the first sampling of the year in the spring (solid fill) and all regrowth between vegetation management events across all plots (striped). Error bars show the standard error for ANPP by treatment, micro-zone, and year across all plots. No statistically significant differences were detected between treatments or micro-zones.

In contrast to micro-zonal patterns in biomass, higher litter levels were observed in U across both growing seasons (Figure 8). In 2023, micro-zone U had significantly greater litter than B in both the AV and PV treatments ($p = 0.009$, $p = 0.002$, respectively). In 2024, this difference was only significant ($p = 0.002$) in the AV treatment, and the PV treatment had no significant differences in litter across micro-zones. Treatment effect varied by micro-zone and year, and in 2023, the PV treatment had significantly lower litter than the AV treatment in micro-zones B and E. In 2024, however, there were no significant treatment-level differences.

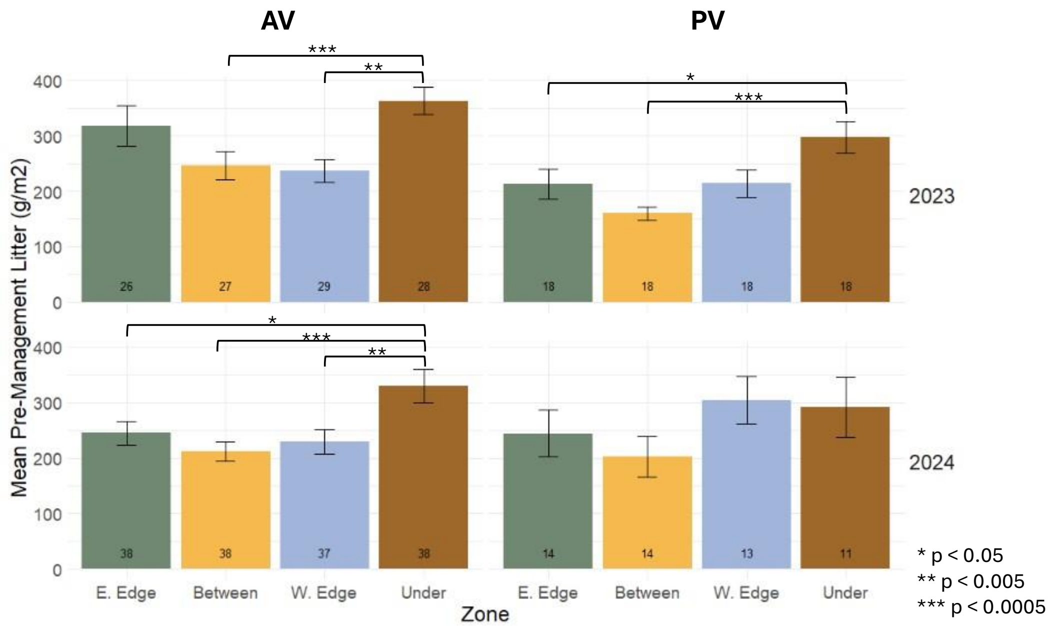


Figure 8. Mean litter (g/m^2) prior to grazing/mowing (i.e. pre-management) by treatment and micro-zone for 2023 and 2024 growing seasons for the AV treatment (left) and PV treatment (right). Sample size is shown at the bottom of each column. Error bars show +/- standard error.

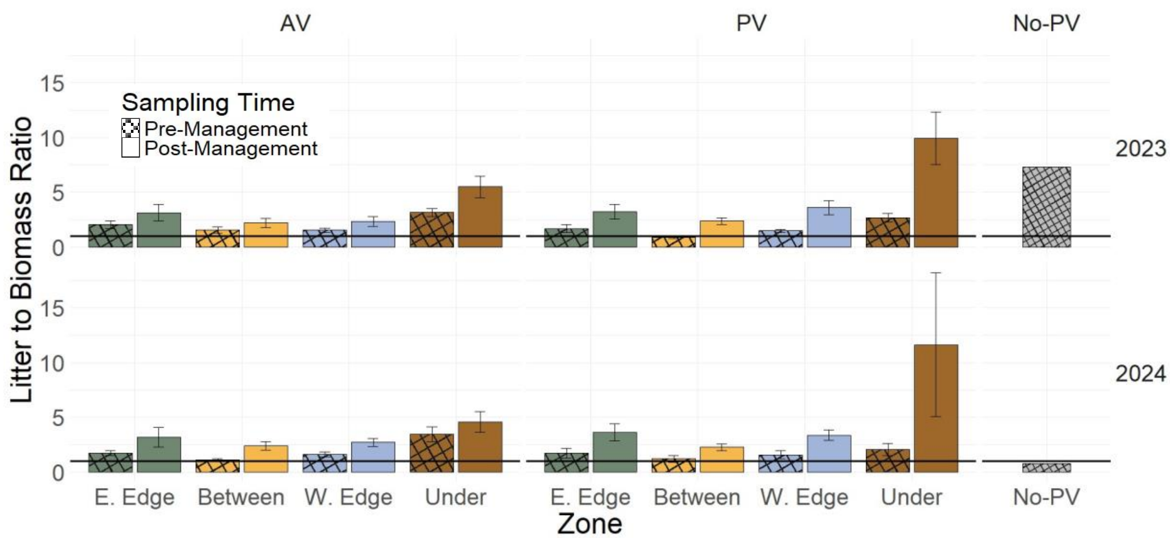


Figure 9. Mean litter to biomass ratio by micro-zone and treatment across all sampling events for 2023 and 2024. Hatched bars show the ratio prior to vegetation management (i.e. grazing or mowing), and solid bars show the ratio following management. Error bars show +/- standard error.

Looking at the relative proportions of litter to biomass across micro-zones (Figure 9), micro-zone U had the highest litter to biomass ratio (> 1, more litter than biomass) in both 2023 and 2024 for both array treatments and both before and after management events ($p < 0.005$). B had the lowest litter to biomass ratio for both treatments and years, while the drip edges in both treatments were around one. The PV treatment had a consistently higher litter to biomass ratio than the AV treatment (except for the Western drip edge); however, no statistically significant differences between treatments within any micro-zone were detected.

3.3 Soils

Soils were predominantly sandy clay loam, however, we observed some plot-to-plot variability in texture across the treatment sites (Supplemental Materials Figures S4 & S5). No significant differences in soil carbon stocks between micro-zones were found at any depth.

Within the array, standing root C was higher across all micro-zones in B; however, this difference was not statistically significant (Figure 11).

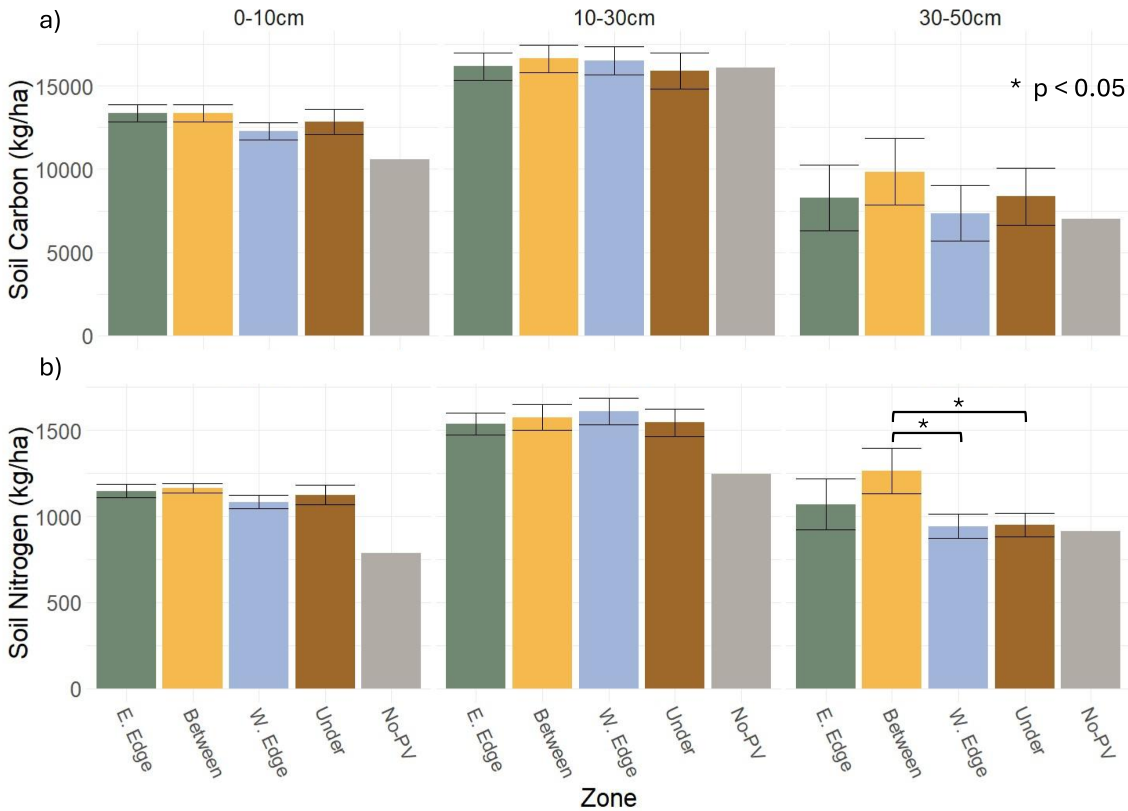


Figure 10. Baseline (a) soil carbon and (b) nitrogen stocks (kg/ha) by micro-zone from initial sampling in April 2023. Stocks are shown per depth increment: the surface layer (0-10 cm) represents a 10-cm interval, while the deeper layers (10-30 cm and 30-50 cm) represent 20-cm intervals, which is why surface carbon and nitrogen stocks appear lower. Error bars show +/- standard error. The comparative no-PV site is excluded from statistical comparison due to previously discussed limitations.

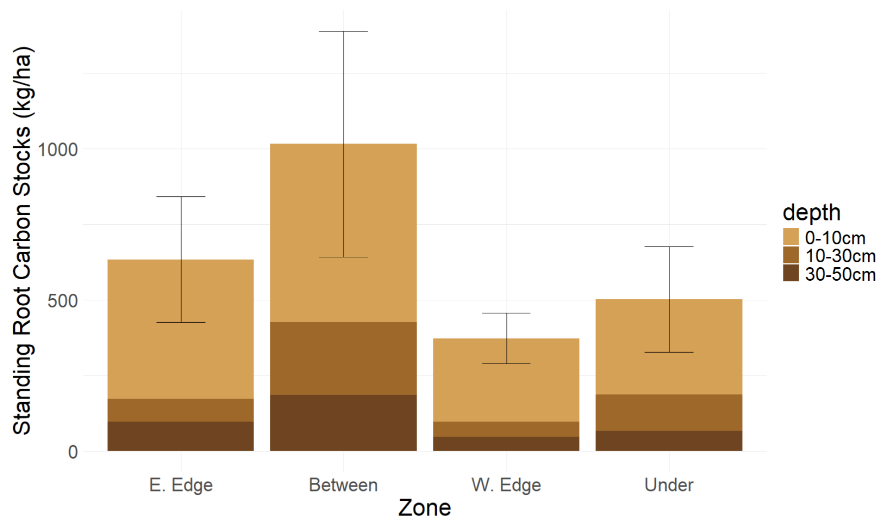


Figure 11. Baseline root carbon by micro-zone and depth. Coarse (>12mm) and fine (>2mm) roots are combined for each depth. Error bars show +/- standard error for total root carbon stocks for all depths.

4. Early treatment-level differences

To understand early differences stemming from land-management practices in the first two years of treatment application, micro-zone level data were aggregated to a treatment mean based on the relative area of each micro-zone (E = 7%, B = 64%, W = 7%, U = 22%). This facilitated a more direct comparison between treatments. Weighing the micro-zone-level ANPP values, treatment-level ANPP values were calculated. The AV treatment had higher ANPP in both 2023 (313.5 g/m2) and 2024 (365.6 g/m2) compared to the PV treatment (285.5 g/m2 and 267.0 g/m2 in 2023 and 2024, respectively). During summer 2024, a full year after the initial application of management treatments, standing biomass levels within the array were similar to standing biomass levels at the no-PV site (Figure 12).

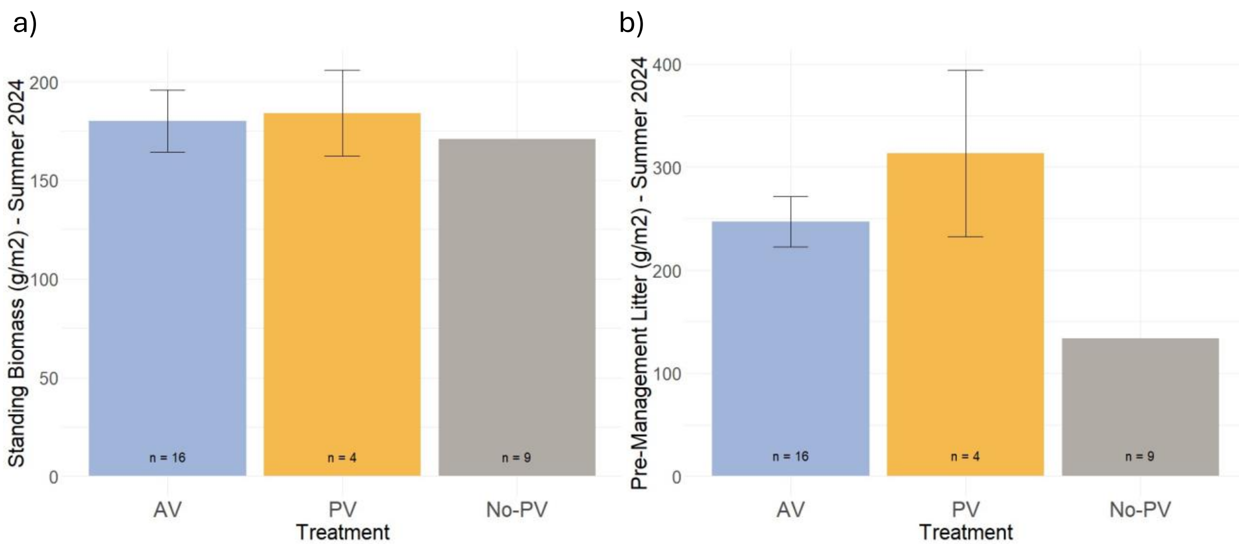


Figure 12. Treatment-level (a) peak standing biomass and (b) litter (area-weighted by micro-zones) in summer 2024. Data from samples taken prior to grazing/mowing events. Error bars show +/- standard error.

5. Discussion

Characterizing the patterned ecological impacts of PV systems integrated with various land management regimes across different climate micro-zones is crucial to the sustainable development of agrivoltaics. This study is one of the first to present field data of this type in the humid subtropical southeastern U.S. Our results highlight a gradient of impacts across different ecosystem variables. We observed significant and consistent differences between micro-zones in primary ecosystem drivers, including solar radiation and precipitation. These translated into significant, but less pronounced, differences in soil moisture and temperature, still reflecting consistent micro-zonal patterns. Despite these differences in growing conditions, however, biomass and soil carbon were consistent across micro-zones throughout the first two years of study. These results highlight both the non-linear response of biomass accumulation to changes in driving environmental factors and the importance of climate-specific context within agrivoltaic systems.

5.1 Microclimate patterning

The presence of PV modules created dynamic patterning of key ecosystem drivers, with alterations to both the amount and timing of environmental drivers, including solar radiation and precipitation reaching the canopy level. Consistent with precipitation inputs, we observed the highest soil moisture levels in the eastern drip edge; however, all the micro-zones within the array maintained higher (although not always statistically significant) soil moisture than the no-PV site. This suggests substantial lateral water flow between micro-zones, as even the U micro-zone, which received very minimal direct precipitation inputs (~140 mm), had elevated soil moisture.

Differences in soil moisture between array micro-zones and the no-PV site were greater during more water-limited periods, highlighting the outsized influence of the modules when soil moisture levels are lower. This is consistent with findings from more arid systems (Barron-Gafford et al., 2019; Choi et al., 2020; Moscatelli et al., 2022; Sturchio et al., 2022) showing elevated soil moisture within PV arrays. The difference between soil moisture in the array and the no-PV site, although smaller, did persist even in wetter conditions, suggesting that these soil moisture impacts from the PV modules may be observed across a wide range of systems and climates.

These results also highlight the influence of the regional climate on PV microclimate patterning. At field sites in more arid Colorado, the tendency towards afternoon precipitation favored higher soil moisture in the western drip edge (Choi et al., 2020; Sturchio et al., 2022), whereas we observed greater precipitation inputs at times that favored the eastern drip edge.

5.2 Vegetation response to micro-zones

Despite the patterns in microclimate variables across micro-zones and in contrast to our hypothesis, no statistically significant differences in ANPP across micro-zones were observed. Micro-zone U typically had lower biomass (compared to other micro-zones, ANPP ranged from 16% higher to 48% lower, n.s.), consistent with most other studies of this type (Adeh et al., 2019; Andrew et al., 2024; Armstrong et al., 2016; Kochendoerfer et al., 2025; Loan & Picon-Cochard, 2022; Moscatelli et al., 2022; Sturchio et al., 2022, 2024). In the AV treatment, micro-zone B had the highest productivity both years; however, we did not see a consistent pattern across the other micro-zones or within the PV treatment.

We also observed significantly higher litter in the U micro-zone, both absolute and relative to the biomass. Moscatelli et al. (2022) reported similar findings within a fixed tilt array in Italy, where they observed almost twice as much litter under the modules compared to between modules (Moscatelli et al., 2022). Several studies have measured a reduction in soil CO_2 effluxes under PV modules (Armstrong et al., 2016; Lambert et al., 2021, Toy et al., 2025), suggesting slower decomposition leading to a greater accumulation of plant litter below the modules. This would also correspond with the reduced soil temperatures in the array during the growing season, since cooler soil temperatures are associated with slower decomposition rates.

5.3 Soil response to micro-zones

During the baseline soil sampling in 2023, we observed no differences in soil carbon stocks across the micro-zones within the array. Sampled only three years after construction, we believe this may be too brief a timeframe to detect measurable differences (Smith, 2004). Studies on soil carbon within PV arrays are limited and report mixed results (Krasner et al., 2025), suggesting that conclusions should not be drawn from the micro-zone-level soil results prior to re-sampling. However, we did observe higher root carbon in micro-zone B compared to other micro-zones. While this difference was not statistically significant, it could suggest the potential direction of change for soil carbon.

Considering both vegetation and soil responses, it is difficult to decipher the impacts of microclimate alterations from legacy construction effects. There are a limited number of studies isolating the impacts from PV construction on ecological indicators, making it difficult to attribute these results exclusively to microclimate alterations, especially in a rather young system like this one.

5.4 Impacts of land management

Aggregating micro-zone data to the treatment level, we can examine the interaction of land management and microclimate alterations. At the treatment level, we saw no significant difference in productivity between management treatments within the array (AV & PV). In summer 2024, a full year after the initial differentiation of land management treatments, treatment-level standing biomass in the array was consistent with the no-PV comparative site. However, as discussed previously, this is caveated with some significant limitations in data collection in the no-PV treatment, as well as pre-existing differences in vegetation between the no-PV site and the array treatments.

Existing research on the impacts of PV modules on grassland productivity reported a 6% to 48% reduction in biomass within the array relative to a control site without modules (Adeh et al., 2019; Andrew et al., 2021, 2024; Armstrong et al., 2016; Kochendoerfer et al., 2025; Kampherbeek et al., 2023; Loan & Picon-Cochard, 2022; Moscatelli et al., 2022; Sturchio et al., 2022, 2024; Weselek et al., 2021), potentially pointing to the influence of the climate region, especially precipitation patterns, on the ecosystem impacts of PV modules. However, variability between sampling design, control site selection (as highlighted in this study), and location across research projects makes direct comparison of these results challenging (Bacon et al., 2024). No differences between the AV and PV treatments were detected for any of the point-in-time sampling events, after a 1-year duration of different land management treatments (i.e., more frequent biomass removal via sheep vs biomass being left on site and managed less frequently with mowing). Grazing pressure within the AV treatment was light, with low to moderate stocking rates (short rotations in relatively large areas), potentially leading to a less dramatic and measurable impact from the management regime.

There was a higher litter to biomass ratio in the mowed treatment, which could be due to several different components of the land management. Sheep trample and bed down on top of live standing vegetation, potentially leading to higher litter accumulation (Mor-Mussery et al., 2021). In contrast, mowing breaks down vegetation into smaller pieces, potentially accelerating decomposition. Additionally, since plots were mowed less frequently than they were grazed, litter in the mowed treatment had longer periods to decompose before the next sampling point.

Notably, several studies have found a decrease in soil carbon within PV arrays compared to nearby controls, suggesting potential construction impacts (Krasner et al., 2025). However, we observed no differences in soil carbon between micro-zones within the array and the no-PV treatment. While this is not a true proxy for a pre-construction comparison, the no-PV comparative site had a similar land-management history and soil, offering a valuable comparison and suggesting that the array construction did not significantly affect soil carbon.

6. Conclusion

Agrivoltaic grazing systems rely on the integration of solar PV with grazing and have significant potential to improve ecosystem impacts of PV development and minimize agricultural displacement. Therefore, understanding the outcomes of these systems requires characterizing the impacts of PV modules on key ecosystem parameters and understanding how these impacts interact with the presence of grazing livestock. This study highlighted the microclimate heterogeneity introduced by PV modules, emphasizing ways in which microclimate alterations appear to vary across climate regions (most notably PV impacts on water dynamics). In contrast to our hypothesis, however, microclimate patterning did not translate into consistent or significant biomass or soil carbon patterning. Future research within long-term agrivoltaics systems is needed to confirm these results, especially for soil properties. Early results comparing differences in land management within the array showed no significant differences in ANPP micro-zone to micro-zone between mowing and grazing. When averaged to the treatment level, ANPP was higher in the AV treatment in both 2023 and 2024, and was similar to the no-PV comparative site a year after the start of the experiment. This study is an important step towards filling a gap in field research within agrivoltaic grazing systems and emphasizes the importance of collecting this type of data across a wide range of climate regions and management systems.

REFERENCES

Adeh, E. H., Good, S. P., Calaf, M., & Higgins, C. W. (2019). Solar PV Power Potential is Greatest Over Croplands. *Scientific Reports*, *9*(1), Article 1. https://doi.org/10.1038/s41598-019-47803-3

Agrivoltaics Map. (n.d.). InSPIRE, National Renewable Energy Lab. Retrieved November 30, 2023, from https://openei.org/wiki/InSPIRE/Agrivoltaics_Map

Andrew, A. C., Higgins, C. W., Smallman, M. A., Graham, M., & Ates, S. (2021). Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System. *Frontiers in Sustainable Food Systems*, *5*. https://www.frontiersin.org/articles/10.3389/fsufs.2021.659175

Andrew, A. C., Higgins, C. W., Smallman, M. A., Prado-Tarango, D. E., Rosati, A., Ghajar, S., Graham, M., & Ates, S. (2024). Herbage and sheep production from simple, diverse, and legume pastures established in an agrivoltaic production system. *Grass and Forage Science*, *79*(2), 294–307. https://doi.org/10.1111/gfs.12653

Andrew, A. C., Monlezun, A. C., Richardson, K., Owen Chase, B., Macknick, J., Plotkin, G., Armentrout, N., Hain, L., Barter, J., Campbell, K., Dotterer, D., Finnegan, D., Gray, J., Harrar, F., Owens, C., Raines, C., & Valdez, E. (2025). *United States Solar Grazing 2024 Census*. American Solar Grazing Association. https://solargrazing.org/us-solar-grazing-2024-census

Armstrong, A., Ostle, N. J., & Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*, *11*(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016

Bacon, T., Monlezun, A. C., Hong, M., Macknick, J., de Vries, N., Edwards-Callaway, L., & Paustian, K. (2025). Agrivoltaic Grazing Systems for a Sustainable Future: A Multi-Disciplinary Review & Gap Analysis. *Earth's Future*, *13*(8), e2024EF005429. https://doi.org/10.1029/2024EF005429

Bacon, T., Ohlert, T., Toy, C., Siggers, J. A., & Sturchio, M. A. (2024). Network science can improve the sustainable development of solar energy. *Environmental Research: Energy*, *1*(4), 043002. https://doi.org/10.1088/2753-3751/ad99dc

Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, *2*(9), Article 9. https://doi.org/10.1038/s41893-019-0364-5

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using **lme4**. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Choi, C. S., Cagle, A. E., Macknick, J., Bloom, D. E., Caplan, J. S., & Ravi, S. (2020). Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure. *Frontiers in Environmental Science*, *8*. https://www.frontiersin.org/articles/10.3389/fenvs.2020.00140

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. *Earth's Future*, *11*(6), e2023EF003542. https://doi.org/10.1029/2023EF003542

Choi, C. S., Macknick, J., McCall, J., Bertel, R., & Ravi, S. (2024). Multi-year analysis of physical interactions between solar PV arrays and underlying soil-plant complex in vegetated utility-scale systems. *Applied Energy*, *365*, 123227. https://doi.org/10.1016/j.apenergy.2024.123227

Graham, M., Ates, S., Melathopoulos, A. P., Moldenke, A. R., DeBano, S. J., Best, L. R., & Higgins, C. W. (2021). Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. *Scientific Reports*, *11*(1), Article 1. https://doi.org/10.1038/s41598-021-86756-4

Grodsky, S., Kochendoerfer, N., McMillan, C. E., Lapierre, P. A., Abbas, R. Z., Morris, S. H., Westbrook, A. S., & DiTommaso, A. (2025). *Co-Location of Sheep Grazing and Solar Energy Production Yields Agrotechnological Synergies* (SSRN Scholarly Paper No. 5125861). https://doi.org/10.2139/ssrn.5125861

Guerin, T. F. (2019). Impacts and opportunities from large-scale solar photovoltaic (PV) electricity generation on agricultural production. *Environmental Quality Management*, *28*(4), 7–14. https://doi.org/10.1002/tqem.21629

Hernandez, R. R., Armstrong, A., Burney, J., Ryan, G., Moore-O'Leary, K., Diédhiou, I., Grodsky, S. M., Saul-Gershenz, L., Davis, R., Macknick, J., Mulvaney, D., Heath, G. A., Easter, S. B., Hoffacker, M. K., Allen, M. F., & Kammen, D. M. (2019). Techno–ecological synergies of solar energy for global sustainability. *Nature Sustainability*, *2*(7), Article 7. https://doi.org/10.1038/s41893-019-0309-z

Kampherbeek, E. W., Webb, L. E., Reynolds, B. J., Sistla, S. A., Horney, M. R., Ripoll-Bosch, R., Dubowsky, J. P., & McFarlane, Z. D. (2023). A preliminary investigation of the effect of solar panels and rotation frequency on the grazing behavior of sheep (Ovis aries) grazing dormant pasture. *Applied Animal Behaviour Science*, *258*, 105799. https://doi.org/10.1016/j.applanim.2022.105799

Krasner, N. Z., Fox, J., Armstrong, A., Ave, K., Carvalho, F., Li, Y., Walston, L. J., Ricketts, M. P., Jordaan, S. M., Abou Najm, M., Hartmann, H. M., Lybrand, R., & Hernandez, R. R. (2025). Impacts of photovoltaic solar energy on soil carbon: A global systematic review and framework. *Renewable and Sustainable Energy Reviews*, *208*, 115032. https://doi.org/10.1016/j.rser.2024.115032

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*(18), 5190–5202. https://doi.org/10.1002/ldr.4101

Lenth, R. V., Banfai, B., Bolker, B., Buerkner, P., Giné-Vázquez, I., Hervé, M., Jung, M., Love, J., Miguez, F., Piaskowski, J., Riebl, H., & Singmann, H. (2025). *emmeans: Estimated Marginal Means, aka Least-Squares Means* (Version 1.11.2-8) [Computer software]. https://cran.r-project.org/web/packages/emmeans/index.html

Loan, M., & Picon-Cochard, C. (2022). *One Year of Grassland Vegetation Dynamics in two Sheep-Grazed Agrivoltaic Systems*.

Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., & Wery, J. (2013). Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? *Agricultural and Forest Meteorology*, *177*, 117–132. https://doi.org/10.1016/j.agrformet.2013.04.012

Mor-Mussery, A., Abu-Glaion, H., Shuker, S., & Zaady, E. (2021). The influence of trampling by small ruminants on soil fertility in semi-arid rangelands. *Arid Land Research and Management*, *35*(2), 189–197. https://doi.org/10.1080/15324982.2020.1827083

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*, e00500. https://doi.org/10.1016/j.geodrs.2022.e00500

NOAA NCEI U.S. Climate Normals Quick Access. (n.d.). Retrieved September 25, 2025, from https://www.ncei.noaa.gov/access/us-climate-normals/#dataset=normals-annualseasonal&timeframe=15&location=GA&station=USW00013869

R Core Team. (2025). *R: A language and environment for statistical computing* [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org/

Rahmaniah, F., & Tay, S. E. R. (2023). Environmental benefits of co-located photovoltaic and greenery systems: A review on the operational performance and assessment framework across climate zones. *Sustainable Energy Technologies and Assessments*, *58*, 103301. https://doi.org/10.1016/j.seta.2023.103301

Randle-Boggis, R. J., White, P. C. L., Cruz, J., Parker, G., Montag, H., Scurlock, J. M. O., & Armstrong, A. (2020). Realising co-benefits for natural capital and ecosystem services from solar parks: A co-developed, evidence-based approach. *Renewable and Sustainable Energy Reviews*, *125*, 109775. https://doi.org/10.1016/j.rser.2020.109775

Smith, P. (2004). How long before a change in soil organic carbon can be detected? *Global Change Biology*, *10*(11), 1878–1883. https://doi.org/10.1111/j.1365-2486.2004.00854.x

Solar Futures Study. (2021). U.S. Department of Energy. https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf

Sturchio, M. A., Kannenberg, S. A., & Knapp, A. K. (2024). Agrivoltaic arrays can maintain semi-arid grassland productivity and extend the seasonality of forage quality. *Applied Energy*, *356*, 122418. https://doi.org/10.1016/j.apenergy.2023.122418

Sturchio, M. A., Macknick, J. E., Barron-Gafford, G. A., Chen, A., Alderfer, C., Condon, K., Hajek, O. L., Miller, B., Pauletto, B., Siggers, J. A., Slette, I. J., & Knapp, A. K. (2022). Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. *Ecosphere*, *13*(12), e4334. https://doi.org/10.1002/ecs2.4334

Toy, C., Heider-Kuhn, N., & Schipanski, M. (2025). Impact of solar energy infrastructure and ecovoltaic management on semi-arid grassland carbon cycling. *Environmental Research Communications*, *7*(10), 105005. https://doi.org/10.1088/2515-7620/ae0b1d

van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

Vervloesem, J., Marcheggiani, E., Choudhury, M. A. M., & Muys, B. (2022). Effects of Photovoltaic Solar Farms on Microclimate and Vegetation Diversity. *Sustainability*, *14*(12), Article 12. https://doi.org/10.3390/su14127493

Weselek, A., Bauerle, A., Hartung, J., Zikeli, S., Lewandowski, I., & Högy, P. (2021). Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agronomy for Sustainable Development*, *41*(5), 59. https://doi.org/10.1007/s13593-021-00714-y

CHAPTER 5: SOLAR PV INFRASTRUCTURE HAD NO LONG-TERM IMPACTS ON SOIL CARBON WITHIN A 14-YEAR-OLD ARRAY IN THE SOUTHEASTERN UNITED STATES[4]

1. Introduction

Transitioning to zero-carbon energy sources is a crucial strategy for reducing global greenhouse gas emissions, and solar photovoltaic (PV) is a key technology in the suite of energy sources required for this transition (Larson et al., 2021). Solar PV is cost-competitive and has expanded rapidly over the last decade (Solar Futures Study, 2021). A large fraction of solar PV is sited on agricultural land (Maguire et al., 2024), and there are concerns about long-term impacts on soil properties and function, both for the ability to return the land to agriculture and for the net environmental impact of the energy generation.

The land-intensive nature of solar PV (van Zalk & Behrens, 2018), in addition to emerging agricultural and ecological synergies (Barron-Gafford et al., 2016; Knapp & Sturchio, 2024; Rahmaniah & Tay, 2023; Randle-Boggis et al., 2020), has motivated the development of agrivoltaic and ecovoltaic approaches to solar PV. In these systems, agriculture and/or ecosystem services are integrated with and co-prioritized alongside energy generation – both of which also rely on soil function.

However, our understanding of the impacts of PV infrastructure on soils is limited, especially when it comes to soil carbon impacts. Soils are slow to show measurable changes in soil organic carbon (SOC), in most cases taking five or more years to show a detectable difference in response to a change in land use management (Smith, 2004). There is limited

[4] Bacon, T., N. de Vries, and K. Paustian. "Solar PV Infrastructure Had No Long-Term Impacts on Soil Carbon Within a 14-Year-Old Array in the Southeastern United States." 2026 [Under review]

research on the longer-term (> five-year) response of SOC to agrivoltaics installations (Supplementary Materials Table S1). Of the studies identified that involved sampling for SOC analysis within solar PV arrays, only two were in systems older than five years (Choi et al., 2020; Moscatelli et al., 2022), highlighting the lack of research in this area. Additionally, a 2025 global systematic review of PV array impacts on soil carbon found that out of the 18 studies on interactions between solar PV and soils, only five measured soil carbon (Krasner et al., 2025).

Within PV arrays, there are three broad sources for impacts on soil properties: array construction, microclimate alterations caused by the PV modules, and site management. The newness of the field, along with the limited number of studies with comprehensive soil sampling, and the wide variability across these three factors, makes it difficult to isolate specific causal factors of SOC change. Additionally, the studies that do include soil sampling and laboratory analyses have a wide range of objectives (understanding the impact of revegetation/different land covers within PV arrays, comparing differences across a region, etc.), and a correspondingly wide range of control conditions, making comparison and generalization between studies difficult.

Construction is perhaps where the most dramatic soil impacts might be expected. Construction practices, especially those that minimize disturbance and equipment traffic, can limit these impacts. However, the nature of PV array installation will always incur some amount of soil disturbance. With limited opportunities for robust, replicated pre- and post-construction sampling, our understanding of construction impacts is nascent. In a humid subtropical system with low-impact construction practices, background environmental conditions had a more dramatic impact than construction itself, with an improvement in soil structure and no decrease in vegetative cover from pre-construction to post-construction sampling, both within the array and in the control treatment (Bacon, Monlezun, de Vries, et al., 2026 *in prep*). Construction of an array in an arid desert system led to soil compaction and a decrease in vegetation cover, where the magnitude of these effects was related to the intensity of construction disturbances (Karban et al., 2025). More intensive construction practices, including grading and topsoil removal, intuitively have a more dramatic effect on soil carbon (Choi et al., 2020; Lambert et al., 2021).

PV modules drive well-documented changes in microclimate and vegetation productivity (Adeh et al., 2019; Andrew et al., 2021, 2024; Armstrong et al., 2016; Barron-Gafford et al., 2016; Choi et al., 2023; Loan & Picon-Cochard, 2022; Moscatelli et al., 2022; Sturchio et al., 2022; Weselek et al., 2021). PV infrastructure has been shown to reduce canopy-level solar radiation, redistribute precipitation, maintain higher soil moisture, and moderate soil temperature (Adeh et al., 2018; Bacon, Monlezun, Hong, et al., 2026 *in prep*; Barron-Gafford et al., 2019; Choi et al., 2023, 2024; Sturchio et al., 2022).

These microclimate alterations can translate into spatial patterns in vegetation productivity, particularly in more arid systems, where vegetation has been shown to increase on the drip edges of the modules that receive greater moisture, paired with advantageous shading in the afternoon (Sturchio et al., 2022). Changes in vegetation productivity – both above and below ground – could result in changes to plant carbon inputs to soil, potentially resulting in SOC patterning across micro-zones. There's also evidence that microclimate alterations within PV arrays drive changes in soil respiration, which could also impact SOC stocks (Armstrong et al., 2016; Lambert et al., 2021; Moscatelli et al., 2022; Siggers et al., 2025; Toy et al., 2025).

A few of the studies that sampled soil carbon across micro-zones found evidence of microclimate impacts, although the effect was not consistent across studies. Siggers et al. found higher SOC on the eastern drip-edge in an arid ecovoltaic system in Colorado, mirroring vegetation productivity patterns (Siggers et al., 2025). In a similar climate region, however, Toy et al. (2025) found the highest SOC stocks directly under PV modules. Conversely, Moscatelli et al. found higher SOC stocks between modules compared to under (Moscatelli et al., 2022). However, most published studies have found no systematic spatial patterning within PV arrays (Armstrong et al., 2016; Bacon, Monlezun, Hong, et al., 2026 *in prep*; Choi et al., 2023; Scholten et al., 2025), and no significant change over time within arrays (Toy et al., 2025).

Layered in with construction and microclimate impacts, management of the land within the array is also anticipated to affect soil carbon stocks. The plant species established, planting practices, use of fertilizers and/or pesticides, and how the vegetation is managed (grazing vs mowing, etc.) could all impact soil carbon stocks. A study comparing solar grazing systems to conventionally mowed arrays across the Northeastern U.S. found an increase in soil carbon stocks within grazed systems (Andrew et al., 2025).

Recognizing the importance of understanding the long-term impacts of PV arrays on soil carbon and the complexity of interacting drivers, this study aimed to assess the impacts of PV modules on soil properties driven by microclimate alterations. We present data from a 14-year-old solar array in the humid-subtropical southeastern United States, comparing soil properties across different micro-zones relative to the PV infrastructure to areas that were not impacted by the array. We hypothesized that we would observe a patterning in soil carbon stocks reflecting the unique microclimate patterning created by the PV modules.

2. Methods

This study was conducted at a single-axis tracking, 1 MW solar PV array in Western Tennessee, USA (mean annual temperature: 17.4 °C, mean annual precipitation: 1395 mm, (*NOAA NCEI U.S. Climate Normals Quick Access*, n.d.)). The site was constructed in 2011, and prior to construction, it was an open grassy area. The site is on a gentle slope, and during construction, the lower area of the array was graded. Following construction, the site was seeded, and grass cover has been maintained throughout the life of the project. Since construction, vegetation at the site has been managed by mowing three to four times a year.

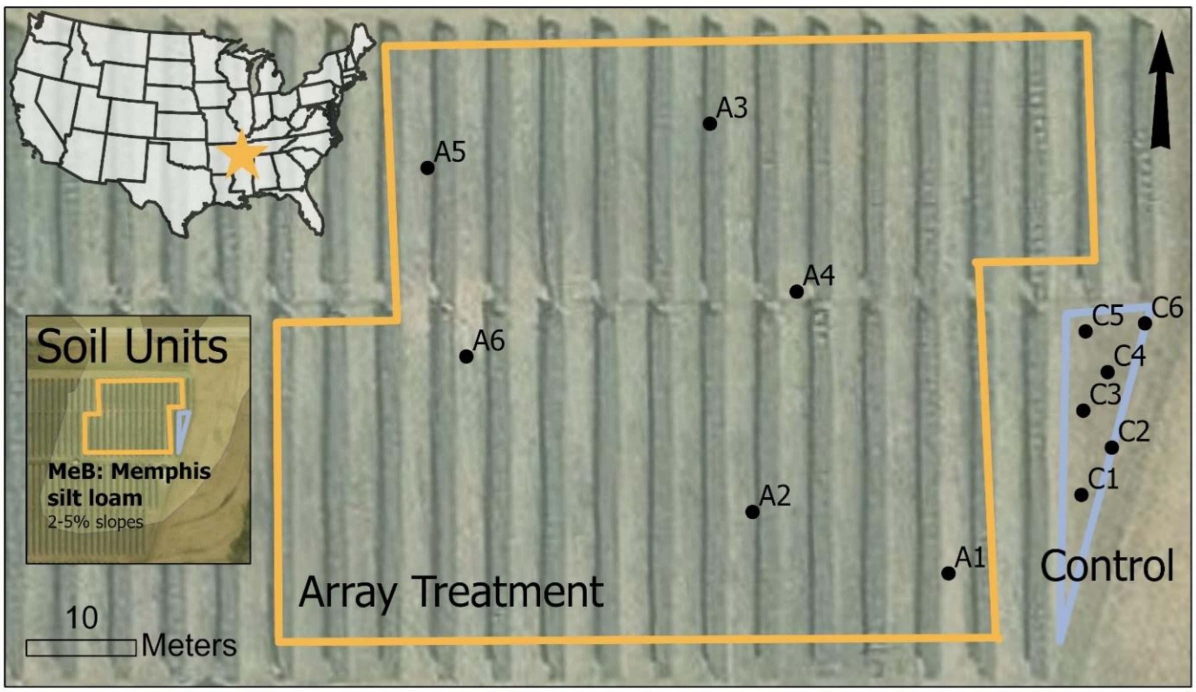


Figure 1. The field site for this research was in Western Tennessee, US. Within the array fence, array and control treatment areas were established, each with six randomized sampling points. Both treatments fell within the same soil unit: Memphis silt loam, 2 to 5% slopes. *Basemap imagery: Esri. Sources: Microsoft, Vantor*

Treatment areas within the array were determined based on consultation with SSURGO soil maps and the array's civil engineering plans. We constrained our sampling to the flattest area of the array, which experienced the least construction disturbance and fell within the same soil unit (Figure 1). The control treatment was located within the array fence, east of the array, and within the same soil unit. This area was never shaded by the PV modules, but experienced similar construction impacts (e.g. any grading/earth work, machinery traffic, re-seeding, etc.) and the same management as the vegetation within the array, allowing us to isolate the effects of the PV infrastructure on soil properties.

Within each treatment area, soil samples were collected at six randomly selected sampling points. Within the array, samples were collected along a transect running perpendicular to rows of modules to capture the heterogeneity across micro-zones (Figure 2). Samples were collected directly under modules (U), along the western drip edge of the modules (W), between rows of modules (B), and on the eastern drip edge (E). In the control, a single soil sample was collected at each sampling point.

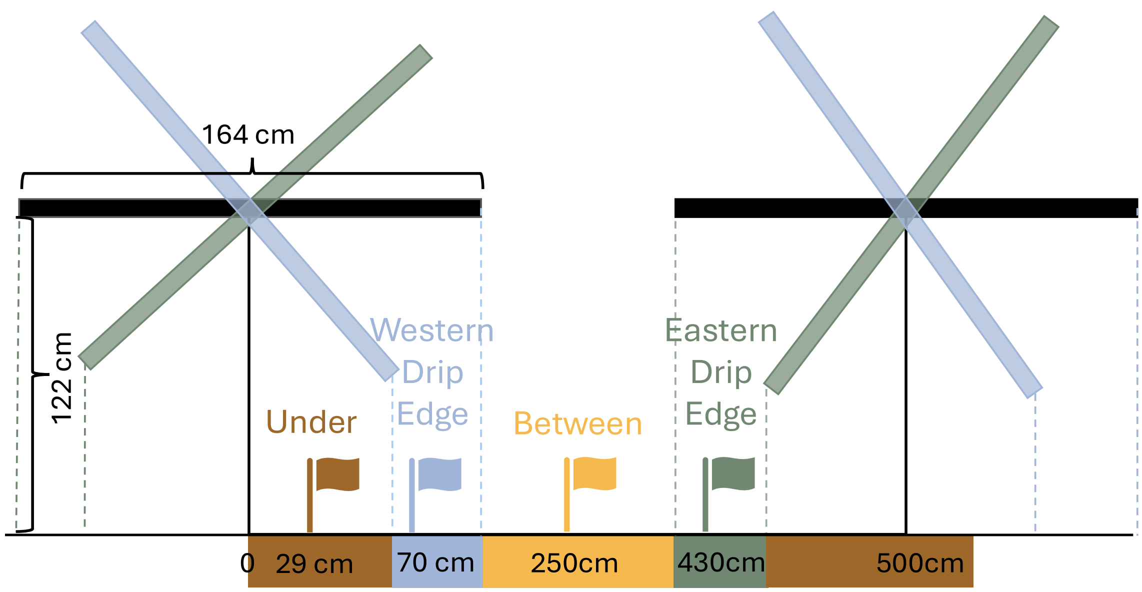


Figure 2. Micro-zones in the study site. Rows of PV modules are spaced 5 meters apart. The torque tube is about 1.2 m off the ground, and the modules are 1.6 m wide. Based on these dimensions, four micro-zones were determined, and soil samples were collected in the center of each micro-zone.

Soil samples were collected using a 5.7 cm diameter bucket auger. Samples were collected to ca. 20cm, and then the volume of the displaced soil was measured with millet seed displacement, based on the volume of packed seed required to fill the hole (Elliott et al., 1999). The same sample hole was then augured to ca. 40cm, and the volume measurement was repeated, and the volume of the 20-40 cm increment was calculated by difference.

Samples were transported to Middle Tennessee State University, where the field moist mass was recorded, and a subsample was oven-dried at 110 °C for 24 hours and then re-weighed to measure the volumetric water content. The soils were then sieved to 8mm and air dried before being transported to Colorado State University for the remaining analysis. Once in Colorado, the soils were de-quarantined (oven-dried at 116 °C for 18 hours) and 2mm sieved. A subsample of each soil was ground and then analyzed for total soil carbon and nitrogen content (%) using an Elemental Analyzer (Costech ECS 4010; Valencia, CA, USA). Fine and coarse roots from the 2 mm and 8 mm sieving, for each sample, were combined and weighed before being combusted for ash-free dry matter, allowing us to estimate total root carbon (Thermolyne CPS-4022P; Dubuque, Iowa, U.S.). A correction factor of 0.45 was assumed for the carbon fraction of ash-free plant litter.

Statistical analysis was conducted in R (R Core Team, 2025) using linear mixed-effect models. The models were fit using the lmer4 package (Bates et al., 2015), and the *emmeans* package (Lenth et al., 2025) was used for post-hoc comparisons. For all variables, micro-zone and depth were treated as fixed effects, while the randomized sample sites were incorporated as random effects. For statistical analysis of soil carbon stocks, sand content was added as a fixed effect. Models were evaluated using diagnostic plots to ensure assumptions were met, and if necessary, variables were log-transformed, which was the case for root carbon stocks.

3. Results

Soils at the site had a high sand fraction (Figure 3a). Mean percent sand was numerically higher with lower variance in the reference site than in the array, however this difference was only marginally significant ($p = 0.053$, full results from statistical analysis available in Supplemental Materials Table S2). Consistent with the high coarse fraction, bulk densities (BD) were quite high across micro-zones (Figure 3b). At both depths, BD values were numerically greater for micro-zone B, but there were no statistically significant differences across micro-zones ($p = 0.076$, Table S2). Comparing between depths, BD was greater in the 20-40cm samples ($p < 0.0001$). Volumetric water content was elevated in all micro-zones relative to the reference site across both depth increments (Figure 3c). However, this difference was only significant between micro-zone W and the reference at 0-20cm ($p = 0.005$), and micro-zone U and the reference at 20-40cm ($p = 0.029$). Of the surface soil samples, micro-zone W had the numerically highest volumetric water content.

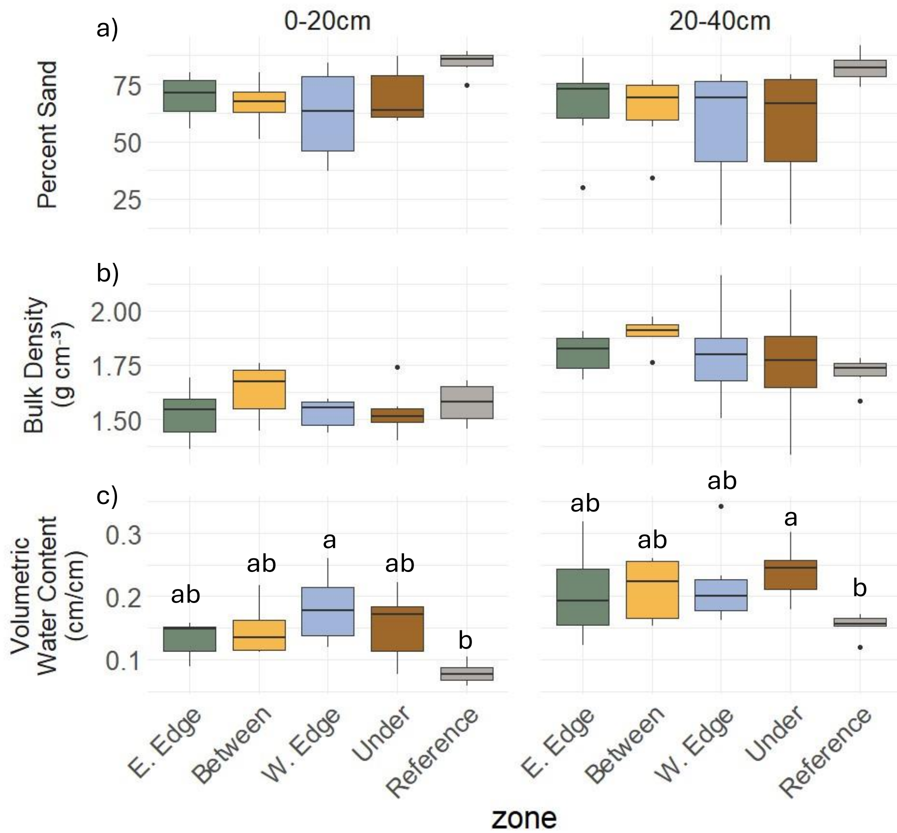


Figure 3. Percent sand (a), bulk density (g/cm3) (b), and volumetric water content (cm/cm) (c) by micro-zone within the array, compared to the reference (gray). Boxplots show the median (center line), interquartile range (box), and 1.5x interquartile range (whiskers). Points beyond the whiskers represent outliers. If there were significant differences between micro-zones, letters above boxes show the results of post-hoc pairwise comparison. Boxes sharing a common letter are not significantly different ($p > 0.05$).

We observed no significant difference in soil carbon or nitrogen stocks between micro-zones across either depth (Figure 4). However, in the 0-20cm samples, there was an apparent pattern across micro-zones for mean soil carbon and nitrogen stocks. Within the array, micro-zone W had the highest numerical mean for soil carbon and nitrogen stocks, followed by B and E, with the lowest stocks in micro-zone U. The reference area had soil carbon stocks similar to micro-zone W, and soil nitrogen stocks similar to micro-zone B. The carbon to nitrogen ratio (C:N) was highest across both depths in the reference area, but this difference was only statistically significant between micro-zone W and the reference in the 20-40cm samples (p =

0.037). The C:N ratio was significantly higher in the 0-20cm samples compared to the deeper soils across all micro-zones ($p < 0.001$, Table S2).

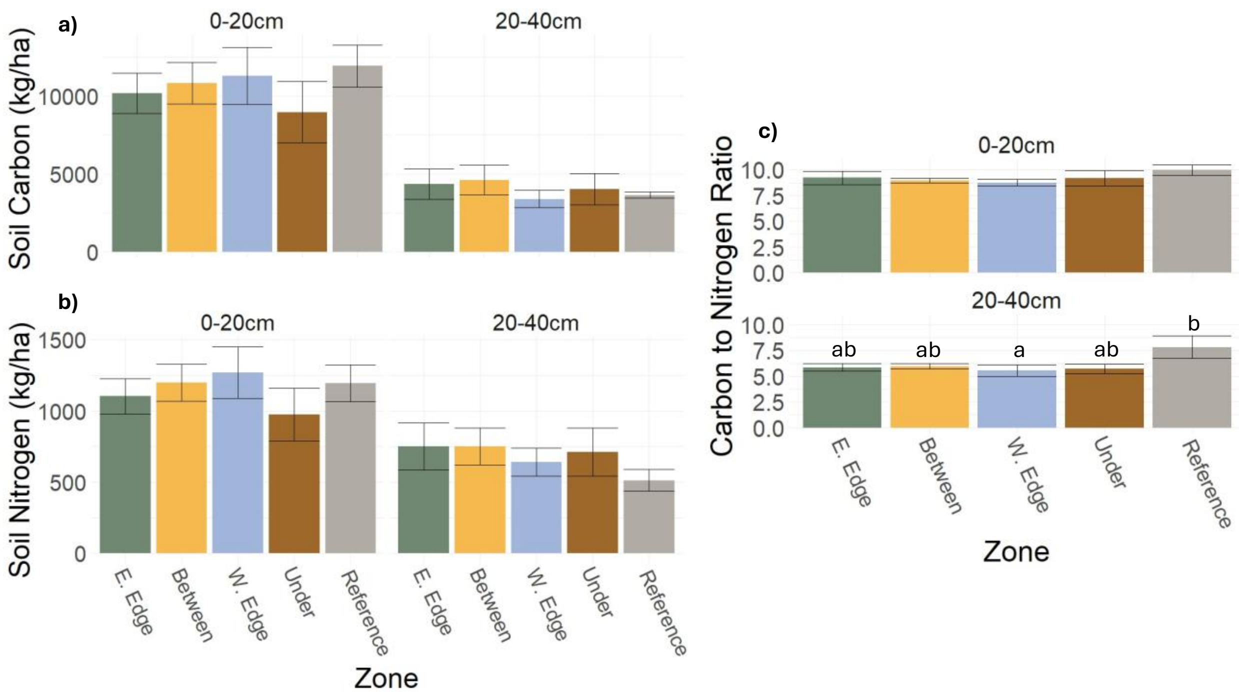


Figure 4. Total soil carbon (a) and nitrogen (b) stocks (kg/ha) by micro-zone. Error bars show +/- the standard error. If there were significant differences between micro-zones, letters above bars show the results of pairwise comparison. Boxes sharing a common letter are not significantly different ($p > 0.05$).

Root carbon stocks followed the same micro-zonal pattern as soil carbon stocks (Figure 5), and while the pattern appears more dramatic, micro-zone still had no significant effect. Most root carbon was concentrated in the 0-20cm samples, with very little root mass in the deeper soil samples, especially in micro-zones U and E.

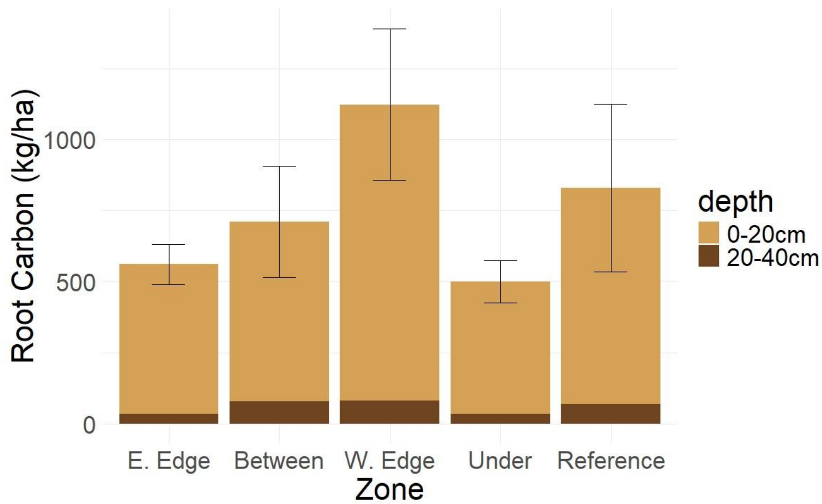


Figure 5. Standing root carbon stocks (kg/ha) across micro-zones. Error bars show +/- the standard error for the total root carbon, summed across both depths.

4. Discussion

Fourteen years after construction, we observed no significant differences in soil physical properties (soil texture and BD) between the array and the reference. Soil texture was significantly sandier than anticipated (based on SSURGO-reported values), and therefore SOC stocks were quite low (<1% C) for perennial grassland in this climate regime, potentially muting the spatial patterning in soil organic matter as a function of the micro-zone differences in temperature and moisture. Sand content was higher in the reference area with lower variance, potentially due to the smaller sampling area.

While not significant, BD was highest between rows of modules, potentially reflecting the higher vehicle and equipment traffic within this micro-zone compared to the micro-zones closer to the PV infrastructure. This difference persisted to 40 cm, highlighting the long-term impacts that land management within PV arrays may have.

Consistent with results from other studies in the region (Bacon et al., 2026, *in prep*) and the broader agrivoltaics and ecovoltaics literature, soil moisture was elevated across all micro-zones within the array compared to the reference conditions. Soil moisture was highest in micro-zone W, potentially reflecting the impacts of the tracking algorithm. Modules at the site tracked the sun east to west over the course of the day, and remained facing west overnight before resetting in the morning, meaning that precipitation that fell overnight favored micro-zone W. The reference site had the lowest variance in soil moisture, potentially attributable to the smaller sampling area or the more consistent conditions. However, it's also important to note that these soil moisture values represent a single point in time, and more continuous measurements would be needed to draw conclusions about patterning specific to this system.

Contrary to our hypothesis, we observed no significant differences in soil carbon or nitrogen stocks across micro-zones within the array or relative to the reference area. This suggests, within the context of this site (climate, soil properties, array dimensions, etc.), that there were no long-term negative impacts of the PV infrastructure on soil carbon or nitrogen stocks. While there were no significant differences across micro-zones, in the surface soils (0-20cm), there was an indication of a consistent patterning within the array (W > B > E > U) that mirrored the patterning observed in root carbon stocks as well. However, soil carbon and nitrogen content were very low in this system. The patterning of soil carbon and nitrogen was likely muted to some degree due to the sandy soils, which are not as conducive to soil carbon accumulation as finer-grained textures (Hassink, 1997; Six et al., 2002).

Mean standing root carbon stocks were highest in micro-zone W (although this difference was not significant), which was also the micro-zone with the highest soil moisture when sampling was conducted. However, as noted, this was a single point-in-time measurement, and additional research is needed to confirm if this is a persistent pattern. If the measured soil moisture is in fact reflective of long-term patterns, the additional moisture in micro-zone W could support greater total productivity in soils with lower water holding capacity, reflected in both the roots and above-ground biomass. However, above-ground biomass data would be necessary to confirm this. Alternatively, the additional panel run-off could lead to exacerbated nutrient leaching, especially given the sandy soils, which could have encouraged a greater investment in belowground biomass (Lehmann & Schroth, 2002).

Within a younger array in the same climate region, the opposite patterning in standing root carbon stocks was observed, with the lowest stocks in micro-zone W (Bacon et al. *in prep*, 2026). This was also the case for standing root mass in a semi-arid system in Colorado (Toy et al., 2025), where standing root mass was highest under PV modules and lowest in micro-zone W, with the root biomass about evenly distributed between surface soils (0-15cm) and deeper soils (15-30cm), hypothesized to facilitate access to more stable deeper soil moisture stores (Toy et al., 2025). These contrasting results emphasize the role of both climate and site-specific factors, like soil texture and tracking algorithm, in shaping root distribution, and highlight the need for further research to elucidate the underlying causes of variability in root patterning.

6. Conclusion

This study found that PV infrastructure had no long-term effects on total soil carbon or nitrogen stocks, compared to a reference area that experienced equivalent management impacts. Across the variables evaluated in this study, there were very few significant differences between any micro-zones within the array or the reference. The only exceptions were soil moisture, which was highest in the micro-zone that likely received the highest precipitation input (Western drip edge), and C:N ratio at 20-40cm, which was significantly lower in micro-zone W compared to the reference. However, this system had very sandy soils with low soil carbon content, so these outcomes may differ in other systems, and the soil texture at our site likely muted soil patterning in response to PV modules.

The influence of these site-specific variables, including soil texture, array geometry, tracking algorithm, and climate, highlights the importance of collecting soil data in a diverse range of systems and reporting these site-specific variables (Bacon et al., 2024). This study provides a valuable data point that, with this soil type and in this climate zone, there is no evidence of long-term, negative impacts of PV infrastructure on soil properties, especially soil carbon and nitrogen stocks.

REFERENCES

Adeh, E. H., Good, S. P., Calaf, M., & Higgins, C. W. (2019). Solar PV Power Potential is Greatest Over Croplands. *Scientific Reports*, *9*(1), Article 1. https://doi.org/10.1038/s41598-019-47803-3

Adeh, E. H., Selker, J. S., & Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLOS ONE*, *13*(11), e0203256. https://doi.org/10.1371/journal.pone.0203256

Andrew, A. C., Antoszewski, K., Goldberg, Z. A., Barter, J., Hain, L., DeSario, A., White, A., Roszell, C., Cole, E., Peterson, S., & Meys, B. (2025). Sheep grazing as sustainable vegetation management for solar energy production in the northeastern USA. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1625483

Andrew, A. C., Higgins, C. W., Smallman, M. A., Graham, M., & Ates, S. (2021). Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System. *Frontiers in Sustainable Food Systems*, *5*. https://www.frontiersin.org/articles/10.3389/fsufs.2021.659175

Andrew, A. C., Higgins, C. W., Smallman, M. A., Prado-Tarango, D. E., Rosati, A., Ghajar, S., Graham, M., & Ates, S. (2024). Herbage and sheep production from simple, diverse, and legume pastures established in an agrivoltaic production system. *Grass and Forage Science*, *79*(2), 294–307. https://doi.org/10.1111/gfs.12653

Armstrong, A., Ostle, N. J., & Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*, *11*(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016

Bacon, T., Monlezun, A. C., de Vries, N., Banuelos, A., Hong, M., & Paustian, K. (2026). *Ecological impacts of solar array construction in a humid subtropical grassland: Natural variation and conservation management outweighed disturbance* [In prep].

Bacon, T., Monlezun, A. C., Hong, M., de Vries, N., & Paustian, K. (2026). *Microclimate, vegetation and soil responses to micro-zonal solar photovoltaic patterning in a humid sub-tropical agrivoltaic grazing system* [In prep].

Bacon, T., Ohlert, T., Toy, C., Siggers, J. A., & Sturchio, M. A. (2024). Network science can improve the sustainable development of solar energy. *Environmental Research: Energy*, *1*(4), 043002. https://doi.org/10.1088/2753-3751/ad99dc

Barron-Gafford, G. A., Minor, R. L., Allen, N. A., Cronin, A. D., Brooks, A. E., & Pavao-Zuckerman, M. A. (2016). The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Scientific Reports*, *6*(1), Article 1. https://doi.org/10.1038/srep35070

Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, *2*(9), Article 9. https://doi.org/10.1038/s41893-019-0364-5

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using **lme4**. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Choi, C. S., Cagle, A. E., Macknick, J., Bloom, D. E., Caplan, J. S., & Ravi, S. (2020). Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure. *Frontiers in Environmental Science*, *8*. https://www.frontiersin.org/articles/10.3389/fenvs.2020.00140

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. *Earth's Future*, *11*(6), e2023EF003542. https://doi.org/10.1029/2023EF003542

Choi, C. S., Macknick, J., McCall, J., Bertel, R., & Ravi, S. (2024). Multi-year analysis of physical interactions between solar PV arrays and underlying soil-plant complex in vegetated utility-scale systems. *Applied Energy*, *365*, 123227. https://doi.org/10.1016/j.apenergy.2024.123227

Elliott, E. T., Heil, J. W., Kelly, E. F., & Monger, H. C. (1999). Soil Structural and Other Physical Properties. In G. P. Robertson, D. C. Coleman, C. S. Bledsoe, & P. Sollins (Eds.), *Standard Soil Methods for Long-Term Ecological Research* (p. 0). Oxford University Press. https://doi.org/10.1093/oso/9780195120837.003.0004

Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil*, *191*(1), 77–87. https://doi.org/10.1023/A:1004213929699

Karban, C. C., Munson, S. M., Kobelt, L. A., & Lovich, J. E. (2025). Short-term ecological effects of solar energy development depend on plant community, soil type and disturbance intensity. *Journal of Applied Ecology*, *62*(4), 945–957. https://doi.org/10.1111/1365-2664.14882

Knapp, A. K., & Sturchio, M. A. (2024). Ecovoltaics in an increasingly water-limited world: An ecological perspective. *One Earth*, *7*(10), 1705–1712. https://doi.org/10.1016/j.oneear.2024.09.003

Krasner, N. Z., Fox, J., Armstrong, A., Ave, K., Carvalho, F., Li, Y., Walston, L. J., Ricketts, M. P., Jordaan, S. M., Abou Najm, M., Hartmann, H. M., Lybrand, R., & Hernandez, R. R. (2025). Impacts of photovoltaic solar energy on soil carbon: A global systematic review and framework. *Renewable and Sustainable Energy Reviews*, *208*, 115032. https://doi.org/10.1016/j.rser.2024.115032

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*(18), 5190–5202. https://doi.org/10.1002/ldr.4101

Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik, E., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K., & Swan, A. (2021). *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final report*. Princeton University. https://www.dropbox.com/s/ptp92f65lgds5n2/Princeton%20NZA%20FINAL%20REPORT%20%2829Oct2021%29.pdf?dl=0

Lehmann, J., & Schroth, G. (2002). Nutrient leaching. In G. Schroth & F. L. Sinclair (Eds.), *Trees, crops and soil fertility: Concepts and research methods* (1st ed., pp. 151–166). CABI Publishing. https://doi.org/10.1079/9780851995939.0151

Lenth, R. V., Banfai, B., Bolker, B., Buerkner, P., Giné-Vázquez, I., Hervé, M., Jung, M., Love, J., Miguez, F., Piaskowski, J., Riebl, H., & Singmann, H. (2025). *emmeans: Estimated*

Marginal Means, aka Least-Squares Means (Version 1.11.2-8) [Computer software]. https://cran.r-project.org/web/packages/emmeans/index.html
Loan, M., & Picon-Cochard, C. (2022). *One Year of Grassland Vegetation Dynamics in two Sheep-Grazed Agrivoltaic Systems*.
Maguire, K., Tanner, S., & Winikoff, J. B. (2024, September 12). *Agricultural Land Near Solar and Wind Projects Usually Remained in Agriculture After Development*. USDA Economic Research Service. https://www.ers.usda.gov/amber-waves/2024/september/agricultural-land-near-solar-and-wind-projects-usually-remained-in-agriculture-after-development
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*, e00500. https://doi.org/10.1016/j.geodrs.2022.e00500
NOAA NCEI U.S. Climate Normals Quick Access. (n.d.). Retrieved September 25, 2025, from https://www.ncei.noaa.gov/access/us-climate-normals/#dataset=normals-annualseasonal&timeframe=15&location=GA&station=USW00013869
R Core Team. (2025). *R: A language and environment for statistical computing* [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org/
Rahmaniah, F., & Tay, S. E. R. (2023). Environmental benefits of co-located photovoltaic and greenery systems: A review on the operational performance and assessment framework across climate zones. *Sustainable Energy Technologies and Assessments*, *58*, 103301. https://doi.org/10.1016/j.seta.2023.103301
Randle-Boggis, R. J., White, P. C. L., Cruz, J., Parker, G., Montag, H., Scurlock, J. M. O., & Armstrong, A. (2020). Realising co-benefits for natural capital and ecosystem services from solar parks: A co-developed, evidence-based approach. *Renewable and Sustainable Energy Reviews*, *125*, 109775. https://doi.org/10.1016/j.rser.2020.109775
Scholten, L., de Goede, R. G. M., Edlinger, A., Van Aken, B. B., & De Deyn, G. B. (2025). Sharing the light, impact of solar parks on plant productivity, soil microbes and soil organic matter. *PLANTS, PEOPLE, PLANET*, *n/a*(n/a). https://doi.org/10.1002/ppp3.70011
Siggers, J. A., Sturchio, M. A., Gordon, L., Mead, S., Smith, M. D., & Knapp, A. K. (2025). Environmental Heterogeneity Imposed by Photovoltaic Array Alters Grassland Soil Microbial Communities. *Global Change Biology*, *31*(7), e70376. https://doi.org/10.1111/gcb.70376
Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, *241*(2), 155–176. https://doi.org/10.1023/A:1016125726789
Smith, P. (2004). How long before a change in soil organic carbon can be detected? *Global Change Biology*, *10*(11), 1878–1883. https://doi.org/10.1111/j.1365-2486.2004.00854.x
Solar Futures Study. (2021). U.S. Department of Energy. https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf
Sturchio, M. A., Macknick, J. E., Barron-Gafford, G. A., Chen, A., Alderfer, C., Condon, K., Hajek, O. L., Miller, B., Pauletto, B., Siggers, J. A., Slette, I. J., & Knapp, A. K. (2022). Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. *Ecosphere*, *13*(12), e4334. https://doi.org/10.1002/ecs2.4334

Toy, C., Heider-Kuhn, N., & Schipanski, M. (2025). Impact of solar energy infrastructure and ecovoltaic management on semi-arid grassland carbon cycling. *Environmental Research Communications*, *7*(10), 105005. https://doi.org/10.1088/2515-7620/ae0b1d
van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023
Weselek, A., Bauerle, A., Hartung, J., Zikeli, S., Lewandowski, I., & Högy, P. (2021). Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agronomy for Sustainable Development*, *41*(5), 59. https://doi.org/10.1007/s13593-021-00714-y

CHAPTER 6: CONCLUSION

Solar PV is one of the most impactful tools for reducing greenhouse gas emissions and mitigating the impacts of climate change (IPCC, 2023). However, the land required for solar PV is significantly higher than for fossil-based sources (van Zalk & Behrens, 2018). This presents both a challenge and an opportunity for the sustainable deployment of solar PV. Multi-use solar PV offers an opportunity to leverage ecological synergies, maintain agricultural lands, and increase land-use efficiency.

The majority of multi-use solar PV projects in the United States are grassland-based systems with either sheep grazing or pollinator habitat (*Agrivoltaics Map*, n.d.). These systems are well-suited for large-scale solar deployment. Empirical data characterizing ecosystem impacts in these systems across a range of PV geometries, climate regions, and management frameworks are essential for guiding sustainable deployment, yet are still quite limited (Bacon et al., 2025). While studies have started to characterize this in more arid and semi-arid systems, research is particularly limited in humid subtropical regions. This dissertation takes a first step towards addressing this gap. Through field work at operational PV arrays in the humid subtropical southeastern United States, I evaluated construction impacts, microclimate alterations, management interactions, and long-term soil impacts.

PV arrays impact ecosystems in myriad ways. The first, and often most dramatic, impacts occur during array construction. Conventional, high-impact construction practices, including vegetation removal, topsoil removal, and grading, can negatively impact the ecological function of the site for years to come (Choi et al., 2020), hampering the potential for multi-use solar PV. Lower-impact construction methods can mitigate these impacts to some extent. Leveraging a before/after control/impact experimental design as described in Chapter 3, we observed a counterintuitive effect on soil properties following array construction in central Tennessee. Three months after construction was completed, we observed strong vegetation recovery, with minimal bare ground or rock. Between pre- and post-construction sampling, soil penetration resistance decreased while hydraulic conductivity increased both inside and outside of the array; in other words, between sampling points, the soil structure at the site improved both where the array was constructed and in the control. Our analysis suggested that environmental factors, land-use history, and longer-term trends at the site had a greater impact on the measured ecosystem indicators than the construction itself. This was likely amplified by the use of low-impact construction practices and the vigorous vegetation cover that was established before construction (Stid et al., 2025).

After construction is completed and a site is operational, the influence of the PV modules on microclimate conditions drives subsequent ecosystem impacts. Chapter 4 characterizes microclimate patterning within a three-year-old site in Georgia. Two years of continuous microclimate data collection highlighted that even in a less water-limited region, land under PV modules still maintained higher soil moisture compared to a non-PV pasture. This difference was most dramatic during drier periods. This study also emphasized the influence of the array tracking algorithm and local climate on microclimate patterning. We observed the highest precipitation inputs and soil moisture in the Eastern drip edge, likely due to the concentration of precipitation events overnight and in the early morning, when panels are facing East – the opposite of what has been observed in semi-arid grasslands in Colorado (Sturchio et al., 2022).

While solar radiation and precipitation inputs varied dramatically across micro-zones, and we observed distinct patterning in soil moisture and soil temperature, these microclimate differences did not translate into significant differences in ANPP, soil carbon stocks, or soil nitrogen stocks. The pasture system showed resilience with the addition of PV infrastructure and associated management practices and was able to maintain high productivity. The retention of higher soil moisture may provide additional benefits during periods of drought, as we've seen in semi-arid systems (Sturchio & Knapp, 2025).

Notably, soil samples from the Georgia site were taken just three years after array construction. It can take upward of five years for soil carbon stocks to show a measurable difference in response to a change in management (Smith, 2004). This motivated the final field study (Chapter 5) on soil properties in a fourteen-year-old PV array, in Western Tennessee, to better understand long-term soil impacts. At this field site, we also observed no impacts on soil carbon or nitrogen stocks related to the presence of the modules. The sandy soils at the site likely muted some of the micro-zone patterning in soil carbon and nitrogen stocks that we might have expected.

Together, these studies suggest several key takeaways. (1) Across all three field sites, we found no evidence of negative impacts on vegetation or soils from the addition of solar PV infrastructure to the region. This supports the resilience of ecosystems in this climate region to solar PV infrastructure and the strong potential for multi-use solar PV. Additionally, (2) this research emphasizes the role of local climate in the ecosystem impacts. However, there do seem to be some common patterns, especially related to elevated soil moisture within the array. (3) In addition to the climate region, site-specific variables, including array geometry, tracking algorithm, and soil texture, all influence the ecosystem response. As research on multi-use solar PV expands, collecting data on these site-specific controls is essential to drawing comparisons across sites and teasing out broader trends and impacts (Bacon et al., 2024).

This research also highlighted the challenges of conducting research within existing, operational PV arrays and collaborating with working farms. The inherent nature of these systems limits the potential for truly randomized experiments. However, conducting research in systems that reflect real-world industry and agricultural practice is essential to understanding the true impacts of solar PV and multi-use solar, and supports larger-scale experiments.

Taking a step back, nearly all the questions in this dissertation – from climate change to soil carbon - come back to sunlight. The Earth receives enough energy from the sun in one hour to meet global energy demand for a year (Hammarström, 2012). Multi-use solar PV systems integrate two diverse pathways for capturing this energy. Solar PV modules use semiconductors to convert the energy from photons to a flow of electrons. Plants capture energy from photons, utilizing photosynthesis to convert CO_2 into carbohydrates. Two different pathways for converting energy from the sun into a stored, usable energy form. One provides an opportunity to avoid carbon emissions; the other provides a tool for drawing down carbon from the atmosphere. Multi-use solar provides a framework for co-locating and integrating these two pathways to improve the sustainability of solar PV.

REFERENCES

Agrivoltaics Map. (n.d.). InSPIRE, National Renewable Energy Lab. Retrieved November 30, 2023, from https://openei.org/wiki/InSPIRE/Agrivoltaics_Map

Bacon, T., Monlezun, A. C., Hong, M., Macknick, J., de Vries, N., Edwards-Callaway, L., & Paustian, K. (2025). Agrivoltaic Grazing Systems for a Sustainable Future: A Multi-Disciplinary Review & Gap Analysis. *Earth's Future*, *13*(8), e2024EF005429. https://doi.org/10.1029/2024EF005429

Bacon, T., Ohlert, T., Toy, C., Siggers, J. A., & Sturchio, M. A. (2024). Network science can improve the sustainable development of solar energy. *Environmental Research: Energy*, *1*(4), 043002. https://doi.org/10.1088/2753-3751/ad99dc

Choi, C. S., Cagle, A. E., Macknick, J., Bloom, D. E., Caplan, J. S., & Ravi, S. (2020). Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure. *Frontiers in Environmental Science*, *8*. https://www.frontiersin.org/articles/10.3389/fenvs.2020.00140

Hammarström, L. (2012). Overview: Capturing the Sun for Energy Production. *Ambio*, *41*(Suppl 2), 103–107. https://doi.org/10.1007/s13280-012-0263-8

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.

Smith, P. (2004). How long before a change in soil organic carbon can be detected? *Global Change Biology*, *10*(11), 1878–1883. https://doi.org/10.1111/j.1365-2486.2004.00854.x

Stid, J. T., Zipper, S., Szydlowski, H. V., Bingaman, J., Anctil, A., & Kendall, A. D. (2025). *Current Knowledge on Low-Impact Ground-Mounted Solar Siting, Construction, and Installation Practices* [Kansas Geological Survey Open-File Report 2025-20]. Kansas Geological Survey. https://www.kgs.ku.edu/Publications/OFR/2025/OFR2025-20.pdf

Sturchio, M. A., & Knapp, A. K. (2025). Evidence of photovoltaic aridity mitigation in semi-arid grasslands. *Environmental Research Letters*, *20*(6), 064047. https://doi.org/10.1088/1748-9326/add94d

Sturchio, M. A., Macknick, J. E., Barron-Gafford, G. A., Chen, A., Alderfer, C., Condon, K., Hajek, O. L., Miller, B., Pauletto, B., Siggers, J. A., Slette, I. J., & Knapp, A. K. (2022). Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. *Ecosphere*, *13*(12), e4334. https://doi.org/10.1002/ecs2.4334

van Zalk, J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

APPENDIX 1: SUPPLEMENTAL MATERIALS FOR CHAPTER 3

Table S1. List of plant species identified at the site (not exhaustive)

Common name	Scientific name	Code	Functional group	Native/exotic
Bermuda grass	*Cynodon dactylon*	CYDA	Warm season	Exotic
Broomsedge bluestem	*Andropogon virginicus*	ANVI2	Warm season	Native
Candy grass	*Eragrostis cilianensis*	ERCI	Warm season	Exotic
Carolina horsenettle	*Solanum carolinense*	SOCA3	Forb	Native
Common vetch	*Vicia sativa*	VISA	Legume	Exotic
Dallis grass	*Paspalum dilatatum*	PADI3	Warm season	Exotic
Globe flatsedge	*Cyperus echinatus*	CYEC2	Sedge	Native
Groundcherry	*Physalis longifolia*	PHLO4	Forb	Native
Hairy aster	*Symphyotrichum pilosum*	SYPI2	Forb	Native
Honey locust	*Gleditsia triacanthos*	GLTR	Shrub	Native
Johnson grass	*Sorghum halepense*	SOHA	Warm season	Exotic
Kentucky bluegrass	*Poa pratensis*	POPR	Cool season	Native/Exotic
Nimbleweed/dropseed	*Muhlenbergia schreberi*	MUSC	Cool season	Native
Nodding thistle	*Carduus nutans*	CANU4	Forb	Exotic
Queen Anne's lace	*Daucus carota*	DACA6	Forb	Exotic
Red fescue	*Festuca rubra*	FERU2	Cool season	Native/exotic
Redtop	*Tridens flavus*	TRFL3	Warm season	Native
Saw greenbriar	*Smilax bona-nox*	SMBO2	Forb	Native
Speargrass	*Heteropogon contortus*	HECO10	Warm season	Native
Spiny amaranth	*Amaranthus spinosus*	AMSP	Forb	Native
Spinyfruit buttercup	*Ranunculus muricatus*	RAMU2	Forb	Exotic
Virginia pepperweed	*Lepidium virginicum*	LEVI3	Forb	Native
Virginia threeseed mercury	*Acalypha virginica*	ACVI	Forb	Native
White clover	*Trifolium repens*	TRRE3	Legume	Exotic
Wintercress	*Barbarea vulgaris*	BAVU	Forb	Exotic
Witchgrass	*Panicum capillare*	PACA6	Cool season	Native

Table S2. Seed mix composition

Kind & Variety	Composition
Bermuda common hulled	11.04%
Serica lespedeza	23.52%
Weeping lovegrass	3.92%
Rye grain	10.78%
Kentucky 31 Raw	34.86%
White dutch clover	1.93%

Table S3. Composition and application rate for pre-construction soil amendments

Amendment	Application rate
Lime	2.2 Mg/ha
Nitrogen	67.2 kg/ha
Phosphorous	134.4 kg/ha
Potassium	89.6 kg/ha
Sulfur	22.4 kg/ha
Boron	1.12 kg/ha
Micronutrient Mix *Boron (1.25%)* *Calcium (5.00%)* *Copper (1.25%)* *Iron (3.50%)* *Manganese (5.00%)* *Sulfur (10.00%)* *Zinc (5.00%)*	20.2 kg/ha

Eq. S1 Whalley et al equations (Whalley et al., 2007)

$$\log_{10}(Q) = 0.35 * \log_{10}(\sigma_w) + 0.93\rho + 1.2623 \text{ where:}$$

Q = penetrometer resistance (kPa)

ρ = bulk density

$$\sigma_w = S * \Psi = \frac{\theta-\theta_r}{\theta_s-\theta_r} * \Psi \text{ (effective stress)}$$

$$\Psi = \frac{1}{\alpha} * \left[\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{-1}{m}} - 1\right]^{\frac{1}{n}} \text{ (matric potential) is estimated from modeled VWC (}\theta\text{))}$$

Where α, n and m are Van Genuchten parameters.

Table S4. Remote Sensing Indicators

Indicator	Description	Source	Spatial Resolution	Equation	GEE Image Collection ID
Net Primary Productivity (NPP)		RAP (Rangeland Analysis Platform)	30 m		projects/rap-data-365417/assets/npp-partitioned-v3
Bare Soil Index (BSI)	Exposed mineral soil	Landsat 8 OLI	30 m	$\frac{(SWIR + Red) - (NIR + Blue)}{(SWIR + Red) + (NIR + Blue)}$	LANDSAT/LC08/C02/T1_L2
Normalized Difference Vegetation Index (NDVI)	Presence & greenness of vegetation	Landsat 8 OLI	30 m	$\frac{NIR - Red}{NIR + Red}$	LANDSAT/LC08/C02/T1_L2

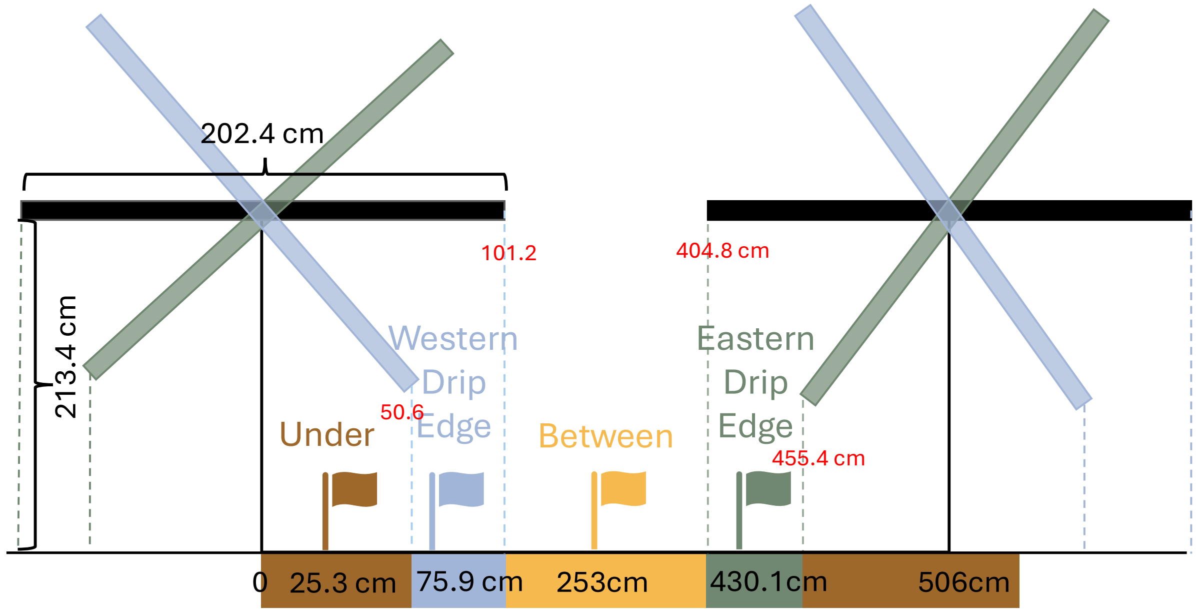


Figure S1. Schematic of micro-zones relative to PV modules. PV modules track the sun from East to West over the course of the day, creating dynamic microclimate zones. We use a four-zone schematic to study the heterogeneity within PV arrays. The under micro-zone (U) is defined as the area beneath the panels that is always directly covered by a module. Conversely the between micro-zone (B) is never directly covered by a module. The eastern (E) and western (W) drip edges are covered for a portion of the day, and are bounded by the module positions when stowed horizontal and when fully tilted east or west. Additional details on this use of micro-zones and the unique microclimates experienced across each zone available in Bacon et al., 2026 (in prep).

Figure S2. Select historic satellite imagery from field site. Imagery sources: Google Earth & National Agricultural Imagery Program (USDA)

APPENDIX 2: SUPPLEMENTAL MATERIALS FOR CHAPTER 4

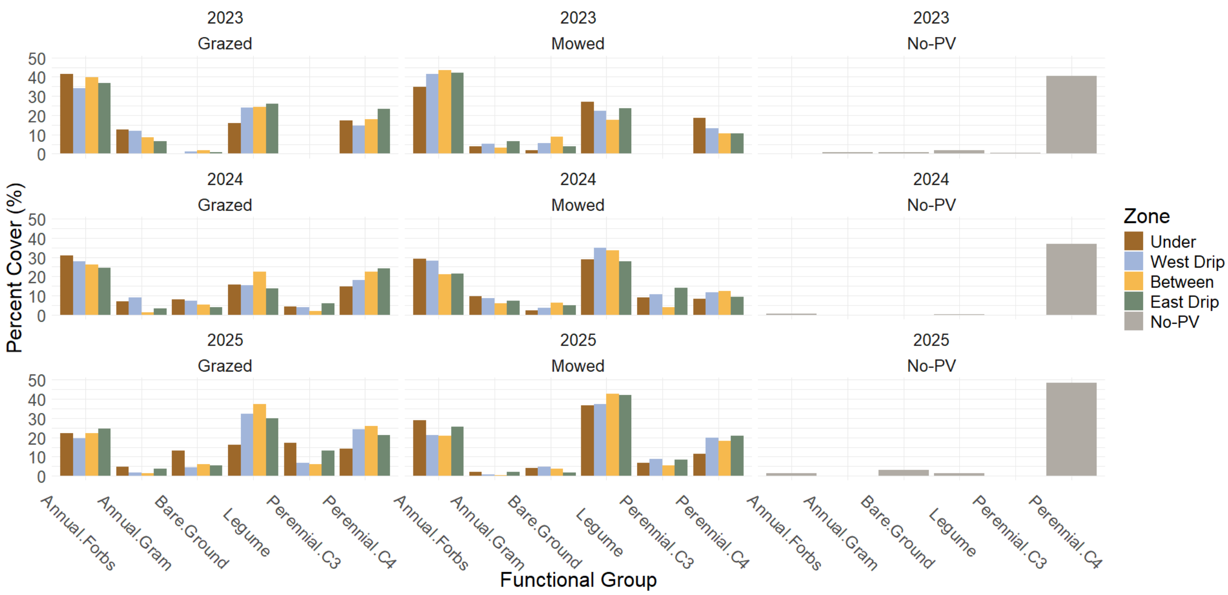


Figure S1. Plant community composition by functional group, measured via the Daubenmire method once each April (2023-2025) in every plot and micro-zone. Bars show the mean of all plots by treatment, year and micro-zone.

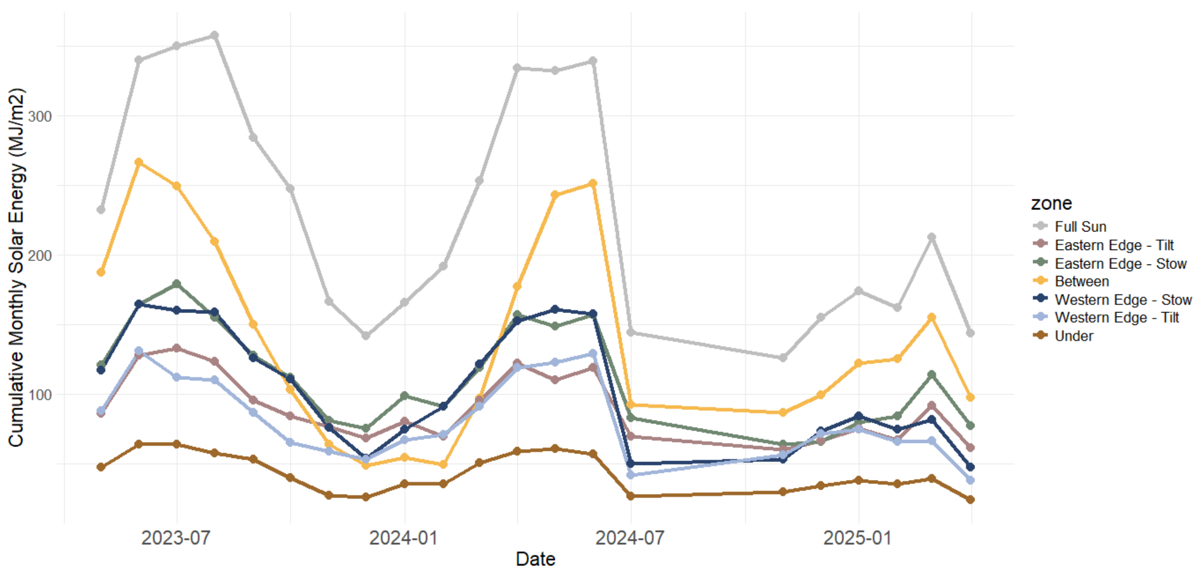


Figure S2. Cumulative monthly solar energy by micro-zone, compared to full sun conditions (grey). Data is not available for August, September, and October 2024 due to equipment malfunctions.

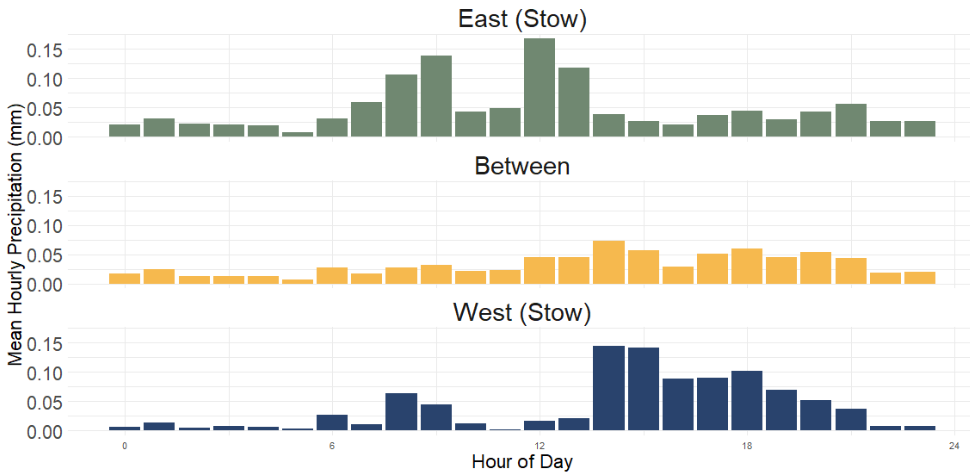


Figure S3. Average hourly precipitation by micro-zone across all months, April 2023 to April 2024.

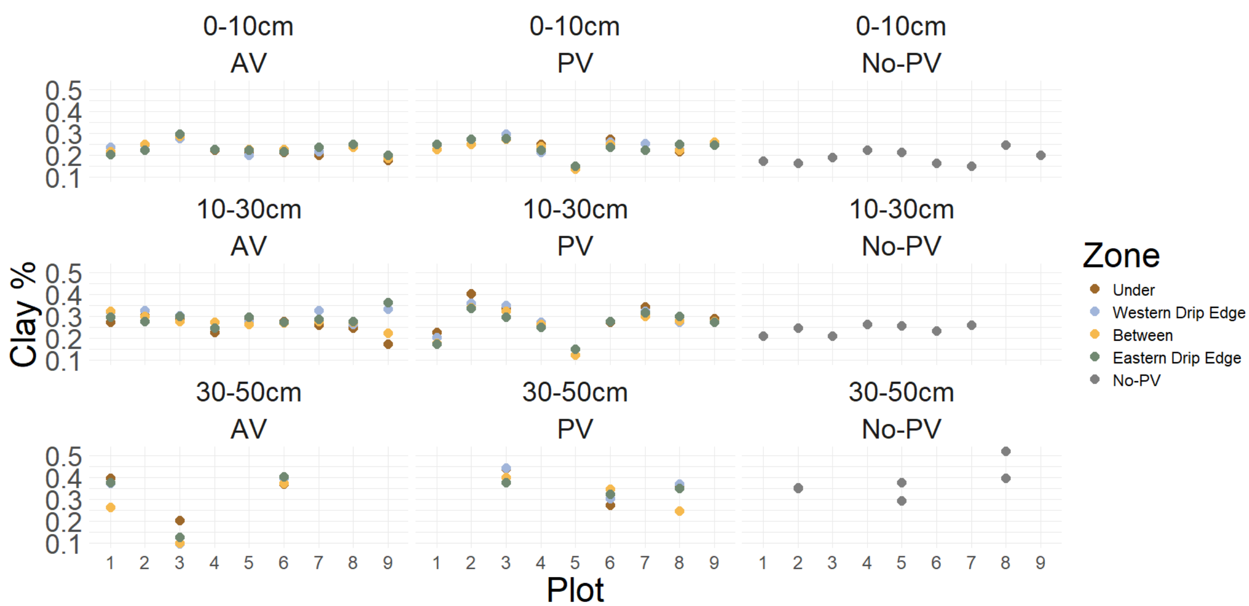


Figure S4. Soil texture (% clay) of baseline samples (April 2023 and April 2024) by treatment, plot, and micro-zone.

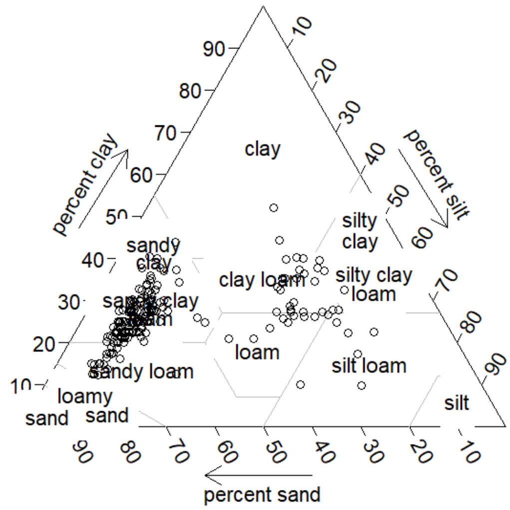


Figure S5. Soil textural triangle for baseline soil samples (April 2023 and April 2024) across all treatments, depths, and micro-zones.

APPENDIX 3: SUPPLEMENTAL MATERIALS FOR CHAPTER 5

Table S1. Research involving soil sampling & lab analysis of soil carbon within solar PV arrays

Paper	Study Focus	Site Location	Site Age	Geometry	Sample Depth	Key Findings
(Armstrong et al., 2016)	Impacts of solar array on microclimate and ecosystem carbon cycling	Westmill Solar Park, UK	3 years	Fixed Tilt	10 cm	Soil properties did not vary between treatments
(Choi et al., 2020)	Effects of revegetation on soil properties in PV arrays	Jefferson County, CO	8 years	Single-Axis Tracking	5 cm	C & N remained lower in PV soil than in reference soil, more coarse particles, however top-soil was removed during construction.
(Choi et al., 2023)	Environmental benefits of maintaining native vegetation within PV arrays	Chisago City, MN	N/A (est. ~ 2-3 years)	Single-Axis Tracking	5 cm	Vegetated solar areas had higher soil C compared to bare soil areas; no significant difference in TC or TN between Veg PV and Control
(Lambert et al., 2021)	Impacts of solar array on soil quality, microclimate, CO2 fluxes, and vegetation	Southern France (3 sites)	5, 2, and 1 year	Fixed-Tilt	10 cm	Soil aggregate stability reduced by construction. No significant differences between abandoned vineyards (preconstruction land cover) and solar parks.
(Moscatelli et al., 2022)	Impacts of PV modules on soil physical & biological properties	Montalto di Castro province, central Italy	7 years	Fixed-Tilt	20 cm	Total organic C and TN were increased significantly, only in the GAP (decreased under)
(Andrew et al., 2025)	Soil organic carbon in agrivoltaic grazing systems	31 sites (28 grazed, 3 non-grazed), northeastern U.S.	Construction 2015-2020, sampling 2022-2024	29 fixed-tilt, 2 single-axis tracking	0-15, 15-30 cm	Soil organic C was higher at grazed sites
(Siggers et al., 2025)	Impacts of environmental heterogeneity on soil microbial communities	Longmont, CO	4 years	Single-axis tracking	15 cm	Higher microbial biomass under panels; OM higher on E edge relative to between rows

	within solar PV arrays					
(Scholten et al., 2025)	Effects of solar PV on plant productivity, soil microbes, and SOM	17 solar parks in the Netherlands	1 to 4 years	Mostly fixed, 3 single-axis tracking	20 cm	No differences in SOM or carbon stocks gap vs below (no control)
(Lambert et al., 2024)	Comparison of restoration techniques at solar arrays	Southeastern France	N/A	Fixed-Tilt	7 cm	Solar panels negatively affected most of the measured variables related to soil biodiversity and functioning.
(Toy et al., 2025)	Impact of PV modules on semi-arid grassland C cycling	Longmont, CO	3 years	Single-axis tracking		No difference in stocks from baseline after 3 years; U had greatest SOC

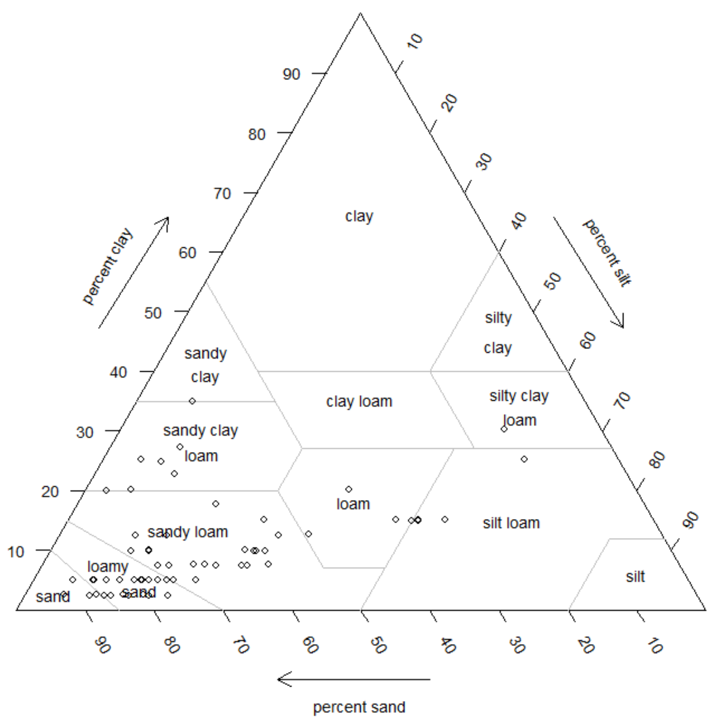


Figure S1. Soil textural classifications for soil samples collected at the field site. Most samples skew heavily towards the bottom left-hand corner of the texture triangle, with high sand content

Table S2. Results from linear-mixed effect models for measured soil properties. Significance column is based on the following thresholds: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; . $p < 0.1$.

Response Variable	**Predictor Variable**	**F**	**df**	***p***	**sig.**
Sand Content (%)	Zone	2.58	4	0.053	.
	Depth	2.89	1	0.097	.
	Zone x Depth	0.38	4	0.824	
Bulk Density (g/cm^3)	Zone	2.32	4	0.076	.
	Depth	66.51	1	< 0.001	***
	Zone x Depth	0.80	4	0.532	
VWC (%)	Zone	4.44	4	0.005	**
	Depth	42.24	1	< 0.001	***
	Zone x Depth	0.60	4	0.662	
Soil Carbon Stocks (kg/ha)	Zone	0.72	3	0.551	
	Depth	60.14	1	< 0.001	***
	Sand %	2.73	1	0.109	
	Zone x Depth	1.19	3	0.332	
Soil Nitrogen Stocks (kg/ha)	Zone	0.59	4	0.672	
	Depth	68.93	1	< 0.001	***
	Zone x Depth	2.10	4	0.096	.
C:N	Zone	2.64	4	0.050	*
	Depth	78.29	1	< 0.001	***
	Zone x Depth	0.47	4	0.760	
Root Carbon Stocks (kg/ha) – log transformed	Zone	2.01	4	0.472	
	Depth	64.30	1	< 0.001	***
	Zone x Depth	1.44	4	0.454	