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Solar energy transitions on agricultural land: soil health impacts from site construction and on-site sheep grazing

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Introduction: Utility-scale solar energy infrastructure in the U.S. has rapidly expanded through the first decades of the 21st Century. In many regions, much of this development has taken place on agricultural land, in some cases billed as a means of preserving agricultural land for the future by removing the panels after retirement and returning the land to food production. While this may indeed be true, relatively little is known of the ecological effects of utility-scale solar development and land use, particularly those that pertain to future or concurrent agricultural uses.

Methods: We present the results of a two-year soil health assessment at three recent utility-scale solar facilities in Southern Pennsylvania. One of these sites uses sheep grazing to manage on-site vegetation, allowing us to also assess potential differences between agrivoltaics vs conventional site management during the early years of operation. We conducted a suite of soil health assessments (both in situ and in a lab) including labile carbon, respiration, wet aggregate stability, surface compaction, and earthworm abundance along transects at each site annually for two years. Identical assessments were also conducted along transects on adjacent land that remains in agriculture at each site for comparison.

Results: We found that site construction has a clear, if modest, impact on soil health, particularly the labile carbon pool and water stabile soil aggregates (both decline), and earthworms, which are more abundant with solar facilities. Soil physical properties show signs of recovery in year 2, while assessed carbon fractions remain depressed throughout the study, with no significant differences found between agrivoltaics and conventional site management as assessed in our study.

Discussion: Our results do not indicate that utility-scale solar is significantly detrimental to soil health, yet it seems clear that site construction does degrade some aspects of soil health. Our results also expand our understanding of the ecological dimensions of solar grazing. While we did not find any increased degradation resulting from sheep grazing, neither did we detect any improvements to soil health as have been documented by other studies in temperate ecosystems. Our study indicates that site construction and management practices should continue to be refined to ensure future and concurrent agricultural land use is not only possible, but profitable.

KEYWORDS

agricultural land use and land use changes, agrivoltaics, soil health, solar development, utility-scale solar energy

Introduction

Utility-scale solar power in the U.S. grew rapidly during the first quarter of the 21st Century, increasing from an average of approximately 45,000 megawatt hours each month in 2001 to approximately 18.2 million megawatt hours/month in 2024 (EIA, 2024). Concurrently, agriculture gained prominence as a nexus of sustainable development for its (often unrealized) potential to simultaneously foster biodiversity and other ecosystem services, support rural development, feed a growing population, and generate renewable energy (Adeh et al., 2019; Rey Benayas and Bullock, 2012; Hernandez et al., 2019; Teague et al., 2016). This raises many questions regarding best practices for solar energy development on agricultural sites—a practice that is quite common in renewable energy development (Adeh et al., 2019; Hedberg et al., 2024). Research on solar development in agricultural settings has expanded significantly across the natural and social sciences yet there remain many unknowns as the renewable energy transition progresses. Among these myriad concerns are the ability of converted solar facilities to provide similar ecosystem services, and the implications of solar conversion for future agricultural land uses after the solar facilities are decommissioned.

In recent decades growing consensus has emerged that the capacity of soil to function as an ecosystem (often referred to as *soil health*) is a critical component of broader ecosystem health, diversity, and the provision of ecosystem services (Davis et al., 2023; Doran, 2002; Kundu and Biswas, 2025; Lal, 2011; Wall, 2004). The concept of soil health encompasses the physical structure, chemical composition, and the biological communities that comprise the soil ecosystem. Researchers have demonstrated the utility of soil health in reducing soil erosion (Du et al., 2022), improving nutrient cycling and retention (Drinkwater and Snapp, 2007), sequestering atmospheric carbon (Eddy and Yang, 2022; Lal, 2016), maintaining and increasing above-ground biodiversity (Bardgett and Van Der Putten, 2014), and increasing food production (Moebius-Clune et al., 2016). Given that the rapid decarbonization of the energy sector is necessary to avoid or limit the catastrophic effects of climate change (Shukla et al., 2019), agricultural land with low tree cover and moderate topography offers numerous advantages for the swift expansion of solar infrastructure (Adeh et al., 2019). While there is an emerging body of research on the ecological impacts of solar infrastructure and potential synergies with agriculture (agrivoltaics) (e.g., Adeh et al., 2018; Andrew et al., 2021; Choi et al., 2020; Lambert et al., 2021), much more study is needed. This ecological knowledge is particularly important to the refinement of best management practices for solar site construction and maintenance and to better inform future land uses on existing agricultural land when current solar facilities phase out after 25–30 years (Curtis et al., 2021).

Here we present the results of a two-year study using soil health as a framework to assess possible ecological impacts that result from the conversion of agricultural land to utility-scale solar infrastructure and the potential effects of on-site management strategies. We focused on soil health over other environmental indicators primarily due to its centrality to agriculture. Given that agricultural land is such an attractive site for solar energy development in the U.S. (Adeh et al., 2019; Goldberg, 2023; Hedberg et al., 2024), and that solar land use can allow for the co-location of agricultural production (Walston et al., 2022) or a return to food production following decommissioning (Hedberg et al., 2024; Spangler et al., 2024), we find the focus on soil health to be particularly important to a sustainable energy transition.

We assessed a suite of established soil health indicators at three sites recently converted from agriculture to utility-scale solar installations in Southern Pennsylvania, United States. The names and specific locations of study sites are anonymized at the request of site developers and

operators. Assessments include a combination of field-based and laboratory methods to measure soil structure, carbon dynamics, and biological activity. All these assessments, discussed in detail in the methods section below, are highly sensitive to management and common practice in soil health assessments. These methods are thus well suited to detecting changes in soil that result from site construction and the initial years of operation. Our comparative case study also provides early indication of differences in soil health that may result from the co-location of agriculture (broadly defined as agrivoltaics), with one site managing vegetation with sheep grazing and the remaining two using conventional mowing. Furthermore, since our study incorporates repeated measurements across a two-year period, it offers some initial insight into potential trends in soil health at similar utility-scale solar facilities to help direct future study. While the length of our study is quite short, it represents an important first step in establishing the knowledgebase necessary to support sustainable solar energy development.

In the remaining sections, we first situate our study in the broader scholarship on solar energy development, followed by a detailed discussion of our study sites and methods. We then present the results for both years of analysis and discuss implications for solar development and future research.

A clarification of terms

Throughout this paper we use the term *utility-scale solar* to describe our study sites. This term is widely used in research literature and across other forms of media, yet it is not consistently defined, which can make comparison across case studies difficult. We follow the U.S. Energy Information Agency (EIA) definition of utility-scale solar as any solar facility with at least 1 MW of generation capacity (EIA, 2023). We thus do not differentiate based on grid connection or whether the facility provides wholesale power or directly supplies consumers through a subscriber model. We are also only referring to solar photovoltaic facilities, which are far more common (Jacobson and Delucchi, 2011), and not concentrated/thermal solar power facilities. All three of our research sites meet these characteristics, and thus our findings are limited to these types of facilities.

Similarly, the term *agrivoltaics* is frequently used by a diverse array of stakeholders to refer to the general practice of co-locating some form of agricultural production and solar photovoltaic energy production. In practice, agrivoltaics take myriad forms, ranging from pollinator habitat to grazing livestock or crop cultivation between or below photovoltaic panel arrays (Walston et al., 2022), and the academic literature tends to use the term broadly. In some contexts (e.g., Japan, Germany, France, Italy), solar facilities designed for agrivoltaics are subject to statutory requirements that mandate things ranging from the height and spacing of panel banks to yield requirements and the division of land use between solar generation and agricultural production within the site (Williams et al., 2025). At the time of writing, there is as-yet no international standard for agrivoltaic design, and neither the U.S. nor the State of Pennsylvania where our study is based have agrivoltaic regulations. We consider agrivoltaics to be a set of practices that manage the co-location of agriculture with solar energy generation. In keeping with the academic literature, we use the term in this general sense.

Literature review

Research on utility-scale solar development is a diverse and rapidly expanding area of scholarship. Here we briefly review three areas of solar energy research to better situate our study within this

emerging field: research on the geography of utility-scale solar development, research on the environmental impacts of solar development, and research on solar grazing.

The geography of utility-scale solar development

Numerous researchers have used GIS and statistical models to analyze the rapid growth of utility-scale solar, both in the U.S. and globally, and better understand the geography of solar development in the coming decades. This research tends to focus on solar-induced land use and land cover change, and the intersection of solar energy development with biodiversity conservation. In particular, numerous studies based in the U.S. have found that solar development tends favor agricultural land in relatively rural areas with proximity to transmission infrastructure (Evans et al., 2023; Hernandez et al., 2015; O'Shaughnessy et al., 2023). Among the many factors that contribute to this trend are the relatively flat topography and lack of forest or built infrastructure that is common at agricultural sites. This research also suggests that there are regional differences for solar induced land use change, with Evans et al. (2023) finding that more than 54% of utility-scale solar development in the Chesapeake Watershed in the Eastern U.S. occurring on agricultural land and Hernandez et al. (2015) finding that 59% of solar development in California (in the Western U.S.) occurred on shrub, scrub, and barren land, with only 20% displacing agriculture.

Scholars have also used similar methods to consider how solar development affects biodiversity conservation, especially territorial approaches like protected areas and biosphere reserves. As with the impact to agricultural land, these studies suggest significant geographic variation. In the Eastern U.S., for instance, Evans et al. (2023) found that protected and natural areas are largely avoided by solar development, indicating minimal conflict with biodiversity conservation. Conversely, Levin et al. (2023) found that even though solar energy development tends to avoid protected areas in the U.S., it has a significant negative impact on migration corridors that connect protected areas or provide movement pathways for climate change-induced migration. Furthermore, Dunnett et al. (2022) found more overlap between solar development on protected area conservation in the southern hemisphere, though they argue that this overlap is not a necessity and could be sufficiently addressed with public policy.

Our research builds on this scholarship by assessing ecological impacts of solar development on agricultural land. The objective of our study is to inform solar siting in the coming decades to ensure that land use change minimizes potential harm to agricultural land or biodiversity conservation.

Environmental impacts of utility-scale solar

While comprehensive reviews of potential environmental impacts from solar energy suggest that there may be numerous areas of concern (Gasparatos et al., 2017; Hernandez et al., 2014; Treasure et al., 2025), the novelty of utility-scale solar means that relatively few field-based studies have quantified specific environmental effects from solar energy development and land use, and more research is needed.

Among the extant studies, several have examined changes to biodiversity resulting from utility-scale solar development. Multiple studies examining floral vegetation change in solar facilities showed a mix of outcomes. Andrew et al. (2021), for instance, found that herbage biomass was significantly reduced in solar facilities (especially when combined with grazing), but that the remaining forage was of much higher nutrient quality for grazing animals. Similarly, Graham et al.

(2021) found that solar panel arrays delay bloom set in wildflowers, but that forage density was higher in solar facilities than in unmodified controls and pollinator activity was not reduced by solar development in cases where high-value ground cover is established. Conversely, Tinsley et al. (2023) found that utility-scale solar facilities significantly reduce bat activity, in keeping with the Levin et al. (2023) finding that solar development can reduce species movement in the broader landscape.

A handful of other studies have examined soil properties and microclimates in relation to the construction of utility-scale solar and solar land use. Both Choi et al. (2020) and Lambert et al. (2021) found that chemical and physical properties are degraded compared to references sites in the Central U.S. and French Mediterranean, respectively. Additionally, Choi et al. (2020) also found that these impacts can persist for years after conversion. Several studies also found that microclimate is altered by solar infrastructure. Adeh et al. (2018) and Armstrong et al. (2016) both found humidity and soil moisture to be higher in solar facilities, with Armstrong et al. (2016), Choi et al. (2020), and Lambert et al. (2021) finding significant reductions in soil and air temperature in the areas under solar panels as well as reduced seasonal and diurnal fluxes in temperature. Relatedly, Kannenberg et al. (2023) found that these changes in microclimate may contribute to reduced vegetative cover but seem to have minimal impact on evapotranspiration and CO₂ flux in vegetative communities in solar facilities.

Our study adds to this area of research by expanding the scope of soil-focused inquiry in both geography and approach. In particular, our use of soil heath as a framework connects research on agricultural sustainability and solar development. In this way, our research will contribute to the development of best practices for solar development to better support future agricultural land uses on retired solar sites.

Solar grazing

The practice of co-locating agriculture and solar electricity generation—often referred to as agrivoltaics—can encompass a wide range of agricultural practices (Dupraz et al., 2011; Al Mamun et al., 2022), yet the most common practice in the United States and many other countries is sheep grazing (American Solar Grazing Association, 2017; Bacon et al., 2025). Solar grazing is an expanding field of research, but as with the other areas of scholarship reviewed here, there are relatively few published studies considering the environmental impacts of the practice.

Several studies have examined changes in forage and herd productivity under solar compared to open pasture sites. The consensus among these studies is that forage biomass may be reduced in solar facilities, but that forage quality tends to improve in terms of nutrient content, leading to similar output in terms of animal products (Andrew et al., 2021; Kampherbeek et al., 2023; Loan et al., 2022). Additionally, and in keeping with research on solar microclimates reviewed above, Kampherbeek et al. (2023) found that sheep tend to spend more time grazing in solar facilities, likely due to milder conditions found there. Only one academic study that we are aware of has examined the effects of solar grazing on soil. Towner et al. (2022) found that across 6 utility-scale solar sites in Minnesota, United States, soil carbon and nitrogen tended to increase with the inclusion of periodic sheep grazing over a five-year period. This study also found that soil compaction can increase over time at grazed solar sites, especially in finer-textured soils.

In many ways, these studies are an extension of the broader literature on the environmental impacts of livestock grazing, and the ability of grazing to support diverse ecosystem services. This is a diverse and extensive literature, and a full review is beyond the scope of this paper. Yet for the purposes of our study, two facets of this field of research should be noted. First, the agricultural practice of grazing livestock is diverse, and many approaches to herd management tend to degrade the environment compared to ungrazed grasslands (Briske et al., 2008, 2011; Conant et al., 2017). Secondly, and perhaps conversely, researchers have clearly identified a subset of grazing practices—generally referred to as adaptive multi-paddock grazing—that show incredible potential to restore soil health, sequester carbon, and support biodiversity conservation (Mosier et al., 2021; Teague et al., 2016; Wang et al., 2015). While this nuance has not yet featured explicitly in the literature on solar grazing, any discussion of the environmental impacts of these practices should be understood in the context of the broader grazing literature. Our research contributes to this scholarship by documenting soil impacts from a specific approach to solar grazing during the early years of operation. This added diversity in knowledge can then support the refinement of this agrivoltaics practice to better support ecosystem health and other sustainability goals.

Study sites and methods

Data was collected for this study at three sites in the southern region of the State of Pennsylvania, United States. These sites cover approximately 120 hectares of agricultural land converted to solar photovoltaic installations in 2020. All study sites are in relative proximity, with sites 2 and 3 approximately 5 km apart and site 1 roughly 40 km to the north of the other sites. All three sites utilize E-W oriented horizontal single-axis tracking photovoltaic arrays with panel banks spaced approximately 6 m apart on-center. The central pivot axes for the panel banks range between 1.5 and 2.5 m in height to account for the rolling topography (Figure 1).

During the study period from 2022 to 2023, site 1 used the co-location of sheep grazing to manage vegetation under the solar panel arrays at a stocking rate of 15–20 sheep/ha, and sites 2 and 3 managed vegetation with conventional mowing. All three sites have similar climate typical of the humid Mid-Atlantic region of the United States, with an average annual temperature of 11.6 °C and an average annual rainfall of 102 cm. The sample collection period in the month of June has an average temperature of 21.6 °C and an average rainfall of 9.8 cm. Additionally, all sites were fully revegetated with the *Fuzz and Buzz*® seed blend designed by the American Solar Grazing Association to provide quality forage for pollinators and grazing



(A)



(B)



(C)

FIGURE 1

Horizontal single-axis tracking solar panel bank installations at (A) site 1, (B) site 2, and (C) site 3. Sheep can be seen grazing beneath panels in image (A). The panel banks in image (B) are an example of maximum mounting height above the surface across the three study sites, with the majority of banks having heights similar to those seen in images (A,C).

livestock in utility-scale solar facilities in the Northeastern United States (ASGA, 2020).

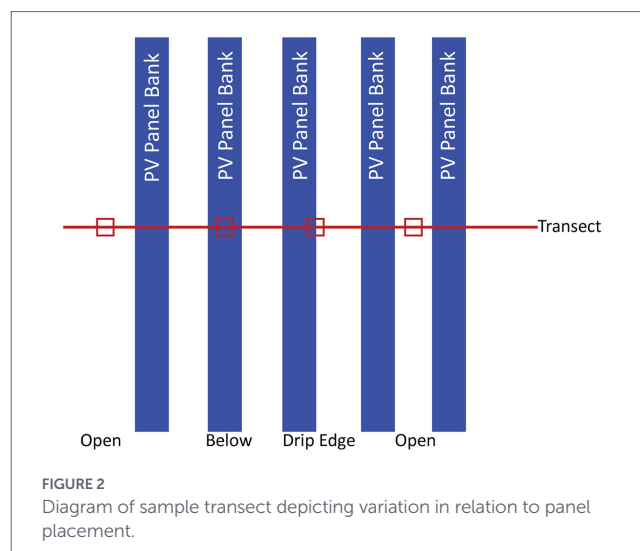
All three sites represent typical agricultural locations in the southern tier of Pennsylvania. Description of soils follow USDA soil taxonomy standards. Site 1 and Site 3 are both located on well-drained Weikert series channery to very channery silt loam soils, which are mesic Lithic Dystrudepts formed on shale bedrock with 27% sand, 52% silt, and 21% clay. Soils at these sites are mildly to moderately sloped between 3 and 15 degrees, with the majority of both sites having slopes below eight degrees. Site 2 is located on the transition between shale and limestone bedrock, with the majority of the installation located on well-drained Hagerstown and Carbo series silty clay loam soils—mesic Typic Hapludalfs on limestone bedrock with 17–18% sand, 52–53% silt, and 30–31% clay. Soils at this site are mildly sloped between three and eight degrees. All three sites have similar agricultural land use histories representing conventionally cultivated hay and feed grain for the dairy industry. Site 1 is a slight deviation from this history as the land was enrolled in the USDA Natural Resource Conservation Service conservation reserve program for 3 years prior to solar development and kept in perennial grasses.

Research design

This study uses a field-based multi-site comparative research design with 2 years of repeated measurements. At each site, a suite of soil health assessments was conducted within the solar facility (i.e., under the panel arrays) and at control locations that represent the background condition for the site—adjacent land with similar soils and land use history that remain in agricultural use. The control location for site 1 is perennial hay to better capture its years in the conservation reserve program, the control for site 2 is conventional hay, and control for site 3 is conventional commodity corn. This design allows for three points of comparison: (1) comparisons between site and control to assess the effects of conversion from agriculture to utility-scale solar, (2) comparison among solar sites to assess differences between grazing and mowing for vegetation management, and (3) comparisons between year-1 and year-2 to assess emerging trends in soil during the initial years of solar land use. We acknowledge that a two-year study period is not sufficient to provide longitudinal data, and we selected soil metrics that are highly sensitive to changes in management to better detect early trend signals. Additionally, given the pace of solar development and the ecological novelty of the land use, even early indications of trends in soil health can provide valuable insight for researchers and solar developers alike.

Field sampling and assessment were conducted along transects with four solar array transects and one control transect for each of the three sites. Sampling and field assessments were conducted in 2 m² quadrats at 12 locations for each solar transect and 15 quadrats along each control transect, yielding 48 solar quadrats and 15 control quadrats for each site in each year. Each transect is approximately 100 m in length. At each quadrat, soil was collected to a uniform depth of 20 cm for laboratory assessment of permanganate oxidizable carbon (POXC), soil respiration, and wet aggregate stability. Each quadrat was also assessed in the field for compaction using a Humbolt H-4210A static cone penetrometer and earthworm abundance using the hot mustard method. Assessments were repeated along each transect in June of 2022 and June of 2023. Methodologies for each assay are briefly described below.

To account for potential variation produced by solar panel placement, each sample transect is further subdivided equally into quadrats directly beneath panels, quadrats on the drip-edge that receive direct runoff from panels, and quadrats in the open space between panels (Figure 2). This



feature also affords the opportunity to test for differences in soil health based on relative panel location. At each study site, sampling and control transects are located in similar soil series: Weikert soils for sites 1 and 3, and Hagerstown-Carbo and Clarksburg soils for site 2.

While the difference in soil between the sites creates some complication in comparisons, our study design ensures valid analysis in two primary ways. First, the primary goal of our analysis is assessing the effects of conversion from agriculture to solar facility, and our design for samples and controls at each site ensures effective and valid analysis. Secondly, the question of the impact of on-site grazing can be validly conducted since the grazed site (site 1) contains the same soils as one of the mowed sites (site 3). Furthermore, the inclusion of site 2 will provide some indication of whether differences in soil type may impact the effects of solar conversion and land use.

Methods

This research employs a suite of soil health methods that utilize both laboratory and in-field assessments that examine labile carbon (POXC, respiration), soil biology (earthworm abundance, respiration), and soil physical structure (compaction, wet aggregate stability). Unless otherwise noted below, all laboratory assessments were conducted in the Soils Lab at Shippensburg University of Pennsylvania.

Permanganate oxidizable carbon (POXC)

Soil organic carbon is the lynchpin of soil health, food webs, and all major global biogeochemical cycles. While organic carbon exists in soil in many different forms, the labile fraction of organic carbon has the highest turnover rate and is thus the most sensitive to management. One of the most important components of labile carbon is the fraction that will undergo an oxidation–reduction reaction in the presence of permanganate ions. POXC (sometimes also called *active carbon*) correlates strongly with relatively stable forms of soil organic matter, and thus represents an important food source for soil biological communities and is thought to be an indicator of soil stability and carbon sequestration (Culman et al., 2012; Huriisso et al., 2016).

Air-dried soil collected from each sampling quadrat was assessed for POXC using the method of Weil et al. (2003). Briefly, 2.5 g of air-dried soil is shaken with 0.2 M KMnO₄ solution. After the reaction is complete

the solution is assessed using a spectrometer for light absorbance at 550 nm. Heavily disturbed soils tend to have low levels of POXC, and higher numbers indicate soil stability, carbon accrual, and increasing soil resources for soil biological communities (Hurisso et al., 2016).

Soil respiration

Unlike POXC, which serves as an indicator of carbon sequestration, soil respiration is an indicator of the size and vigor of the soil microbial community and the rate at which this microbiome is consuming organic matter and releasing nutrients (this assay is sometimes referred to as short-term mineralizable carbon). In this way, soil respiration allows for the assessment of two important aspects of ecosystem function. First, respiration offers a measurement of soil biology and thus the foundation of food webs (Moebius-Clune et al., 2016). Secondly, soil respiration serves as an indication of microbially-mediated nutrient cycling (Franzuebbers et al., 2000; Hurisso et al., 2016), which is a critical ecosystem service.

Soil respiration was determined in the lab by measurement of evolved CO₂ following the rewetting of air-dried soil via the alkali trap method (Franzuebbers et al., 2000; Wollum and Gomez, 1970). Briefly, 20 g of air-dried soil was measured into a 50 mL beaker and hydrated with distilled water to 50% water-filled pore space. Hydrated soil was then sealed in a pint mason jar with a 10 mL beaker containing 0.5 N KOH solution (alkali trap). Evolved CO₂ reacts with the KOH solution, becoming K₂CO₃, which alters electrical conductivity along a defined curve. After a four-day incubation at room temperature, the electrical conductivity was assessed for each trap using an electrical conductivity meter to determine the volume of evolved CO₂. This laboratory assessment represents *potential* soil respiration and is thus not necessarily reflective of what is happening in the field at any given moment, as this varies with changes in climate and soil moisture.

Earthworm abundance

Macroinvertebrates, particularly earthworms, are key indicators of soil health and are an important linkage between soil quality and broader ecosystem health (Doran and Zeiss, 2000). The soil macroinvertebrate community is also highly sensitive to management changes, including changes in soil structure and moisture that may be affected by solar installations. While species richness and functional diversity are important indicators, abundance in terms of individual counts is much easier to replicate and has been found to serve as an effective biological indicator for soil health and biodiversity (Doran and Zeiss, 2000; Gabriel et al., 2010).

At each sampling quadrat, earthworm abundance was assessed using a modified hot mustard extraction method of Lawrence and Bowers (2002). Briefly, 7 L of water containing 50 g of mustard powder is poured from a sprinkler can over a 0.25 m² wooden frame after vegetation is removed. The mustard solution is poured over the ring until the soil is saturated (roughly 1.5 L). All earthworms that rise to the surface during a 10-min duration were counted. The mustard extraction is non-toxic, harming neither macroinvertebrates nor surrounding vegetation. All collected earthworms were returned to the soil after assessment.

Soil compaction

Soil compaction is an indication of the loss of pore space in the soil profile. The loss of soil pore space can reduce water infiltration, air

circulation, root development, and soil biodiversity. Significant compaction can result from erosion, repeated tilling, overgrazing, heavy machinery traffic, or built infrastructure (Magdoff and Van Es, 2021). Existing research is inconclusive on the extent to which utility-scale solar installations impact soil compaction.

Soil compaction was assessed by measurement of surface hardness using a Humbolt H-4210A static cone penetrometer. To ensure optimal conditions and accurate comparisons between sites, compaction was assessed 2–3 days after rainfall to ensure that soil is at field capacity for moisture. The penetrometer was pushed through the soil profile with measurements recorded in kg/cm² to a depth range of 0–15 cm. Assessment of subsurface compaction was attempted in the field, but soils at the research sites were too hard and rocky to allow consistent measurement without damaging field equipment. The highest resistance reading was recorded for each sampling site. Lower resistance indicates healthier soil, and resistance readings above 21 kg/cm² are considered a critical threshold that inhibits root development and (other) biological activity (Magdoff and Van Es, 2021). Due to drought conditions in Southern Pennsylvania in 2023 we were not able to repeat compaction measurements at site 3.

Wet-aggregate stability (WSA)

Soil aggregates are larger clumps of soil that bind together mineral and organic components of soil via organic matter, microbial communities, and other biological activity. These aggregates are an important component of soil structure and are strongly correlated with agronomic and biological functions in soil (Amézqueta, 1999; Moebius-Clune et al., 2016). Wet aggregate stability refers to the ability of soil aggregates to hold together and maintain structure during high-impact water events such as rainstorms and sprinkle irrigation. Poor aggregate stability tends to lead to increased runoff and erosion, soil compaction, and decreased biological activity in soils.

Wet aggregate stability (WSA) was assessed in the lab using the sprinkle infiltrometer method developed for the Cornell Comprehensive Soil Health Assessment (Moebius-Clune et al., 2016). Due to technical challenges with our rainfall simulator, it was more efficient to contract with the Cornell Soil Health Lab at Cornell University to assess wet aggregate stability for this study. Air dried samples were delivered to Cornell in December of 2023 for analysis.

Data analysis

Data was analyzed using a combination of statistical methods to optimize results and best capture the nuances in the entire dataset. These tests include two sample *t*-tests, nested and mixed model ANOVA, and Poisson regression for the assessment of earthworm abundance. All data was examined to assure that all the assumptions of statistical tests were met prior to analysis. All statistical analysis was conducted in the R statistical environment.

For each of the three study sites, statistical comparisons were made between sample transects and the control transect using two-sample *t*-tests. ANOVA was also used to test variation based on relative panel locations at each site. In this case, data was grouped based on relative location of panel arrays (under, drip edge, open) and control. Pair-wise comparisons were made using the Tukey *post-hoc* test.

Comparisons between sites were made using nested ANOVA with *post-hoc* tests for pairwise comparisons. A nested model was used to account for intra-site variation and differences between sites that

cannot be controlled for in field-based studies. In this case, transects were nested within sites. This method of assessment was also used to assess potential study-wide trends in variation based on relative panel location and for comparing sampling years.

Earthworm abundance was quantified using counts of earthworms, necessitating different statistical methods. Earthworm counts were assessed by fitting and comparing Poisson regression models (a type of generalized linear model). Unlike significance tests used for other variables in this study, Poisson regression methodology assesses the strength of different factors in predicting the observed count of earthworm. Statistical significance is determined by calculated *p*-values of the coefficients in the model, as well as by using ANOVA to compare the predictive power of different models.

Results

The results of data analysis are summarized for each study year in [Tables 1, 2](#), multi-year comparisons are summarized in [Tables 3, 4](#) contains data related to panel variations. Detailed reporting for each statistic follows below. Any differences discussed are statistically significant, unless otherwise noted. Study results indicate that site conditions can be an important mediating factor for soil health effects, but when considered in total, this study indicates three primary findings. First, the construction of utility-scale solar at these sites had a clear effect on most soil health factors assessed in this study. Secondly, repeat measurement indicates differences among the factors assessed in this study, with physical properties showing early signs of recovery, carbon either remaining neutral or declining, and earthworms more likely within the solar arrays across the study period. Lastly, the use of sheep grazing to manage on-site vegetation showed no effect on soil carbon dynamics as assessed here, but it did correlate with observed changes in soil physical properties.

Soil carbon

The two fractions of soil organic carbon assessed here both tend to decline under solar conversion and land use, with POXC showing the strongest response. All three sites show a significant ($p < 0.000$) loss of POXC compared to the control transect. This relationship holds true regardless of relative panel placement and the presence of sheep grazing and persists across both study years (differences between

sample years are not significant). The response for soil respiration is not as uniform as with POXC, yet the overall trend is decline in respiration. In the first year of sampling, soil respiration was significantly lower compared to the control transect at site 1 ($p < 0.000$) and site 3 ($p < 0.05$), with all three sites showing significant decline from year 1 to year 2. Respiration rates in year 2 also showed declines in the control transects compared to year 1, resulting in changes in statistical comparisons in the second year of analysis. At sites 1 and 2, the decline in respiration within the solar facilities was larger than declines in the control transects, resulting in statistically significant differences for both sites. Site three saw large declines in both solar and control transects such that the statistical differences between samples was no longer present in year 2. As with POXC, there is no indication in our data that sheep grazing had any impact on respiration.

There are several factors related to site construction that may have contributed to observed changes in soil carbon. All three sites experienced complete revegetation during conversion, with site 1 and site 3 also receiving grading to recontour the surface (grading was most significant at site 3). Some loss of POXC may be due to erosion, as well as accelerated decomposition of organic matter induced by soil aeration during construction disturbance. Additionally, the magnitude of decline in POXC at sites 1 and 3 is much more significant than at site 2 (32% loss vs. 18% compared to controls), which suggests that POXC declines may increase with the intensity of construction related disturbance. It is also possible that the deeper and finer-textured limestone soils found at site 2 proved better at retaining organic carbon during site construction.

Observed declines in respiration suggest an interaction between several factors, including land use and other unassessed factors. Respiration declined significantly in the first year of analysis at sites 1 and 3, which have relatively poorer soils and saw more significant construction-related disturbance. Given that respiration and POXC tend to correlate ([Hurisso et al., 2016](#)), the relationship between respiration and POXC seems consistent with factors related to site conversion. The continued decline of respiration in year 2 compared to POXC may indicate an ongoing process related to site construction, with respiration responding on a longer time scale than POXC. It is also possible that un-tested factors such as climate variation also reduced respiration in year 2. This latter possibility seems reasonable considering that respiration also declined on control transects in year 2. In any case, our results suggest that in the early years of operation, the solar land use practices found at our study sites do not promote increased soil microbial activity, which is consistent with other studies ([Lambert et al., 2021](#)).

TABLE 1 Year 1 assessment results (mean) for solar arrays and controls for each site.

	Site 1		Site 2		Site 3	
	Yr 1	Control	Yr 1	Control	Yr 1	Control
Surface hardness (kg/cm ²)	42.22 ^{a,b}	32.65	29.55	30.07	33.74	33.18
Earthworms (Count/sample)	1.062	0	3.977 ^a	0.8	1.809 ^c	1
POXC (ppm)	541.7 ^a	793.3	524.5 ^a	635.8	524.9 ^a	768.2
CO ₂ (mg/kg dry soil)	11.971 ^a	14.93	11.225	11.761	16.581 ^c	19.38
Water stable aggregates (%)	53.26 ^{a,d}	71.61 ^c	46.89	43.92 ^c	45.89 ^a	78.23 ^c

^a $p < 0.000$ vs. control.

^b $p < 0.000$ vs. other sites.

^c $p < 0.05$ vs. control.

^dSignificant differences between sites likely unrelated to factors assessed in study.

TABLE 2 Year 2 assessment results (mean) for solar arrays and controls for each site.

	Site 1		Site 2		Site 3	
	Yr 2	Control	Yr 2	Control	Yr 2	Control
Surface hardness (kg/cm ²)	30.71 ^{a,c}	40	29.75 ^a	37.87	NA	NA
Earthworms (Count/sample)	0.0217 ^c	0.06667	2.614 ^a	0.6	1.812 ^a	0.1333
POXC (ppm)	516.2 ^a	805.8	538.8 ^a	683.9	516.6 ^a	616
CO ₂ (mg/kg dry soil)	7.891 ^a	12.178	8.422 ^a	10.664	6.892	7.76
Water stable Aggregates (%)	74.32 ^{a,c}	86.03 ^c	54.35	54.88 ^c	54.08 ^a	65.17 ^c

^a*p* < 0.000 vs. control.^b*p* < 0.05 vs. control.^c*p* < 0.000 vs. other sites.^d*p* < 0.01 vs. other sites.^eSignificant differences between sites likely unrelated to factors assessed in study.

TABLE 3 Comparison of year 1 and year 2 assessment results (mean) for each site.

	Site 1		Site 2		Site 3	
	Yr 1	Yr 2	Yr 1	Yr 2	Yr 1	Yr 2
Surface hardness (kg/cm ²)	42.22	30.71 ^a	29.55	29.75	33.74	NA
Earthworms (Count/sample)	1.06	0.02 ^b	3.98	2.61 ^a	1.81	1.81
POXC (ppm)	541.70	516.20	524.50	538.80	524.90	516.60
CO ₂ (mg/kg dry soil)	11.97	7.89 ^a	11.23	8.42 ^c	16.58	6.89 ^a
Water stable aggregates (%)	53.26	74.32 ^a	46.89	54.35 ^c	45.89	54.08 ^c

^a*p* < 0.000 vs. year 1.^b*p* < 0.01 vs. year 1.^c*p* < 0.001 vs. year 1.

TABLE 4 Assessment results (mean) based on panel variation for year 1 and year 2.

	Open		Drip edge		Below	
	Yr 1	Yr 2	Yr 1	Yr 2	Yr 1	Yr 2
Surface hardness (kg/cm ²)	32.98 (34.7)	31.49	33.29 (32.88)	24.09 ^d	39.55 ^b (40.29)	35.14 ^d
Earthworms (Count/sample)	2.09	1.30 ^c	3.20 ^c	2.20 ^{c,e}	1.87	0.95 ^c
POXC (ppm)	512.40	529.50	501.80	525.70	577.30 ^b	517.00 ^d
CO ₂ (mg/kg dry soil)	13.17	7.45 ^c	12.84	7.56 ^c	13.57	8.19 ^c
Water stable aggregates (%)	46.81	59.25 ^c	46.81	60.68 ^c	52.75 ^a	62.82 ^d

^a*p* < 0.05 vs. other panel locations.^b*p* < 0.01 vs. other panel locations.^c*p* < 0.000 vs. other panel locations.^d*p* < 0.01 vs. year 1.^e*p* < 0.000 vs. year 1.

Two values are reported for surface hardness in the first year to allow for comparisons between years due to the inability to sample Site 3 in year 2. Parenthetical values are adjusted for interannual comparison.

Panel variation - soil carbon

Differences in soil carbon based on panel variation generally show no significant differences or else mirror the results from broader inter-annual comparison. For instance, general decline in respiration in year 2 are also found at all three relative panel locations. Yet data from year 1 did show one clear pattern that warrants further investigation, particularly via longitudinal analysis to assess the emergence of long-term patterns. In aggregate, POXC was significantly higher in year-1 quadrats directly below the panel banks compared to those on the drip edge

or in the open space between panels (*p* < 0.01). A similar pattern was not observed for respiration, with no difference produced by relative panel location. It should be noted, however, that the lab method of assessing respiration that we used for this study represents *potential* carbon mineralization, and it is possible that *in-situ* respiration in the solar fields differ based on relative panel location. This pattern in POXC did not persist in year 2, which suggests that the effect could be ephemeral. Yet given the relatively short duration of our study, future research should explore these dynamics to determine if long-term patterns in soil carbon emerge in solar facilities.

Physical properties

Assessments of soil physical properties indicate mixed impacts across study sites. Year 1 results suggest that site construction has no impact on compaction (see Table 1). The exception is site 1, where compaction is significantly higher compared to the control transect. However, this site is grazed with sheep to manage vegetation, which may explain much of the difference between sites in year 1. A review of permitting and site construction plans for all three sites indicates that contractors were obligated to restore all disturbed areas such that they contain at least 18 inches of friable, uncompacted topsoil¹. Results suggest that this was sufficient to remediate any construction related compaction at sites 2 and 3, whereas the successive disturbances of construction and sheep grazing at site 1 may have led to significant compaction in the first year of sampling. Interestingly, compaction in year 2 was significantly reduced at site 1 and held constant at site 2, while the control transects that remained in conventional agriculture saw significant increases in compaction. These early results suggest that utility-scale solar has lower physical impact to soils than some conventional agriculture, and that co-locating sheep grazing may be restorative to soil physical properties.

Like results for soil respiration, both sites that received surface grading (sites 1 & 3) saw significant decreases in WSA in year 1, while site 2 showed no change. In this case it is likely that measures used at sites 1 and 3 to remediate compaction (discing, screening, amending imported topsoil, etc.) weakened soil aggregates at these sites. This decline in WSA compared to controls at sites 1 and 3 persisted in the second year of analysis, however, all three sites saw significant increases in year 2. Interestingly, the greatest percent increase in year 2 is found at the grazed site, which saw a 28% increase over year 1—nearly double the increase found at the other sites. When considered together, our assessments of soil physical properties suggest that the conversion of agricultural land to utility-scale solar can degrade some soil physical properties, but that these impacts are relatively small and may be short-lived compared to the lifespan of a typical solar facility.

Panel variation - physical properties

Differences in physical properties connected to panel variation show similar patterns to those found with soil carbon; significant differences are either only found in year 1 (surface hardness and WSA) or mirror general interannual comparisons (WSA). In year 1, sampling locations below the panel banks showed significantly higher water-stable aggregates and surface hardness. It is possible that some of the observed differences are a result of a decrease in direct interaction with precipitation below the panels, as decreased soil moisture can elevate surface hardness. Since these patterns do not persist in year 2, it is impossible to draw meaningful conclusions without further study.

The observed increase in WSA in year two is also found across panel locations, which also eliminates any significant difference between relative panel locations. The same is not observed for surface hardness, where inter-annual differences are found in the drip edge and below locations but not in open quadrats. While much of this can be attributed to changes in surface hardness at site 1, the short

duration of our study is not sufficient to draw conclusions and more study is necessary to better understand possible variations caused by panel location.

Earthworms

Observation of earthworm count data across the study's three sites show considerable variation between locations (see Tables 1, 2), which suggests that additional factors may contribute to earthworm counts beyond those assessed here. It should also be noted that seasonal variation in soil moisture and temperature affect earthworm abundance, and our sample collection in June may underestimate earthworm counts relative to other periods. Model fitting initially included all soil factors assessed in this study as well as dummy variables for site, transect, and relative panel location. Model tuning found that only site and transect were significant in predicting earthworm abundance.

Site was highly significant ($p < 0.000$), with earthworms far less likely to be found at site 1, which includes grazing, in both sample years. Modeling also indicates significant differences between sites 2 & 3, however, suggesting that grazing alone is not the best explanation for observed differences. Additionally, earthworms were significantly more likely in the solar facilities compared to control transects at sites 2 and 3 in both sample years. Possible explanations include differences in soil moisture and soil temperature within the solar arrays. Other studies have found that temperature is cooler on average and soil moisture better regulated in areas under solar land use (Adeh et al., 2018; Armstrong et al., 2016). These factors should be examined in relation to earthworm abundance in future studies. Earthworm counts declined significantly across all three sites in year 2. This may be due to decreased precipitation in year 2 (5.1 cm in year 2 vs. 5.9 cm in year 1), though more years of repeated measurements are necessary to understand potential climatic effects.

In addition to having the lowest abundance of earthworms, site 1 also showed no difference between transects in the solar facility and the controls across both sample years. Given that this is the only grazed site, it is reasonable to assume that grazing may be a factor in observed differences. However, the significant variation among all three sites and the relatively narrow scope of our study necessitate further research to better understand the relationship between earthworm abundance and solar land uses (including solar grazing).

Panel variation - earthworms

As with other assessed variables, assessment of differences in earthworm abundance mirrors other inter-annual comparisons, with significant declines in year two observed across panel locations. Interestingly, earthworm abundance is the only assessed factor in this study that showed a persistent pattern across both sample years, with earthworms significantly more likely to be found along the drip edge of panel banks compared to other locations. It is reasonable to consider that this is due in part to differences in soil moisture caused by panel placement. Whereas the area beneath panel banks receive reduced rainfall, the drip edge has the inverse effect by collecting rainfall from across the panel surface and concentrating the runoff in a relatively small area. It should be noted, too, that the location of the drip edge changes across a 24-h period due to the movement of the horizontal single-axis tracking arrays at these sites, which may moderate the overall impact. More significant inference is beyond the scope

¹ These documents were made available by the developer for our study sites. We omit specific citation information here to maintain the anonymity of sites.

of this study, but our findings do indicate that the relationship between solar-induced hydrological changes and soil ecology warrants further inquiry.

Discussion and Conclusion

The results of this study offer a clear picture of the initial effects to soil health that may arise from the conversion of agricultural land to utility-scale solar. First, our results make clear that there are some environmental impacts that result from site construction, as there are with any land use change. Based on our assessment, the site construction process results in the loss of soil carbon in forms that are most readily accessible to the biological community (POXC). Our findings also show that in some cases the size and vigor of the microbial community (respiration) can be diminished with solar conversion. Two years of repeat assessment suggest that labile carbon and microbial activity do not recover from these effects in the initial years of solar land use, which is in keeping with other research examining soil carbon in similar solar facilities (Choi et al., 2020; Lambert et al., 2021; Treasure et al., 2025). Water-stable aggregates did accrue in our study, and given that soil aggregates tend to correlate with organic matter and microbial activity (Amézqueta, 1999; Magdoff and Van Es, 2021), long-term study should be undertaken to better assess soil carbon dynamics during the lifecycle of a utility-scale solar facility.

Our study also indicates that some of the soil physical properties we assessed are impacted by site construction, but that these effects may be shorter lived than those observed in soil carbon. Mandated soil remediation practices employed at these three sites following grading and contouring appear to sufficiently address soil compaction, but they may degrade other aspects of soil physical structure as evidenced by the significant loss of WSA at sites 1 and 3. Yet our findings suggest that soil physical structure may recover relatively quickly under solar land use. There is also some indication that solar land use may increase earthworm abundance, perhaps by modifying soil moisture and temperature regimes. Future research should examine the effects of solar land uses on macroinvertebrates in diverse site conditions to better understand these relationships.

Finally, this study suggests that the incorporation of sheep grazing to manage on-site vegetation at solar facilities such as these has relatively little short-term impact on the soil ecosystem. There is some evidence in our study that sheep grazing and site construction may interact to increase soil compaction during the first year of operation, but this effect did not persist in the second year of assessment and WSA showed strong recovery. Interestingly, we found that grazing had no impact on labile soil carbon as it was assessed in our study. While there is relatively little soil-focused scholarship on solar grazing in the academic literature, our findings differ from other research in this regard. For instance, Towner et al. (2022) found that the inclusion of sheep grazing tended to increase total organic carbon across six utility-scale solar facilities in Minnesota, USA, over a period of 4 years. The findings of Towner et al. are also in keeping with recent research in other fields indicating that certain ruminant grazing management practices are highly effective at sequestering carbon in the soil (Mosier et al., 2021; Teague and Kreuter, 2020; Teague et al., 2016; Wang et al.,

2015). We do not dispute the findings from this body of research, yet our study indicates that they should not be broadly applied to all solar grazing.

There are important differences between the grazing practices used in Towner et al. (2022) and our study that may help explain our divergence in findings. Sheep stocking rates at the grazed site in our study and those in the Towner et al. (2022) study are similar—500–700 sheep at 20–30 sheep/ha—but the solar sites assessed in Towner et al. were only grazed for 2–3 weeks each season. This grazing approach closely resembles adaptive multi-paddock grazing (AMP), which is defined by short-duration, high-intensity grazing followed by long recovery periods ranging anywhere from 6 to 8 weeks to a year or more (Teague and Kreuter, 2020). Importantly, nearly all studies in the grazing literature that find improved soil health are specifically examining AMP systems. At site 1 in our study, 500–700 sheep are regularly rotated through the site for the entire season—a rotation scheme that is intended to replace mechanical mowing to manage vegetation under the panel banks. This type of high-intensity rotational grazing is effective for these purposes but may not be optimized for improving soil health. At the same time, it is also true that our research shows no indication that the co-location of sheep grazing and utility-scale solar infrastructure as practices at our sites is harmful to soil health compared to mowing. It is also vital to note that the benefits and drawbacks of solar grazing reach far beyond the relatively limited scope of ecological factors assessed here. Our findings provide useful data for improving solar grazing strategies, but these ecological parameters alone are not enough to justify or prohibit the practice in the future.

Much of the impacts found in our dataset are likely related to the site construction process, especially grading and contouring, yet there is little indication that solar as an on-going land use significantly degrades soil health compared to other land uses—including the conventional agriculture that it frequently replaces. And while long-term study is needed, our findings do not give any early indication that future agricultural land uses will be significantly limited by utility-scale solar.

The results of our study offer an opportunity for the solar development industry, regional planners, and land managers to refine siting and land use practices to expand the scope of benefits associated with solar energy. Conversion to solar has relatively minor environmental impacts, and as other researchers have demonstrated, agricultural land offers many advantages for solar energy development (Adeh et al., 2019; Evans et al., 2023; O'Shaughnessy et al., 2023). At the same time, agricultural soil is increasingly seen as a carbon sink with tremendous potential to mitigate climate change (Conant et al., 2017; Hayek et al., 2020; Teague et al., 2016; Wang et al., 2015). Our data suggests that utility-scale solar—with or without grazing—as it is deployed across our study sites may not offer synergy with that particular climate goal, even as it reduced emissions from the energy sector.

To that end we suggest two promising avenues for future research. First, solar developers should continue to partner with researchers to develop and assess site construction practices for utility-scale solar that minimize the loss of soil organic carbon and the disruption of microbial communities. Secondly, we recommend expanding research on agrivoltaics—both grazing and crop production—to develop agricultural practices that sequester carbon over multiple time scales. Both of these research agendas will require significant collaboration between developers, farmers, research teams, and many other stakeholders to develop, execute, and assess field-based experiments. This

approach will likely require additional resources to be successful, yet the potential benefits for climate mitigation, environmental health, and rural development are significant. We hope that this study, along with others like it, will help catalyze participatory research collaborations and contribute to a more robust renewable energy future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

RH: Validation, Project administration, Data curation, Visualization, Formal analysis, Methodology, Writing – review & editing, Conceptualization, Investigation, Writing – original draft, Funding acquisition, Supervision. ST: Investigation, Writing – review & editing, Data curation, Formal analysis. CJ: Supervision, Conceptualization, Resources, Writing – review & editing, Project administration, Funding acquisition.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2026.1786348/full#supplementary-material>

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