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Sheep grazing as sustainable vegetation management for solar energy production in the northeastern USA

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The expansion of solar photovoltaic production necessitates the need for vegetation management at solar sites. Solar grazing, an agrivoltaic (APV) approach involving vegetation management with livestock, is a rapidly growing solution to fill this need. Despite approximately 7–11% of existing installed solar capacity utilizing solar grazing in 2024, solar grazing research is still limited. The purpose of this study was to collect baseline data on how sheep grazing within commercial solar energy sites influences soil health, forage nutritive quality, and pasture conditions compared to mechanical mowing, along with understanding economic considerations for graziers, in the northeastern USA. *In situ* data was collected at 28 grazed and 3 non-grazed commercial solar sites in the northeastern USA from 2022 to 2024. At each site, samples were collected in "open space" (OS) - areas that were not directly underneath panels - and "under solar panel" (UP)—areas that were directly under solar panels. Soil health was monitored by collecting top-soil (0–15 cm) and sub-soil (15–30 cm) samples at grazed and non-grazed sites. Pasture Condition Scoring (PCS) was used to measure the pasture condition of only the grazed sites following the United States Department of Agriculture (USDA) Natural Resources Conservation Services (NRCS) Pasture Condition Scoring Sheet. Forage quality was assessed via exclusion cage harvesting methods. Organic matter, predicted soil protein, and active carbon values were all significantly higher at grazed sites than non-grazed sites ($p < 0.001$). Despite several differences among individual indicators, the overall total PCS score did not change over the study period. Forages harvested from UP in 2023 had significant higher crude protein (CP) content and significant better digestibility than those values observed in OS areas. Economic analysis emphasized the importance of long-term contracts and site control for the economic feasibility of grazing by demonstrating that costs can be reduced and become comparable to conventional mowing costs over time. Overall, this study highlights the potential for solar grazing as a beneficial alternative to mechanical mowing for enhanced ecologically sustainable vegetation management at solar sites, promoting biodiversity, soil health, forage quality, and local production.

KEYWORDS

solar grazing, soil health, pasture conditions, ecosystem health, forage quality, agrivoltaics, sheep production

1 Introduction

Solar photovoltaic (PV) energy generation is part of a global effort to decarbonize energy production. PV power has been identified as the leading form of renewable energy technology and is presently the fastest-growing energy source (Tabassum et al., 2021). Utility-scale solar has rapidly expanded in the U.S. with over 200,000 megawatts (MW) of installed capacity and an estimated additional installation of 30,000–40,000 MW expected by 2029 (Solar Energy Industries Association, 2024). The expansion of solar necessitates the need for vegetation management at these sites to ensure proper power generation. Solar grazing offers an economically comparable alternative to mechanical mowing with the potential for sustainable land management and simultaneous agricultural production (McCall et al., 2023).

However, as PV development gains traction, there is the potential for conflict in land use between farming and solar site installations (Goldberg, 2023). Utility-scale solar development is land-intensive, and installation can have negative environmental impacts that transform soil ecological function and impact hydrologic, vegetative, and carbon dynamics (Choi et al., 2020). As utility-scale solar installations continue to expand, the need for sustainable vegetation management that prioritizes soil health improvement and biodiversity enhancement is growing (Stewart et al., 2025).

To address this need, solar grazing, which involves vegetation management with the use of livestock, has been a growing industry in the past decade (Kochendoerfer and Thonney, 2021). Solar grazing is a form of agrivoltaics (APV), a multi-use land management strategy combining agricultural and solar energy production. The American Solar Grazing Association (ASGA) United States 2024 Census reported that approximately 113,050 sheep were grazing 129,000 acres across over 500 solar sites nationally, representing an estimated 18,000–26,000 MW of solar power plants being grazed (Andrew et al., 2025). These numbers account for vegetation management on approximately 7–11% of existing installed solar capacity. The ASGA Solar Grazing Census was the first broadly organized effort dedicated to reporting the scope and reach of solar grazing, making it difficult to track the growth of the industry over time. However, a factsheet released in 2021 estimated that 15,000 acres of solar land were being grazed by sheep, demonstrating a large increase in the usage of grazing as vegetation management (ASGA, 2021). Furthermore, the practice of solar grazing has been identified as a more uniformly accepted strategy than conventional vegetation management options, such as mechanical removal and prescribed burning (Brunson and Shindler, 2004).

Despite the rapid growth of this APV approach, solar grazing research is still limited. Past research on solar grazing has primarily investigated animal behavior and production value; however, there is less research on how this APV approach influences forage quality, soil health, and overall ecosystem health (Andrew et al., 2021; Sharpe et al., 2021; Maia et al., 2020; Kochendoerfer et al., 2021).

The purpose of this study was to collect baseline data on how sheep grazing within commercial solar energy sites influences: (a) Soil health, (b) Forage nutritive quality, and (c) Pasture conditions, along with (d) Understanding economic considerations for graziers, in the northeastern USA. Full ecosystem service benefits take time to be fully observed, and soil, forage, ecological, and economic characteristics related to solar grazing are largely impacted by region, climate, and site history. As such, this study provides a baseline, examining a short-term, region-specific study area, upon which future studies can build.

2 Materials and methods

2.1 Sites

This study was conducted to collect baseline data on the impact of sheep grazing within commercial solar energy sites on soil health, forage nutritive quality, and pasture conditions in the northeastern USA. Additionally, the study addresses economic considerations for graziers. The sites selected included 28 grazed solar sites and 3 non-grazed, conventionally managed solar sites in the northeastern USA. The sites were primarily located in New York, with a total of 25 sites in the state. To capture a broader range of the northeast, 3 sites were located in Pennsylvania, 2 in Connecticut, and 1 in Massachusetts. All the sites were submitted randomly, with the only criterion that they were currently grazing, or would begin grazing before the trial commenced, as a form of vegetation management. The forage types used on these sites were typically cool season grasses and legume mixtures. There was no minimum criterion for present forage, but sites that reflected the previous types of land use were desired. As such, the sites reflected a diversity of seedings, with some incorporating contractors' mixtures, and others representing more typical hay or pasture mixtures. The sites varied mainly in size from approximately 3–40 acres, though one site was closer to 100 acres. 29 sites consisted of fixed panels, while the remaining 2 used single-axis tracking panels. The sites were constructed between 2015 and 2020. The study sites' most predominant reported prior land use was croplands (including hay and corn), followed by open fields (including fallow land) and woodlands. Prior to solar panel installation, none of the sites had a recent history of being grazed. Solar sites in this study were initially solely constructed for the purpose of energy generation, with local graziers later joining the operation to create APV sites. Most sites in this study were in the early years of utilizing PV. Several of the sites had employed mechanical vegetation management, and some of the grazed sites incorporated solar grazing before the start of this study. Graziers with experience in solar grazing were sought out to participate in this study. The sites in this study were selected based on their ability to continue solar grazing and provide research access throughout the study period, which allowed information collection about innovative co-location strategies. The sites selected relied on the willingness of all parties involved in the solar site maintenance to allow access to the sites for data collection, along with sharing information.

2.2 Measurements

Sample collection began in spring 2022 and was completed in spring 2024. All soil and forage samples were collected at both the non-grazed and grazed solar sites. The samples were collected in areas under solar panels (UP) and in open space (OS) areas without direct shade from the panels. UP and OS samples were designed to be representative of the area. To accomplish this, subsamples were taken from various areas in the OS and UP zones. Table 1 outlines the

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TABLE 1 Timeline of sampling methods.

Sampling method	Spring 2022	Fall 2022	Spring 2023	Fall 2023	Spring 2024
CASH sampling collection	■				■
Basic nutrient analysis sampling collection	■		■		■
Forage sampling collection	■	■	■	■	
PCS	■	■	■	■	■

timeline of sampling methods, with shaded sections representing collection periods.

Soil health was monitored by collecting top-soil (0–15 cm) and sub-soil (15–30 cm) samples in the pre-grazing season from the OS and UP areas at grazed and non-grazed sites. GPS coordinates were identified to ensure the same location was monitored each year. A main location was selected for each location site, and 4 subsamples were collected around the main location, resulting in one composite sample created by 5 subsamples. In total, 2 soil samples were taken in the OS areas, and 2 soil samples were taken in the UP areas at each sampling date (Figure 1). To collect the samples, a hole was dug to approximately 15 or 30 cm deep for top-soil or sub-soil collections, respectively. A vertical, rectangular slice of soil was taken from one side of the hole, measuring approximately 5 cm x 15 cm x 8 cm. The subsamples for each area were placed in a clean bucket, thoroughly mixed, and 32–40 oz. of the composite sample was sent to Cornell Soil Health Laboratory for analysis. Overall, 4 composite samples per site were collected, with one each for top-soil OS, top-soil UP, sub-soil OS, and sub-soil UP locations. Comprehensive Assessment of Soil Health (CASH) analysis was completed with the top-soil collections in 2022 and 2024 (Cornell Soil Health Laboratory, 2025). Cornell Soil Health Laboratory's basic nutrient analysis tests were done for all years using the sub-soil (Cornell Soil Health Laboratory, 2025).

Pasture Condition Scoring (PCS) was used to measure the pasture condition of only the grazed sites. PCS was developed for use on grazed sites, and several of the indicators (grazing utilization and livestock concentration areas) would not apply to non-grazed sites. PCS was conducted and recorded following the United States Department of Agriculture (USDA) Natural Resources Conservation Services (NRCS) Pasture Condition Scoring Sheet. Indicators evaluated in PCS were desirable plants, percent legumes, live plant cover, plant diversity, soil cover, utilization and severity, livestock concentration areas, compaction and regeneration, plant vigor, and pasture erosion. PCS scores for each category were reported on a scale of 1–5, with higher numbers representing ideal conditions, resulting in a maximum total possible score of 50. The NRCS Guide to Pasture Condition Scoring should be consulted for a more detailed methodology for collection (USDA, 2020). PCS was collected in the spring pre-grazing season and the fall post-grazing season for each year at each grazed site. At some sample sites, PCS data were incomplete; instead of two PCS scores representing UP conditions and OS conditions separately, only one data point was collected for the entire study area. Rather than invalidate this data, all PCS data used for yearly and seasonal comparisons were combined into an average value (AVG) to represent conditions across each of the study areas. This limited the ability to examine differences under and between solar panels but allowed us to examine trends in overall field conditions from year to year.

Forage quality was assessed via exclusion cage harvesting methods. Two individual exclusion cages, measuring approximately 0.25m^2, were placed at each grazed and non-grazed site. One exclusion cage was placed in the UP area, and one was placed in the OS area at each site. The cages served as controls by excluding portions of the solar site from grazing to compare the relative productivity between grazed and non-grazed areas. The cages were harvested in spring and fall in 2022 and 2023 by using electric shears or harvest knives to cut the forage to 7–10 cm above soil level. The collected sample was weighed prior to sending it to Dairy One Forage Laboratory to undergo forage analysis (Dairy One, 2025). Following harvest, a new area was pre-cut before reinstalling the exclusion cage to prepare for the next sampling date.

2.3 Surveys

Two surveys were created using the Sogolytics online software. The survey questions can be accessed in the Supplementary materials. The first survey was completed by the solar graziers of the selected solar sites. The Solar Grazier Survey (SGS) consisted of 57 questions, with a combination of short answers, multiple choice, and yes/no response types. The SGS was designed to gain insight into the technical aspects of agricultural co-location on solar sites to help inform land-use management decisions. The questions consisted of identifying and contact information, site identification, and grazing management information. The second section of the SGS asked participants to provide information regarding the operation and management costs of their operation. The survey concluded by asking what challenges graziers have experienced, and what can be done to strengthen the relationship between graziers and solar companies and asset managers. The SGS was sent via email to all 12 of the participating graziers, with one grazier opting to receive and complete the survey via mail. The survey was initially sent in November 2022, with multiple reminder emails sent through spring 2023 to encourage maximum response rate. The SGS was completed by 9 graziers, who managed 19 of the 28 grazed sites in the study and 2 of the 3 non-grazed sites. Two graziers did not attempt to complete the survey, while 1 grazier submitted incomplete responses. Multiple efforts were made to complete missing responses, but communication attempts were unsuccessful. The responses from the survey by the 9 graziers were assumed to only pertain to individual sites in the study.

The solar companies and asset managers associated with the selected sites in this study completed the second survey. The Solar Company Survey (SCS) consisted of 35 questions, with a combination of short answers and yes/no response types. The survey began by asking for respondent identification and contact information. Questions were then asked for each site that the solar company/asset manager was responsible for. These questions involved panel type,

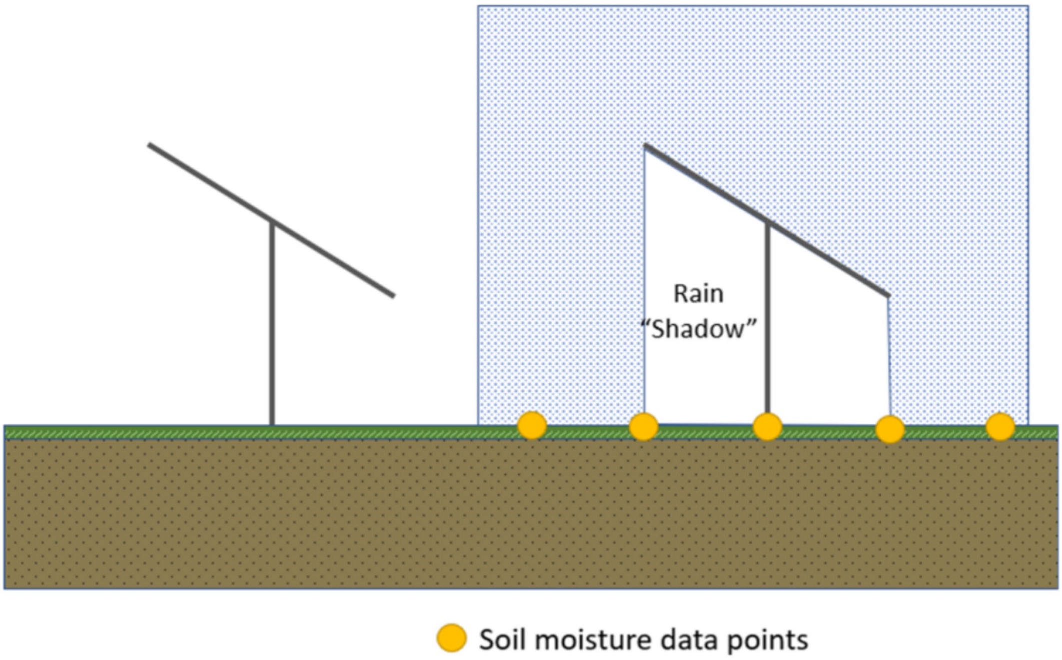

FIGURE 1
Soil sample collection protocol schematic. Created by E. Cole.

total acres of managed vegetation, fencing type, site history, and whether any modifications were made to accommodate solar grazing. The second section asked for each site's cost information regarding conventional vegetation management and solar grazing vegetation management. The survey concluded with questions about overall satisfaction of livestock grazing compared to conventional vegetation management, and if grazing partners provided supplemental mowing or if a separate contract was necessary. The SCS was emailed in February 2023 to the 14 solar companies/asset managers participants responsible for the associated solar sites in the study. Several reminder emails were sent throughout the survey period through spring 2023. Despite the repeated reminders, only 2 responses were received, representing 3 out of the 31 sites. Due to the low response rate, the information from the SCS was excluded from the results of this study.

2.4 Economic analysis

The economic analysis was conducted using the responses from the SGS. The survey asked questions that were both for the whole operation (i.e., capital costs), and for costs that were required on a yearly basis (i.e., annual costs), which were separated in order to calculate average annual costs for grazing and conventional vegetation management per acre. Costs were also given in terms of MW, determined by multiplying the per acre cost by 6. Using 6 acres as a reference is consistent with reports from the Solar Energy Industries Association (SEIA) that 5 to 7 acres per MW of generating capacity are required for a utility-scale solar power plant (SEIA, 2025). First, capital costs for each grazier were multiplied by an "acre factor" for each site, which was calculated by dividing the acres for each site by the total acres grazed by each grazier, to estimate the capital costs for each site. Capital costs were also adjusted by being divided by varying numbers of years (i.e., 3 and 5 years) based on typical contract lengths. These modified capital costs were then added to the annual cost amount for each site. This amount was divided by the acreage amount for each site to calculate the annual cost per acre for each site, which was then used to calculate the average annual grazing costs per acre across 19 sites. It is important to note that the average annual cost of mowing per acre only includes annual costs and does not include any capital costs. Finally, qualitative data (i.e., textual answers) helped to understand cost information to support analysis.

2.5 Forage and soil sampling statistical analysis

Soil health and PCS data were analyzed using the "ggbetweenstats" function from the "ggplot" package in R. In cases where there were two values compared (CASH data and fall PCS data), Welch's t-test was used to determine statistical significance between means. In cases where three values were compared (CASH data, fall PCS data, and spring PCS data), Welch's one-way analysis of variance (ANOVA) was used to determine statistical significance between means. *p*-values of 0.05 or less were considered statistically significant and were identified in tables as bolded italic text.

3 Results

3.1 Individual CASH indicators and total CASH scores

Several of the soil health indicators showed significant differences between grazed and non-grazed sites (Table 2; bolded values). Organic matter, predicted soil protein, and active carbon values were all significantly higher at grazed sites than non-grazed sites ($p < 0.001$). Soil pH was lower in non-grazed sites ($p = 0.02$), with values of 5.58 and 6.11, respectively. The only biological indicator that showed no significant difference is soil respiration. Active carbon, extractable phosphorus, and extractable potassium were significantly lower in non-grazed sites ($p < 0.001$; Table 2). High phosphorus levels are a concern, and 10 sample sites had phosphorus levels over 100 ppm. While not statistically significant, non-grazed sites tended to have a lower average total CASH score than grazed sites, with scores of 69.20 and 77.75, respectively (Table 2).

Between 2022 and 2024, aggregate stability significantly decreased at grazed sites from 59.86 to 46.21% ($p < 0.001$) and 58.16 to 45.26% ($p < 0.01$) in OS and UP, respectively, and on non-grazed sites from 66.68 to 42.18% ($p = 0.02$) (Table 3). Aggregate stability was the only measurement that was significantly different between 2022 and 2024 (Table 3). However, soil pH tended to be lower in 2024 (Table 3).

Overall CASH scores did not change significantly during the study period (Figure 2).

In particular, pH and aggregate stability are worth noting. It is possible that pH decreases over time due to graziers being unable to lime due to accessibility constraints. Additionally, variability of weather over the study period could have attributed to differences in indicators (Figure 3). Aggregate stability could be trending downward due to yearly shifts between drought and flood (see Table 3).

3.2 Total PCS scores and individual indicators

Despite several differences among individual indicators, the overall total PCS score did not change over the study period (Table 4; Figure 4). With average total PCS scores of 33.28, 33.12, and 33.43 in 2022, 2023, and 2024, respectively.

Livestock concentration areas' average score significantly improved from 3.52 to 4.24 in fall 2022 and fall 2023, representing improved conditions ($p < 0.001$). Plant vigor also significantly increased between seasons from the first to the last year ($p < 0.001$). The soil compaction score increased from an average of 2.92 to 3.65, representing improved conditions, from spring 2022 to 2023 ($p < 0.001$). The PCS average erosion value increased from 3.98 to 4.46 between fall 2022 and fall 2023 ($p = 0.03$). This higher indicator value represents a lower occurrence of erosion in fall 2023.

TABLE 2 2024 CASH results for all grazed and non-grazed sites.

CASH score indicators	Grazed mean	Non-grazed mean	*P*-value
Predicted available water capacity (g water/g soil)	0.25 (*n* = 54)	0.24 (*n* = 6)	**0.04**
Surface Hardness (psi)	187.17 (*n* = 23)	118.75 (*n* = 2)	0.06
Subsurface Hardness (psi)	264.47 (*n* = 22)	296.88 (*n* = 2)	0.27
Aggregate Stability (%)	46.12 (*n* = 54)	42.18 (*n* = 6)	0.56
Organic Matter (%)	4.58 (*n* = 54)	3.54 (*n* = 6)	**<0.001**
Predicted Soil Protein (mg/g soil)	8.89 (*n* = 54)	7.40 (*n* = 6)	**<0.001**
Soil Respiration (mg CO_2/g soil)	0.89 (*n* = 54)	1.02 (*n* = 6)	0.57
Active Carbon (ppm)	622.49 (*n* = 54)	457.05 (*n* = 6)	**<0.001**
Soil pH	6.11 (*n* = 54)	5.58 (*n* = 6)	**0.02**
Extractable Phosphorus (ppm)	18.93 (*n* = 54)	6.03 (*n* = 6)	**<0.001**
Extractable Potassium (ppm)	168.56 (*n* = 54)	47.90 (*n* = 6)	**<0.001**
Overall Score (CASH Score)	77.75 (*n* = 54)	69.20 (*n* = 6)	0.07

TABLE 3 2022 vs. 2024 CASH results from grazed sites.

CASH score indicators	2022	2024	P-Value
Predicted available water capacity (g water/g soil)	0.24 (*n* = 50)	0.25 (*n* = 54)	0.11
Surface hardness (psi)	250.03 (*n* = 24)	187.17 (*n* = 23)	0.12
Subsurface hardness (psi)	275.19 (*n* = 19)	264.47 (*n* = 22)	0.73
Aggregate stability (%)	59.86 (*n* = 50)	46.21 (*n* = 54)	**<0.001**
Organic matter (%)	4.54 (*n* = 50)	4.58 (*n* = 54)	0.88
Predicted soil protein (mg/g soil)	8.15 (*n* = 50)	8.89 (*n* = 54)	0.15
Soil respiration (mg CO_2/g soil)	0.79 (*n* = 50)	0.89 (*n* = 54)	0.14
Active carbon (ppm)	557.58 (*n* = 50)	622.49 (*n* = 54)	0.07
Soil pH	6.38 (*n* = 50)	6.11 (*n* = 54)	0.06
Extractable phosphorus (ppm)	34.00 (*n* = 50)	18.93 (*n* = 54)	0.12
Extractable potassium (ppm)	471.55 (*n* = 50)	168.56 (*n* = 54)	0.28
Overall score (CASH Score)	76.20 (*n* = 50)	77.75 (*n* = 54)	0.55

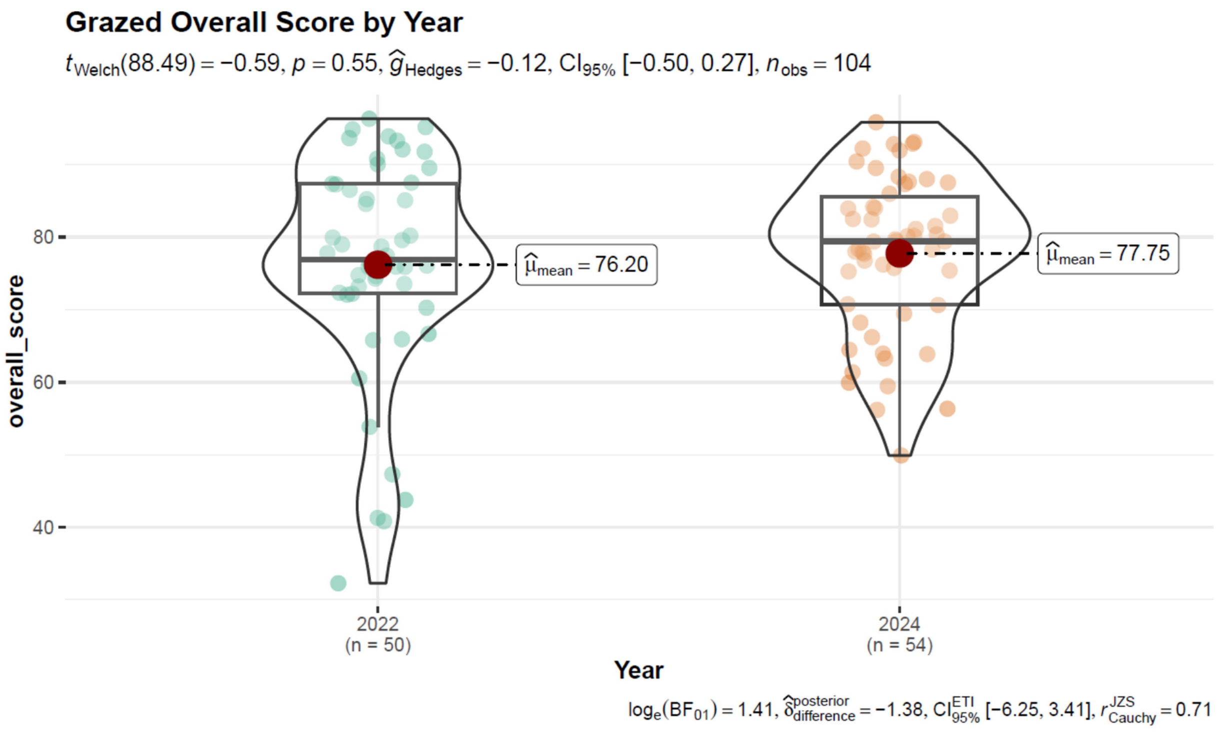

FIGURE 2
Overall CASH scores at the study period's beginning (2022) and end (2024). Dots represent individual values, box plots show the distribution of values (25% in each quarter), and figure outlines show grouping of values within the distribution. Dots falling beyond the extent of the box plots are outliers.

3.3 Nutritive value and dry matter production of forages

Forages harvested from UP in 2023 had significantly higher crude protein (CP) content and significantly better digestibility than those values observed in OS areas (Table 5). CP was significantly higher in all seasons and years ($p < 0.001$) when harvested from UP (Table 5). Non-digestible fiber content, measured as Acid Detergent Fiber (ADF), was significantly lower ($p = 0.02$) when harvested from UP in fall 2023 (Table 5). Another measure of digestibility, Neutral Detergent Fiber (aNDF), was significantly lower ($p = 0.03$) in the UP area in fall 2023 (Table 5).

The kg of dry matter (DM) of forages per acre were determined for OS and UP areas for spring and fall (Table 6). In the spring, OS areas experienced DM production that was significantly higher than in UP areas, with mean values of 3,016.2 kg DM/acre and 2,058.4 kg DM/acre, respectively ($p = 0.01$). OS areas in fall had mean DM production values of 2,460 kg DM/acre compared to UP areas with a mean DM production of 1,766.2 kg DM/acre ($p = 0.02$).

3.4 Economic costs of solar grazing

Annual costs reported included site preparation, mechanical vegetation maintenance, rotation costs, transportation, and animal and field maintenance. The average annual costs per acre associated with grazing were $1,119.17. To estimate this value on a per MW basis, it was assumed that 1 MW of solar energy production encompassed 6 acres, as based on estimates from SEIA. This assumption would report that the average annual costs of grazing per MW were roughly $6,714.99. The average site acreage in this study was 17.78 acres, resulting in average annual grazing costs per average site of $19,898.84.

Capital costs included adult ewes, lambs, site equipment, fencing, rams, and guardian animals. Assuming that capital costs could be spread over 5 years, the cost of grazing was found to be $507.72 per acre or $3,046.32 per MW. These numbers could decrease over time if operations expand over longer periods. If extended over 10 years, grazing costs could be lowered to $416 per acre ($2,496 per MW), or $386 per acre ($2,316 per MW) in costs for 15-year operations. For the 2 control sites, the cost of vegetation maintenance using mowing instead of grazing was reported to be $337.50 per acre or $2,025.00 per MW (Figure 5).

The short answer questions in the SGS used to provide economic data, highlighted repeated reported challenges of coordinating grazing and mowing, needing to improve the condition of the external fence, and poor vegetation management (i.e., seeding) when solar energy infrastructure was installed on the site, while noting that stable water supply was a key to success. Many of these challenges are reflected in annual and capital costs reported per acre (Table 7).

4 Discussion

4.1 Various soil parameters were improved with solar sheep grazing despite climatic variables and a short study period

Prioritizing soil health is essential for ensuring the land can remain in agricultural use after a solar site is decommissioned and provides legitimacy for solar development as temporary uses (Spangler et al., 2025). Soil health is defined as the ability of the soil

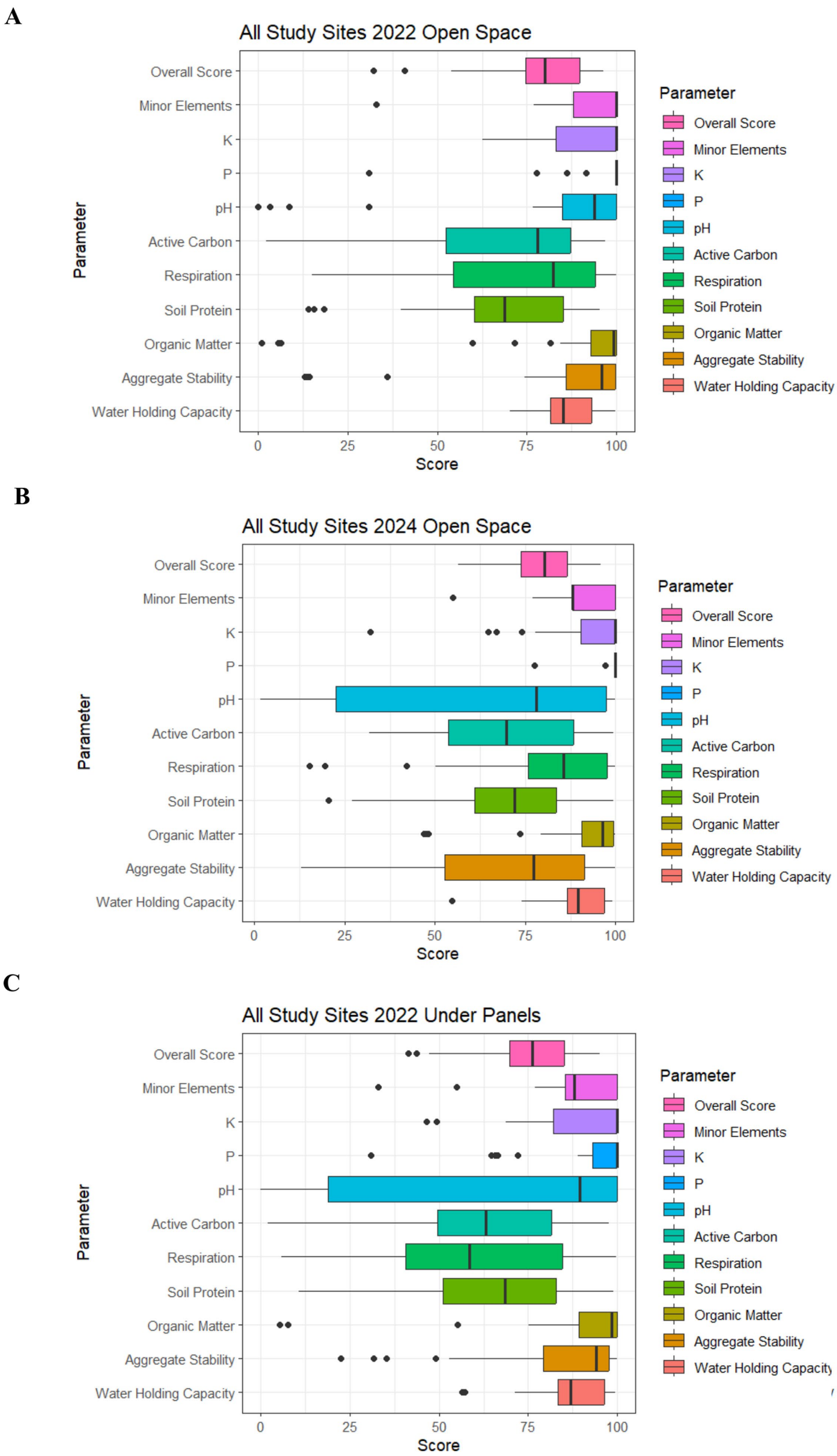

FIGURE 3 (Continued)

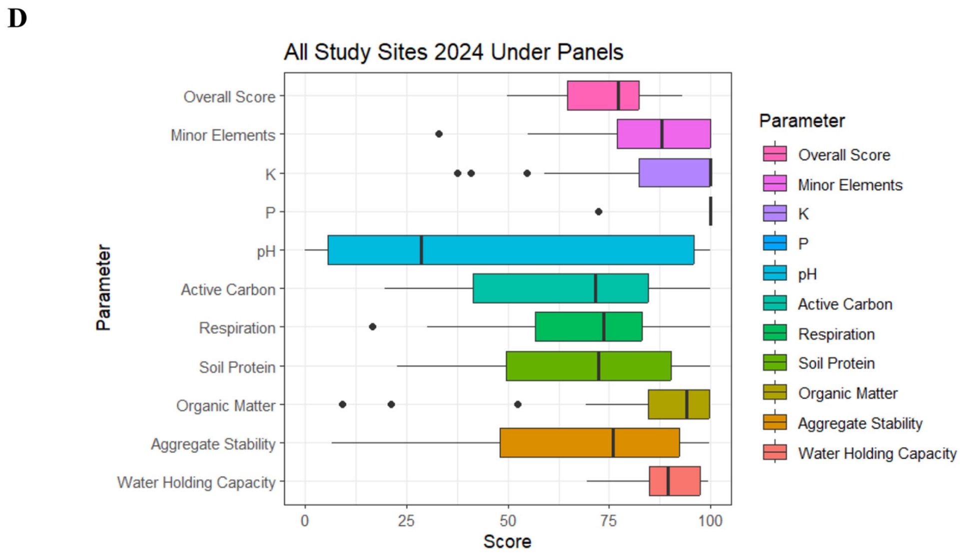

FIGURE 3
CASH individual scores for all study sites taken **(A)** in OS areas in 2022, **(B)** in OS areas in 2024, **(C)** in UP areas in 2022, and **(D)** in UP areas in 2024.

TABLE 4 PCS mean indicator scores for all study sites separated by season.

PCS indicators	Fall 2022	Fall 2023	*P*-value	Spring 2022	Spring 2023	Spring 2024	*P*-value
% Desirable Plants	3.52	3.62	0.79	3.88	3.45	3.56	0.39
% Legumes by Dry Weight	1.76	2.10	0.41	2.40	1.38	1.65	0.06
Live plant cover	3.28	3.88	**0.02**	3.32	3.48	3.63	0.43
Plant diversity	3.52	3.62	0.79	3.88	3.45	3.56	0.39
Plant residue	3.17	3.66	0.06	3.08	3.33	3.13	0.49
Grazing utilization	4.00	3.50	0.12	3.83	3.40	4.25	**0.04**
Livestock concentration areas	3.52	4.24	**<0.001**	3.88	3.92	4.44	**0.03**
Soil compaction	3.21	3.44	0.43	2.92	3.17	3.65	**<0.001**
Plant vigor	3.32	4.26	**<0.001**	3.48	4.07	4.17	**<0.001**
Erosion	3.98	4.46	**0.03**	4.08	4.12	4.24	0.75

to function as a living system, sustain plant and animal productivity, enhance or maintain water and air quality, and promote animal and plant health (Meena, 2019). A challenge with predicting how the soil will react to solar panel installation and solar grazing is a lack of long-term studies, emphasizing the importance of in-field trials such as this work.

The differences seen in soil health in grazed sites (increased predicted available water capacity, organic matter, predicted soil protein, active carbon, soil pH, extractable phosphorus, and extractable potassium) could have been impacted by the presence of sheep on the land, leading to improved nutrient cycling. However, if the study period was longer, it is possible that a negative difference in soil respiration would be observed. Due to the plethora of biotic and abiotic factors contributing to soil respiration, many studies have been unable to fully predict how respiration may respond to environmental changes over a broad range of environmental and biological conditions (Xu et al., 2004). Soil respiration is affected by soil temperature, seasonality, and rainfall events (Xu et al., 2004). Additionally, high-intensity grazing can lead to decreased soil erosion by reducing the total microbial, bacterial, and fungal community (Zhao et al., 2017; Li et al., 2024; Li et al., 2018).

Conversely, organic matter and active carbon can be leading indicators, meaning that they improve first, with respiration following. Melero et al. (2009) studied the short (3 years) and long-term (16 years) effects on soil organic carbon fractions, including total organic carbon and active carbon, determining that the active carbon content was the most reliable indicator for assessing the short- and long-term impact of soil disruption. Soil organic matter can be enhanced through diverse seed mixtures, cover crops, reduced tillage, and rotational grazing, creating more stable surface structures that are less prone to erosion (Meena, 2019). Due to organic matter and active carbon having significantly higher values in grazed sites than non-grazed sites, this could further support that respiration may improve on grazed

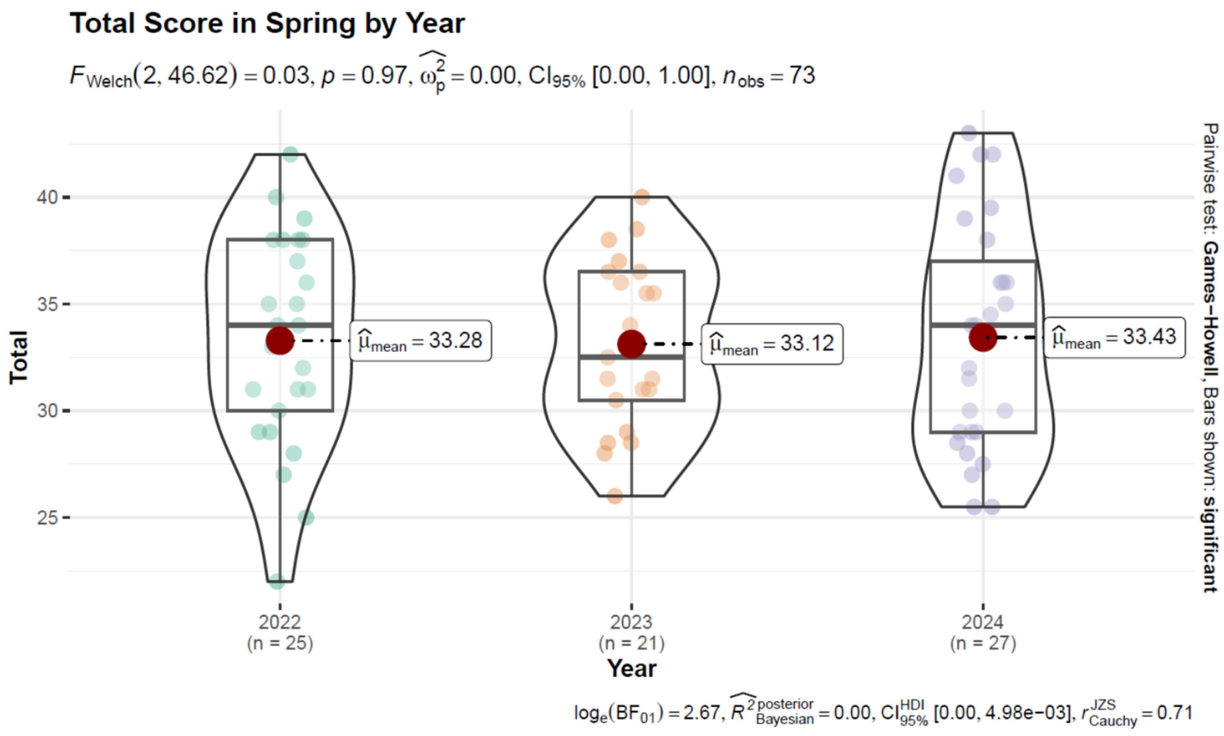

FIGURE 4
Annual PCS total scores for all study years. Dots represent individual values, box plots show the distribution of values (25% in each quarter), and figure outlines show grouping of values within the distribution. Dots falling beyond the extent of the box plots are outliers.

TABLE 5 Significance levels and mean values for forage nutritive quality tests in the OS and UP areas from the 2022 and 2023 seasons.

Forage nutritive test	Spring 2022 (*n* = 59)			Spring 2023 (*n* = 54)			Fall 2022 (*n* = 54)			Fall 2023 (*n* = 58)		
	OS	UP	*P*-value	OS	UP	*P*-value	OS	UP	*P*-value	OS	UP	*P*-value
ADF	38.89	37.42	0.11	37.51	35.81	0.14	36.86	36.40	0.63	37.41	34.28	**0.02**
aNDF	62.28	61.10	0.41	60.20	59.00	0.70	58.23	57.54	0.74	58.60	53.83	**0.03**
CP	10.54	16.06	**<0.001**	10.48	15.17	**<0.001**	15.24	17.93	**<0.001**	14.40	19.53	**<0.001**

TABLE 6 Mean values and significance levels for DM production in the OS and UP areas during spring and fall.

DM production	Spring			Fall		
	OS (*n* = 48)	UP (*n* = 44)	*P*-value	OS (*n* = 54)	UP (*n* = 50)	*P*-value
kg DM/acre	2994.58	2058.44	**0.01**	2460.87	1766.25	**0.02**

sites over time, despite not demonstrating significant differences in this short-term study.

Various studies support these findings of improved soil health resulting from grazing. For example, Towner et al. (2022) found that implementing sheep grazing on solar sites significantly increased the total carbon storage by 10–80% and increased the content of soil nitrogen. The magnitude of those changes correlated with grazing frequency, which is a common finding in grazing research. Multiple studies have reported that moderate grazing can increase soil organic matter, soil health, and crop yields compared to non-grazing, but heavy grazing can reduce these benefits (Franzluebbers and Stuedemann, 2008; Li et al., 2008; Tracy and Zhang, 2008; Maughan et al., 2009). This suggests the importance of continued soil testing throughout grazing to properly manage grazing intensity and management practices with climate, region, and forage type to protect soils from degradation (Abdalla et al., 2018).

The higher soil pH values in grazed sites in 2024 show the potential for solar grazing to improve solar site soil health. This value suggests that grazing allowed for soil pH to reach near optimal soil pH levels (optimal = 6.0; Agriculture and Horticulture Development Board, 2025). Similar to other soil factors described above, grazing intensity can impact the pH of grazed sites. In a global meta-analysis performed by Lai and Kumar (2020), moderate grazing increased pH

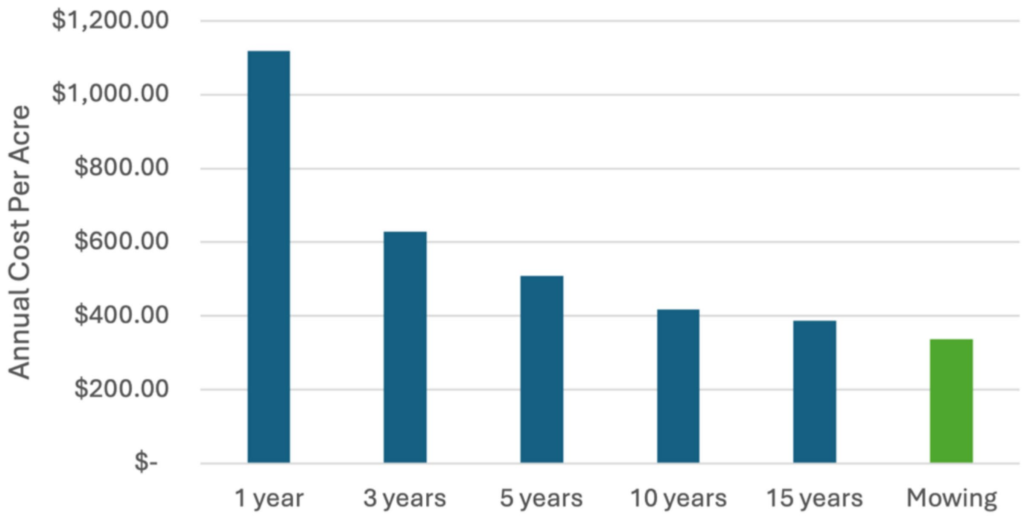

FIGURE 5
Annual cost of grazing per acre (blue) with different distributions of capital costs as compared to mowing (green).

TABLE 7 Enterprise budget based on average costs reported (ACR) per acre.

Annual costs	ACR per acre ($)	Capital costs	ACR per acre ($)
Site preparation (gaining access to the site, fencing, water)	119.28	Adult ewes	395.93
Mechanical vegetation maintenance	78.49	Lambs	179.85
Rotation costs (including preparation of new paddock fencing if applicable)	72.94	Site equipment (including feed bunks, water troughs, grain storage facilities, signage, gate locks, and other equipment)	142.29
Transportation	39.84	Fencing	130.14
Animal and pasture health: purchasing feed, salt, other minerals; veterinary costs; conducting soil and/or forage tests	15.97	Rams	34.34
		Guardian animals	19.01
Total	326.52	Total	901.56

by 4.1%. Data collection on the frequency of graziers liming their fields can provide insight into how pH can be impacted as a result.

The reason for the decrease in aggregate stability in OS and UP areas is unclear, though it's possible that weather variability over the study period contributed to the decrease. Over the study period, the northeastern USA experienced drought in 2022 and historic floods in 2023. This assumption is supported by Algayer et al. (2014), who reported factors such as rain amount and intensity, and air temperature and humidity as explanatory factors for changes in aggregate stability. Monitoring effects at the aggregate scale is essential for understanding how soil properties affect erodibility and can serve as a first step before scaling up to consider other environmental or anthropogenic factors impacting soil health (Dowdeswell-Downey et al., 2023).

Overall total CASH scores for both years experienced a non-significant upward trend (Moebius-Clune et al., 2017). With a short timespan seen in this study, it is difficult to conclude if this trend is a result of improved conditions via grazing, or if it is possibly due to annual variation in field conditions. A longer study period would add additional clarity to this trend. CASH cores at both the beginning and ending of the study period fell into the "high functioning" category, which includes ratings between 60 and 80. These scores suggest non-limiting levels of soil process functioning, and soil management approaches can be maintained as is or improved (Moebius-Clune et al., 2017). The numbers recorded here are based on soil tests the Cornell Soil Health Laboratory has received. The score presented may not always fully capture the condition of the pasture, demonstrating the importance of evaluating individual laboratory results.

High phosphorus levels may be of concern. Extractable phosphorus is the measure of phosphorus available to forages and is an essential plant macronutrient that varies with soil pH and mineral composition (Moebius-Clune et al., 2017). High phosphorus as runoff from pastures is a potential non-point source pollutant that is influenced by surface cover, forage height, damage from trampling during grazing, surface slope, and soil moisture and phosphorus (Haan et al., 2006). In contrast, low phosphorus values indicate insufficient phosphorus available to plants (Moebius-Clune et al., 2017). Soil phosphorus can also be impacted by grazing intensity, soil depth, and climate (Lai and Kumar, 2020). Forages will react to available phosphorus levels on a species basis, with native perennial species being especially sensitive to increases in phosphorus (Dorrough et al., 2011). Despite 10 sample sites experiencing high phosphorus levels, the majority of samples in this study experienced phosphorus ratings in the optimal or near-optimal range, suggesting that soil management should be maintained at the existing functionality for the majority of the sites (Moebius-Clune et al., 2017).

Many of the reported soil results confirm the need for continuous monitoring of soil health to properly manage the sites. Monitoring throughout a solar site's lifespan allows for ongoing assessment of impacts via climate, livestock type, grazing intensity, level of plant productivity, and evolutionary history of grazing on soil health (Lai and Kumar, 2020; Eldridge et al., 2016; Kimuyu et al., 2014; Paz-Kagan et al., 2016; Proulx and Mazumder, 1998; Milchunas and Lauenroth, 1993).

4.2 Grazing has the potential to improve pasture condition indicators at solar sites over time

PCS involves the visual evaluation of 10 indicators, which are measured on a scale of 1–5, with 5 representing ideal conditions. Adding the individual markers together results in a maximum score of 50, with a high PCS value reflecting a well-managed site where animal and plant productivity is sustained or enhanced. The average scores from 2022 to 2024 stayed relatively consistent, suggesting the site would benefit from further improvement (USDA, 2020). However, it is important to note that a high or low value in any of the individual marker categories can influence the overall PCS value. In future studies, it would be beneficial to determine PCS for UP and OS areas separately to assist in identifying which areas of the site would benefit from improvement.

Additionally, the timing of data collection and weather events may influence PCS characteristics. The NRCS Guide to Pasture Condition Scoring highlights the importance of evaluating the pastures at the same time each year to more accurately note condition changes of the pasture (USDA, 2020). While the research team prioritized collecting samples and performing PCS at the same time for each period, there were occasional delays related to gaining site access for those sites that changed ownership during this study. These delays may have unintentionally affected differences in some PCS scores.

Differences in spring grazing utilization shown can likely be explained by the timing of data collection. Spring PCS data were collected before animals had grazed the site, which led to an overabundance of 5's, and on some sites, that indicator was skipped. Differences in plant vigor between years may also be explained by weather variation across study years. Drought conditions in 2022 likely reduced plant vigor, while very wet conditions in 2023 likely increased it. It is worth noting that plant vigor is evaluated last, as previous indicators in the PCS assessment provide insight into the productivity and health of the pasture (USDA, 2020).

Soil compaction scores increased in spring 2024, representing more favorable conditions. This contrasts with Donkor et al. (2002), which found that grazing effects on soil properties were more evident in fall than in spring. Compaction is impacted by soil properties such as texture, organic matter, water content, and other environmental conditions (Mapfumo et al., 1999). The differences between these studies' results and the factors impacting compaction highlight the importance of long-term evaluation to evaluate the effects of grazing on a site basis.

A promising finding from this study was the increase in erosion PCS assessment values from fall 2022 to fall 2023. However, erosion values in the spring seasons were not significantly different. Erosion value average scores in fall 2023 and all spring seasons suggest that only minor changes are needed to enhance productivity and the environment (USDA, 2020). Solar panel installation can require extensive landscape modification that transforms soil ecological function and vegetative cover, requiring solutions to maximize plant growth and minimize soil erosion (Choi et al., 2020). Results from this study suggest that grazing has the potential to maintain soil stability.

In future studies, PCS data should be collected for additional periods to accurately capture scores for plant vigor and grazing utilization. Additional PCS performance points can include peak forage supply periods, low forage supply periods, and plant stress periods, such as drought or very wet conditions (USDA, 2020).

4.3 Forage quality at solar sites provides favorable grazing conditions

Forages harvested from UP in 2023 had significantly higher CP content and significantly better digestibility than those values observed in OS areas. The significantly higher CP content and better digestibility from UP areas in 2023 suggest that grazing sites may experience enhanced forage quality when APV is incorporated, due to the shading effects from the panels provided higher quality forage in 2023. The higher CP and lower aNDF in UP are consistent with previous solar grazing studies (Andrew et al., 2021). CP and lower aNDF values found UP areas in this study indicate higher forage quality may be achieved in the shaded areas present in APV systems. This is consistent with the impacts of shade on perennial forages in temperate climates (Lin et al., 2001; Kephart and Buxton, 1993).

While stocking density was not measured in this study, improved forage quality provided from shaded areas may allow animals to graze later into the season, as was seen in Andrew et al.'s (2021) study. The difference in forage quality can be attributed to the quality of light received by forages under shade, influencing the annual growth cycle, leading to variation in seasonal production patterns (Krueger, 1931; Hassanpour Adeh et al., 2018). Furthermore, stocking rate and grazing period have been shown to influence the animal intake and forage quality in grazing studies (Glindemann et al., 2009; Lin et al., 2012). Grazing has been shown to provide improved forage quality as new aboveground tissue with high CP replaces grazed forage, with these effects seen seasonally (Nowak and Caldwell, 1984; van Staalduinen and Anten, 2005; Sturchio et al., 2024). Due to this seasonal variation, it is important to assess the dietary nutrient content of forage and management strategies multiple times throughout the season (Ma et al., 2014). Systematic monitoring provides insight into the impacts of grazing within solar systems, allowing for stocking rates to be adjusted to balance vegetation management, animal production, and sustainability goals (Stewart et al., 2025; Launchbaugh, 1969).

As with many of the results reported from this study, there are regional differences in forage quality and production that can experience fluctuations from weather changes, such as drought or wetter periods. The APV approach of solar grazing has the added challenge of balancing these changes with site vegetation management needs (Stewart et al., 2025). Diverse forage species that are shade tolerant and resistant to waterlogging can be beneficial for enhancing productivity and persistence in solar sites; however, the establishment and persistence of these diverse forages can be particularly difficult in regions prone to climatic extremes (Andrew et al., 2024; Stewart et al., 2025). This further supports the need for continued studies that encompass longer time frames and multiple regions.

Despite a short study period, these results suggest the potential of the shade effects seen in solar sites to improve forage quality, despite lower forage production seen in UP areas, creating a more favorable environment for sheep grazing. This is supported by Sturchio et al. (2024), who determined that grazing increased forage protein content later into the growing season compared to control sites, indicating that grazing within a solar array is unlikely to negatively impact forage quality. This study did not involve botanical compositions; this could be improved upon in future studies to evaluate the presence and quality of individual pasture species in the microclimatic zones.

4.4 Key costs of solar grazing highlight the benefits of long-term contracts

Costs can be reduced and become comparable to conventional mowing costs over time with long-term contracts and site control for the economic feasibility of grazing. These costs are greatly impacted by location, with other reports of income for solar graziers ranging from $262/acre in the broader eastern U. S. to $509/acre in New York (Kochendoerfer et al., 2021).

The survey was limited by its completion rate (68%) and the omission of questions concerning labor. Certain attempts were made to remediate some of the complications of the survey through follow-up correspondence with two of the graziers; however, there were certain constraints. For example, one grazier provided data on labor, which raised the cost on average $95 per acre for sites that were grazed and $32 per acre for sites that were not grazed. Swanson et al. (2023) determined that graziers reported 14.75 h/week to on-site labor, 8.17 h/week to travel between the home farm and solar sites, and 5.67 h/week on business administration. While these numbers do not specify an estimate of costs associated with labor, they do highlight an average amount of time spent operating a solar grazing business. Better accounting for labor could demonstrate the importance of water resources at solar energy sites. In this analysis, sites that required hauling water cost $238.56 more per acre than sites that did not haul water. This does correspond with graziers reporting in the survey that hauling water was a major challenge and elsewhere reported as a major expense.

Despite its challenges, the survey and corresponding economic analysis identified key costs, which include site prep, sheep purchases, and transport, and emphasized the importance of long-term contracts that likely determine grazing viability. Long-term contracts demonstrate the opportunity for solar grazing to be more profitable than traditional agricultural scenarios. Gasch et al. (2025) determined that, despite differences in operational approaches, earnings before interest, tax, depreciation, and amortization margins were higher in solar grazing models at 200 kW and 465 MW compared to traditional agriculture industry values due to the reliable revenue source of solar grazing contracts.

4.5 Study limitations and future directions

This study served as a baseline for future research. While statistically significant results were achieved that suggest solar grazing can lead to site improvement, some limitations impact the reporting of results. Soil health indicators change over long time periods. The three-year study period was long enough to start to see some trends, but when examining the data, most of the differences could also be attributed to weather variations. A longer-term study of grazing on solar sites would yield more insights into soil health changes brought about by grazing. This is especially true for comparisons between the OS and UP zones of the study area. Some benefits from improved soil health may take 5–10 years to become measurable, demonstrating that it is possible that this short-term study may not fully capture the change in soil health (USDA, 2022). Additionally, including additional microclimatic zones would further strengthen the data.

Furthermore, this study relied on voluntary site access and occurred in several different states. This created the challenge of ensuring consistency, both with sampling dates and with having a controlled location and environment. It is possible that many of the indicators measured were impacted by the management decisions of the farmers. Several of the farmers involved in this study had to travel long distances to access their grazing sites and had to renegotiate contracts partway through the study period. This delayed access to the site until later in the spring, after the farmer intended to begin grazing, necessitating mowing. Uncertainties like these can impact a farmer's willingness to implement management and resource-intensive practices, like prescribed grazing, that would have a positive impact on soil health. This emphasizes the need for long-term contracts highlighted in the socioeconomic data analysis. Site access issues also impacted the timing of fieldwork across sites. This has the potential to impact PCS results as well as some of the CASH indicators that are impacted by temperature and collection timing, like respiration.

The economic survey analysis experienced limitations that may be improved upon in future studies related to the validity, completeness of data, and amount of data to find significant statistical conclusions, as only 21 of the 31 sites were accounted for in the analysis. First, when analyzing the data, it is not clear that graziers were reporting commensurate information. Second, certain graziers only partially filled out the survey. Relatedly, there could have been better data collection on previous investments or resources outside of purchases, as there were questions asked about animals and equipment purchased, but not previous ownership. There was also no data collected on how long the grazier had been maintaining, or planned to maintain, each site, so it was not possible to presume that capital costs could be spread out over time. Third, there was not enough data to run statistical analyses (i.e., linear regression), especially because the sample size of non-grazing sites was too small; therefore, findings were only descriptively presented.

Future surveys should refine current questions and include additional questions that pertain to the costs of vegetation management. First, current questions can be refined to ensure that they apply to the sampled sites. Second, there were clear data gaps in conducting cost analysis concerning existing grazier resources (i.e., how many ewes were owned before solar grazing and currently) and labor required for each site. Third, it is important to ask about the distance the grazier travels to the site, which would help estimate costs associated with time and expenses (e.g., fuel) associated with transportation. Finally, there should also be questions on hired labor and where they are based. Future surveys may also benefit from verbal interviews to establish trust and rapport while allowing for the ability to ask clarifying questions.

Future research can improve by:

- Utilizing a longer-term study
- Including additional microzones within the sampling protocol
- Strengthening survey efforts by refining current questions and incorporating verbal interviews

5 Conclusion

Solar PV sites benefit from animal grazing through increases in soil health and cost-effective mowing services. Likewise, grazing systems benefit from the presence of solar panels through increases in forage quality. Grazing is a practice that is already considered in the suite of climate smart agriculture practices, and results of this study demonstrate that those soil health building benefits can be sustained when it is combined with solar array infrastructure.

Despite a relatively short study period of three years for soil health and PCS parameters, and two years for forage quality parameters, significant benefits were seen. These benefits support the need for an ecosystem-based approach to vegetation management at solar sites. Grazed sites showed potential for improved soil indicators, such as higher organic matter, improved soil compaction, and stabilized erosion risks.

Along with individual soil indicators, average total CASH scores remained in "excellent functioning" levels throughout the study period. In addition to soil health benefits, improved forage quality was seen. The shading effect from solar panels led to improved CP and forage digestibility in some instances, providing favorable conditions for grazing livestock.

While these results are positive, this study could be improved to further evaluate how modifications in grazing rotation management under solar panels influence soil health, forage quality, and yields to further optimize environmental outcomes in these systems. Additionally, though various PCS categories for the study period improved, total scores suggested that the productivity and/or environment would benefit from continued enhancement.

The results presented demonstrate an opportunity for further improvement. Significant impacts found in this study on available water capacity indicate grazing may increase resilience to drought in solar grazing sites. Additionally, this study shows that incorporation of grazing into solar sites can increase soil carbon content, posing potential for this practice to enhance sequestration on solar sites.

Descriptive results from the SGS on economic factors demonstrated the need for long-term contracts and potential for grazing to be cost-competitive with mowing. Furthermore, solar grazing encourages local production of sheep and could reduce the need for importing products. There is a need for additional research on the scalability of solar grazing; however, there is potential for APV to provide long-term profitability despite market fluctuations (Gasch et al., 2025).

While many of the parameters investigated were highly dependent on climate, region, grazing management, and collection timing, this study serves as a baseline with early signs of improved site conditions from solar grazing. The benefits seen support the need for evolving policies and incentive programs that promote sustainable agriculture and renewable energy.

Overall, this study highlights the potential for solar grazing as a beneficial alternative to mechanical mowing for enhanced ecologically sustainable vegetation management at solar sites, promoting biodiversity, soil health, forage quality, and local production.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AA: Data curation, Project administration, Writing – original draft, Writing – review & editing, Supervision. KA: Writing – review & editing, Methodology, Data curation, Investigation, Writing – original draft. ZG: Investigation, Data curation, Writing – original draft, Formal analysis, Writing – review & editing. JB: Project administration, Funding acquisition, Writing – review & editing, Writing – original draft, Conceptualization, Investigation. LH: Writing – review & editing, Conceptualization, Funding acquisition, Writing – original draft, Methodology. AD: Investigation, Methodology, Writing – review & editing, Data curation, Writing – original draft. AW: Writing – review & editing, Methodology, Data curation, Investigation, Writing – original draft. CR: Investigation, Data curation, Writing – review & editing, Writing – original draft, Methodology. EC: Writing – review & editing, Methodology, Writing – original draft, Visualization. SP: Writing – review & editing, Writing – original draft. BM: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research 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.2025.1625483/full#supplementary-material

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