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Sheep Grazing Impacts on Soil Health and Pasture Quality at Commercial Solar Sites in Northeastern USA

Solar Sheep Grazing and Site Conditions

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Abstract. As solar sheep grazing continues to gain traction, it is important to emphasize soil health and pasture quality. Therefore, this study was performed to collect in-field data from 28 grazed and 3 non-grazed commercial solar sites to determine how grazing influences solar site health, associated ecosystem health, forage nutritive quality, and pasture conditions at Northeastern United States of America solar sites from 2022-2024. The majority of the selected sites were previously cropland. Construction of sites was between 2015-2020 with local graziers later joining the operation to create agrivoltaic systems. Sites were selected by their ability to contribute to the knowledge base over the duration of the study, provide relevant information about innovative co-location strategies and the willingness of all parties involved in the solar site maintenance to share information. Solar grazed sites tended to (p=0.06) have higher soil organic matter than non-grazed sites, with values of 4.14% and 3.70% respectively. Soil pH was significantly higher (p=0.01) in grazed sites, with an average of 6.20 compared to 5.81 in non-grazed sites, demonstrating the potential for solar grazing to improve solar site soil health. Crude protein was consistently significantly higher (p<0.001) in under panel areas for all seasons and years, while better digestibility was seen in under panel areas in Fall 2023. While not statistically significant (p=0.07), pasture condition scores increased between 2022 and 2023, suggesting that sheep grazing may have the potential to improve solar site pasture quality over time. Overall, solar sheep grazing helps to create a beneficial dual-use environment.

Keywords: Solar Grazing, Soil Health, Pasture Conditions, Ecosystem Health, Forage Quality

1. Introduction

Solar photovoltaic (PV) energy generation plays an important role in the global effort to transition to energy production that prioritizes reducing greenhouse gas emissions, helping to mitigate negative impacts on climate. It is reported that solar PV has the potential to account for up to half of the total global electricity generation by the year 2050 [1]. As solar energy development gains traction, there is a growing conflict in land use between solar site installations and farming in communities across the Northeastern region of the United States of America (USA). The states in this study have policies and initiatives that require an increase in renewable energy development which are accelerating the pace of this conflict. In order to reach these renewable energy goals and sustain agriculture, new solutions and compromises are being pursued. One way to address this is by adapting agrivoltaics, a dual-use land strategy that combines agricultural and solar energy production. Solar grazing, which involves vegetation management with the use of livestock, has been a growing industry in the past decade [2]. Past research on solar grazing has largely focused on behavior and liveweight gain; however, there is limited research on how this popular agrivoltaic approach influences forage nutrient quality, soil health, and overall ecosystem health [3, 4, 5]. Additionally, in 2018 the first Cornell Atkinson Center-funded research project involved one solar array and the health and well-being of sheep followed by a survey for solar operators across Northeastern USA [6]. The study was preliminary and lacked information that could guide solar professionals or farmers going forward. As such, the purpose of this study was to collect in-field data on how solar sheep grazing influences soil health, associated ecosystem health, forage nutritive quality and pasture conditions at 28 grazed and 3 non-grazed commercial solar sites in Northeastern USA. The sites and their history are described within the materials and methods section. Our preliminary analysis of this data from 2022 and 2024 suggests solar grazing can enhance forage quality and impact soil health parameters in multiple ways.

2. Materials and methods

This study was conducted to compare pasture quality and soil health at commercial solar sites with and without sheep grazing for vegetation management. This study was performed at 28 grazed solar sites and 3 non-grazed sites with sample collection beginning in Spring 2022 and completed Summer 2024. The sites were located primarily in New York with a total of 25 sites in the state, but also included 3 locations in Pennsylvania, 2 locations in Connecticut, and 1 location in Massachusetts. The sites ranged from 1.42 to 15.38 hectares (ha), with one site being 40.06 ha. 29 sites used fixed panels while the remaining 2 sites used single-axis tracking panels. Sites were constructed between 2015-2020. The majority reported prior land use of the sites was croplands (including hay and corn), followed by open fields (including fallow land), and finally woodlands. When selecting sites, graziers were sought out who were already solar grazing as a form of agrivoltaics. As such, the solar sites were constructed for the purpose of energy generation, with local graziers later joining the operation to create agrivoltaic sites, allowing for this baseline research to take place. Sites were selected by their ability to contribute to the knowledge base over the duration of the study, provide relevant information about innovative co-location strategies and the willingness of all parties involved in the solar site maintenance to share information.

Figure 1. *An example of a solar grazed site. Photo courtesy of A. Desario.*

All soil and forage samples were collected at both the non-grazed and grazed sites. Additionally, these samples were collected in areas under solar panels (UP) and in open space (OS) areas without direct shade from the panels.

Pasture conditions were measured only on grazed sites using Pasture Condition Scoring (PCS). PCS was recorded following the United States Department of Agriculture (USDA) Natural Resources Conservation Services (NRCS) Pasture Condition Scoring Sheet in the summer pre-grazing season and again in the fall post-grazing season for each year at each grazed site [7].

Two individual exclusion cages measuring 60.96 cm were placed at each grazed and non-grazed site with one in the UP treatment and one in the OS treatment (*Figure 2)*. These cages served as controls to the portions of the solar site that are grazed to compare the relative productivity between grazed and non-grazed sites. The cages were harvested in the summer and fall of each year by using electric shears or harvest knives to cut the forage to 7-10 cm above soil level. The sample was then weighed and sent to Dairy One Forage Laboratory to undergo forage analysis [8]. Following harvest, a new area was pre-cut and the exclusion cage was re-installed to prepare for the next sampling date.

Figure 2. *An example of an exclusion cage. Photo courtesy of A. Desario.*

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 treatments at grazed and non-grazed sites, resulting in 4 composite samples per site. GPS coordinates were identified to ensure the same location was monitored each year. A main location was selected, and 4 subsamples were collected around the main location, resulting in one composite sample created by 5 subsamples. To collect the samples, a hole was dug approximately 30 cm deep. 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 treatment were placed in a clean bucket, thoroughly mixed, and 32-40 oz of the composite sample was sent to Cornell Soil Health Laboratory to undergo analysis [9].

3. Results and discussion

3.1 Pasture condition scoring

There was not a significant difference (p=0.07) between the total pasture condition scores (PCS) between 2022 and 2023 with values of 33.01 and 34.83 out of 50 respectively (*Figure 3*). A high PCS value reflects a well-managed site with plant and animal productivity being sustained or enhanced. According to the National Resources Conservation Services scoring guidelines, the PCS values reported for 2022 and 2023 suggest that the productivity and/or the environment at the sites would benefit from further improving the site [7]. The lower scores seen in 2022 may have resulted from drought conditions during the testing period. Despite the difference in total PCS scores not being statistically significant, the increase in 2023 shows that grazing may have the potential to improve solar site pasture quality over time. The 2023 scores were at the verge of falling into the next PCS tier of 35-45, which involves only minor changes to enhance the site [7].

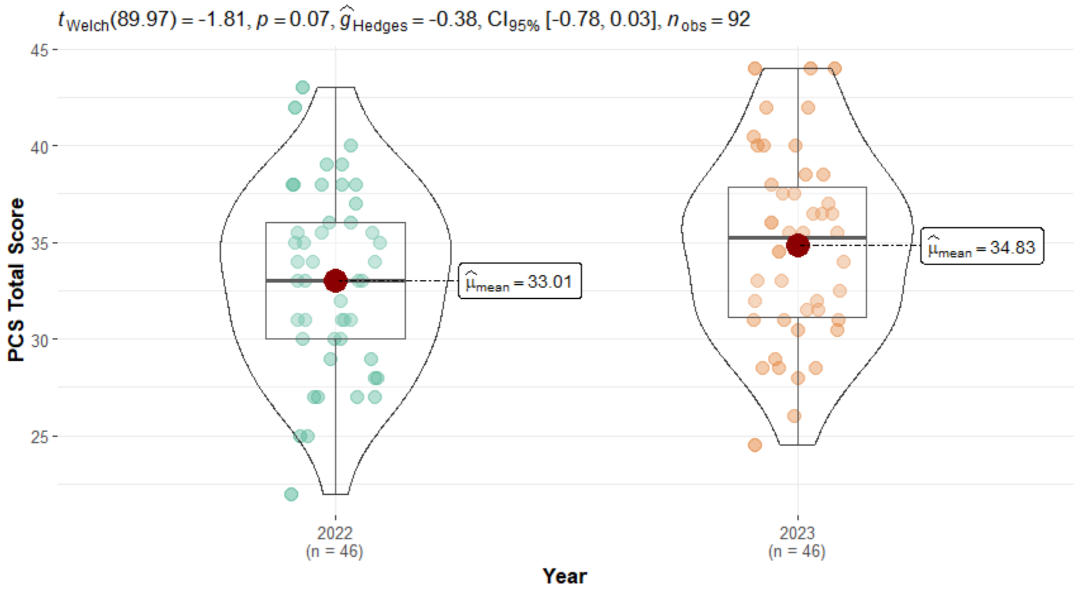

Figure 3. *Overall average pasture condition scores for 2022 and 2023. The maximum total score possible is 50, and higher values represent ideal site conditions.*

It is important to note that several categories are used to determine PCS, and a high or low value in one of these categories can influence the overall PCS value. In most cases, there was no significant difference between yearly seasons (*Table 1*). Individual scoring categories that experienced the most statistical difference between seasons was livestock concentration areas in the Fall (p<0.001), soil compaction in the Spring (p<0.001), and plant vigor in both Fall (p<0.001) and Spring (p<0.001). For most cases, the PCS values increased, demonstrating improved site conditions.

Table 1. *PCS Scores for all study sites separated by season. Scores range from 1-5 with 1 being poorest site conditions and 5 being ideal site conditions.*

	Fall 2022 (n=21)	**Fall 2023** (n=25)	**P-Value**		**Spring 2022** (n=25)	**Spring 2023** (n=21)	**Spring 2024** (n=27)	**P-Value**
% Desirable Plants	3.52	3.62	.79		3.88	3.45	3.56	.39
% Legumes by Dry Weight	1.76	2.10	.41		2.40	1.38	1.65	.06
Live Plant Cover	3.28	3.88	.02		3.32	3.48	3.63	.43
Plant Diversity	3.52	3.62	.79		3.88	3.45	3.56	.39
Plant Residue	3.17	3.66	.06		3.08	3.33	3.13	.49
Grazing Utilization	4.00	3.50	.12		3.83	3.40	4.25	.04
Livestock Concentration Areas	3.52	4.24	**<.001**		3.88	3.92	4.44	.03
Soil Compaction	3.21	3.44	.43		2.92	3.17	3.65	**<.001**
Plant Vigor	3.32	4.26	**<.001**		3.48	4.07	4.17	**<.001**
Erosion	3.98	4.46	.03		4.08	4.12	4.24	.75

To attempt to avoid a large difference in values between OS areas and UP areas, most of our sites were calculated by determining PCS values in the OS and UP areas individually. However, this data wasn't collected at every site. For those sites that were unable to be measured this way, a score that was representative of the whole site was recorded. For sites with two separate PCS values, we combined the values and averaged them to reflect conditions between and under panels (AVG) PCS value. This equal weighting of values approach was appropriate due to the row spacings of the solar panels. By including AVG PCS results we were able to compare results across all study sites, as seen in *Table 1*.

OS had significantly (p<0.001) higher scores for erosion, correlating with less observed evidence of erosion, than UP and the AVG scores (p=0.01, *Figure 4*). It is suggested from some previous modelling results that solar panels may increase erosion due to the higher energy and velocity of water draining from the panels and causing soil erosion below the panels [10]. This phenomenon may account for the lower erosions scores seen in UP areas. However, despite the lower scores in the UP area, there was no overall significant differences in erosion when adjusted for the season (*Table* 1).

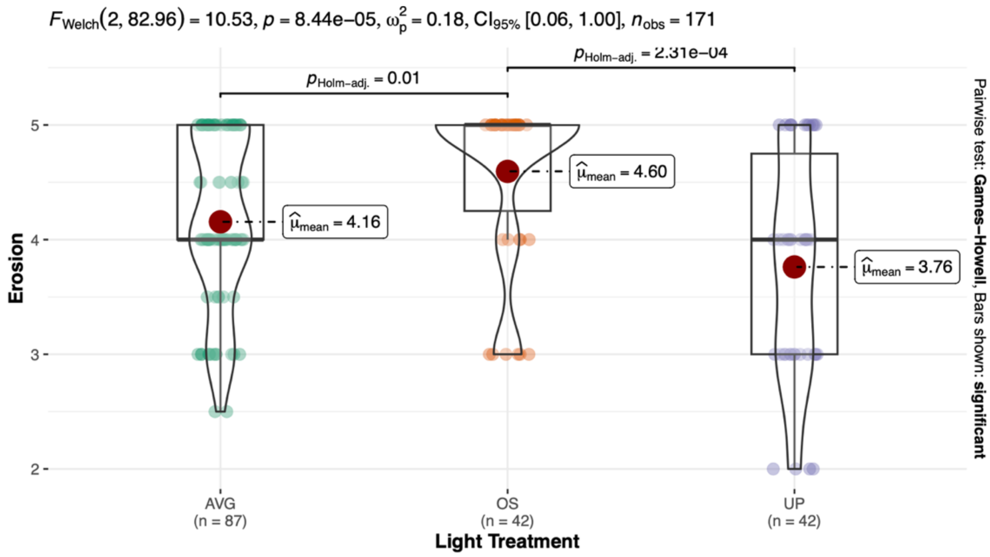

Figure 4. *Soil erosion PCS values for AVG, OS, and UP. Scores range from 1-5 with higher values representing ideal site conditions.*

3.2 Effects of solar panels on forage quality

Forages harvested from under panels in 2023 had significantly higher crude protein (CP) content and significantly better digestibility than those values observed in open space areas (*Table 2*). This suggests that grazing sites may experience enhanced forage quality when agrivoltaics are incorporated as the shading effects from the panels provided higher quality forage in 2023. CP was significantly higher in in all seasons and years (p<0.001) when harvested under panels (*Table 2*). This is supported by existing literature that found higher CP in shaded areas [11]. Non-digestible fiber content, measured as Acid Detergent Fiber (ADF), was significantly lower (p=0.02) when harvested from under panels (UP) in Fall 2023 (*Table 2*). Another measure of digestibility, Neutral Detergent Fiber (aNDF), was significantly lower (p=0.03) in the UP treatment in Fall 2023 (*Table 2*). The higher CP and lower aNDF under panels are consistent with previous solar grazing studies [3].

Table 2. *Significance levels and mean values for forage nutritive quality tests in the open space (OS) and under panel (UP) areas from the 2022 and 2023 seasons.*

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

3.3 Effects of grazing on soil health

Averaged between the two years, soil organic matter at grazed sites tended to (p=0.06) be significantly greater than non-grazed sites with average values being 4.14% and 3.70% respectively (*Table 3*). It is worth mentioning that the sample size of non-grazed sites was much smaller (n=18) than grazed sites (n= 143). Soil pH was also significantly (p=0.01) higher in grazed sites than non-grazed sites, with an average of 6.20 and 5.81 respectively (*Table 3).*

Table 3. *p-values and mean values for soil organic matter and pH in grazed or non-grazed sites and open space or under panel areas averaged across 2022 and 2023.*

	Grazed or Non-Grazed			Open Space or Under Panel		
Soil Test	SG (n=143)	NG (n=18)	P-value	OS (n=81)	UP (n=80)	P-value
OM%	4.14	3.70	0.06	4.12	4.05	0.75
pH	6.20	5.81	0.01	6.20	6.12	0.53

The higher soil organic matter and pH values in grazed sites demonstrates the potential for solar grazing to improve solar site soil health. Larger soil organic matter values help to reduce soil compactibility [12]. Additionally, grazing allows for soil pH to reach near optimal soil pH levels (optimal=6.0; [13]).

3.4 Conclusions

This study demonstrates the ability of solar grazed agrivoltaic systems to have the potential to enhance forage quality and improve soil health. Crude protein and lower aNDF values for 2023 in UP areas suggested a higher forage quality for shaded areas present in agrivoltaic systems.

Additionally, while not statistically significant, an increase in overall PCS values was seen in 2023, showing that grazing may improve pasture quality over time. Grazed solar sites contained higher soil organic matter and pH levels, suggesting grazing may have the ability to continually improve soil health at solar sites. Overall, solar sheep grazing helps to create a beneficial dual-use environment.

3.5 Limitations and Future Directions

A noticeable limitation to this study is the short sampling timeframe. Some benefits from improved soil health may take 5-10 years to become measurable, demonstrating that it is possible that with this short-term study is not fully capturing the change in soil health [14]. 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. Planning for a potential follow-up data collection in the future would prove beneficial while using this initial work to establish a baseline.

Data availability statement

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

Author contributions

All authors listed have contributed greatly to the work through a combination of field efforts and preparing the report. Alyssa Andrew assisted with project administration and supervision, data curation, and writing and reviewing the paper. Lexie Hain contributed to the conceptualization, methodology and funding acquisition stages. Jonathan Barter assisted with conceptualization, administration, investigation and reviewing. Allison Desario and Caro Roszell contributed to data curation, investigation, and methodology. Zachary Goldberg, Dr. White, and Kevin Antoszewski contributed to data curation and analysis, investigation, visualization, and writing and reviewing.

Competing interests

The authors declare that they have no competing interests.

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