Impacts of Dual-Use Solar on Soil Health in Massachusetts

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1 Executive Summary

Agrivoltaics (dual-use solar) co-locates photovoltaic (PV) electricity generation with crop production, creating a overhead structure that alters solar radiation, hydrology, and disturbance regimes. Although agrivoltaic research has historically emphasized crop yield and energy tradeoffs, soil effects are increasingly recognized as central to long-term agronomic viability and ecosystem services, including infiltration, aggregation, nutrient cycling, and soil carbon (C) storage (Carvalho et al., 2024; Krasner et al., 2025).

American Farmland Trust (AFT) was a sub-awardee of UMass on the U. S. Department of Energy Award DE-EE0009374, "Impacts of Dual-Use Solar on Crop Productivity and the Agricultural Economy in Massachusetts and Beyond". This research project comprised multiple Agricultural Solar Tariff Generation Unit (ASTGU) sites in Massachusetts.

AFT's role was to collect and analyze soil data relevant to soil health, as well as assist in reporting and communication of results. AFT collected replicated data to evaluate the temporal impacts of the solar arrays at all sites, pre and post construction environmental data at some sites, and within array replicated data across microclimates at one site, with which to perform statistical analyses and identify significant impacts

This study evaluated soil health responses to agrivoltaic (dual-use solar) systems across three agricultural contexts in Massachusetts—one hayfield and two vegetable production sites—using replicated field sampling, mixed-design repeated-measures statistical analyses, and within-array spatial assessments. Soil physical, chemical, and biological indicators were measured over multiple years to assess both treatment effects (agrivoltaic vs. control) and temporal dynamics following solar array installation.

Overall, results indicate that soil health outcomes under agrivoltaic systems were driven more strongly by management practices, temporal variability, and micro-scale environmental conditions than by the presence of solar panels alone. Where agrivoltaic effects were detected, they were most often expressed as differences in how soils changed over time or differed by site context.

1.1 Key Findings

- **Agrivoltaic effects were most evident in annual dynamics, not uniform treatment differences.** Across sites, relatively few soil health indicators exhibited statistically significant treatment × year interactions. Where interactions were detected, they indicated differing trajectories over time rather than differences between agrivoltaic and control plots.

- **Soil chemical and biological indicators showed the clearest agrivoltaic signals.** At the Monson hayfield site, soils beneath the solar array experienced a smaller decline in pH and a greater reduction in soil respiration over time compared to control soils. At the Grafton vegetable site, soil microbial respiration was significantly impacted by proximity to panel microclimates. These patterns suggest agrivoltaic influences on soil microclimate and moisture conditions that affect microbial activity and chemical buffering.

- **Soil physical indicators varied by site and management context.** At vegetable sites, bulk density differed between agrivoltaic and control plots; however, no site exhibited a significant treatment × year interaction for bulk density, indicating no evidence of progressive compaction following installation. At the Hadley site, bulk density showed a significant treatment effect but did not change differentially over time, suggesting persistent site or management contrasts rather than ongoing infrastructure-driven compaction. At the Grafton site, bulk density showed a significant treatment effect, with bulk density trends over time best explained by contrasting tillage regimes .

- **Within-array variation revealed important micro-scale processes.** At the Grafton vegetable site, soil respiration varied substantially within the agrivoltaic array and was strongly and positively related to soil moisture across bed locations in relation to panel microclimates. This finding demonstrates that moisture redistribution within arrays—rather than panel presence alone—was a dominant driver of soil biological activity at fine spatial scales.

- **Early agrivoltaic soil responses in vegetable systems were subtle.** At the Hadley site, where pre-construction data were available, most soil health indicators changed similarly over time in agrivoltaic and control plots. This suggests that, within intensively managed annual vegetable systems, short-term agrivoltaic effects on soil health may be difficult to detect relative to year-to-year environmental variability and management impacts.

1.2 Cross-Cutting Themes

Context matters: Soil texture, crop system, baseline conditions, and management intensity strongly influenced soil responses to agrivoltaic systems.

Scale matters: Whole-plot treatment comparisons may obscure important within-array processes driven by soil moisture and microclimate heterogeneity.

Time matters: Detecting agrivoltaic impacts on soil health—particularly physical properties—likely requires longer monitoring periods than are typical of short-term field studies.

1.3 Implications

Differences in soil condition between agrivoltaic and control areas should be interpreted cautiously, particularly in the absence of pre-construction baselines or when treatment effects are not accompanied by temporal divergence. Future agrivoltaic research and project design should prioritize pre-construction soil characterization, long-term monitoring, and spatially explicit sampling approaches to better capture the mechanisms—particularly soil moisture dynamics—through which agrivoltaic systems influence soil function. Such approaches will be essential for informing agrivoltaic designs and management strategies that support both agricultural productivity and long-term soil health.

2 Literature Review

Recent systematic reviews of photovoltaic–soil interactions emphasize that soil outcomes are strongly shaped by pre-installation land use, construction disturbance, vegetation management, and panel configuration, often more so than panel presence alone (Carvalho et al., 2024; Krasner et al., 2025). In humid temperate regions such as the Northeast United States, where soils are frequently glaciated, moderately acidic, and subject to freeze–thaw cycles, understanding how agrivoltaics alters soil microclimate and structure is especially important.

Across field experiments and syntheses, soil effects in agrivoltaic systems emerge through four interacting pathways.

2.1 Radiation and Energy Balance Shifts

PV shading reduces shortwave radiation reaching the soil surface, typically moderating soil temperature extremes and reducing peak evaporative demand. In a tomato agrivoltaic study, soil temperatures under PV structures differed by as much as 7.7°C compared to open-sun controls, demonstrating the potential magnitude of microclimatic modification (Scarano et al., 2024).

Similarly, in a temperate German agrivoltaic system including celeriac and potato, reduced photosynthetically active radiation (~30% reduction) was associated with decreased summer soil temperatures beneath panels (Weselek et al., 2021). These moderated temperature regimes may influence microbial activity, root growth dynamics, and moisture retention—processes directly tied to soil health in vegetable systems.

2.2 Water Redistribution and Soil Water Balance

PV arrays intercept rainfall and create heterogeneous throughfall patterns, concentrating water along drip lines while sheltering soil beneath panels. Marrou et al. (2013c) quantified soil water stocks and fluxes in lettuce and cucumber systems under PV structures and demonstrated measurable alterations in evapotranspiration and water balance dynamics relative to open-field controls.

In humid temperate regions, such redistribution may reduce soil evaporation in sheltered zones while increasing localized infiltration near panel edges. Weselek et al. (2021) similarly reported changes in soil moisture distribution associated with agrivoltaic structures in Germany, reinforcing that water-mediated mechanisms are central to soil response.

2.3 Disturbance, Compaction, and Vegetation Shifts

Construction-phase impacts—including grading, heavy equipment traffic, and altered drainage—can increase compaction and modify infiltration pathways. Conversely, long-term management practices such as perennial groundcover establishment, reduced tillage, and controlled grazing may enhance soil carbon storage and aggregation relative to conventional annual cropping systems (Carvalho et al., 2024; Krasner et al., 2025).

Systematic reviews consistently conclude that soil carbon trajectories under solar development are management-dependent rather than technology-determined (Carvalho et al., 2024; Krasner et al., 2025). For Northeast vegetable systems, this distinction is critical, as conversion from annual tilled systems to perennial vegetated solar understories may stabilize or increase soil carbon stocks, whereas poorly managed installation disturbance may degrade soil structure.

2.4 Soil Biological Activity and Carbon Cycling

Soil biological responses may occur even when bulk soil carbon remains unchanged. A NYSERDA-funded field study across multiple Hudson Valley solar sites found that total soil carbon and nitrogen did not differ significantly among beneath-panel, between-row, and reference zones; however, soil respiration was consistently lower beneath panels (NYSERDA, 2025). Microbial biomass remained relatively stable across microsites, suggesting altered metabolic activity rather than reduced microbial abundance. At one site converted from forest, declines in pH and aggregate stability were also observed (NYSERDA, 2025).

These findings suggest that agrivoltaic-induced microclimate shifts may influence soil biological function in ways not immediately detectable through total carbon measurements alone.

2.5 Evidence from Vegetable-Focused Agrivoltaic Field Studies

Weselek et al. (2021) evaluated an agrivoltaic system in southwestern Germany within an organic crop rotation including celeriac and potato. The study reported reduced summer soil temperatures and altered soil moisture dynamics under panels relative to open controls, indicating meaningful changes in the soil physical environment.

French agrivoltaic experiments provide complementary mechanistic evidence. Marrou et al. (2013a, 2013b, 2013c) demonstrated that partial shading under PV arrays affects crop radiation-use efficiency, evapotranspiration, and soil water flows in lettuce and cucumber systems. These studies collectively establish that PV shelter can alter the soil–crop water balance, potentially affecting infiltration, soil moisture retention, and nutrient dynamics.

2.6 Northeast U.S. Vegetable Trials

In Massachusetts, Doubleday et al. (2025) conducted a three-year agrivoltaic trial with broccoli, peppers, kale, and Swiss chard. Yield responses varied substantially among years, suggesting that agrivoltaic performance in humid temperate climates is climate-dependent. Importantly, the authors note that additional environmental monitoring—particularly soil moisture and temperature—would strengthen interpretation of observed yield patterns (Doubleday et al., 2025). This highlights a current limitation in Northeast agrivoltaic research: soil health metrics are not yet routinely integrated into vegetable-focused trials.

In New York, Sturchio et al. (2025) evaluated radish and radicchio production within an energy-optimized agrivoltaic array. The study found suppressed fall biomass associated with reduced irradiance levels, illustrating potential seasonal light constraints at higher latitudes. While soil metrics were not central to the study, the findings imply that soil moisture moderation may not fully offset reduced radiation in late-season vegetable systems (Sturchio et al., 2025).

2.7 Soil Health Indicators under Solar Development in the Northeast

The NYSERDA (2025) field study provides the most comprehensive soil-health dataset currently available for the Northeast. Across three solar developments, total soil carbon and nitrogen were similar across microsites; microbial biomass was stable; however, soil respiration was consistently reduced beneath panels. Additionally, at a formerly forested site, panel-associated conditions coincided with lower pH and reduced aggregate stability (NYSERDA, 2025). These results emphasize two key conclusions for Northeast agrivoltaic vegetable systems: soil responses are microsite-specific, and different indicators may respond in divergent ways.

2.8 Synthesis for Northeast Vegetable Agrivoltaic Systems

Across temperate-climate agrivoltaic studies, the most consistent soil-related findings include:

- Moderated soil temperature extremes beneath panels (Scarano et al., 2024; Weselek et al., 2021).
- Altered soil water distribution and evapotranspiration patterns (Marrou et al., 2013c; Weselek et al., 2021).
- Management-dependent soil carbon outcomes (Carvalho et al., 2024; Krasner et al., 2025).
- Shifts in soil biological activity without corresponding changes in total soil carbon (NYSERDA, 2025).

For Northeast vegetable systems specifically, the literature suggests that soil moisture buffering and reduced heat stress may benefit crops during episodic summer drought, but reduced irradiance may constrain late-season productivity (Doubleday et al., 2025; Sturchio et al., 2025). Direct soil health data from vegetable agrivoltaic trials remain limited, underscoring the need for integrated soil monitoring in future studies.

3 Experimental design

Soil sampling protocol methodology was consistent for each measure. However, experimental design was unique at each site in order answer numerous research questions, based on array construction, farm management, and crop type.

Research questions are as follows:

- RQ 1. Are soils under solar panel installations in dual-use solar sites significantly different from soils not under panels in the same sites?

- RQ 2. Does the installation of dual-use solar arrays cause a measurable and/or significant change in soil quality characteristics?
- RQ 3. How do solar array rain shadow effects influence soil health under solar panels?

To evaluate the impact of agrivoltaics on soil health and answer RQ1 & RQ2, this project utilized a replicated plot design. Four sampling plots within each treatment (control and treatment) served as replicates for the experimental design and were sampled in multiple years. Treatment was considered the soils under and between the solar arrays, and control was considered the soil outside the area affected by solar arrays. To answer RQ 2 samples were collected prior to array construction and again post construction, with a minimum of 4 replicated sampling locations. To answer RQ 3, additional sampling was done in fall 2023 at the Grafton Vegetable site. To evaluate the influence of the array rain shadow effects on soil health, we sampled using a nonrandom complete block design within a single year.

3.1 Soil Health Testing Protocols

The concept of soil health integrates "the chemical, physical, and biological processes of soil that are important for sustained productivity and environmental quality." For this research, soil health analysis was conducted using the Cornell Comprehensive Assessment of Soil Health (CASH). The Cornell Framework is a comprehensive assessment of soil health based on measurements of indicators that represent critical soil processes, including soil organic matter, respiration, aggregate stability, active carbon, a soil protein index, soil texture, soil compaction via penetrometer, and nutrient concentrations in ppm. Details of the testing procedures can be found here: https://soilhealth.cals.cornell.edu/manual/. Specific protocol used in this research are described in section 1.2 and Appendix A of this document.

Bulk density was measured using an oven-dried intact core method to assess soil physical condition and potential compaction differences between agrivoltaic and control plots. Undisturbed soil cores were collected using standardized coring equipment. At each sampling location, bulk density cores were extracted from representative, undisturbed areas and dried to constant mass prior to calculation of bulk density (g cm^{-3}). Bulk density sampling frequency varied by site based on study design and data availability. At the Hadley vegetable site, bulk density was measured repeatedly across multiple years, enabling evaluation of both treatment effects and temporal dynamics using mixed-design repeated-measures analysis.

At the Grafton vegetable site, a higher volume of replicated samples were taken to evaluate specific individual soil health indicators, aggregate stability and respiration, where the goal was to evaluate changes due to location relative to the array. Aggregate stability and active carbon were selected as soil health indicators for this because they respond most quickly to changes management practices.

Soil sampling protocol methodology was identical at each site. However, experimental design was unique at each site in order to answer specific research questions, based on array construction, farm management, and crop type.

3.2 Experimental sites

Three sites were established in time to be included in AFT's soil health research. The Monson site, aka Million Little Sunbeams Farm, is a hay site constructed prior to the onset of data collection. The Grafton Vegetable array, aka Knowlton Farm, and the Hadley site both produce vegetable crops.

Table 1. *Dual-use solar research sites and experimental design notes*

Site name	Field type	Soil data being collected by AFT	Baseline data collection date	Experimental design notes	Data collection
Grafton Vegetable	Vegetable	CASH, bulk density, soil compaction via penetrometer	Jan 2021 preconstruction, June 2022, post construction	Replicated unpaired. RQ1, RQ2, RQ3	CASH in fall annually 2022 through 2024. Penetrometer annually. BD in 2022 and 2024. Aggregate stability and respiration
Monson	Hay	CASH, soil compaction via penetrometer	Post-construction in July 2022 July 2024	Replicated unpaired RQ1	CASH in Spring 2022, annually thereafter through. Penetrometer annually.
Hadley	Vegetable	CASH, bulk density, soil compaction via penetrometer	November 2022, April, 2023, annually	Replicated, paired RQ1, RQ2	CASH in Fall 2022, annually thereafter until 2024. BD annually. Penetrometer annually.

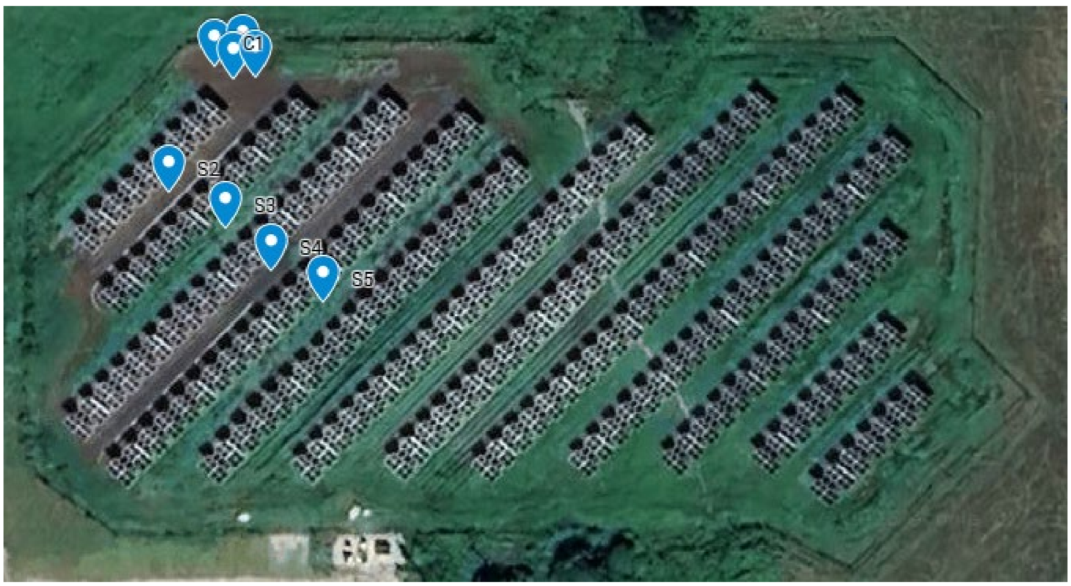
3.2.1 Monson Hay Site

The solar array at the Monson, MA site (Million Little Sunbeams Farm) was constructed prior to the initiation of this research project. The crop at this site is hay, grown on fields historically producing cut hay for dairy production. The control was a section of the field with similar historical management and no solar panels installed. At this site solar panels were bifacial tracking design, while all other sites had fixed panels.

All soil data at this site was collected after construction of the site. Soil health samples were collected in June 2022 from the control and treatment (within solar array) and then collected again in 2024 from the same plot locations. Penetrometer readings were taken in 2022 and 2024. The data analysis at this site was limited because there was no pre-construction data.

3.2.2 Grafton Vegetable Site

This experiment evaluated the difference between soils under the solar array versus no solar array. Prior to solar array construction, this plot was a holding area for animals with numerous rocks that were removed to plant annual crops. Crops selected were butternut squash (*Cucurbita moschata*), a fruiting warm season annual, and lettuce (*Lactuca sativa*) and leafy cool season annual.



There were four beds in each bay, separated by a line of solar panels, which made up one replicate (see Figure 3). All four beds in the first replicate extended into an unshaded area to serve as the control. Each replicate included four beds of one crop, followed the next year by the other crop.

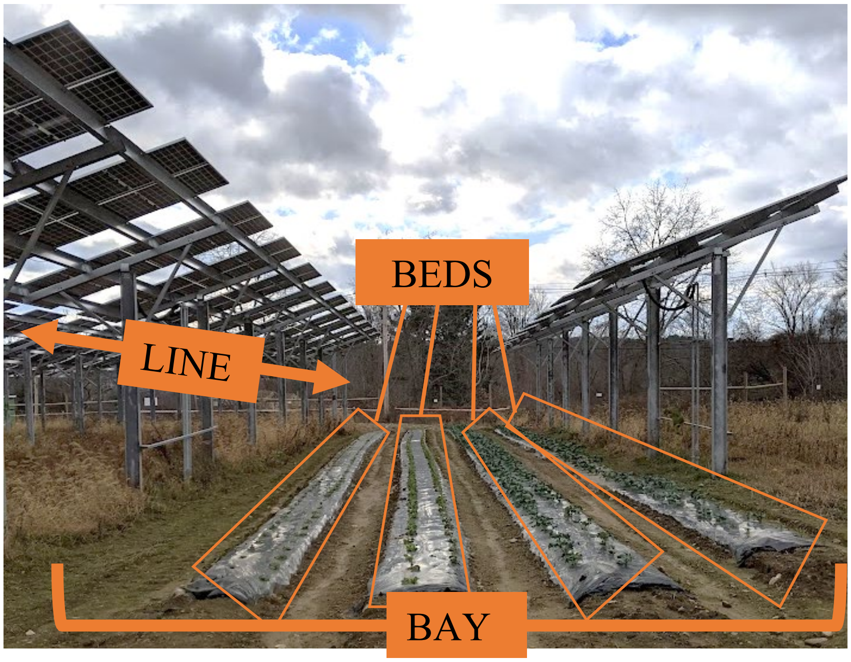


Figure 3. Illustration of language used to describe locations within the field at vegetable research sites. Image source: Sam Glaze-Corcoran PhD, UMass Amherst.

CASH samples were collected as composite from the four control plots and the four treatment plots. In the final year, we evaluated differences in bed location relative to the solar array by evaluating soil characteristics that are highly responsive to management practices: aggregate stability and respiration.

3.2.3 Hadley Vegetable Site

The Hadley vegetable site was in agricultural production prior to construction of the agrivoltaic array. The field was considered a lower quality soil by the farm owner. The control area was selected on either side of the array,

3.2.4 Sites Not Developed

The Grafton Grazing site was not developed time for inclusion in this research. For twenty-five years the land was not managed, and subsequent growth of young pine trees had to be removed to develop the dual use array. The very rocky soil needed to be raked and picked of large rocks and boulders. Lime was needed to moderate soil pH, and new pasture needed to be established, which wasn't done until 2025.

A site in Dighton, MA was expected to be in development during the spring and summer of 2023, and preconstruction samples were taken. However, development was not completed in time to be conducted.

4 Data Treatment & Statistical Analysis

All soil health data were compiled and evaluated for completeness prior to statistical analysis. Analyses were conducted in R (RStudio Team, 2022) using packages designed for factorial and repeated-measures experimental designs. Data preparation and visualization were supported by the *tidyverse* suite of packages (Wickham et al., 2019), including *dplyr* for data manipulation and *ggplot2* for figure generation (Wickham, 2016; Wickham et al., 2022), with descriptive statistics summarized using the *table1* package (Rich, 2025).

4.1.1 Repeated Measures and Mixed-Design ANOVA

To evaluate the effects of agrivoltaic treatment, time, and their interaction on soil health indicators, mixed-design analyses of variance (ANOVA) were conducted using the afex::aov_ez() function. This approach accommodates repeated measurements collected from the same sampling locations over multiple years, while simultaneously testing between-plot treatment effects (Pagliari et al., 2022).

For these analyses, individual sampling locations (soil sampling points) were specified as the subject identifier, year was treated as a within-subject (repeated measures) factor, and treatment (agrivoltaic vs. control) was treated as a between-subject factor. A representative model structure is shown below:

```
<<
model_ph <- afex::aov_ez(
id = "Point",
dv = "ph",
data = HadleySoil,
within = "Year",
between = "Treatment")
>>
```

This modeling framework allows for formal testing of:

- The main effect of treatment, indicating overall differences between agrivoltaic and control soils;
- The main effect of year, indicating temporal change across the study period; and
- The treatment × year interaction, indicating whether soil properties changed differently over time in agrivoltaic versus control plots.

ANOVA models were fit using Type III sums of squares, appropriate for unbalanced designs and common in ecological field studies. Statistical significance was assessed using F-tests, with degrees of freedom estimated using methods implemented in afex and rstatix to account for repeated measures structure (Singmann et al 2021; Kassambara 2022).

4.1.2 Interpretation of Effects

Where a statistically significant treatment × year interaction was detected, results were interpreted as evidence that soil properties responded differently over time between agrivoltaic and control plots. In cases where only main effects were significant and interactions were not, differences were interpreted cautiously, particularly for sites lacking pre-construction baseline data.

4.1.3 Within-Array and Mixed-Effects Analyses

For analyses focused on within-array spatial variability, such as bed location effects at the Grafton vegetable site, linear mixed-effects models were used. These models incorporated plot as a random effect to account for non-independence of observations and evaluated environmental predictors (e.g., soil moisture) as fixed effects. This approach allowed assessment of fine-scale drivers of soil biological activity beyond whole-plot treatment comparisons.

5 RESULTS

5.1 HAYLAND SOIL DIFFERENCES AT MONSON SITE

Soil health indicators at the Monson hayfield site were evaluated to compare soils beneath the solar array with adjacent non-array control areas and to assess how these differences changed over time. Because all soil data at this site were collected after construction of the solar array, analyses focused on detecting temporal trends and treatment × year interactions, rather than attributing baseline differences directly to agrivoltaic installation.

Soil health data from 2022 and 2024 were analyzed using mixed-design repeated-measures ANOVA to test for main effects of treatment (agrivoltaic vs. control), year, and their interaction.

5.1.1 Soil Chemical and Biological Indicators

Significant treatment × year interactions were detected for soil pH and soil respiration, indicating that these variables changed differently over time in agrivoltaic and control plots.

Soil pH declined across the site between 2022 and 2024; however, the magnitude of this decline differed by treatment. Soils beneath the solar array experienced a smaller decrease in pH compared to soils outside the array, resulting in a significant treatment × year interaction. This pattern indicates that the presence of solar panels was associated with buffered temporal changes in soil acidity, rather than a static difference between treatments.

Soil respiration also declined over time across the site, but the reduction was significantly greater beneath the solar panels than in the control plots. The significant treatment × year interaction for respiration indicates that microbial activity decreased more rapidly over time under the agrivoltaic array. This result suggests a treatment-specific temporal response rather than a pre-existing difference between locations.

5.1.2 Soil Physical Indicators

Subsurface hardness exhibited a significant treatment × year interaction. In 2022, subsurface hardness was greater in the control plots than beneath the solar array. By 2024, subsurface hardness values converged between treatments, indicating a relative reduction in the difference observed initially. This interaction suggests that subsurface compaction dynamics differed over time between agrivoltaic and control areas, though the absence of pre-construction measurements limits causal attribution.

Surface hardness declined substantially between years in both treatments, reflecting a strong temporal effect. No significant treatment effect or treatment × year interaction was detected, indicating that changes in surface penetration resistance were driven by site-wide factors such as soil moisture conditions or management rather than by agrivoltaic treatment.

5.1.3 Soil Carbon and Nutrient Indicators

Several soil carbon and nutrient indicators—including organic matter, total carbon, soil organic carbon, and total nitrogen—exhibited significant main effects of treatment but did not show significant treatment × year interactions. In these cases, mean values differed between agrivoltaic and control plots, but the direction and magnitude of change over time were similar in both treatments.

Because baseline (pre-construction) data were not available for the Monson site, these main effects cannot be attributed confidently to the installation of the solar array. Instead, they likely reflect pre-existing spatial variability in soil conditions or historical management differences between the areas selected as agrivoltaic and control plots.

5.1.4 Summary of Monson Site Results

Overall, results from the Monson hayfield site indicate that temporal dynamics were a dominant driver of soil health change, with agrivoltaic treatment influencing the trajectory of select indicators rather than producing uniform differences across all soil properties. Significant treatment × year interactions for soil pH and respiration suggest that soils beneath the solar array experienced distinct temporal patterns in chemical conditions and microbial activity. In contrast, most soil physical and nutrient indicators changed similarly over time in both agrivoltaic and control plots, underscoring the importance of site-wide environmental conditions and management in shaping soil health outcomes at this location.

Data from the Monson site was evaluated for observable differences comparing soil health measures among soils within solar panel arrays versus soils outside of solar panel arrays.

Significant differences based on the interaction of time and treatment were detected in soil pH, respiration, and subsurface hardness.

- Soil pH decreased significantly for all soils across the site between 2022 to 2024, but the amount of change was influenced by the presence of solar panels. Soil pH dropped less under solar panels.
- Respiration also reduced over time across the whole site, but dropped significantly more under the solar panels.
- Subsurface hardness was significantly greater in the control that the treatment in 2022, and then within similar ranges in 2024

There are some soil health parameters that were different by treatment but did not have significant interaction effect between treatment and year. In these cases, we cannot ascribe the differences to the treatment, as we do not have baseline data and cannot assume the control & treatment sites were not different before the treatment was installed.

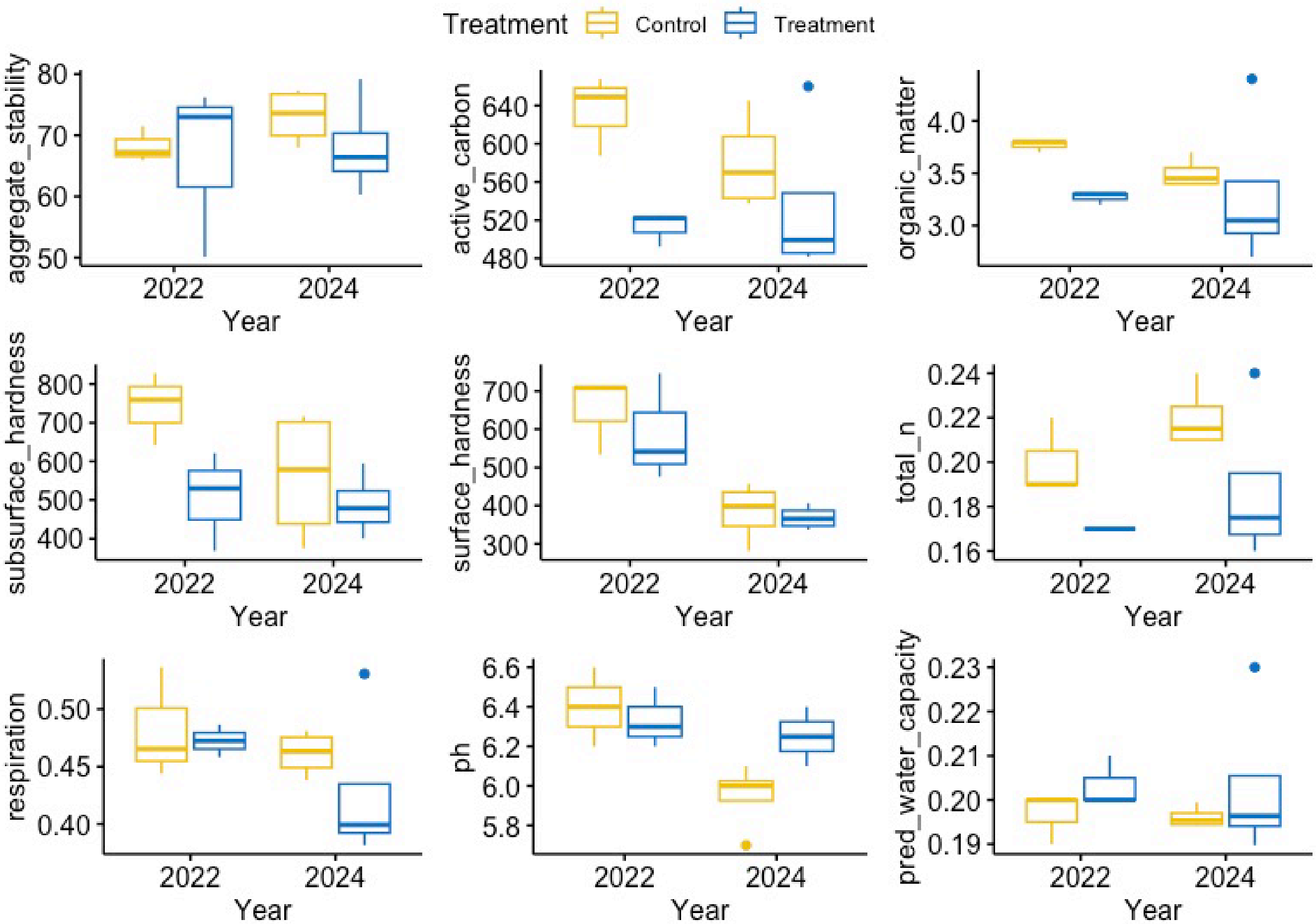


Figure 1. Soil health parameters at Monson Site in 2022 and 2024.

Table 2. Descriptive statistics for soil health parameters at Monson site.

Soil health measure	2022 Control (N=3)	2022 Treatment (N=3)	2024 Control (N=4)	2024 Treatment (N=4)
Aggregate stability %				
Mean (SD)	68.2 (2.93)	66.4 (14.2)	73.1 (4.55)	68.1 (8.00)
Median [Min, Max]	67.2 [65.9, 71.5]	73.0 [50.1, 76.2]	73.6 [68.0, 77.3]	66.4 [60.3, 79.2]
Active carbon (ppm)				
Mean (SD)	635 (42.0)	513 (17.8)	580 (50.1)	535 (84.3)
Median [Min, Max]	649 [587, 668]	522 [492, 524]	570 [537, 645]	499 [481, 660]

Organic matter (%)				
Mean (SD)	3.77 (0.0577)	3.27 (0.0577)	3.50 (0.141)	3.30 (0.753)
Median [Min, Max]	3.80 [3.70, 3.80]	3.30 [3.20, 3.30]	3.45 [3.40, 3.70]	3.05 [2.70, 4.40]
Subsurface hardness (psi)				
Mean (SD)	743 (94.2)	506 (128)	562 (171)	488 (81.8)
Median [Min, Max]	759 [641, 828]	530 [368, 621]	578 [375, 716]	478 [400, 594]
Surface hardness (psi)				
Mean (SD)	651 (101)	588 (141)	384 (77.9)	369 (31.1)
Median [Min, Max]	709 [534, 710]	542 [476, 747]	398 [281, 458]	366 [338, 406]
Total nitrogen (%)				
Mean (SD)	0.200 (0.0173)	0.170 (0)	0.220 (0.0141)	0.188 (0.0359)
Median [Min, Max]	0.190 [0.190, 0.220]	0.170 [0.170, 0.170]	0.215 [0.210, 0.240]	0.175 [0.160, 0.240]
Respiration (mg CO_2/g)				
Mean (SD)	0.482 (0.0483)	0.472 (0.0142)	0.461 (0.0195)	0.428 (0.0691)
Median [Min, Max]	0.465 [0.444, 0.536]	0.472 [0.458, 0.487]	0.463 [0.438, 0.481]	0.399 [0.382, 0.531]
pH				
Mean (SD)	6.40 (0.200)	6.33 (0.153)	5.95 (0.173)	6.25 (0.129)
Median [Min, Max]	6.40 [6.20, 6.60]	6.30 [6.20, 6.50]	6.00 [5.70, 6.10]	6.25 [6.10, 6.40]
Available water capacity (g/g)				
Mean (SD)	0.197 (0.00577)	0.203 (0.00577)	0.196 (0.00238)	0.203 (0.0182)
Median [Min, Max]	0.200 [0.190, 0.200]	0.200 [0.200, 0.210]	0.195 [0.194, 0.199]	0.196 [0.190, 0.230]

Table 3. Repeated measures ANOVA analysis for soil health parameters at Monson site.

Soil health measure	Effect	df	MSE	F	ges	p.value
Organic matter	Treatment	1, 4	0.02	51.86 **	.861	.002
	Year	1, 4	0.02	12.57 *	.622	.024

	Treatment:Year	1, 4	0.02	0.39	.049	.566
Soil organic carbon	Treatment	1, 4	0.02	27.03 **	.742	.007
	Year	1, 4	0.03	8.31 *	.544	.045
	Treatment:Year	1, 4	0.03	0.92	.117	.391
Total carbon	Treatment	1, 4	0.02	34.22 **	.772	.004
	Year	1, 4	0.03	9.12 *	.579	.039
	Treatment:Year	1, 4	0.03	0.90	.120	.396
Total nitrogen	Treatment	1, 4	0.00	39.06 **	.804	.003
	Year	1, 4	0.00	2.23	.244	.210
	Treatment:Year	1, 4	0.00	2.23	.244	.210
Respiration	Treatment	1, 4	0.00	3.88	.433	.120
	Year	1, 4	0.00	20.81 *	.524	.010
	Treatment:Year	1, 4	0.00	8.45 *	.309	.044
Active carbon	Treatment	1, 4	2445.75	14.99 *	.778	.018
	Year	1, 4	174.55	16.36 *	.214	.016
	Treatment:Year	1, 4	174.55	2.24	.036	.209
Aggregate stability	Treatment	1, 4	79.91	1.40	.191	.302
	Year	1, 4	39.19	0.40	.032	.562
	Treatment:Year	1, 4	39.19	1.45	.106	.295
Subsurface hardness	Treatment	1, 4	23346.41	3.80	.466	.123
	Year	1, 4	2065.84	4.23	.079	.109
	Treatment:Year	1, 4	2065.84	6.01 +	.109	.070
Surface hardness	Treatment	1, 4	12080.24	0.69	.111	.452
	Year	1, 4	4687.46	31.87 **	.690	.005
	Treatment:Year	1, 4	4687.46	0.06	.004	.815

Available water capacity	Treatment	1, 4	0.00	0.41	.067	.557
	Year	1, 4	0.00	4.72 +	.260	.096
	Treatment:Year	1, 4	0.00	4.85 +	.265	.092
pH	Treatment	1, 4	0.05	1.37	.224	.306
	Year	1, 4	0.01	20.45 *	.446	.011
	Treatment:Year	1, 4	0.01	15.36 *	.376	.017

Signif. codes: 0 '*' *0.001* '**' *0.01* '*' 0.05 '+' 0.1**

5.2 VEGETABLE FIELD SOIL DIFFERENCES AT HADLEY SITE

The Hadley vegetable site provided a unique opportunity to evaluate soil health responses to agrivoltaic development because soil samples were collected both prior to construction and in multiple years following installation. Soil health indicators were analyzed using mixed-design ANOVA to test for main effects of treatment (agrivoltaic vs. control), year, and treatment × year interactions.

5.2.1 Soil Physical Indicators

Surface hardness differed between agrivoltaic and control plots prior to construction, with lower surface hardness observed in areas designated for the agrivoltaic array. Following construction, this pattern reversed: surface hardness values were higher within the agrivoltaic plots than in the control in the final year of sampling. This shift resulted in a significant treatment × year interaction, indicating that surface hardness changed differently over time between treatments.

Subsurface hardness declined substantially over time in both treatments, reflecting strong temporal effects. Mixed-design ANOVA indicated a significant main effect of year, but no consistent treatment effect or treatment × year interaction. These results suggest that changes in subsurface compaction were driven primarily by site-wide factors such as management practices, soil moisture conditions, or seasonal variability rather than by the agrivoltaic infrastructure itself.

Bulk density exhibited a significant main effect of treatment at the Hadley site ($p = 0.024$), with higher mean bulk density values observed in agrivoltaic plots compared to control plots across sampling years. However, no significant main effect of year or treatment × year interaction was detected. This indicates that while bulk density differed between agrivoltaic and control plots, there was no evidence that bulk density diverged over time following solar array installation.

The absence of a treatment × year interaction suggests that observed differences reflect persistent site or management contrasts rather than progressive soil compaction associated with solar array infrastructure instrallation or agrivoltaic managment. Given the intensity of annual management activities at this site, including tillage and traffic, bulk density patterns are best interpreted cautiously and within the broader context of field-scale soil disturbance rather than as a direct or worsening impact of the solar array.

5.2.2 Soil Chemical Indicators

Soil pH declined over time across both treatments, with mixed-design ANOVA detecting a significant main effect of year. No significant treatment effect or treatment × year interaction was observed, indicating that temporal drivers such as environmental conditions or nutrient management influenced soil acidity similarly in both agrivoltaic and control plots.

Organic matter and total nitrogen concentrations showed modest variation across years but did not exhibit significant treatment effects or interactions. These results suggest that short-term agrivoltaic development did not measurably alter soil carbon or nitrogen pools at the Hadley site during the study period.

5.2.3 Soil Biological Indicators

Soil respiration varied across years but did not differ significantly between agrivoltaic and control plots. No significant treatment × year interaction was detected, indicating that temporal fluctuations in microbial activity were consistent across treatments. Active carbon and aggregate stability followed similar patterns, with strong year effects but limited evidence of treatment-specific responses.

5.2.4 Summary of Hadley Site Results

Overall, results from the Hadley vegetable site indicate that temporal variation and management effects exerted stronger influences on most soil health indicators than agrivoltaic treatment during the study period. While surface hardness exhibited a significant treatment × year interaction and bulk density differed by treatment, the absence of treatment × year interactions for bulk density and other soil physical indicators indicates no evidence of progressive compaction following installation. Most chemical and biological soil properties changed similarly over time in both agrivoltaic and control plots, suggesting that early soil responses at this site were shaped primarily by pre-existing soil conditions, annual management practices, and environmental variability rather than by the presence of the solar array alone.

5.2.5 Figures and Tables for Results at Hadley Site

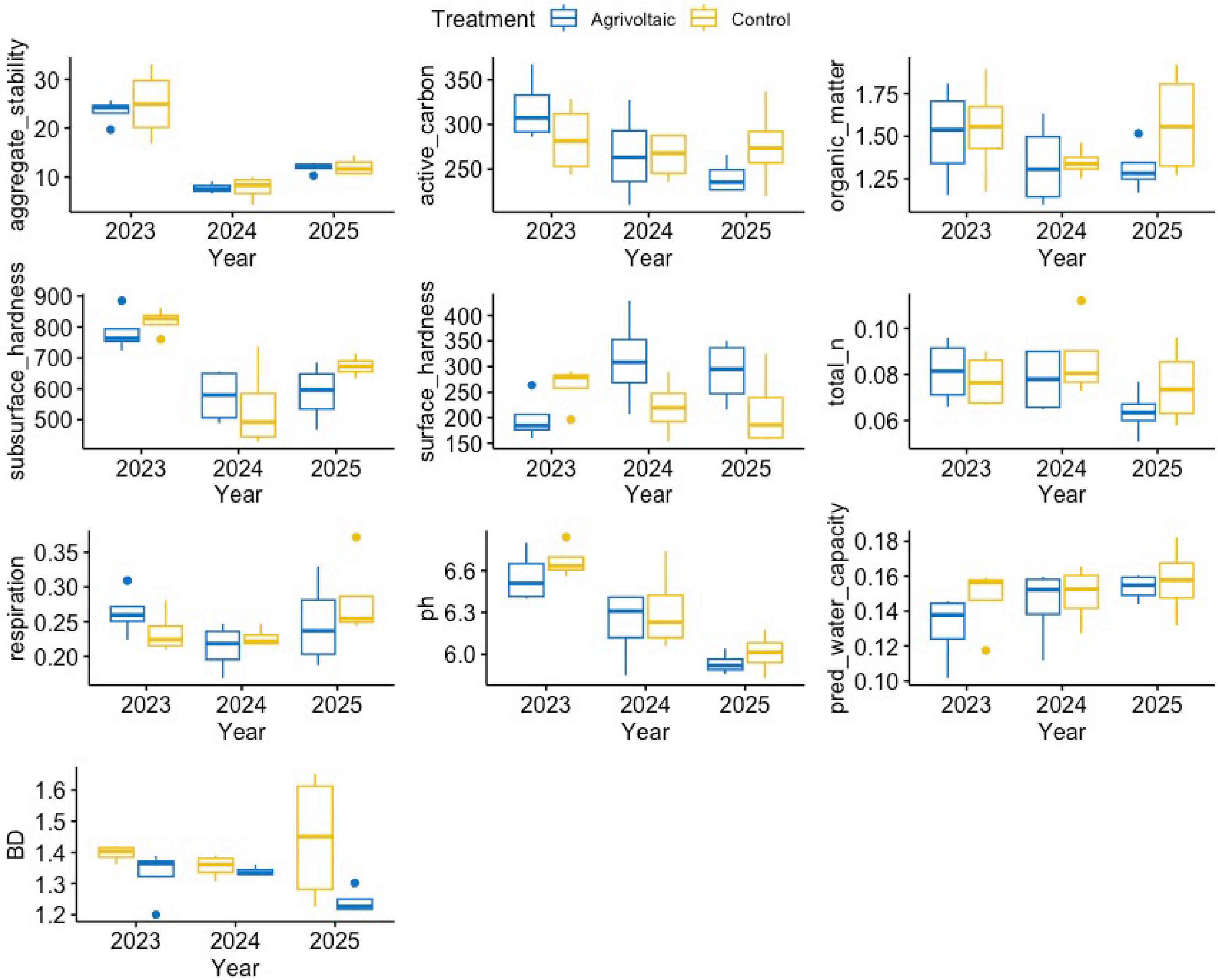


Figure 2. Soil health parameters at Hadley site pre-construction 2023, 2024 and 2025.

Table 4. Descriptive statistics for soil health measures at Hadley site.

	Preconstruction (2023)		**Year 1 (2024)**		**Year 2 (2025)**	
Soil health measures	**Agrivoltaic (N=4)**	**Control (N=4)**	**Agrivoltaic (N=4)**	**Control (N=4)**	**Agrivoltaic (N=4)**	**Control (N=4)**
Aggregate stability %						
Mean (SD)	23.5 (2.60)	25.0 (7.28)	7.70 (1.09)	7.72 (2.55)	11.9 (1.17)	12.1 (1.86)
Median [Min, Max]	24.2 [19.7, 25.7]	24.9 [16.9, 33.1]	7.56 [6.58, 9.13]	8.32 [4.24, 9.98]	12.3 [10.2, 12.9]	11.7 [10.4, 14.5]

Active carbon (ppm)						
Mean (SD)	317 (36.8)	284 (40.3)	266 (50.4)	265 (27.1)	241 (18.5)	276 (48.1)
Median [Min, Max]	307 [286, 367]	281 [244, 329]	263 [210, 327]	268 [236, 289]	235 [227, 266]	273 [219, 337]
Organic matter (%)						
Mean (SD)	1.51 (0.291)	1.55 (0.296)	1.34 (0.252)	1.35 (0.0871)	1.31 (0.146)	1.58 (0.318)
Median [Min, Max]	1.54 [1.15, 1.81]	1.56 [1.17, 1.89]	1.31 [1.10, 1.63]	1.34 [1.25, 1.46]	1.28 [1.17, 1.52]	1.56 [1.27, 1.92]
Subsurface hardness (psi)						
Mean (SD)	784 (69.9)	819 (42.4)	576 (87.6)	538 (140)	586 (95.4)	673 (33.7)
Median [Min, Max]	763 [724, 885]	827 [760, 861]	580 [489, 655]	492 [430, 737]	596 [467, 685]	672 [633, 714]
Surface hardness (psi)						
Mean (SD)	198 (45.1)	261 (43.7)	313 (91.9)	221 (56.8)	289 (63.2)	214 (77.8)
Median [Min, Max]	185 [160, 264]	279 [196, 290]	308 [208, 429]	219 [154, 290]	295 [216, 350]	186 [159, 325]
Total nitrogen (%)						
Mean (SD)	0.0813 (0.0141)	0.0775 (0.0117)	0.0778 (0.0142)	0.0865 (0.0175)	0.0638 (0.0106)	0.0753 (0.0171)
Median [Min, Max]	0.0815 [0.0660, 0.0960]	0.0765 [0.0670, 0.0900]	0.0780 [0.0650, 0.0900]	0.0805 [0.0730, 0.112]	0.0635 [0.0510, 0.0770]	0.0735 [0.0580, 0.0960]
Respiration (mg CO_2/g)						
Mean (SD)	0.263 (0.0350)	0.235 (0.0320)	0.213 (0.0344)	0.227 (0.0134)	0.248 (0.0636)	0.281 (0.0606)
Median [Min, Max]	0.260 [0.224, 0.309]	0.224 [0.210, 0.281]	0.218 [0.169, 0.247]	0.222 [0.218, 0.247]	0.237 [0.187, 0.329]	0.255 [0.244, 0.372]
pH						
Mean (SD)	6.56 (0.186)	6.67 (0.121)	6.22 (0.264)	6.32 (0.303)	5.94 (0.0772)	6.01 (0.146)
Median [Min, Max]	6.51 [6.40, 6.80]	6.64 [6.56, 6.84]	6.31 [5.85, 6.41]	6.23 [6.06, 6.74]	5.92 [5.86, 6.04]	6.02 [5.83, 6.18]
Available water capacity (g/g)						
Mean (SD)	0.131 (0.0204)	0.147 (0.0201)	0.144 (0.0221)	0.149 (0.0168)	0.154 (0.00765)	0.157 (0.0210)
Median [Min, Max]	0.138 [0.102, 0.146]	0.157 [0.117, 0.159]	0.152 [0.112, 0.160]	0.153 [0.127, 0.165]	0.155 [0.144, 0.161]	0.158 [0.132, 0.182]

Bulk density (g/cm3)						
Mean (SD)	1.40 (0.0255)	1.33 (0.0867)	1.36 (0.0369)	1.34 (0.0148)	1.44 (0.213)	1.24 (0.0405)
Median [Min, Max]	1.40 [1.36, 1.42]	1.36 [1.20, 1.39]	1.36 [1.31, 1.39]	1.33 [1.33, 1.36]	1.45 [1.23, 1.65]	1.23 [1.22, 1.30]

Table 5. Repeated measures ANOVA analysis for soil health parameters at Hadley site.

Soil health measure	Effect	df	MSE	F	ges	p.value
Aggregate stability	Treatment	1, 6	19.41	0.09	0.008	0.776
	Year	1.30, 7.83	12.84	70.02 ***	0.844	<.001
	Treatment:Year	1.30, 7.83	12.84	0.16	0.012	0.762
Active carbon	Treatment	1, 6	1468.26	0	<.001	0.988
	Year	1.71, 10.23	1753.2	2.72	0.233	0.118
	Treatment:Year	1.71, 10.23	1753.2	1.56	0.148	0.254
Organic matter	Treatment	1, 6	0.09	0.72	0.056	0.429
	Year	1.88, 11.28	0.05	1.51	0.113	0.262
	Treatment:Year	1.88, 11.28	0.05	0.84	0.066	0.449
Surface hardness	Treatment	1, 6	4516.86	1.62	0.087	0.25
	Year	1.36, 8.17	6107.05	0.66	0.067	0.484
	Treatment:Year	1.36, 8.17	6107.05	3.50 +	0.274	0.09
Subsurface hardness	Treatment	1, 6	11411.62	0.4	0.033	0.55
	Year	1.47, 8.82	7298.2	23.47 ***	0.655	<.001
	Treatment:Year	1.47, 8.82	7298.2	1.47	0.106	0.272
Total nitrogen	Treatment	1, 6	0	0.46	0.046	0.522
	Year	1.52, 9.12	0	3.06	0.159	0.104
	Treatment:Year	1.52, 9.12	0	1.15	0.066	0.342
Respiration	Treatment	1, 6	0	0.24	0.007	0.644
	Year	1.32, 7.91	0	1.75	0.191	0.23
	Treatment:Year	1.32, 7.91	0	0.88	0.106	0.408
pH	Treatment	1, 6	0.07	0.78	0.069	0.412
	Year	1.37, 8.23	0.04	32.27 ***	0.696	<.001
	Treatment:Year	1.37, 8.23	0.04	0.03	0.002	0.93
Available water capacity	Treatment	1, 6	0	0.71	0.067	0.432
	Year	1.55, 9.32	0	2.67	0.148	0.128

	Treatment:Year	1.55, 9.32	0	0.48	0.03	0.585
Bulk density	Treatment	1, 6	0.01	8.97 *	0.241	0.024
	Year	1.18, 7.08	0.02	0.08	0.01	0.826
	Treatment:Year	1.18, 7.08	0.02	1.67	0.18	0.242

Signif. codes: 0 '*' *0.001* '**' *0.01* '*' 0.05 '+' 0.1**

5.3 Vegetable Field Soil Differences at Grafton site

Soil health indicators at the Grafton vegetable site were evaluated across three years (Year 0, Year 1, and Year 2) to assess differences between agrivoltaic and control plots and to examine temporal trends following solar array installation. Overall, most soil health parameters changed similarly over time in both treatments, with relatively few statistically significant year × treatment interactions detected.

5.3.1 Soil Physical Indicators

Surface hardness and subsurface hardness increased over time in both agrivoltaic and control plots. This pattern indicates a site-wide temporal effect rather than a treatment-specific response to the solar array. Increases in soil penetration resistance across both treatments are commonly associated with changes in soil moisture conditions, field traffic, seasonal timing of sampling, or management practices rather than structural impacts of photovoltaic infrastructure alone.

A marginally significant year × treatment interaction was detected for surface hardness (p = 0.09). However, because surface hardness increased in both treatments and the interaction did not meet conventional significance thresholds, this result should be interpreted cautiously. The observed pattern suggests that any differential effect of the solar array on soil surface resistance was small relative to broader site-level drivers.

Initial bulk density measurements were collected in the fall of 2022, after construction of the solar array, and therefore reflect post-construction soil conditions rather than baseline differences. Bulk density differed significantly between agrivoltaic and control plots at the Grafton site (treatment effect, p = 0.006). Agrivoltaic plots were subject to annual tillage associated with vegetable production, while soils in the control plots were subject to reduced or absent tillage disturbance. By 2024, bulk density values in agrivoltaic plots had declined, but were still higher than in the control plots, however no significant year × treatment interaction was detected for bulk density.

5.3.2 Soil Chemical Indicators

Soil pH exhibited statistically significant differences over time; however, these changes were associated with documented lime applications in 2023 and 2024 rather than the presence of the solar array. Both agrivoltaic and control plots showed increases in pH following liming, indicating that management interventions were the dominant driver of pH dynamics at this site.

Organic matter and total nitrogen concentrations did not show strong treatment effects. While mean values varied slightly between agrivoltaic and control plots across years, repeated measures analyses indicated that temporal variation was more influential than treatment. These findings suggest that short-term agrivoltaic impacts on soil carbon and nitrogen pools were minimal at the Grafton site during the study period.

5.3.3 Soil Biological Indicators

Soil respiration increased over time in both treatments, reflecting changes in environmental conditions and management rather than a direct response to solar panels. No strong or consistent treatment effect on respiration was detected at the whole-plot scale. This contrasts with findings from other sites in the study where respiration was reduced beneath panels, highlighting the importance of site context and management history.

Active carbon and aggregate stability also varied over time, but treatment effects were generally weak or non-significant. These indicators, which respond relatively quickly to changes in management, did not show consistent divergence between agrivoltaic and control plots at the field scale.

5.3.4 Figures and Tables of Results at Grafton site

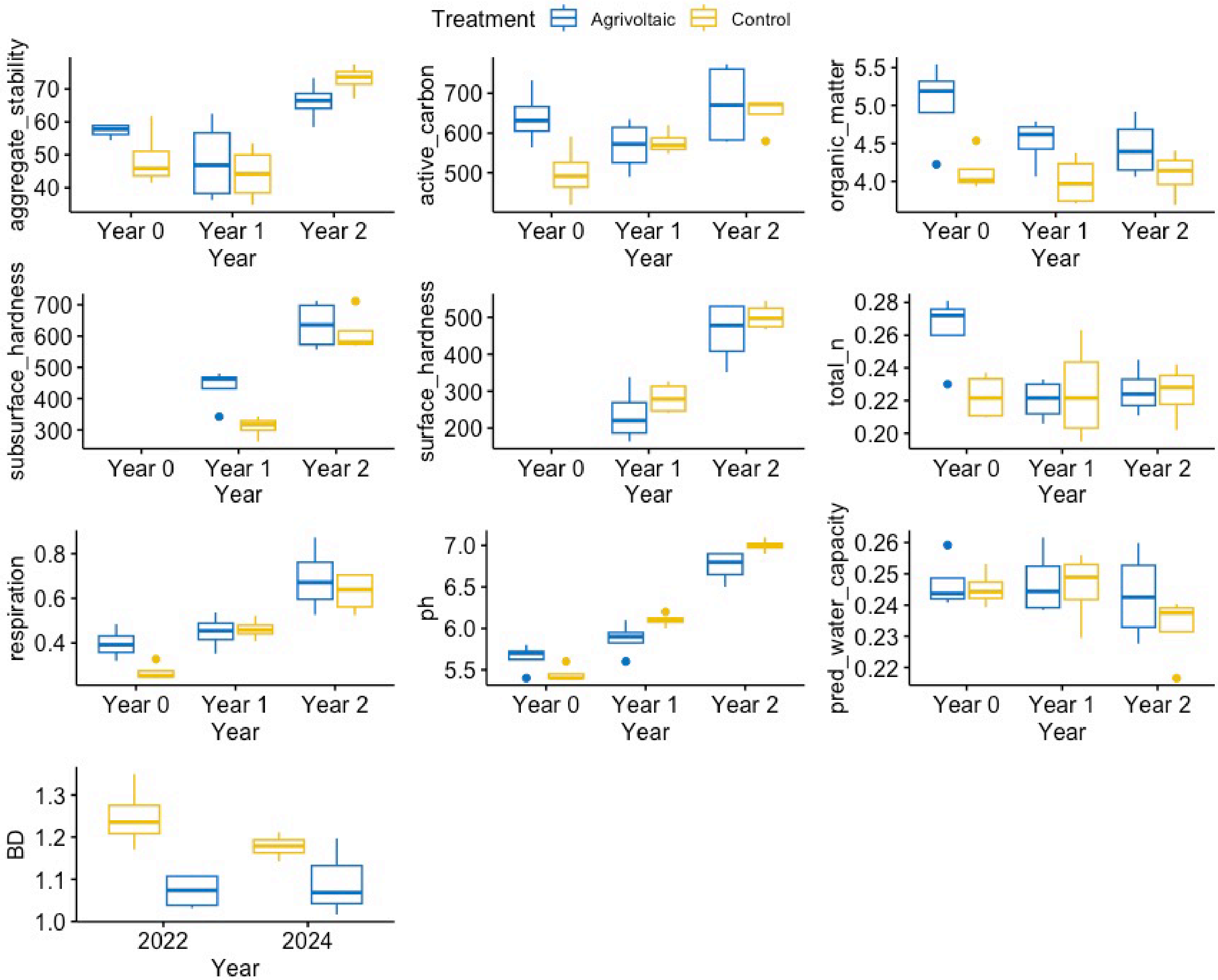


Figure 3. Soil health measures at Grafton site in 2022, 2023, and 2024.

Table 5. Descriptive statistics for soil health measures at Grafton site.

	Year 0 (2022)		Year 1 (2023)		Year 2 (2024)	
Soil health measures	**Agrivoltaic (N=4)**	**Control (N=4)**	**Agrivoltaic (N=4)**	**Control (N=4)**	**Agrivoltaic (N=4)**	**Control (N=4)**
Aggregate stability %						
Mean (SD)	57.3 (2.21)	48.7 (8.98)	48.1 (12.6)	44.2 (8.51)	66.1 (6.12)	73.0 (4.36)

Median [Min, Max]	57.8 [54.4, 59.2]	45.9 [41.5, 61.7]	46.8 [36.3, 62.5]	44.2 [34.8, 53.5]	66.5 [58.4, 73.3]	73.7 [67.1, 77.5]
Active carbon (ppm)						
Mean (SD)	640 (70.3)	498 (71.5)	567 (65.7)	577 (31.1)	673 (107)	650 (46.8)
Median [Min, Max]	631 [564, 733]	492 [419, 591]	572 [490, 634]	570 [548, 620]	670 [578, 773]	672 [580, 676]
Organic matter (%)						
Mean (SD)	5.04 (0.569)	4.13 (0.276)	4.52 (0.321)	4.01 (0.326)	4.44 (0.394)	4.09 (0.306)
Median [Min, Max]	5.19 [4.22, 5.54]	4.02 [3.94, 4.54]	4.62 [4.07, 4.79]	3.97 [3.71, 4.38]	4.39 [4.06, 4.92]	4.14 [3.69, 4.40]
Subsurface hardness (psi)						
Mean (SD)	NA (NA)	NA (NA)	437 (63.6)	310 (34.3)	635 (79.1)	611 (67.4)
Median [Min, Max]	NA [NA, NA]	NA [NA, NA]	463 [343, 480]	318 [263, 343]	636 [557, 713]	580 [570, 711]
Surface hardness (psi)						
Mean (SD)	NA (NA)	NA (NA)	235 (76.3)	281 (42.9)	460 (86.9)	502 (36.2)
Median [Min, Max]	NA [NA, NA]	NA [NA, NA]	220 [163, 338]	279 [241, 327]	478 [352, 531]	497 [468, 545]
Total nitrogen (%)						
Mean (SD)	0.264 (0.0230)	0.223 (0.0140)	0.221 (0.0127)	0.225 (0.0308)	0.226 (0.0147)	0.225 (0.0172)
Median [Min, Max]	0.272 [0.230, 0.281]	0.222 [0.210, 0.237]	0.222 [0.206, 0.233]	0.222 [0.195, 0.263]	0.224 [0.211, 0.245]	0.228 [0.202, 0.242]
Respiration (mg CO_2/g)						
Mean (SD)	0.397 (0.0691)	0.269 (0.0394)	0.449 (0.0769)	0.462 (0.0469)	0.686 (0.149)	0.628 (0.0928)
Median [Min, Max]	0.392 [0.321, 0.484]	0.253 [0.243, 0.328]	0.455 [0.352, 0.536]	0.458 [0.409, 0.522]	0.672 [0.526, 0.874]	0.639 [0.525, 0.709]
pH						
Mean (SD)	5.65 (0.173)	5.45 (0.100)	5.88 (0.206)	6.10 (0.0816)	6.75 (0.191)	7.00 (0.0816)
Median [Min, Max]	5.70 [5.40, 5.80]	5.40 [5.40, 5.60]	5.90 [5.60, 6.10]	6.10 [6.00, 6.20]	6.80 [6.50, 6.90]	7.00 [6.90, 7.10]
Available water capacity (g/g)						
Mean (SD)	0.247 (0.00843)	0.245 (0.00584)	0.247 (0.0108)	0.246 (0.0116)	0.243 (0.0146)	0.233 (0.0110)
Median [Min, Max]	0.244 [0.241, 0.259]	0.244 [0.239, 0.253]	0.244 [0.238, 0.262]	0.249 [0.229, 0.256]	0.242 [0.228, 0.260]	0.238 [0.217, 0.240]

Bulk density (g/cm3)						
Mean (SD)	1.25 (0.0759)	1.07 (0.0417)			1.18 (0.0293)	1.09 (0.0930)
Median [Min, Max]	1.24 [1.17, 1.35]	1.07 [1.03, 1.11]			1.18 [1.14, 1.21]	1.07 [1.02, 1.20]

Table 6. Repeated measures ANOVA analysis for soil health parameters at Grafton site.

Soil health measure	Effect	df	MSE	F	ges	p.value
	Treatment	1, 6	96.68	0.22	0.019	0.656
	Year	1.44, 8.64	62.15	25.94 ***	0.675	<.001
Aggregate stability	Treatment:Year	1.44, 8.64	62.15	2.78	0.182	0.125
	Treatment	1, 2	4702.95	0.75	0.058	0.477
	Year	3, 6	8108.59	1.23	0.341	0.376
Active carbon	Treatment:Year	3, 6	8108.59	0.19	0.073	0.901
	Treatment	1, 6	0.21	9.79 *	0.45	0.02
	Year	1.86, 11.17	0.11	2.48	0.171	0.131
Organic matter	Treatment:Year	1.86, 11.17	0.11	1.55	0.114	0.253
	Treatment	1, 6	4516.86	1.62	0.087	0.25
	Year	1.36, 8.17	6107.05	0.66	0.067	0.484
Surface hardness	Treatment:Year	1.36, 8.17	6107.05	3.50 +	0.274	0.09
	Treatment	1, 6	11411.62	0.4	0.033	0.55
	Year	1.47, 8.82	7298.2	23.47 ***	0.655	<.001
Subsurface hardness	Treatment:Year	1.47, 8.82	7298.2	1.47	0.106	0.272
	Treatment	1, 6	0	2.4	0.118	0.172
	Year	1.68, 10.10	0	2.48	0.216	0.137
Total nitrogen	Treatment:Year	1.68, 10.10	0	3.22 +	0.263	0.089
	Treatment	1, 6	0.02	1.32	0.128	0.294
	Year	1.44, 8.67	0.01	56.47 ***	0.759	<.001
Respiration	Treatment:Year	1.44, 8.67	0.01	2.59	0.126	0.139
	Treatment	1, 6	0.03	1.63	0.113	0.249
	Year	1.29, 7.74	0.03	206.72 ***	0.948	<.001
pH	Treatment:Year	1.29, 7.74	0.03	7.25 *	0.392	0.024
	Treatment	1, 6	0	0.9	0.052	0.379
	Year	1.73, 10.35	0	1.64	0.148	0.239
Available water capacity	Treatment:Year	1.73, 10.35	0	0.45	0.045	0.622
Bulk density	Treatment	1, 5	0	20.63 **	0.565	0.006

	Year	1, 5	0.01	0.59	0.075	0.477
	Treatment:Year	1, 5	0.01	0.96	0.116	0.372

Signif. codes: 0 '*' *0.001* '**' *0.01* '*' 0.05 '+' 0.1**

5.3.5 Within-Array Bed Location Analysis

In the final year of the study, additional sampling was conducted within the agrivoltaic array to evaluate soil health indicators by bed location relative to the solar panels (e.g., under-panel vs. between-panel positions). Aggregate stability and respiration varied across bed locations, reflecting spatial heterogeneity in moisture distribution and microclimatic conditions within the array.

Aggregate stability tended to be lower in drier bed positions and higher in locations receiving greater moisture inputs, such as near panel drip edges. Soil respiration followed a similar pattern, with higher values observed in wetter microsites and lower values in drier locations. These results indicate that micro-scale variation in moisture availability within the agrivoltaic system influenced soil biological and physical processes more strongly than the overall presence or absence of solar panels.

To further evaluate drivers of spatial variability in soil biological activity within the agrivoltaic array at the Grafton vegetable site, a linear mixed-effects model was used to assess the relationship between soil moisture and soil respiration across bed locations. The model included soil moisture as a fixed effect and plot as a random intercept to account for repeated measurements within plots.

Soil moisture was a significant positive predictor of soil respiration (estimate = 0.0549, SE = 0.0137, $t = 4.02$, df = 11, $p = 0.002$). Higher soil moisture was associated with increased microbial respiration across bed locations within the array. This relationship indicates that micro-scale variation in moisture availability exerted a strong influence on soil biological activity, independent of plot-level differences.

Random effects associated with plot explained a substantial portion of the variance in respiration (plot-level SD = 0.172), while residual variability was relatively small (residual SD = 0.061), suggesting consistent moisture–respiration responses within plots. These findings reinforce that heterogeneous moisture distribution within the agrivoltaic system—rather than the presence of solar panels per se—was a primary driver of observed variation in soil respiration. These results align with observed patterns in respiration across bed locations, where wetter microsites consistently exhibited higher respiration rates than drier positions within the array.

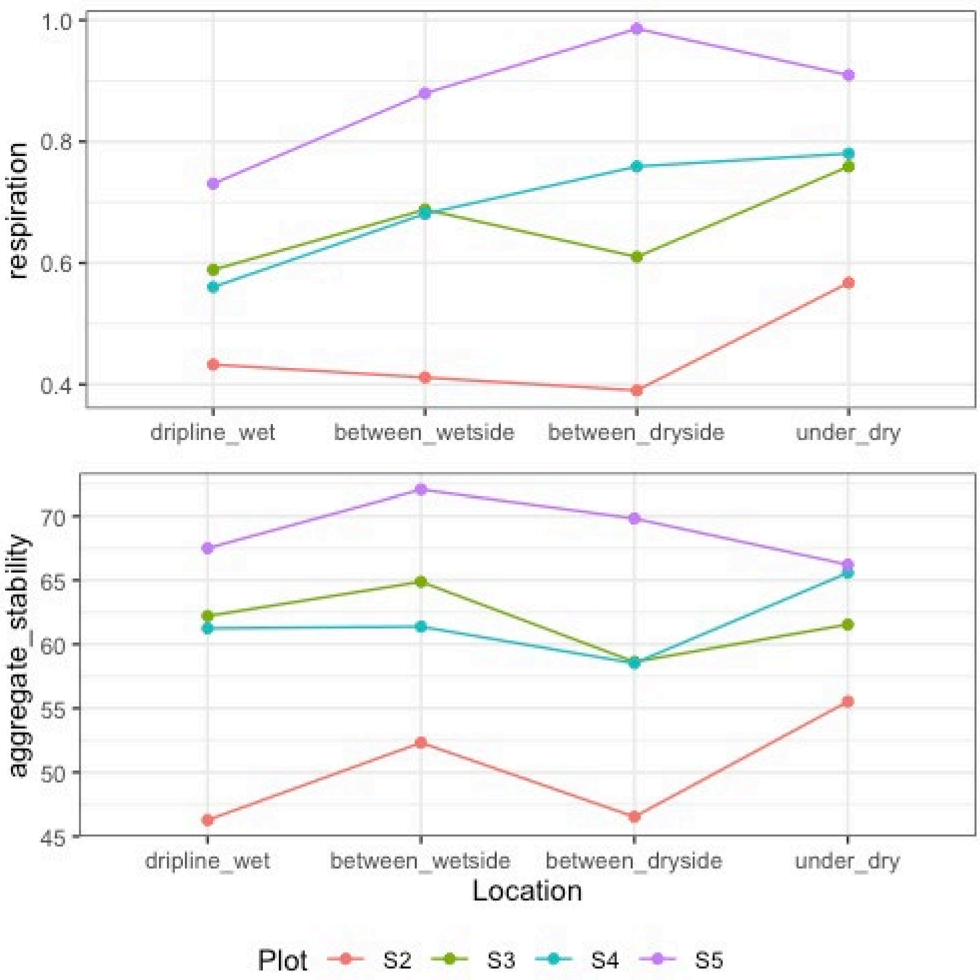


Figure 4: Aggregate stability and respiration by plot and location at Grafton site.

Table 7. Summary statistics for within-array soil respiration and aggregate stability at the Grafton site. *Values are means ± SD (n = 4 per location) for respiration (mg CO_2 g^{-1} soil, 4-day total) and water-stable aggregate stability (%). Locations reflect sampling positions relative to panel dripline and between-panel zones, arranged here by expected moisture gradient*

Location	n	Respiration (mean)	Respiration (SD)	Aggregate Stability (mean)	Aggregate Stability (SD)
Under panel	4	0.754	0.141	62.215	4.915
Between panels, dry side	4	0.686	0.251	58.374	9.512

Between panels, wet side	4	0.665	0.192	62.657	8.202
Under dripline	4	0.578	0.122	59.309	9.116

5.3.6 Summary of Grafton Site Results

Taken together, results from the Grafton vegetable site indicate that site-wide management history, soil disturbance during site preparation, liming, and temporal environmental variation exerted stronger influences on soil health indicators than agrivoltaic infrastructure during the study period. While localized differences in soil condition were observed within the solar array, particularly related to moisture-driven microsite variability, agrivoltaic treatment effects at the whole-field scale were limited.

6 Discussion

This study evaluated soil health responses to agrivoltaic systems across three agricultural contexts in Massachusetts: a hayfield (Monson) and two vegetable production sites (Hadley and Grafton). Across sites, results indicate that temporal variation, management practices, and micro-scale environmental conditions exerted stronger and more consistent influences on soil health indicators than the presence of solar panels alone. Where agrivoltaic treatment effects were detected, they were most often expressed as differences in the trajectory of change over time, rather than as static differences between agrivoltaic and control soils. This pattern is consistent with recent syntheses showing that soil responses under solar development are management-dependent rather than technology-determined (Carvalho et al., 2024; Krasner et al., 2025).

6.1.1 Treatment Effects in the Absence of Pre-Construction Baselines

At the Monson hayfield site, all soil sampling occurred after array construction, limiting the ability to attribute main treatment effects directly to agrivoltaic installation. However, the detection of significant treatment × year interactions for soil pH and respiration indicates that soils beneath the solar array experienced distinct temporal dynamics compared to control soils.

Soils beneath the array exhibited a smaller decline in pH over time, suggesting a buffering effect relative to soils outside the array. Similar buffering of soil chemical conditions beneath photovoltaic panels has been reported in other agrivoltaic and solar-soil studies and is often attributed to altered rainfall interception, redistribution, and reduced evaporative demand (Moscatelli et al., 2022; Luo et al., 2024). In humid temperate systems, heavy precipitation events can drive short-term soil acidification through leaching of base cations, and agrivoltaic structures may modify these processes by altering water inputs to the soil surface.

Soil respiration also declined over time at the Monson site, but the reduction was significantly greater beneath the solar panels than in the control plots. Reduced soil respiration beneath panels has been documented across multiple agrivoltaic studies, including long-term research in Italy (Moscatelli et al., 2022) and recent northeastern U.S. solar developments (NYSERDA, 2025). These reductions are commonly attributed to moderated soil temperatures and reduced radiation reaching the soil surface, which can slow microbial metabolic activity without necessarily reducing microbial biomass.

In contrast, soil carbon and nutrient indicators at Monson exhibited significant main effects of treatment but no treatment × year interactions. In the absence of baseline data, these differences cannot be confidently attributed to agrivoltaic installation and likely reflect pre-existing spatial variability or historical management differences. This distinction reinforces conclusions from systematic reviews that emphasize the importance of pre-installation land use and management history in shaping observed soil carbon patterns under solar development (Carvalho et al., 2024; Krasner et al., 2025).

6.1.2 Early Agrivoltaic Responses in Vegetable Systems

At the Hadley vegetable site, where pre-construction data were available, most soil health indicators changed similarly over time in agrivoltaic and control plots. While surface hardness exhibited a treatment × year interaction, bulk density showed a significant main effect of treatment without a corresponding treatment × year interaction. This indicates that bulk density differed between agrivoltaic and control plots but did not increase or diverge over time following installation.

The absence of a temporal interaction suggests that differences in bulk density are more likely attributable to site-specific factors or management practices rather than to progressive compaction caused by agrivoltaic infrastructure. In intensively managed annual vegetable systems, short-term agrivoltaic effects on soil physical properties may therefore be difficult to distinguish from background variability associated with tillage, traffic, and seasonal soil moisture conditions.

These findings suggest that early soil responses following agrivoltaic installation in vegetable systems may be subtle and easily overshadowed by annual management practices, including tillage, traffic, and crop rotation. Similar conclusions have been drawn from agrivoltaic vegetable trials in the Northeast, where year-to-year weather variability and management effects were stronger drivers of system performance than panel presence alone (Doubleday et al., 2025; Sturchio et al., 2025). In intensively managed annual systems, short-term agrivoltaic effects on soil health may therefore be difficult to detect without longer monitoring periods.

6.1.3 Management-Driven Soil Physical Responses

Results from the Grafton vegetable site further highlight the importance of management context when interpreting soil physical indicators. Bulk density differed significantly between agrivoltaic and control plots, but measurements were collected in the fall of 2022 after construction. This could be due to the soil disturbance caused by installation of the array, however without pre-construction data the inference is limited. Soils beneath the array were subject to annual tillage associated with vegetable production, while control plots experienced reduced or absent tillage. This trend in the agrivoltaics could be attributed to the effects of annual tillage on reducing compaction in the soil surface. Although the strength of our inference is limited, our data points to a possible pattern where installation of agrivoltaics increases soil compaction, which is then remediated to some degree by tillage within agrivoltaics.

This interpretation aligns with broader agronomic literature showing that annual tillage temporarily reduces bulk density, while reduced-tillage systems often exhibit higher bulk density in the short term despite improvements in aggregate stability and long-term soil structure. Systematic reviews of solar-soil interactions similarly conclude that soil physical outcomes are strongly shaped by post-installation management rather than by panel presence alone (Carvalho et al., 2024; Krasner et al., 2025).

6.1.4 Micro-Scale Controls on Soil Biological Activity

Within-array analyses at the Grafton site revealed that micro-scale variation in soil moisture was a dominant driver of soil respiration. Mixed-effects modeling demonstrated a strong positive relationship between moisture and respiration across bed locations, indicating that higher soil moisture consistently supported greater microbial activity within the array.

This finding aligns with mechanistic agrivoltaic studies showing that photovoltaic structures redistribute rainfall and modify soil moisture patterns, creating localized zones of enhanced or reduced biological activity (Marrou et al., 2013c; Weselek et al., 2021). Similar moisture-mediated responses have been observed in northeastern solar sites, where total soil carbon remained stable while respiration varied spatially beneath panels (NYSERDA, 2025).

Importantly, this within-array signal contrasts with the relatively weak whole-plot treatment effects observed at the Grafton site, illustrating that agrivoltaic influences on soil health may be most evident at finer spatial scales not captured by traditional treatment-control comparisons.

6.1.5 Synthesis Across Sites

Across all three study sites, relatively few soil health indicators exhibited statistically significant treatment × year interactions, indicating that most soil properties responded similarly over time in agrivoltaic and control plots. Where agrivoltaic effects were detected, they were primarily expressed through changes in soil chemical conditions (pH) and microbial activity (respiration). While select soil physical indicators (e.g., bulk density at the Hadley site) differed by treatment, the absence of treatment × year interactions across sites indicates no evidence of progressive physical change attributable to agrivoltaic infrastructure.

These results are consistent with recent reviews emphasizing that agrivoltaic soil responses are context-dependent and mediated through indirect microclimatic and hydrologic pathways rather than direct technological effects (Carvalho et al., 2024; Krasner et al., 2025; Tan et al., 2025).

6.1.6 Implications for Agrivoltaic Research and Design

Collectively, these findings highlight the importance of incorporating pre-construction baselines, long-term monitoring, and spatially explicit sampling designs in agrivoltaic soil health research. Binary comparisons between panel and non-panel areas may obscure meaningful micro-scale processes operating within arrays, particularly those related to soil moisture dynamics (Marrou et al., 2013c; Weselek et al., 2021).

Future agrivoltaic research should prioritize longer study durations, standardized documentation of management practices, and integrated microclimate measurements to better resolve the mechanisms by which agrivoltaic systems influence soil function. Such approaches will be critical for developing agrivoltaic designs and management strategies that support both agricultural productivity and long-term soil health in temperate production systems.

7 APPENDICES

7.1 APPENDIX A: CASH SOIL HEALTH SAMPLE COLLECTION PROTOCOLS

Methods for obtaining a soil sample are based on the protocols from the Cornell Comprehensive Assessment of Soil Health (CASH). Figures and language are from the Cornell CASH manual (Moebius-Clune et al., 2016).

1. Identify a minimum of four locations for soil sampling across the treatment, and 4 samples across the control area that are representative of the field. Avoid irregularities, like a low depression or a rock. In our sampling design we use 5 points in a compass pattern
2. Avoid collecting or combining soil samples from:
   - Wheel tracks or drive lanes, field borders, depressions, or other odd areas within the field
   - Areas with historically lower or higher productivity
   - Different landscape positions
   - Fields with different crops or rotations, or the same crops with a different management
   - Row versus inter-row areas
   - Eroded areas
   - Saturated soil
3. At each sub sampling location:
   a. Remove surface debris.
   b. Use a flat spade to dig a small hole about 8” deep.
   c. From the side of the hole, take a vertical, rectangular slice of soil 6” deep and 2” thick. The top and bottom of the slice should be the same thickness. Use a ruler.
   d. Place in a clean bucket.
4. Repeat at each subsampling location.
5. Mix samples thoroughly in the bucket and transfer ~ 6 cups of soil into a one gallon size sealed bag.
6. Label each unique sample and transport them in a cooler, away from heat and sunlight.
7. Mail to lab as soon as possible.

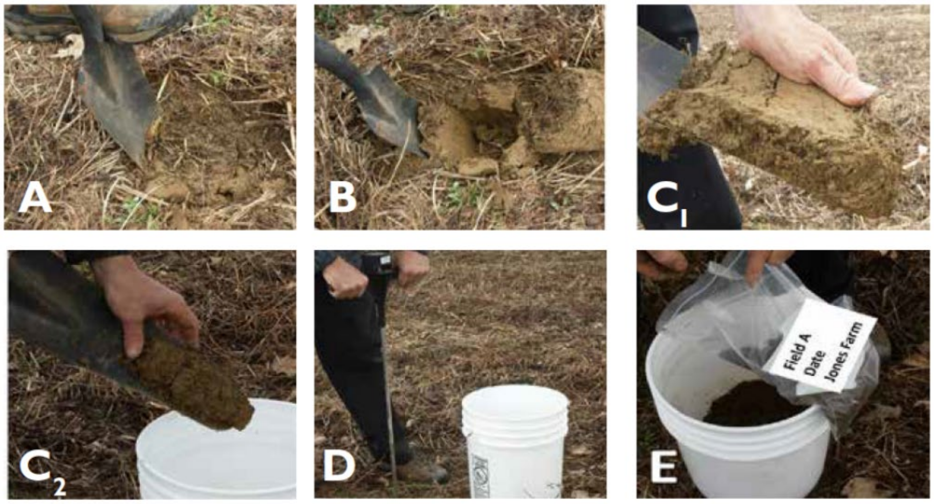


FIGURE 2.08 A - E. The steps of taking a soil health sample. The microorganisms in the soil are sensitive to heat. Keep samples out of direct sunlight and keep as cool as possible during sampling and storage. Store samples in a refrigerator or cold room after returning from the field and ship to Cornell as soon as possible.

7.2 Appendix B: Lessons Learned

1. Experimental design and budget are complicated. There are many challenges to design experiments around undeveloped agrivoltaic sites. We would recommend selecting sites that are already constructed, because development is stop-and-start, often held up by building or permitting delays. It's difficult to communicate with developers, take pre-construction samples, manage budget periods, and manage hiring of support staff. It's also nearly impossible to create an experimental design and appropriate budget for a site that does not yet exist.
2. Farmer selection is crucial to obtain data that is of value. Work with experienced farmers whose interest is primarily agronomic, as opposed to farmers who are primarily motivated by agricultural adders and solar payments. Work on sites that have been in agricultural production previously, with well-managed soils of appropriate pH and nutrient concentrations. It's hard to interpret data from fields that are not productive to start with. Ideally farmers would have control over their on-farm operations, so that field activities occur on time and with sufficient communication.
3. Broad and active project management is required. It is complicated to navigate experimental design, competing farmer needs, and scientific rigor. Projects may have multiple parties, intermediaries, and numerous participants. Active project management is needed to coordinate between numerous researchers, solar developers, consultants, legal teams, farm owners, and field managers.
4. Challenges of on-farm research. Farmer priorities and timing, getting sensors out of field, measuring yield. Asking farmers to manage fields as they normally would, but yet research throws a wrench in the works in terms of sensors in the way, the need to record keep.
5. Adequate controls are necessary. Absence of adequate controls should be a deal breaker. Construction activities and fence perimeter limit that amount of area left for control. A large enough area is required to take a sufficient number of samples. There should also be a robust plan for pre-construction sampling, which is often timing-dependent or stop and start.
6. Stipends should be included for farmer participation. It takes a lot of time for each farmer to communicate with researchers and to collect data. Engagement should be rewarded.
7. Soil texture affects everything. For example, dry sandy soils won't perform well during excessive heat, regardless of influence of agrivoltaics. From the outset of the experiment, soil texture should be considered.
8. Soil preparation is required prior to production. There may be a need to assess interference of rocks, plan for rock picking in cultivated beds, and leave time for adjusting soil pH
9. Soil health changes occur over longer periods of time, so it's not effective to do 2-year study.
10. There are different motivations between solar developers compared to researchers. Tension arises in these multi-partner projects when some parties are promoting agrivoltaics success when researchers must remain neutral and wait for data to inform their conclusions. Some farmers are primarily participating in this research because it's a contract requirement, and not because they want to or have the capacity.
11. Refine MDAR's Dual Use Shading Tool https://massgov.github.io/DOER/doer.html This tool currently does not consider slope. Grade does affect shadow length, so further study should refine this tool. Additionally, it should validate PAR predictions with actual field data.

12. Study the differences between different array configurations. Each site has one spacing and array type, which makes it difficult to compare sites. Dual use solar is not a singular treatment: there are fixed arrays, tracking arrays, and a wide variation in spacing. Regional differences in soil texture, crop requirements, microclimates make it very difficult to interpret data to recommend new technology and design on additional sites.
13. Wireless sensors vastly increased overall costs and logistics. Large amounts of data need to be budgeted for in terms of data management and analysis.
14. Construction of sensors and stands. Microclimate sensors are usually designed to be permanently installed, but in annual cropping systems or rotational grazing, this is not possible. Removable sensors and stands took a lot of time to transport, install, remove temporarily, re-install, and store over winter.
15. Inflation. Significant lag time can occur between cost quotes for grant proposals, and contract actuation. With a two year delay and high inflation, most material costs had doubled.

7.3 Appendix D: References

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