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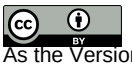
Low solar grazing densities support beneficial insects in agrivoltaic systems

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Title: Low solar grazing densities support beneficial insects in agrivoltaic systems

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Abstract:

Solar grazing - the co-location of livestock grazing and photovoltaic energy production - is rapidly expanding globally to mitigate land-use conflicts. Solar facilities are increasingly sited on agricultural land, where both sheep grazing and the promotion of agriculturally beneficial insects are recognized as facilitators of multi-functional agroecosystems, yet how stocking rate shapes beneficial insect communities remains poorly understood. We conducted a replicated, three-year experiment testing six stocking rates (0–10 sheep ha^{-1}) at an operational 18MW solar facility, sampling bees and lady beetles across three years and four grazing rotations per year. Light grazing at 2 sheep ha^{-1} supported 38% greater beneficial insect abundance than ungrazed controls, driven primarily by an 83% increase in honey bees. High stocking rates (≥8 sheep ha^{-1}) reduced bee abundance by 42–68% and significantly changed insect community composition. A companion study identified 8 sheep ha^{-1} as the agrotechnological optimum, but our results identify 2 sheep ha^{-1} as the agroecological optimum in our study region, where beneficial insect abundance and flock health are maximized. These optima did not coincide, indicating a clear tradeoff between ecological and operational objectives. However, at 4 sheep ha^{-1}, beneficial insect communities remained statistically indistinguishable from ungrazed controls while vegetation management effectiveness was greater than at 2 sheep ha^{-1}. Together these results define a synergy–tradeoff boundary with direct implications for targeting agroecological outcomes via the operations and maintenance of solar grazing facilities.

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Introduction:

Solar energy development is accelerating globally, with the largest proportion of new installations being built on cropland (Kruitwagen *et al* 2021, Gallaher *et al* 2026). This has positioned agrivoltaics - the co-location of agricultural activities and solar energy production - as a promising solution to the competing land-use demands of food security, energy generation, and biodiversity conservation (Barron-Gafford *et al* 2019, Campana *et al* 2025), and there is increasing interest to identify management practices that optimize the benefits of these multi-use systems (Hernandez *et al* 2019, Grodsky 2021). Solar grazing - the practice of using livestock, especially sheep, to manage vegetation in photovoltaic arrays - is currently implemented across approximately 7-11% of solar installations in the United States and represents one of the most widely adopted agrivoltaic practices globally (Andrew *et al* 2025, Stewart *et al* 2025, Handler and Pearce 2022). Solar grazing offers clear agrotechnological synergies: sheep control vegetation growth that would otherwise shade solar panels, thereby reducing the need for mechanical mowing and herbicide application, while solar infrastructure provides shade that can reduce heat stress and water requirements for livestock (Kochendoerfer *et al* 2025, Andrew *et al* 2025, Carvalho Fonsêca *et al* 2023).

Promoting beneficial insects is increasingly recognized as an additional source of synergy in solar ecosystems: solar facilities managing for native vegetation have been associated with greater pollinator abundance and diversity relative to conventional pre-solar land uses such as intensive agriculture (Walston *et al* 2021). Pollinators from solar sites have also been observed foraging in adjacent croplands, indicating the potential for ecosystem service spillover to surrounding agricultural landscapes (Walston *et al* 2023). Furthermore, beekeeping is successfully implemented in solar facilities (Dolezal *et al* 2021), with bee pollination service values from UK solar parks alone estimated at £5.9 million annually (Armstrong *et al* 2021). Global agroeconomies are fundamentally dependent on insect pollination: in the United States alone, more than 100 crops rely on insect pollinators, contributing over $18 billion annually to the economy (Calderone 2012). Globally, pollination services are valued at up to half a trillion USD, making insect pollination one of the most economically important ecosystem services in the world (Lautenbach *et al* 2012, Khalifa *et al* 2021, Klein *et al* 2007). Other beneficial insects contribute to biological control: predatory species such as lady beetles (Coccinellidae) suppress populations of aphids and other herbivorous pests, providing services that underpin crop health and reduce reliance on chemical inputs (Symondson *et al* 2002, Kundoo and Khan 2017). Therefore, the co-location of sheep grazing and beneficial insects on the same facility may be an economically and ecologically attractive management option.

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Despite the recognized value of these services, little is known about how solar grazing affects the insect communities that provide them. In conventional pastures, low-to-moderate grazing intensities support diverse plant and insect communities by maintaining open, structurally heterogeneous vegetation (Sharma Acharya *et al* 2024, Lázaro *et al* 2016). On the other hand, intensive grazing can remove floral resources, compact soil, and destroy nesting sites for ground nesting insects (Tadey 2023). Within solar facilities, microclimate effects of panel shading such as reduced temperature extremes, altered soil moisture, spatially heterogeneous light availability, as well as seed mixes used, create habitat conditions that differ fundamentally from open grasslands, potentially modifying how insect communities respond to grazing disturbance (Lec'hvien *et al* 2025). A companion study conducted in the same set-up as our study identified 8 sheep ha^{-1} as the optimal stocking rate for balancing vegetation management success and sheep flock health (Kochendoerfer *et al* 2025), but whether this agrotechnological optimum aligns or conflicts with ecological objectives for beneficial insects remains unknown. With solar grazing now practiced on over 100,000 acres in the United States alone (Andrew *et al* 2025), and expanding rapidly worldwide, the absence of ecologically grounded stocking rate guidance represents a significant management gap.

To address this knowledge gap, we established a replicated, multi-year experiment to assess the effects of solar grazing intensity on beneficial insect communities. Specifically, we investigated the effects of varying sheep stocking rates (0-10 sheep ha^{-1}) on the beneficial insect community, as well as on the different insect subgroups wild bees, honey bees and lady beetles.

Materials and methods

We conducted a replicated, three-year experiment (2020–2022) at the Cascadilla Community Solar facility, an operational 18 MW ground-mounted photovoltaic installation in Dryden, New York, USA. The facility is located in the humid continental climate zone of the northeastern United States, characterized by warm summers, cold winters, and relatively high annual precipitation. We assigned six sheep stocking rate treatments (0, 2, 4, 6, 8, and 10 sheep ha^{-1}) to paddocks within five solar arrays in a split-split-plot design, with fallow (i.e. regrowth from the seedbank without additional seeding) and legume seed-mix vegetation plots nested within each paddock. The legume seed mix (Kings Agriseeds, Lancaster, Pennsylvania, USA) contained *Melilotus alba*, *Melilotus officinalis*, *Trifolium pratense*, *Trifolium repens*, and *Lotus corniculatus*, applied at 16.8 kg/ha. See Table S1 for a list of the 15 plant species with the most cover in the two vegetation plot types.

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The five individually fenced solar arrays measured 4.2, 4.4, 1.9, 4.6 and 4.6 ha respectively, and each array was further divided into six equally sized grazing paddocks. Paddock sizes ranged from 0.32 to 0.76 ha and measured between 92.5-356.6m in length and 22-77.5m in width (Fig. S1). From May 1 to October 15 each year, a total of 124 sheep grazed on the site. Each of the six paddocks within an array was randomly assigned one of six stocking rate treatments: 0 (control), 2, 4, 6, 8, or 10 sheep per hectare. Control paddocks were mowed once per year to simulate standard vegetation management practices. The total number of sheep was adjusted by array size to maintain consistent stocking rates across years. Grazing was rotated thought the arrays to allow pasture rest and regrowth. Sheep grazed across four rotations per year throughout the study period: 5 days per array in May (Rotation 1), 10 days in June/July (Rotation 2), 10 days in August (Rotation 3) and 7 days in September/October (Rotation 4), with rest periods of 20, 40, 40 and 28 days, respectively. Only one array was stocked at any given time.

At the beginning of each rotation, right before the sheep moved into the paddocks, we sampled insects using standardized sweep netting within both fallow and legume plots. In each vegetation type plot, we performed 30 standardized sweeps along the center of the plot. All treatment paddocks in the array actively grazed by sheep were sampled for insects on the same day. We identified beneficial insects to the lowest feasible taxonomic level and assigned them to taxonomic groups: wild bees, honey bees (*Apis mellifera*), and lady beetles (Coccinellidae). To provide more context on the study system, we examined whether plant species richness and diversity, both overall and partitioned by native status, varied with stocking rate using data from a parallel vegetation survey conducted within the same experimental system. Because sampling dates and plot-level replication did not fully align between the vegetation and insect datasets, formal statistical integration of vegetation and insect responses was not possible, and the results should be interpreted accordingly.

We performed all statistical analyses using R software (v4.4.1; R Core Team 2024). We analyzed abundance, species richness, and Hill diversity (q = 1) separately for overall beneficial insects, wild bees, honey bees, lady beetle adults, plant richness and plant Hill diversity (q=1) using generalized linear mixed models (GLMMs) in the R package *glmmTMB* (v1.1.10; Brooks *et al* 2026). We included stocking rate (categorical factor with six levels), plot vegetation type (categorical factor with two levels, legume and fallow), year, and rotation (categorical variable with four levels) as fixed effects and arrays as random intercepts. We assessed overall significance of fixed effects using Type III Wald χ^2 tests. For each model, we calculated estimated marginal means (EMMs) using the *emmeans* package (v1.11.2.8, Lenth *et al* 2026). We conducted pairwise comparisons with Benjamini–Hochberg correction for multiple testing. We generated compact letter displays (CLDs) using the *multcomp* package (v1.4.28,

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Hothorn *et al* 2026) to summarize statistically distinguishable treatment groups. The ungrazed, mowed control (0 sheep ha^{-1}) served as the reference level for all treatment contrasts. We assessed community composition of beneficial insects using non-metric multidimensional scaling (NMDS) and permutational multivariate analysis of variance (PERMANOVA) on Bray-Curtis dissimilarities, with homogeneity of dispersion tested via *betadisper* (all tests implemented in the R packages *vegan* v.2.6.8 and *pairwiseAdonis* v0.4.1, Oksanen *et al* 2026, Martinez Arbizu 2020). We identified treatment-associated indicator species using the group-equalized IndVal.g statistic (*indicspecies* package v1.8.0; Cáceres *et al* 2025). We provide full methodological and statistical details in the Supplementary Material.

Results

Over the three-year study period, we conducted a total of 865 sampling events. In these samples, we observed a total of 2445 beneficial insects (1960 bees and 485 lady beetles), representing 53 different species (46 bee species and 7 lady beetle species). Of the bees, 856 individuals (43.7%) were honey bees. We present a list of all observed species in Table S2.

At our solar facility in the northeastern United States, overall beneficial insect abundance was significantly affected by stocking rate and year but not plot vegetation type (i.e. legume of fallow plots; Table 1). The 2 sheep ha^{-1} treatment was the only treatment to show a significantly higher beneficial insect abundance compared to other treatments, and it supported 38% higher beneficial insect abundance than the ungrazed control. Beneficial insect abundance at stocking rates of 4-10 sheep ha^{-1} were statistically indistinguishable from the control treatment (Fig. 1A, Table S3). Beneficial insect abundance was approximately 37% and 36% lower in 2021 and 2022 than in 2020, respectively (Fig. S2). Species richness and diversity showed no significant response to stocking rate or plot vegetation type (Fig. 1B-C), but both declined in years 2021 and 2022 relative to 2020 (Table 1, Fig. S2). The narrow range of diversity values partly reflects the high proportion of single-species samples (59%), which constrained variation in Hill q = 1 estimates.

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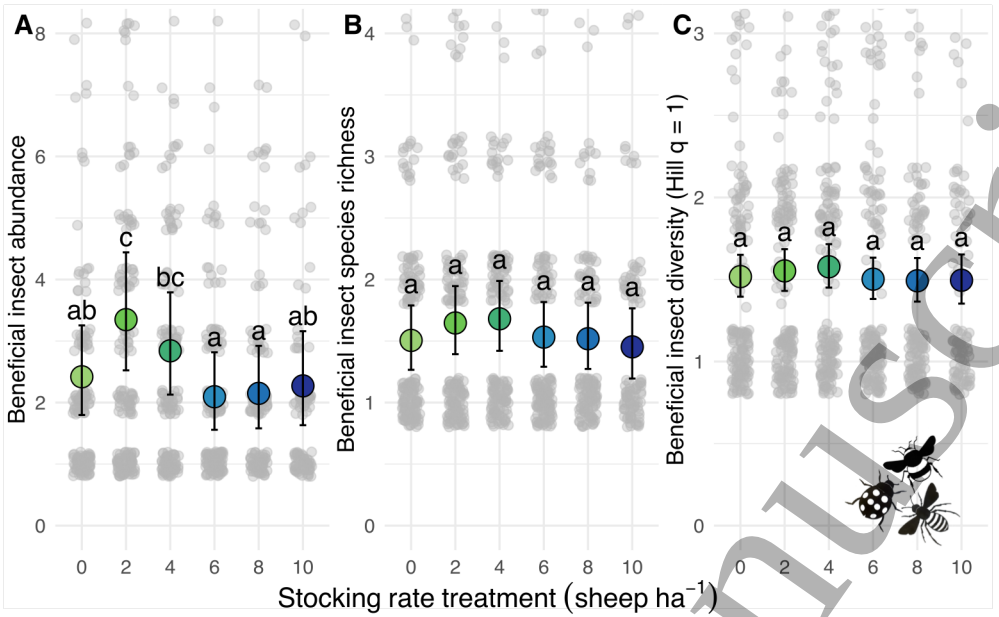


Figure 1: (A) Beneficial insect abundance**, (B)** species richness, and **(C)** diversity across stocking rate treatments. Grey dots represent raw observations (jittered horizontally for visibility; y-axis capped at the 95th percentile of observed values for better readability), and filled circles represent model-estimated marginal means (EMMs). Bars indicating Benjamini-Hochberg adjusted 95% confidence intervals, averaged over plot vegetation type and year. Circles sharing the same letter do not significantly differ from one another.

Table 1. Type III Wald chi-square tests from generalized linear mixed models for overall beneficial insect abundance, richness, and diversity. Statistically significant effects are printed in bold.

Response variable	Fixed effect	χ^2	df	p
Abundance	Stocking rate	26.12	5	**<0.001**
	Year	57.10	2	**<0.001**
	Plot vegetation type	0.20	1	0.652
Richness	Stocking rate	8.27	5	0.142
	Year	47.37	2	**<0.001**
	Plot vegetation type	0.68	1	0.411
Diversity (Hill q = 1)	Stocking rate	3.30	5	0.654
	Year	8.54	2	**0.014**
	Plot vegetation type	0.10	1	0.748

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When considering specific taxonomic groups, we found that wild bee abundance, richness, and diversity showed no significant response to stocking rate nor plot vegetation type across any metric (Table 2, Fig. S3A-C). Wild bee abundance and richness varied significantly among grazing rotations and years (Fig. S4A-B; Fig. S5A-B), while diversity showed no significant variation across either factor (Table 2).

Honey bee abundance showed the most pronounced treatment response across all response variables and taxonomic groups, declining significantly with increasing stocking rate (Table 2, Fig. 2). The 2 sheep ha^{-1} treatment supported 83% greater honey bee abundance than the ungrazed control, while stocking rates of 6, 8, and 10 sheep ha^{-1} supported 42%, 45%, and 68% fewer honey bees respectively (Table S4). These results identify honey bee abundance as the primary driver of the overall beneficial insect response to stocking rate. Honey bee abundance also varied significantly among years, with counts lower in 2021 and 2022 relative to 2020 (Table 2, Fig S5).

Table 2. Type III Wald chi-square tests from generalized linear mixed models for wild bee, honey bee, and lady beetle abundance, richness, and diversity. Statistically significant effects are printed in bold.

Taxon	Response variable	Fixed effect	χ^2	df	p
Wild bees	Abundance	Stocking rate	2.90	5	0.715
		Rotation	20.91	3	**<0.001**
		Year	33.58	2	**<0.001**
		Plot vegetation type	0.44	1	0.509
	Richness	Stocking rate	3.36	5	0.644
		Rotation	21.49	3	**<0.001**
		Year	11.17	2	**0.004**
		Plot vegetation type	0.61	1	0.435
	Diversity (Hill q = 1)	Stocking rate	1.72	5	0.887
		Rotation	0.53	3	0.912
		Year	0.64	2	0.727
		Plot vegetation type	0.28	1	0.594
Honey bees	Abundance	Stocking rate	47.83	5	**<0.001**
		Year	8.84	2	**0.012**
		Plot vegetation type	0.33	1	0.565

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Lady beetles	Abundance	Stocking rate	3.98	5	0.553
		Rotation	9.14	3	**0.027**
		Year	10.72	2	**0.005**
		Plot vegetation type	1.46	1	0.227
	Richness	Stocking rate	8.63	5	0.125
		Year	27.29	2	**<0.001**
		Plot vegetation type	7.55	1	**0.006**
	Diversity (Hill q = 1)	Stocking rate	1.17	5	0.947
		Year	0.39	2	0.824
		Plot vegetation type	0.01	1	0.928

Lady beetle abundance, species richness, and diversity showed no significant response to stocking rate treatment (Table 2). Abundance and richness differed significantly among years, with abundance and richness being higher in 2021 and 2022 compared to 2020 (Table 2, Fig. S6). Lady beetle species richness was significantly lower in legume plots than fallow plots (Table 2, Fig. S7).

To provide additional context of the study system, we examined plant species richness and diversity data from a vegetation survey conducted within the same experimental system. Total plant species richness was significantly affected by stocking rate ($\chi^2 = 18.998$, df = 5, $p = 0.002$; Table S5), with the highest richness observed at 8 sheep ha^{-1} (Fig S8A). When partitioned by native status, native plant species richness was also significantly affected by stocking rate ($\chi^2 = 27.462$, df = 5, $p < 0.001$) and was highest at 2 sheep ha^{-1}, while non-native plant species richness was highest at 8 sheep ha^{-1} ($\chi^2 = 73.181$, df = 5, $p < 0.001$; Fig. S8A). Plant diversity (Hill q = 1) followed a similar pattern, with native plant diversity highest at 2 sheep ha^{-1} ($\chi^2 = 21.709$, df = 5, $p < 0.001$; Table S6) and non-native plant diversity highest at 8 sheep ha^{-1} ($\chi^2 = 73.526$, df = 5, $p < 0.001$; Fig. S8B). Formal statistical integration of these vegetation data with our insect community results was not possible due to differences in sampling design between the two datasets.

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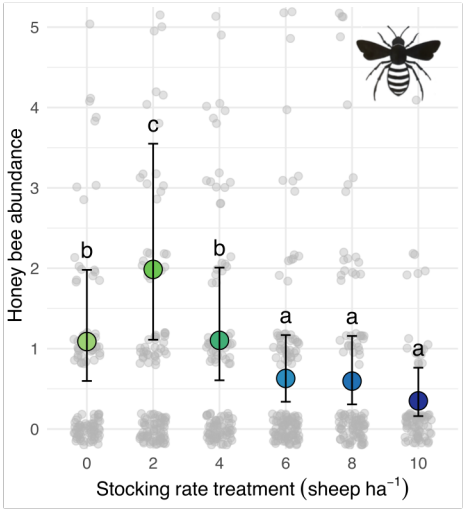


Figure 2: Honey bee abundance across stocking rates. Grey dots represent raw observations (jittered horizontally for visibility; y-axis capped at the 95th percentile of observed values for better readability), and filled circles represent model-estimated marginal means (EMMs). Bars indicate Benjamini-Hochberg-adjusted 95% confidence intervals, averaged over year and rotation. Circles sharing the same letter do not significantly differ from one another.

Indicator species analysis identified two bee species significantly associated with specific stocking rate treatments. *Apis mellifera* (honey bee) was a significant positive indicator of the 2 sheep ha^{-1} treatment (A = 0.293, B = 0.504, IndVal.g = 0.384, p = 0.011, Fig. 3B), indicating moderate specificity to this treatment and presence in approximately half of all 2 sheep ha^{-1} samples. *Lasioglossum zonulum* was a significant positive indicator of the 10 sheep ha^{-1} treatment (A = 0.391, B = 0.128, IndVal.g = 0.224, p = 0.006, Fig. 3B), with moderate specificity but low fidelity, reflecting that this ground-nesting sweat bee was rarely recorded overall but occurred disproportionately at the highest stocking rate.

Community composition differed significantly among stocking rates (PERMANOVA: $R^2 = 0.019$, p = 0.002, Fig. 3), with homogeneous dispersion across treatment groups (betadisper: p = 0.192), confirming genuine centroid differences. Communities at ≥8 sheep ha^{-1} were compositionally distinct from 0–4 sheep ha^{-1} assemblages (all pairwise $p \leq 0.025$, Table S7), while communities at low-to-moderate stocking rates were indistinguishable from one another. This threshold was consistent across all three years (Treatment × Year: p = 0.109).

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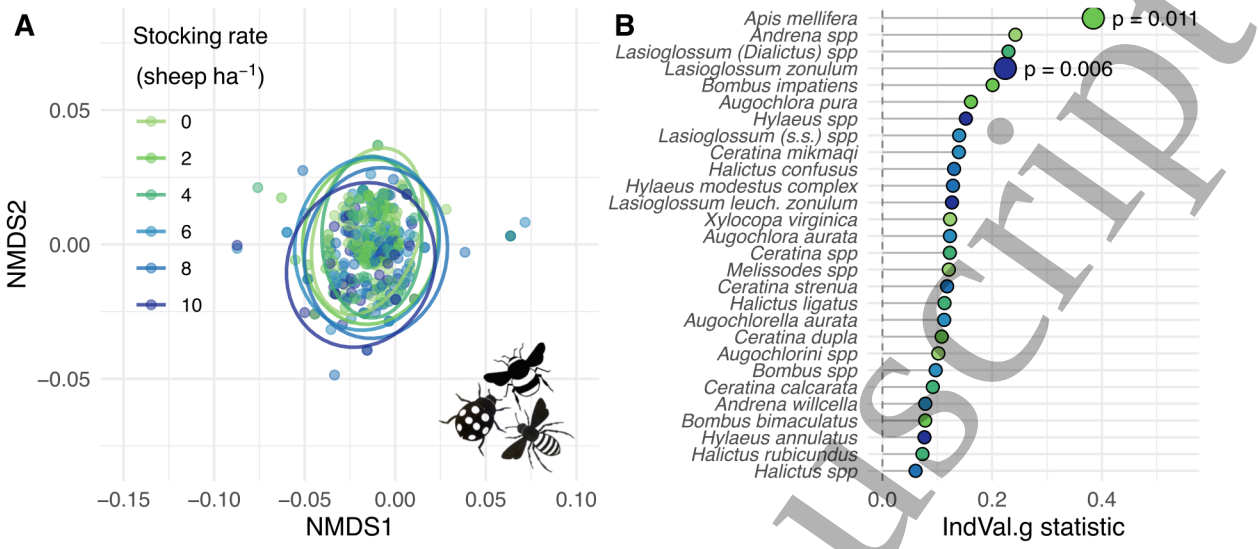


Figure 3: **(A)** Non-metric multidimensional scaling (NMDS) ordination of beneficial insect community composition across stocking rate treatments. Each point represents one sampling event, colored by stocking rate treatment. Ellipses represent 95% confidence intervals around group centroids. Axis limits are restricted to the main cluster of sampling events; 5 of 386 sites fall outside the displayed range. NMDS stress = 0.099. **(B)** Indicator species analysis of bee communities across stocking rate treatments. IndVal.g statistics are shown for all 28 bee species retained in the analysis (≥3 occurrences), colored by their most strongly associated treatment. Large points denote statistically significant associations.

Discussion

Our results demonstrate that sheep stocking rate is a significant determinant of beneficial insect abundance and community composition in typical solar grazing systems of the northeastern United States. The most striking finding was the pronounced response of honey bee abundance to stocking rate, peaking at 2 sheep ha^{-1} (+83% relative to ungrazed controls) and declining substantially at stocking rates ≥6 sheep ha^{-1} (−42 to −68%). This pattern drove the overall beneficial insect abundance response and was independently confirmed by the indicator species analysis. By contrast, wild bee and lady beetle communities were insensitive to stocking rate across all metrics, suggesting that different taxonomic groups can respond to different aspects of grazing-modified solar habitat, such as floral resource availability, vegetation structure, or prey availability.

The contrasting responses of honey bees and wild bees may reflect differences in foraging ecology and sensitivity to floral resource availability. Honey bees are central-place foragers with colony-level resource demands that make them particularly sensitive to site-level floral abundance (Seeley 1986, Bertleff *et al* 2025). Light grazing at 2 sheep ha^{-1} likely maintains a high local native floral resource availability, whereas heavy grazing can remove flowers and reduce vegetation heterogeneity (Tadey 2023, Lázaro *et*

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al 2016). Although no managed honey bee colonies were present at our site, our results are relevant to the growing practice of solar apiculture: our findings suggest that in our study region, the stocking rate chosen for vegetation management directly determines the quality of the habitat available for co-located honey bee colonies.

The insensitivity of wild bees to stocking rate across all metrics may partly reflect their ecological diversity: averaging responses across 47 species in our analyses may obscure opposing effects at the species level, and wild bees may be more responsive to landscape-level resources than to within-site stocking rate variation (Bertleff *et al* 2025, Hopfenmüller *et al* 2014). Furthermore, competitive interactions with honey bees may also play a role; honey bees are highly abundant, generalist foragers known to competitively displace wild bees from preferred floral resources (Elbgami *et al* 2014, Magrach *et al* 2017), and their pronounced abundance peak at 2 sheep ha^{-1} may suppress wild bee use of the highest-quality foraging habitat at light stocking rates.Interestingly, we identified *L. zonulum* as a significant indicator of the 10 sheep ha^{-1} treatment. This small, ground-nesting sweat bee may benefit from the open, heavily disturbed ground surface at high stocking rates, which could provide suitable nesting substrate (Streitberger *et al* 2025, Nelson *et al* 2023). The contrast between *A. mellifera* and *L. zonulum* suggests that grazing intensity shapes bee community composition through multiple mechanisms, consistent with findings from conventional pastures (Sharma Acharya *et al* 2024).

Our results also revealed marked temporal dynamics: bee abundance and richness declined in 2021 and 2022 relative to 2020, while lady beetle abundance and richness increased over the same period. Bee communities may respond to succession- or climate-driven variation in floral resource availability or phenological shifts (Ogilvie *et al* 2017), while rising lady beetle populations may reflect prey availability dynamics as the vegetation community developed after the seeding phase (Lin and Pennings 2018, Evans and Toler 2007). Interannual variation in temperature and precipitation likely contributed to the observed patterns, as insect activity is closely linked to climatic conditions (Cohen *et al* 2025). In addition to interannual patterns, we also observed substantial within-year variability in wild bee abundance and richness, with both metrics highest during rotations 2 and 3 (June-August). This pattern points to seasonal phenology as the dominant driver of within-year wild bee community dynamics at our site, where insect activity peaks during the summer months.

These temporal dynamics have practical management implications: understanding how insect communities shift across years and seasons in response to interannual climatic variation, plant community succession, and seasonality may inform decisions about whether periodic vegetation interventions in addition to grazing, such as reseeding with flowering forbs or targeted mowing to adjust for successional

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trajectories, are needed to sustain beneficial insect communities over multi-year timescales. Longer-term monitoring beyond the three-year study period would be valuable to determine whether treatment effects stabilize or intensify as the site matures. The strong within-seasonal signal observed in wild bee communities further suggests that more granular seasonal stocking strategies, such as reduced stocking rates during peak pollinator activity periods, could reduce ecological costs while maintaining vegetation management effectiveness. Additional management levers, including grazing duration, rotation frequency, and timing of grazing, may offer further opportunities to better integrate vegetation management and insect conservation goals and could be explored in future studies.

Notably, we found no evidence that legume plots supported greater beneficial insect abundance, richness, or diversity relative to fallow plots, which is likely because the dominant plant species were similar across the vegetation type plots. This result is consistent with the companion study finding that legume seeding did not improve vegetation management outcomes relative to regrowth from the seedbank (Kochendoerfer *et al* 2025). Together, these results suggest that vegetation regrowth from the seedbank can be as effective as intentional seeding for supporting both management and pollinator goals at solar facilities established on old fields in the northeastern United States, potentially reducing establishment costs for operators. However, seed mixes intended to benefit pollinators can take several years to fully establish and reach peak floral resource provision (Neal 2019), and our three-year study period may not have captured the full potential benefit of intentional seeding relative to natural regrowth. We further found that total plant species richness and diversity was highest at 8 sheep ha^{-1}, mainly driven by non-native plant species, while native plant species richness and diversity were significantly higher at 2 sheep ha^{-1} compared to all other stocking rates. While we were not able to formally test the effects of native plant species richness on the abundance of beneficial insects, this raises the possibility that native plant species may be particularly important for bee abundance in solar grazing, consistent with findings from other contexts (Pardee and Philpott 2014, Morandin and Kremen 2013).

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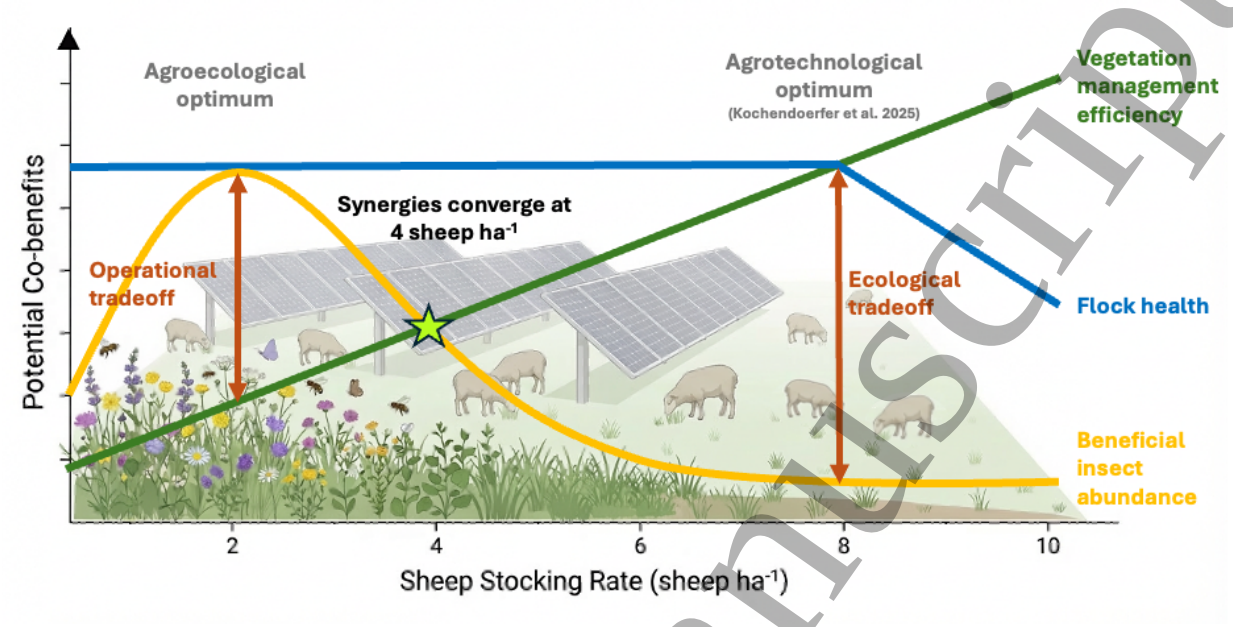


Figure 4: Conceptual schematic illustrating how the co-benefits of beneficial insect abundance, flock health, and vegetation management efficiency vary across sheep stocking rates in our solar grazing system. The figure highlights the agroecological optimum (2 sheep ha^{-1}), the agrotechnological optimum (8 sheep ha^{-1}), the trade-offs between ecological and operational objectives, and an intermediate stocking rate (4 sheep ha^{-1}) where these objectives converge.

Our results, interpreted alongside the companion study (Kochendoerfer *et al* 2025), reveal two distinct optima that can inform solar-grazing management decisions (Fig. 4). At 2 sheep ha^{-1}, beneficial insect abundance, and honey bee abundance in particular, was maximized, representing what we define as the agroecological optimum where pollinator abundance and sheep-flock health are maximized. Because pollinator abundance is closely linked to visitation rates and pollination service delivery (Woodcock *et al* 2019, Vázquez *et al* 2005), this optimum indicates elevated potential for pollination service provision. At 8 sheep ha^{-1}, vegetation management success and flock health are maximized, representing an agrotechnological optimum (Kochendoerfer *et al* 2025). These two optima do not coincide, and the gap between them defines an explicit management tradeoff: optimizing for operational goals comes at a measurable ecological cost, and optimizing for ecological goals comes at an operational cost. Solar facility operators and managers can therefore make deliberate decisions about which objective to prioritize - a choice that will depend on the specific goals of the facility, contractual vegetation management requirements, and any biodiversity or ecosystem service commitments embedded in planning permissions or certification schemes. However, our results suggest that this

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tradeoff need not be framed as a binary choice. At 4 sheep ha^{-1}, honey bee abundance and overall beneficial insect communities remain statistically indistinguishable from ungrazed controls, while vegetation management effectiveness is greater than at 2 sheep ha^{-1}. In our system, 4 sheep ha^{-1} therefore represents the stocking rate at which agroecological and agrotechnological synergies converge: provision of meaningful vegetation management and conservation of the ecological integrity of the beneficial insect community (Fig. 4). This rate may serve as a practical reference point for solar grazing guidelines seeking to balance operational and conservation objectives, though its applicability to other facilities will depend on site-specific vegetation conditions, array configuration, and regional context.

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Data Availability Statement

Data used in this paper are available in the Supporting Information of Kochendoerfer et al. 2025 (DOI: 10.1016/j.agsy.2025.104403) and/or can be obtained from co-author and data steward Niko Kochendoerfer.

Ethical Statement

All procedures involving sheep were approved by the Cornell University Institutional Animal Care and Use Committee (protocol 2016-0069)

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