Acta fytotechn zootechn, 28, 2025(2): 157–170
http://www.acta.fapz.uniag.sk

Original Paper

Combined Effects of Vertical Agriphotovoltaics and Sown Vegetation Strips: a Simulation Study

Jan Štrobach[1], Hana Vašková[1], David Hájek[2], Ladislav Jílek[2], Petr Novák[3], Přemysl Štranc[4], Daniel Štranc[4], Jiří Skuhrovec[1], Pavel Saska[1]*

[1]*Czech Agrifood Research Centre, Functional Biodiversity group, Prague, Czech Republic*
[2]*Czech Agrifood Research Centre, Agricultural Engineering and Technology group, Prague, Czech Republic*
[3]*Czech University of Life Sciences Prague, Faculty of Engineering, Prague, Czech Republic*
[4]*Stradlova s. r. o., Prague, Czech Republic*

Article Details: Received: 2025-01-17 | Accepted: 2025-04-02 | Available online: 2025-06-30

https://doi.org/10.15414/afz.2025.28.02.157-170

Agriphotovoltaics (APV) represents a promising option for combining food and electricity production. Furthermore, flowering strips can be additionally implemented along with APV to support farmland biodiversity and associated ecosystem services. However, these two concepts have never been investigated in one study. In this work, we investigated a combination of two types of sown strips ("Fodder strip" and "Nectareous strip" as defined in Czech legislation) and simulations of vertical APVs affect invertebrate and plant communities in strips and in winter wheat crop. Following a multitaxonomic approach, sampling was conducted in 2023 and 2024 using pitfall traps, pan traps, sweep netting and phytocoenological relevés. In most cases, the catches of the studied taxonomic groups were positively affected by the sown strips, nonetheless some of the more mobile groups were unaffected or negatively affected. The strip type affected aphid catch only, and the presence of APV simulation affected the abundance of aphids and sap beetles. The plant communities differed between modalities, but the effect of the simulation was rather weak. We also discuss the relevance of using simulations instead of real solar panels. Our study suggests that vertical APVs in combination with sown strips of flowering vegetation can be a viable option for sustainable agroecosystem management.

Keywords: agrivoltaics, flowering strips, seminatural habitats, multitaxonomic approach, communities

1 Introduction

Solar energy utilisation, or photovoltaics offers enormous potential to meet a large part of the global demand for renewable energy. At the same time it presents a significant challenge because of requirements for large areas for these installations. This is problematic especially where photovoltaic parks compete with agriculture (Dupraz et al., 2011; Adeh et al., 2019). One innovative approach that attempts to bridge this conflict is the concept of agriphotovoltaics (APV) (Goetzberger & Zastrow, 1982). This concept considers a synergistic combination of renewable energy production (solar) and agricultural production, which can involve growing crops or livestock farming (Goetzberger & Zastrow, 1982; Dupraz et al., 2011; Barron-Gafford et al., 2019; Adeh et al., 2019). This approach maximizes the efficiency of land use by enabling its dual use – for food and energy production at the same time. Moreover, this concept opens new opportunities for farmers, who can increase their economic stability by combining income from the sale of energy and agricultural products (Dupraz et al., 2011; Schneider et al., 2023). Research shows that appropriate coupling of solar energy and agriculture can even lead to higher crop yields due to milder temperatures and lower water loss through evaporation under solar panels (Barron-Gafford et al., 2019). Two main types of APV systems can be

***Corresponding Author:** Pavel Saska, Czech Agrifood Research Centre, Functional Biodiversity group, Prague, Czech Republic, +420 233 02 24 16
pavel.saska@carc.cz https://orcid.org/0000-0003-1397-2987

distinguished. Horizontal systems are more common and include solar panel installations above the crop (Dupraz et al., 2011; Barron-Gafford et al., 2019), whereas vertical systems consist of rows of panels placed within the crop, pasture or orchard (Ma Lu et al., 2024). While horizontal systems have been used in practice, vertical systems are still scarce.

How APV systems affect biodiversity in farmlands remains unknown. The effects of conventional PV systems on biodiversity have received some attention (e.g., Randle-Boggis et al., 2020; Menta et al., 2023), but owing to the different natures of these installations, the results are difficult to apply to APVs (Schwarz & Ziv, 2024). In particular, vertical APV systems have considerable potential to support farmland biodiversity, as their installations create strips of uncultivated land analogous to seminatural habitats.

A promising approach to promote biodiversity is the integration of APVs with flowering strips. The decline in insect diversity, especially of pollinators, is largely attributed to the loss of natural habitats and intensification of agriculture, which reduces the number of suitable sites for nesting, foraging and breeding (e.g., Benton, Vickery, & Wilson, 2003; Wagner, 2020). Flowering strips, which are established on arable land or intensively managed permanent grasslands, serve as important elements for enhancing biodiversity in agriculturally degraded landscapes (Kowalska, Antkowiak, & Sienkiewicz, 2022). They provide reproduction sites, shelter and food for insects and other animals (Haaland, Naisbit, & Bersier, 2011; Stroot et al., 2022), which increases ecosystem services such as crop pollination and natural pest control (Campbell et al., 2017).

We are aware of no studies that would focus on the environmental effects of the combination of vertical APV installation with flowering strips, even though possible synergies between photovoltaic technologies and the environment have been anticipated (Hernandez et al., 2019; Schneider et al., 2023). In this study, simulations of vertical APV installations have been employed in combination with two types of sown strips ("Fodder" and "Nectareous strips" according to Czech national legislation) as the first step in the assessment of the possible effects of vertical APV installations on farmland biodiversity. Multitaxonomic approach was adopted, using four sampling methods (pitfall traps, pan traps, sweeping and phytocoenological relevés).

2 Materials and Methods

2.1 Study Site

The study was conducted in an intensively managed agricultural landscape located approximately 9 km southwest of the town of Rakovník, Czech Republic, in 2023 and 2024. The study site (50.0598189 N, 13.6245094 E, altitude 461 m a. s. l.) is located in a region with a continental climate with an average annual precipitation of 583 mm, an average annual air temperature of 9 °C and loamy soils. The study site was previously a conventionally managed field of 4.69 ha. Since autumn 2022, the field has been dedicated to the future installation of a vertical APV plant combined with sown strips. During the study years, the main crop was winter wheat (see Table 1 for field management details).

Table 1 Crop management in the 2022/2023 and 2023/2024 cropping seasons

Cropping season 2022/2023		Cropping season 2023/2024	
Activity	date	activity	date
Stubble tillage 20 cm	27. 7. 2022	stubble tillage 20 cm	13. 8. 2023
Tillage 20 cm	5. 9. 2022	tillage 20 cm	14. 9. 2023
Silwet Star (additive: 1 $l \cdot ha^{-1}$), MARKATE 50 (insecticide: 50 $g \cdot l^{-1}$ Lambda-Cyhalothrin, 0.1 $l \cdot ha^{-1}$) Clinic (herbicide: glyphosate 360 g, 2 $l \cdot ha^{-1}$)	30. 9. 2022	sowing, winter wheat cv. LG Keramik	25. 9. 2023
Fertilization NP-S (ammonium N 22.5%, P_2O_5 18.5%, SO_3 18%, 90 $kg \cdot ha^{-1}$)	11. 10. 2022	fertilization NP-S (ammonium N 22.5%, P_2O_5 18.5%, SO_3 18%, 90 $kg \cdot ha^{-1}$)	26. 9. 2023
Sowing, winter wheat cv. Solindo CS	12. 10. 2022	Retacel Extra R 68 (regulator, 0.5 $kg \cdot ha^{-1}$), LEXIN (auxiliary herbal preparation, 0.25 $kg \cdot ha^{-1}$)	27. 3. 2024
Karate Zeon 5 CS (insecticide: lambda-cyhalothrin – 50 g, 0.15 $kg \cdot ha^{-1}$), BeFlex (herbicide: beflubutamid 500 g, 0.35 $l \cdot ha^{-1}$), ADETO (herbicide: 500 $g \cdot l^{-1}$ flufenacet, 0.35 $kg \cdot ha^{-1}$)	7. 11. 2022	fertilization: LAD 27 (1/2 nitrate N + 1/2 ammonium N 26.2%, $CaCO_3$ + $MgCO_3$ 20%, 125 $kg \cdot ha^{-1}$)	28. 3. 2024
Fertilization: LAD 27 (ammonium N: 13.5%, nitrate N: 13.5%, MgO total 4.1%, MgO water soluble 1%, 200 $kg \cdot ha^{-1}$)	23. 3. 2023	fertilization: LOVODAM 30 (total N 30%, amidic 15%, 100 $l \cdot ha^{-1}$)	10. 4. 2024
Fertilization: granular urea (amidic N 45%, 160 $kg \cdot ha^{-1}$)	20. 4. 2023	saracen max (herbicide: florasulam 200 g, tribenuron-methyl 600 g, 0.025 $kg \cdot ha^{-1}$) PEEDY (adjuvant 0.1 $l \cdot ha^{-1}$) fyto-fitness basic (auxiliary herbal preparation, 1 $kg \cdot ha^{-1}$)	15. 4. 2024
MARKATE 50 (insecticide: 50 $g \cdot l^{-1}$ Lambda-Cyhalothrin, 0.1 $l \cdot ha^{-1}$) Retacel Extra R 68 (regulator 0.7 $kg \cdot ha^{-1}$) Šaman (adjuvant: 0.4 $l \cdot ha^{-1}$) Corello (herbicide: pyroxsulam – 75 g, 125 $g \cdot ha^{-1}$) Folit P 500 SL (fertilizer 1 $l \cdot ha^{-1}$) LEXIN (auxiliary herbal preparation, 0.4 $l \cdot ha^{-1}$) Lister komplex cereals SL (fertilizer 1 $l \cdot ha^{-1}$)	26. 4. 2023	fertilization: LOVODAM 30 (total N 30%, amidic 15%, 100 $l \cdot ha^{-1}$)	17. 5. 2024
Harvest	23. 7. 2023	Harvest	27. 7. 2024

2.2 Study Design

Six sown strips were established inside the field (Figure 1). The strips were 6 m wide and 50 m long, and the neighbouring strips were 50 m away from each other. The strips covered approx 5% of the field area. Two types of flower strips were sown in three replicates and alternately, and the seed mixtures used for strip establishment (Seed Service, Ltd., Vysoké Mýto, Czech Republic) followed the national subsidy titles 'Nectareous strips' and 'Fodder strips' (Ministry of Agriculture, 2015). The species of seeds were selected from the list to account for flowering time, plant height (to avoid shading of the PV panels), and suitability for pollinators or herbivores (Table 2). Sowing was carried out on 30 September 2022, and the stands were mulched to a stubble height of 0.15 m in early September 2024. No fertilizers or crop protection products were applied to the area of the strips.

Simulations of the vertical APV panels were erected in two halves of the sown strips in April 2023. The simulations consisted of a wooden construction column, with fields between the poles wrapped with groundcover polypropylene (PPH) 100 foil 105 cm wide. The dimensions and position of the wrapped fields were the same as those planned for a real vertical APV installation. The maximum height of the construction was 320 cm, with the lower edge being 80 cm above ground. The relevance of using this simulation was justified by our microclimatic measurements conducted at the experimental site in Prague-Ruzyně. These validating measurements were taken by temperature sensors (type TMS-4, TOMST, Prague, Czech Republic) from May–June 2023 (12:00–19:00 hod.) at a height of 30 cm above ground to minimize interference from vegetation. Data were collected in areas shaded by the simulation and by real photovoltaic panels, under

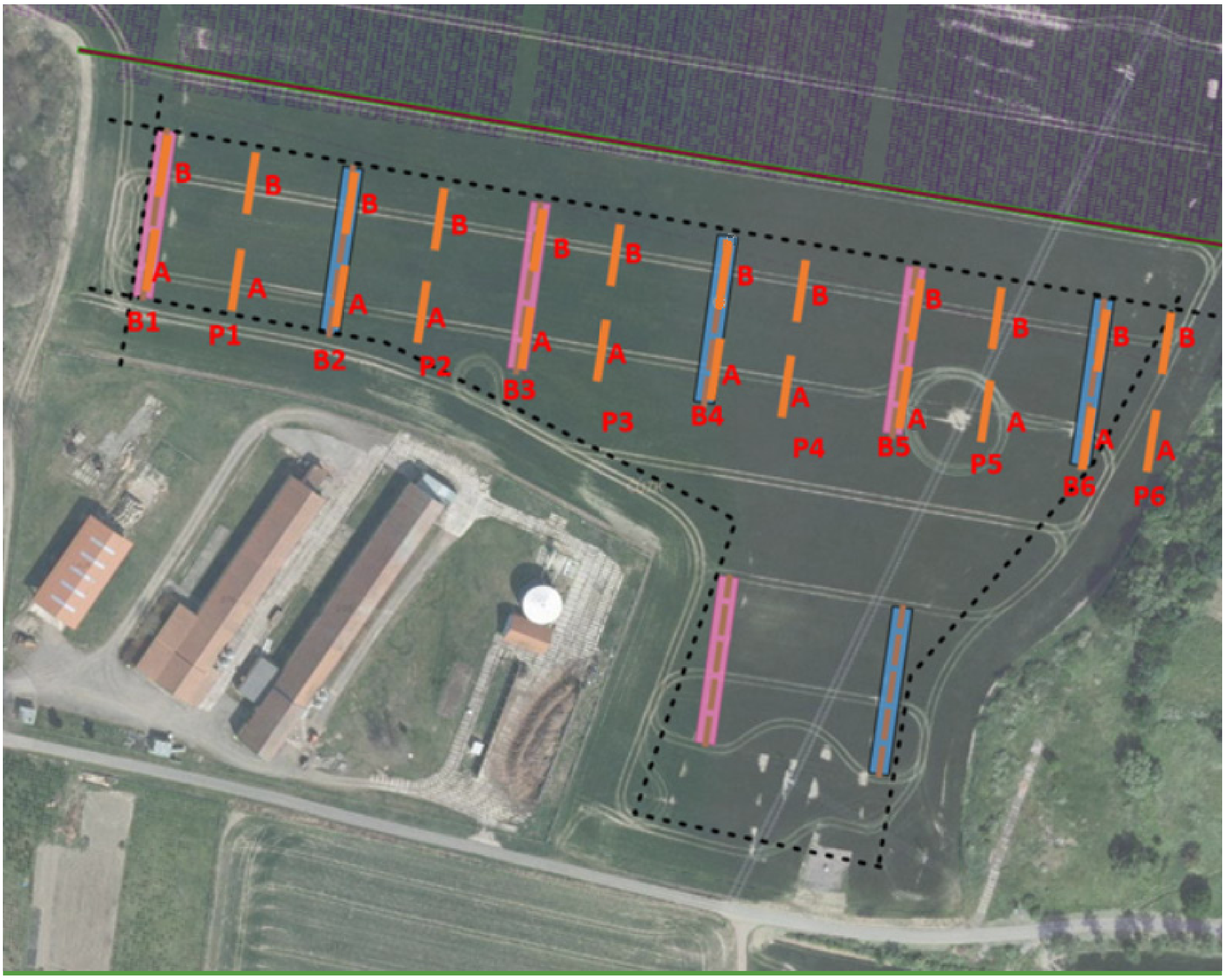

Figure 1 Arrangement of the sown strips in the locality Zavidov, Czech Republic
purple – Nectareous strips; blue – Fodder strips; orange lines – individual sample stands (two pitfall traps, two sets of pan traps and one sweep netting walk). Sown strips were marked B1-6 and the corresponding controls in the crop P1-6. Stands within each strip or control were denoted A/B. The simulations were placed in strips B1 and B2

the simulations or panels, and outside of the shaded area (control). As the difference in the mean temperature between the areas shaded by the simulation and PV panels was only -0.35 ±0.026 °C (a negative sign indicates a lower temperature under the simulation conditions), we consider this type of construction as a relevant simulation for the vertical APV installation if microclimatic conditions under the installations are of concern.

2.3 Arthropod Sampling and Focal Taxa

To obtain the most representative overview of arthropods occurring at the locality, multiple sampling methods were employed simultaneously (Štrobl et al., 2019). These included sweep-netting, pan traps and pitfall traps. Sampling was conducted from May to October 2023 and from April to June 2024. Sampling was repeated at approximately monthly intervals (2023: 2. 5., 7. 6., 3. 7. 27. 7., and 3. 10.; 2024: 29. 4., and 19. 6.). The pan and pitfall traps were exposed for 7 days starting with the dates specified above, and sweep netting was performed for one day during the period of trap exposure.

The pan trap method is the most efficient method for monitoring pollinators and other flying insects. The traps were made of plastic dishes (volume 350 ml, diameter 11.5 cm, and depth 5.6 cm), which were spray painted with yellow, white and blue colours following the protocol of the European Pollinator Monitoring Scheme (Potts et al., 2020), to cover the widest range of the species possible. The traps were placed together attached to the wooden pole at the height of the vegetation and filled with a saline solution (50 g NaCl per 1 litre of water + a drop of odourless detergent). As the height of the vegetation varied over the study period, the height of the trap was adjusted accordingly. In each flower strip, four sets of pan traps were placed in a line separated by approx 12 m, and another four sets were placed inside the crop in between the strips, approximately 25 m inside the crop measured from the edge of the strips, and parallel to the line of traps inside the sown strip. In total, 48 sets of pan traps were exposed. In 2023, all three colours of traps were used, whereas in 2024, only white- and yellow-coloured dishes were used. For the purpose of this analysis, the catches from all the pan trap colours were pooled together. When emptied, the content of traps was poured through a fine sieve, and the filtered arthropods and debris were transferred to plastic bags equipped with a label and fixed in 70% ethanol. In the laboratory, the samples were stored at -23 °C until processing.

The communities of ground-dwelling arthropods were studied using pitfall traps. The traps were plastic cups (volume 250 ml and diameter of the opening 7 cm) half-filled with the same saline solution as that used for the pan traps. The traps were placed in the ground so that the opening was level with the soil surface and covered by a metal roof to reduce the risk of flooding. Pitfall traps

Table 2 Mixture of plant species for the establishment of experimental flower strips

	Species	Seeding rate ($kg \cdot ha^{-1}$)	Cultivar
Fodder strip	*Avena nuda*	65	Rertag C1
	*Panicum miliaceum**	15	Rubikon C1
	Brassica oleracea conv. *acephala* var. *medullosa*	0.8	Boma C1
	Fagopyrum esculentum	15	Kora C2
	*Phalaris canariensis**	15	Judita C1
	Phacelia tanacetifolia	5	Boratus C1
	*Linum usitatissimum**	20	Floral C1
	*Pisum sativum**	30	Eso C1
Nectareous strip	*Trifolium pratense*	15	Garant c1
	*Anthyllis vulneraria**	15	Atyl
	*Onobrychis viciifolia**	15	
	Vicia sativa	15	Nukian C2
	Medicago sativa	15	Giula C1
	*Sinapis alba**	1	Andromeda C1
	Fagopyrum esculentum	5	Kora C2
	Phacelia tanacetifolia	1	Boratus C1
	*Carum carvi**	3	Rekord C1

* species sown but not found in the relevés

Table 3 List of taxonomic groups monitored per method of sampling

Method	Taxonomic groups
Pitfall traps	Mollusca, Araneae, Isopoda, Diplopoda, Chilopoda, Dermaptera, Auchenorrhyncha, Aphidoidea, Heteroptera, Coleoptera (Carabidae (incl. larvae), Staphylinidae, Coccinellidae, Curculionidae and other families), Formicidae
Sweep-netting	Araneae, Auchenorrhyncha, Aphidoidea, Heteroptera, Psocoptera, Neuroptera (incl. larvae), Coleoptera (Coccinellidae (incl. larvae), *Oulema* spp. (incl. larvae), Curculionidae, and other families), Hymenoptera (Parasitica), Diptera (Syrphidae (incl. larvae), and others), Lepidoptera (incl. larvae), all other orders
Pan traps	Araneae, Auchenorrhyncha, Aphidoidea, Heteroptera, Neuroptera, Coleoptera (Staphylinidae, Cantharidae, Coccinellidae (incl. larvae), Nitidulidae, *Oulema*, Curculionidae, and other families), Hymenoptera (Parasitica, Aculeata, *Apis mellifera*, *Bombus* spp.), Diptera (Syrphidae (incl. larvae) and other families), Lepidoptera, others

were placed in approx 1 m distance from the poles with pan traps. Thus, a total of 48 pitfall traps were installed at the locality. The process of emptying was as described for the pan traps.

Sweep netting was performed using a net (diameter of 35 cm), and 20 sweeps were made evenly between the two neighbouring stands with pan traps. On each sampling date, 24 sweep-netting samples were taken. All the collected individuals were transferred to a plastic bag with 70% ethanol, which was equipped with a label and stored as described above.

In the laboratory, the samples were processed in white trays, and the number of representatives per taxonomic group was counted. The taxonomic groups considered in this study are listed in Table 3. As the catch of some of the groups was low, the groups were pooled for subsequent analysis whenever meaningful (e.g., beetle families).

2.4 Vegetation Survey

Plant biodiversity was assessed using phytocoenological relevés (Moravec, 1994). Owing to the high number of weeds in some plots, the size of each sample was set to 0.1 m2. For each sample, the plant species composition and abundance were recorded. The exact placement of the census square was random within the sown strip or within the crop (approx 25 m from the crop edge). Altogether, eight phytocoenological relevés were taken from each flower strip and crop; thus, 96 relevés were assessed on each sampling date.

2.5 Data Analysis

Owing to the nature of the data, two analytical approaches were used for statistical evaluation. The analysis was conducted in R Version 4.3.3 (R Core Team, 2024). Arthropod data were analysed using generalized linear models (GLM), where the abundance of a particular taxonomic group was the response variable. The explanatory variables varied according to the research question to test: the effect of the presence of the sown strips (strip vs. crop), the effect of the strip type (fodder vs. nectareous), and the effect of the simulation (simulation present or absent). Thus, three different models were fitted for each combination of collection methods and taxonomic groups. As the response data were counts, data fitting was started with Poisson errors, but owing to excessive overdispersion, the final models were fitted with quasi-Poisson errors (Crawley, 2007). Statistical significance was assessed via the F test.

The vegetation data were analysed via nonmetric multidimensional scaling (NMDS) and function metaMDS (vegan package; Oksanen et al., 2024), followed by PERMANOVA, which used the function adonis2 (vegan package; Oksanen et al., 2024) to identify differences in community composition between the types of habitats (crop and the two types of sown strips). Empty samples (no noncropped plants were recorded) were excluded from the analysis. The indicator species for each type of habitat were identified using the function multipatt (indicspecies package; De Cáceres & Legendre, 2009). The analysis was repeated, including and excluding the species that were sown into the strips, to reveal the true differences in the wild flora.

3 Results and Discussion

3.1 Results

In total, 90,800 invertebrate individuals were collected using the three methods of sampling. The pitfall traps captured 13,596 individuals, sweep netting captured a further 13,665 individuals, and 63,539 specimens were collected by colour pan traps. The pitfall traps were dominated by spiders (Araneae), ground beetles (Carabidae), rove beetles (Staphylinidae), other families of beetles (Coleoptera) and true bugs (Heteroptera) (Table 4). Sweep netting was dominated by "other" dipterans (Diptera, except Syrphidae), aphids (Aphidoidea), beetles, true bugs, spiders and, to a lesser extent, true hoppers (Auchenorrhyncha), hoverflies (Syrphidae) and "parasitic wasps" (Hymenoptera: Parasitica) (Table 4). The pan traps were dominated by sap beetles (Nitidulidae), mainly pollen beetles (*Brassicogethes* spp.), closely followed by Diptera (Table 4). Other abundant groups included hoverflies, aphids, solitary bees (Aculeata) and *Apis mellifera* (Table 4). The remaining taxonomic groups were much less abundant, and none of the other groups constituted more than 2% of the catch per method (Table 5).

3.1.1 Presence of Sown Strips

The presence of the sown strips significantly positively affected the catch of all five most abundant groups of arthropods found in the pitfall traps (Table 4; Figure 2). This effect was much less consistent in the case of sweep netting: the presence of sown strips positively affected the catch of beetles, true bugs and hoverflies only, whereas the catch of the remaining five dominant taxonomic groups remained unaffected by the presence of the sown strips (Table 4). The response of arthropods to the presence of sown strips was most variable in the case of pan traps. Among the six most abundant taxa collected, the sown strips had a positive influence on the catch of sap beetles (Nitidulidae), solitary bees (Aculeata) and honeybees (*Apis mellifera*); a negative influence on the catch of hoverflies; and no effect on Diptera or aphids (Table 4).

3.1.2 Sown Strip Type

The type of the sown strip, whether fodder or nectareous, had no effect on arthropod catch, irrespective of the method used (Figure 3), with the exception of aphids, which were collected from a greater number of individuals in the fodder strip than in the nectareous strip when the pan traps were used (Table 4).

Table 4 Overview of the GLM (quasipoisson) results for the most abundant groups of arthropods and three different types of comparisons

Collecting method Taxon	N	Model 1 crop vs. sown strips	Model 2 fodder vs. nectareous strips	Model 3 control vs. simulation
Pitfalls				
Araneae	6.594	<	NS	NS
Carabidae	4.604	<	NS	NS
Staphylinidae	924	<	NS	NS
Coleoptera[1]	511	<	NS	NS
Heteroptera	324	<	NS	NS
Sweep netting				
Diptera[2]	4.854	NS	NS	NS
Aphidoidea	3.971	NS	NS	NS
Coleoptera	1.914	<	NS	NS
Heteroptera	1.096	<	NS	NS
Araneae	767	NS	NS	NS
Auchenorrhyncha	375	NS	NS	NS
Syrphidae	324	<	NS	NS
Parasitica[3]	323	NS	NS	NS
Pans				
Nitidulidae	27.087	<	NS	<
Diptera[2]	25.995	NS	NS	NS
Syrphidae	1.840	>	NS	NS
Aphidoidea	1.624	NS	>	<
Aculeata[4]	1.354	<	NS	NS
Apis mellifera	1.236	<	NS	NS

Model 1: Catch size ~ Site (field interior vs. sown strips); Model 2: Catch size ~ Strip type (fodder vs. nectareous strip); and Model 3: Catch size ~ Simulation (simulation absent or present). Only groups that constituted more than 2% of the catch were analysed
1 – other than Carabidae and Staphylinidae; 2 – other than Syrphidae; 3 – hymenopteran parasitoids; 4 – other than *Apis mellifera*
The < > signs indicate that the comparison was significant at $\alpha = 0.05$, and the direction of the sign points to the nature of the effect; thus, < for Model 1 indicates that significantly more individuals were found in the sown strips than within the crop, for example

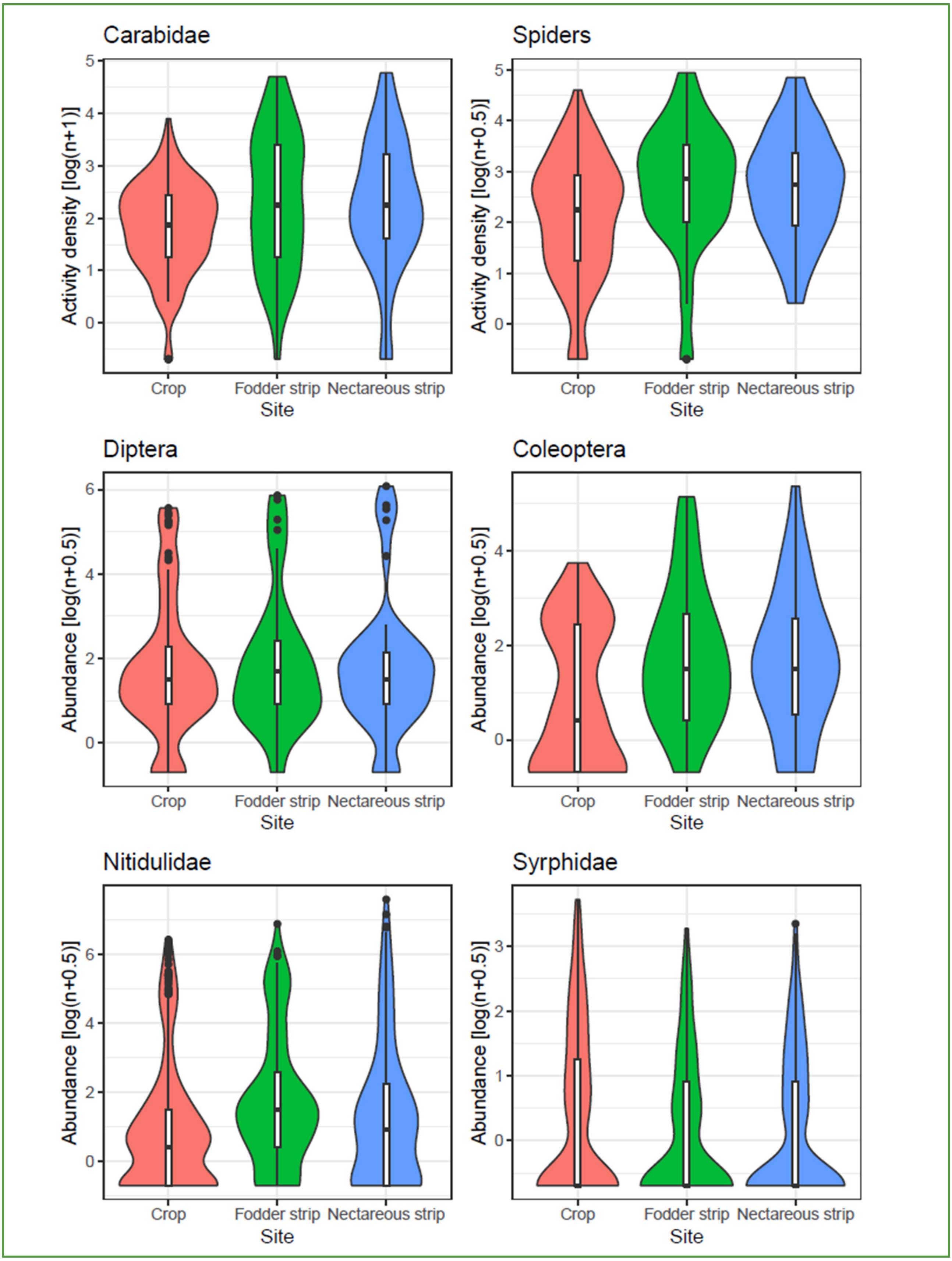

Figure 2 Examples of variation in catch size with habitat
The vertical line inside the boxplots indicates the median, and the range of the box indicates the interquartile range; the shape of the violin refers to the spread of the point along the *y*-axis

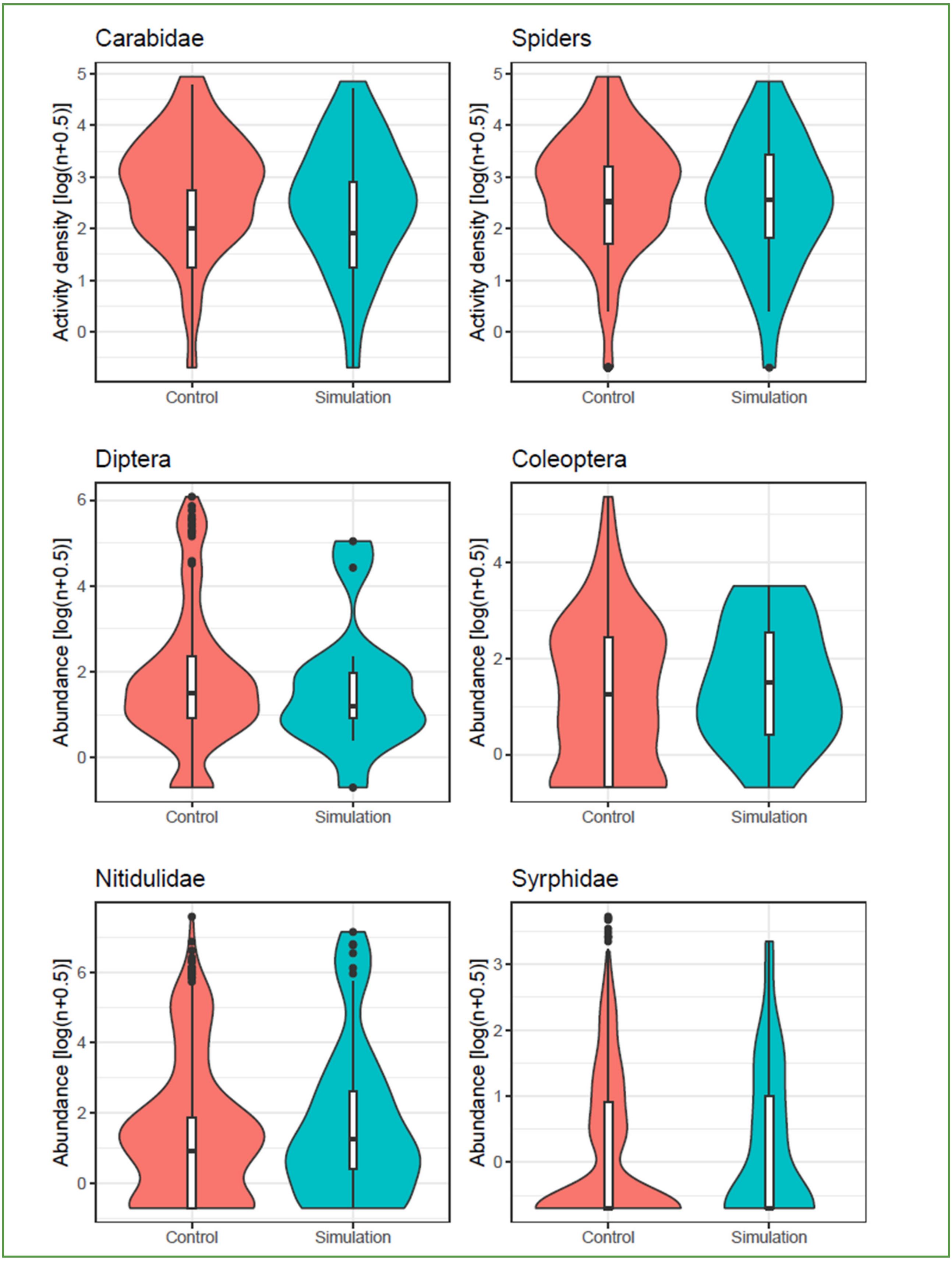

Figure 3 Examples of the variation in catch size with habitat
The vertical line inside the boxplots indicates the median, and the range of the box indicates the interquartile range; the shape of the violin refers to the spread of the point along the *y*-axis

Table 5 Catch size for taxonomic groups that each comprised less than 2% of the catch per collection method

Pitfall traps		Sweep netting		Pan traps	
Taxon	*n*	Taxon	*n*	Taxon	*n*
Isopoda	110	Other	84	Parasitica	894
Diplopoda	187	Neuroptera	23	other Coleoptera	791
Chilopoda	39	Psocoptera	14	Staphylinidae	644
Mollusca	46	Lepidoptera	7	Heteroptera	387
Formicidae	94			other	366
Aphidoidea	54			Auchenorrhyncha	302
Dermaptera	65			Curculionidae	259
Orthoptera	34			Araneae	228
Other	7			Cantharidae	127
				Lepidoptera	121
				Coccinellidae	101
				Oulema spp.	92
				Chrysopidae	32

3.1.3 Presence of Vertical APV Simulations

Similarly, APV simulation had a very limited effect on the monitored groups of arthropods, as in the vast majority of them, the effect was not statistically significant (Table 4). The only exceptions were again provided by the pan traps: more individuals of pollen beetles and aphids were found with simulations than with the control sites (Table 4).

3.1.4 Vegetation

Altogether, 12,156 individual plants were counted in the vegetation relevés. The survey recorded 69 species of plants, 54 of which were wild plants. Thirteen species each composed >2% of the total number of individuals, which included four sown species (*Triticum aestivum*, *Trifolium* spp., *Trifolium pratense* and *Phacelia tanacetifolia*) and seven species of wild plants (*Tripleurospermum inodorum*, *Galium aparine*, *Viola arvensis*, *Fallopia convolvulus*, *Fumaria officinalis*, *Apera spica-venti*, *Capsella bursa-pastoris*, *Veronica arvensis*, and *Thlaspi arvense*). Overall, these species composed 76.4% of individuals, and *Tripleurospermum inodorum*, the most dominant species in our relevés, alone composed 13.1% of all the recorded individuals. In contrast, nine species were found in only one individual, including *Adonis aestivalis*, a species of conservation concern.

When all the plant species were included in the analysis, the vegetation of the field was rather well separated from that of the two types of sown strips (Figure 4A). Nectareous and fodder strips were not well separated in the NMDS plot (Figure 4A). The results of the PERMANOVA, however, suggested that the communities of all three types of habitats were significantly different from each other (Table 6). The characteristic species for the fodder strip were *Avena nuda*, *Brassica oleracea*, *Lysimachia arvensis*, *Cerastium arvense*, *Atriplex patula*, *Sisymbrium officinale*, and *Chamerion angustifolium*, and the following 12 species were characteristic of the nectareous strip: *Trifolium* spp., *Trifolium pratense*, *Daucus carota*, *Medicago sativa*, *Vicia sativa*, *Melilotus albus*, *Trifolium repens*, *Fagopyrum esculentum*, *Lolium perenne*, *Trifolium hybridum*, *Matricaria discoidea*, and *Sinapis arvensis*. No characteristic species was identified for the crop.

Table 6 Significance of differences in the vegetation community between the habitat types, as assessed by PERMANOVA

Compared pairs	All species			Wild species only		
	R^2	F	P	R^2	F	P
Crop × fodder strip	0.118	41.116	<0.001	0.053	17.190	<0.001
Crop × nectareous strip	0.175	65.313	<0.001	0.036	11.178	<0.001
Fodder strip × nectareous strip	0.153	60.096	<0.001	0.009	2.770	0.004
Simulation × control	0.011	5.212	<0.001	0.003	1.776	0.048

Figure 4 NMDS plot of all phytocoenological relevés
A – complete dataset, B – only naturally occurring species were considered; the samples are distinguished according to their habitat; for species EPPO codes, please refer to https://gd.eppo.int/

Although much less clear separation between the three types of habitats was found when only the wild flora was considered (Figure 4B), PERMANOVA revealed that all three communities were significantly different from each other (Table 6). The characteristic species were *Cerastium arvense*, *Atriplex patula*, *Chamerion angustifolium* and *Sisymbrium officinale* for the fodder strip and *Matricaria discoidea*, *Sinapis arvensis* and *Consolida regalis* subsp. *paniculata* for the nectareous strip. However, no characteristic species were identified for the crop.

According to PERMANOVA, the presence of the APV simulations significantly affected the community composition regardless of whether all species or only wild species were included in the analysis (Table 6); however, the difference was only weak for the communities of the wild species. Nine species (entire community) were found to be characteristic of the sites with simulations: *Phacelia tanacetifolia*, *Medicago sativa*, *Capsella bursa-pastoris*, *Chenopodium album*, *Matricaria chamomilla*, *Avena nuda*, *Vicia sativa*, *Sonchus oleraceus* and *Myosurus minimus* when only wild species were considered.

3.2 Discussion

Our study provided important insights into how vertical agriphotovoltaics (APV) in combination with sown flower strips might affect invertebrate and plant diversity in farmlands. The results confirmed that the presence of sown strips had a clearly positive effect on the abundance of certain invertebrate groups, which is consistent with previous findings in which sown strips increased resource availability, habitat heterogeneity, and overall arthropod biodiversity (e.g., Haaland, Naisbit, & Bersier, 2011; Tschumi et al., 2015).

The presence of sown strips positively influenced the abundance of the five most common arthropod groups collected using pitfall traps, demonstrating their importance for biodiversity in agroecosystems. This aligns with studies showing that sown strips provide essential resources and habitats for ground-dwelling arthropods (Haaland, Naisbit, & Bersier, 2011; Tschumi et al., 2015). When sweep nets were used, the effects were less consistent, benefiting only beetles, true bugs, and hoverflies, likely because of their dependence on the floral resources often provided by sown strips (Bianchi, Booij, & Tscharntke, 2013). Other taxa might require different habitat characteristics or have greater mobility, reducing their reliance on these strips. The pan traps revealed more variability: sap beetles, solitary bees, and honeybees benefited from the sown strips, while hoverflies were negatively affected, and no effects were observed for Diptera or aphids. This reflects the specific ecological needs of different taxa, such as floral resources for bees versus broader habitat preferences for hoverflies (Jauker et al., 2009). Overall, these findings highlight the value of sown strips for promoting biodiversity while underscoring the need to tailor their design to benefit a broader range of arthropods.

The type of sown strip (fodder or nectareous) played no significant role in the vast majority of the groups tested, indicating that both types of strips provide similar benefits for supporting invertebrate diversity. This is consistent with findings that different sown strip compositions often support comparable levels of biodiversity, provided that they include key floral and structural resources (Tschumi et al., 2015). An exception was observed for aphids, whose abundance was greater in the fodder strips when they were sampled with pan traps. This specific effect could be related to differences in vegetation composition, as fodder strips may include plant species that serve as suitable hosts for aphids or provide better microclimatic conditions for their development. Additionally, differences in food availability for aphid predators or mutualists, such as ants, between the strip types could play a role. Further investigations into plant-insect interactions and vegetation structure in these sown strips would help clarify the mechanisms underlying this pattern (Holland et al., 2015).

The presence of APV simulations had only a very limited impact on the monitored arthropod groups. Statistically significant effects were detected solely in pan traps, where the abundance of pollen beetles and aphids was greater in the presence of APV simulations than in the control sites. This result is also interesting from the farmer's perspective, as both groups are important crop pests.

The plant communities differed between the types of habitats, and inside the crop, they were much less diverse than they were in the sown strips. This is not surprising, as the crop was managed in a way typical for the area, which included the use of herbicides. The differences in spontaneous flora between the types of strips were also significant, which may have resulted from differences in vegetation architecture and canopy closure between the two types of strips, which were affected by the composition of the seed mixture. Weed germination and establishment are highly dependent on the availability of gaps in the vegetation and competition for light (Martinková & Honěk, 2024); therefore, the nature of the sown species and their competitiveness could explain this result. Otherwise, the entire experimental area was managed identically before the strips had been established; therefore, the previous management was not expected to affect the observed differences. Interestingly, some rare weed species were recorded in the sown strips: *Adonis aestivalis*, *Myosurus minimus*, *Aphanes arvensis* and *Papaver argemone*. This finding indicates that rare species benefit from including seminatural habitats in croplands, as these are used as refuges.

The mechanisms of the potential effects of APVs on biodiversity might involve altering the microclimate by shading and possibly also by emitting accumulated heat. Since this study was based on using simulated APV installation, a question arises regarding how close the conditions created by these simulations were to real APV. Temperature data showed that the mean difference between areas shaded by solar panels and simulated panels was less than 0.5 °C, which is too small to expect that any ecologically meaningful effects can be manifested in the time scale at which the observations were made. For example, the activity of epigeic arthropod species is affected by temperature, and to double the catch, a change in temperature of 8 °C is needed (Saska et al., 2013). By using the same relationship between the change in the catch and change in temperature (Saska et al., 2013) and the value of the mean difference in temperature observed between the real and simulated panels (ΔT = 0.35 °C), a magnitude of difference in the catch size of 1.03 can be expected between the simulation and a real APV installation. This is a truly negligible effect. Flying insects are capable of thermoregulating by utilizing the heat developed by their flight muscles (Lahondere, 2023) and are also highly mobile; thus, we do not expect any direct differences to be observed if real solar panels are used instead of simulations. Similarly, the thermal window for germination and seedling establishment is much wider in plants (most often approximately 23 °C; Honěk et al., 2014). The observed temperature difference could have only a very minor effect on the early-stage establishment and plant community composition. Thus, the simulations should represent a good proxy for real APV installations in terms of their effects on biodiversity.

4 Conclusion

Within scientific literature, this is the first study that has approached the effects of vertical APV on biodiversity. Our study suggests based on simulations that vertical APV in combination with sown strips of flowering vegetation can be a viable option for sustainable agroecosystem management, as no detrimental effects on biodiversity were found in the sown strips with simulations compared to the strips without them. In fact, we could only detect some differences between the simulations and control strips in two out of 19 combinations of taxon and method of collection studied, and week effects on wild flora. At the same time, the positive effects of implementing sown vegetation strips in the crops were supported. The results align with the general conclusions of studies that have suggested that careful implementation of modern technologies, such as agrivoltaics (e.g., Dupraz et al., 2011; Barron-Gafford et al., 2019), can coexist with biodiversity-enhancing measures such as sown strips without jeopardizing their ecological benefits. Our studies suggest that vertical APV, which integrate production and environmental functions, can be a viable option for sustainable agroecosystem management. However, a successful case study of a fully operational vertical APV installation is needed to support the results and conclusions of our study and to enhance the understanding of the long-term impacts of APV on the biodiversity and economic sustainability of such systems.

Acknowledgements

This study was funded by the Czech Technological Agency, Project No. SS05010243 awarded to D.H. We would like to thank Helena Uhlířová and Hana Smutná for excellent technical assistance in the field as well as in the laboratory. We also thank Markéta Simotová, Nikola Pecníková, Amir Murat and Marek Šroub for their help with sample processing.

References

Adeh, E.H. et al. (2019). Solar PV power potential is greatest over croplands. *Scientific Reports*, 9(1), 11442. https://doi.org/10.1038/s41598-019-47803-3

Barron-Gafford, G.A. et al. (2019). Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands. *Nature Sustainability*, 2(9), 848–855. https://doi.org/10.1038/s41893-019-0364-5

Benton, T.G., Vickery, J.A., & Wilson, J.D. (2003). Farmland biodiversity: is habitat heterogeneity the key? *Trends in Ecology & Evolution*, 18(4), 182–188. https://doi.org/10.1016/S0169-5347(03)00011-9

Bianchi, F.J.J.A., Booij, C.J.H., & Tscharntke, T. (2013). Sustainable pest regulation in agricultural landscapes: A review on landscape composition, biodiversity, and natural pest control. *Proceedings of the Royal Society B: Biological Sciences*, 280(1756), 20131261. https://doi.org/10.1098/rspb.2006.3530

Campbell, A.J. et al. (2017). Getting More Power from Your Flowers: Multi-Functional Flower Strips Enhance Pollinators and Pest Control Agents in Apple Orchards. *Insects*, 8(3), 101. https://doi.org/10.3390/insects8030101

Crawley, M.J. (2007). *The R Book*. John Wiley & Sons Ltd.

De Cáceres, M., & Legendre, P. (2009). Associations between species and groups of sites: indices and statistical inference. *Ecology*, 90(12), 3566–3574. https://doi.org/10.1890/08-1823.1

Dupraz, C. et al. (2011). Combining solar panels and food crops to improve land use efficiency: A concept and its implications for agrivoltaics. *Renewable Energy*, 36(9), 2457–2460. https://doi.org/10.1016/j.renene.2011.03.005

Goetzberger, A., & Zastrow, A. (1982). On the Coexistence of Solar-Energy Conversion and Plant Cultivation. *International Journal of Solar Energy*, 1, 55–69. https://doi.org/10.1080/01425918208909875

Haaland, C., Naisbit, R.E., & Bersier, L.F. (2011). Sown wildflower strips for insect conservation: A review. *Insect Conservation and Diversity*, 4(1), 60–80. https://doi.org/10.1111/j.1752-4598.2010.00098.x

Hernandez, R.R. et al. (2019). Techno-ecological synergies of solar energy for global sustainability. *Nature Sustainability*, 2, 560–568. https://doi.org/10.1038/s41893-019-0309-z

Holland, J.M. et al. (2015). Managing habitats on farmland for insect pollinator conservation. *Biological Conservation*, 182, 215–222. https://doi.org/10.1016/j.biocon.2014.12.009

Honek, A. et al. (2014). Plasticity of the thermal requirements of exotherms and adaptation to environmental conditions. *Ecology and Evolution*, 4(15), 3103–3112. https://doi.org/10.1002/ece3.1170

Jauker, F. et al. (2009). Pollinator dispersal in an agricultural matrix: Opposing responses of wild bees and hoverflies to landscape structure and distance from main habitat. *Landscape Ecology*, 24(4), 547–555. https://doi.org/10.1007/s10980-009-9331-2

Kowalska, J., Antkowiak, M., & Sienkiewicz, P. (2022). Flower Strips and Their Ecological Multifunctionality in Agricultural Fields. *Agriculture*, 12, 1470. https://doi.org/10.3390/agriculture12091470

Lahondere, Ch. (2023). Recent advances in insect thermoregulation. *Journal of Experimental Biology*, 226(18), jeb245751. https://doi.org/10.1242/jeb.245751

Ma Lu S. et al. (2024). Data on the effects of a vertical agrivoltaic system on crop yield and nutrient content of barley (*Hordeum vulgare* L.) in Sweden. *Data in Brief*, 57, 110990. https://doi.org/10.1016/j.dib.2024.110990

Martinkova, Z., & Honek, A. (2024). Effect of gap size in grass cover on the percentage and rate of dandelion achene germination. *Weed Research*, 64(5), 376–383. https://doi.org/10.1111/wre.12657

Menta, C. et al. (2023). Can grasslands in photovoltaic parks play a role in conserving soil arthropod biodiversity? *Life*, 13(7), 1536. https://doi.org/10.3390/life13071536

Ministry of Agriculture. (2015). Nařízení vlády č. 75/2015 Sb., o podmínkách provádění agroenvironmentálně-klimatických opatření a o změně nařízení vlády č. 79/2007 Sb., o podmínkách provádění agroenvironmentálních opatření, ve znění pozdějších předpisů. Available at: https://mze.gov.cz/public/portal/mze/legislativa/pravni-predpisy-mze/uplna-zneni/narizeni-vlady-2015-75

Moravec, J. (1994). *Fytocenologie*. Academia.

Oksanen, J. et al. (2024). _vegan: Community Ecology Package_. R package version 2.6-8. Available at: https://CRAN.R-project.org/package=vegan

Potts, S. et al. (2020). Proposal for an EU Pollinator Monitoring Scheme, EUR 30416 EN. Publications Office of the European Union. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC122225

Randle-Boggis, R.J. et al. (2020). Realizing co-benefits for natural capital and ecosystem services from solar parks: a co-developed, evidence-based approach. *Renewable and Sustainable Energy Reviews*, 125, 109775. https://doi.org/10.1016/j.rser.2020.109775

R Core Team. (2024). *_R: A Language and Environment for Statistical Computing_*. *R Foundation for Statistical Computing*, Vienna, Austria. Available at: https://www.R-project.org/

Saska, P. et al. (2013). Temperature effects on pitfall catches of epigeal arthropods: a model and method for bias correction. *Journal of Applied Ecology*, 50, 181–189. https://doi.org/10.1111/1365-2664.12023

Schneider, A.K. et al. (2023). Drawing transformation pathways for making use of joint effects of food and energy production with biodiversity agriphotovoltaics and electrified agricultural machinery. *Journal of Environmental Management*, 335, 117539. https://doi.org/10.1016/j.jenvman.2023.117539

Schwartz, R., & Ziv, Y. (2024). Shedding light on biodiversity: reviewing existing knowledge and exploring hypothesised impacts of agrophotovoltaics. *Biological Reviews,* 100(2025), 855–870. https://doi.org/10.1111/brv.13165

Stroot, L. et al. (2022). Establishment of wildflower strips in a wide range of environments: A lesson from a landscape-scale project. *Restoration Ecology*, 30(4), e13542. https://doi.org/10.1111/rec.13542

Štrobl, M. et al. (2019). Impact of an invasive tree on arthropod assemblages in woodlots isolated within an intensive agricultural landscape. *Diversity and Distribution*, 25(11), 1800–1813. https://doi.org/10.1111/ddi.12981

Tschumi, M. et al. (2015). Tailored flower strips promote natural enemy biodiversity and pest control in adjacent crops. *Journal of Applied Ecology*, 52(3), 895–904. https://doi.org/10.1111/1365-2664.12653

Wagner, D.L. (2020). Insect Declines in the Anthropocene. *Annual Review of Entomology*, 65, 457–480. https://doi.org/10.1146/annurev-ento-011019-025151