

Effects on pollinator-flower visit frequency observed between shade conditions beneath white backed, black backed, and bifacial simulated solar panels placed over *Symphytum officinale* and *Pentaglottis Sempervirens*, during summer 2021 in Hertfordshire, UK.

A report submitted as the examined component of the Project Module SXE390

Jamie Halford

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Abstract

The increasing use of ground-mounted solar photovoltaics offers opportunities to enhance site biodiversity. UK solar parks commonly constitute panel arrays over managed meadows. Optimising installations to benefit pollinators presents opportunities to mitigate continuing declines in abundance and diversity of pollinators. Solar parks influence on pollinators is only a recent area of research, one which so far has neglected examining the specific effects of differing types of solar panel backing sheet.

This study observed pollinators (89% *Bombus*) beneath temporarily placed simulated panels, representing 'black'-backed, 'white'-backed, and 'bifacial' panels, along with an unshaded 'control'. These four treatments were observed from May to August in plots of naturally occurring *Symphytum officinale*, and *Pentaglottis sempervirens*. Twenty-six hours of pollinator counts were analysed, to determine differences in pollinator-flower visit frequency between treatments, and whether effects differ between pollinator species.

No significant differences in overall mean pollinator-flower visit frequencies were found between panel types, but a significant difference was found between the 'black' and 'control' (0.89 and 1.7 visits/flower/h respectively).

Differing responses were seen between three dominant pollinators species: *B. terrestris*, indicated strongest preference for 'control', *B. hypnorum* indicated aversion to 'black', *B. pratorum* showed no significant difference between treatments. These species-specific effects warrant further investigation.

The different panel types caused different lighting conditions. Results suggest general preference for foraging in well-lit areas, other factors, e.g. obstruction, may be influential. Differences between 'control', 'white', and 'bifacial' were not significant, so the extent of any effect remains unresolved. Bumblebees readily use habitat below panels although may be influenced by availability of adjacent sunlit areas.

Solar park developers may optimise pollinator use by limiting excessively dark shading, providing large corridors of sunlit areas alongside panel arrays. Further study is required examining effects amongst specific pollinator types, across a broader range of plant species.

[296 words]

Contents	Page number
Abstract	i
Contents	ii
List of figures and tables	iii
1. Introduction.	1
1.1 Background	1
1.2 Existing publications	1
1.3 Knowledge gap	2
1.4 Research question, hypotheses	3
2. Methods	4
2.1 Experimental set up	4
2.2 Data collection, count protocols	4
2.3 Method of analysis	6
3. Results	7
3.1 Overview	7
3.2 Combined pollinator analysis	8
3.3 Analysis of individual species/groups	9
3.4 Analysis of illuminance	12
3.5 Analysis of temperature below panels	13
4. Discussion	14
4.1 Observed pollinator diversity	14
4.2 Visit frequency differences	14
4.3 Association with illuminance	16
4.4 Possible influence of patchy light	16
4.5 Other influential factors	16
4.6 Further shortcomings	17
5. Conclusion	18
5. References	19
6. Glossary	22

List of figures	Page number
Figure 2.1 Diagram of simulated solar panel over observation plot.	5
Figure 2.2 Photos of three simulated panels , black-backed, white-backed and bifacial.	5
Figure 3.1 Pollinator species/groups observed as a proportion of all visits.	7
Figure 3.2 Mean & SD of pollinator-flower visit frequency for each treatment.	8
Figure 3.3 Mean visit frequencies for each treatment amongst main pollinator groups observed.	9
Figure 3.4 Visit frequency plotted against illuminance.	12
Figure 3.5 Visit frequency plotted against temperature	13

List of tables

Table 1.1 Comparison of common solar backing sheets	2
Table 3.1 Tukey-Kramer test statistics for pairwise comparisons, all pollinators	9
Table 3.2 Summary table of statistical analysis of individual species/groups.	11

1. Introduction

1.1 Background

The need to transition to low carbon energy sources is driving increases in installation of ground mounted photovoltaic panels, for which the UK has more than 400 'solar parks' contributing 13.5 GW of installed capacity (BEIS, 2020).

It is currently agricultural good practice to create productive meadow as a shared land use beneath solar arrays (Scurlock, 2014), including grazing of small livestock along with potential for enhanced plant-pollinator diversity.

Pollinators provide critical ecosystem services, contributing to the seed set of many agricultural and wild plants essential for ecosystem health and food security. The UK has experienced significant declines in pollinators; Powney et al. (2019) showed 1/3 of 353 UK species of bees and hoverflies decreased in occupancy (area over which they are found) between 1980 and 2013, listing habitat loss, pesticide use, and climate change as principal causes. Novel approaches to restoring habitat need to be developed to create pollinator food sources over wider landscapes.

1.2 Existing publications

Solar parks represent a novel land use change with significant environmental impacts. Armstrong et al. (2016) found the altered light conditions and shelter from installations cause changes in microclimate, soil, carbon cycling and vegetation. Such influences may have direct impacts on pollinator life cycles depending on the extent and direction of change: solar park installations have potential to cause loss or fragmentation of existing rich habitat, but may also be sited in poorer diversity agricultural landscapes, giving opportunities for improvement, if appropriately managed.

In a systematic review of the influence of solar parks on pollinator diversity Blaydes et al. (2021) highlight further negative impacts on pollinators due to use of non-selective herbicides and excessive summer cutting/grazing. However, their review shows that with appropriate design and management solar parks can create significant pollinator benefits. They systematically reviewed evidence of intervention effects and assigned confidence levels, resulting in a number of recommendations including: appropriate intensity and timing of cutting/grazing, creation of vegetation heterogeneity, boundary hedges and reproduction resources (tussocks, banks, ditches), connectivity to semi natural habitat, provision of abundant, rich, seasonally long foraging resources, and promotion of microclimate variation.

Notably, Blaydes et al. (2021) identify floral abundance and richness as the primary benefits to pollinators. Lack of flower availability is a main driver of pollinator decline (Lowe et al., 2021). To further inform optimisation of solar parks for the benefit of pollinator requires better understanding of pollinator behaviour. Graham et al. (2021), in the context of US agrophotovoltaics, specifically looked at the impact on pollinator-plant communities, examining plant composition and pollinator behaviour below solar arrays (full shade), between arrays (partial shade) and in full sun plots. They found relative increases in floral abundance and delayed bloom timing in partial shade. Pollinator abundance, richness and diversity was seen to be similar between partial shade and full sun but lower in full shade. They also observed seasonal differences amongst species, across shade variations, suggesting shade gradation may create niche partitioning, but failing to show how specific species may be influenced by differing shade. Despite the above, flower visit rates were not seen to differ between treatments, likely explained by lowered floral abundance in shade.

These reductions seen beneath arrays need to be considered amongst other possible benefits: Graham et al. (2021) discuss temporal and spatial variations in the microclimates impacting plant physiology and morphology, which appear to increase diversity and resilience to extremes. Resilience of pollinator foraging resources may be as important as quantity. They propose that panel shade may also provide transit corridors. But species-specific effects need more study.

Neither Blaydes et al. (2021) or Graham et al. (2021) focused on novel approaches, or experimental arrangements of panels. A study by Biesmeijer et al. (2020) in the Netherlands examined pollinator biodiversity within solar parks under experimental melliferous (honey yielding) plant mixes and differing periodicity of maintenance, in a site with wide inter array gaps. Although not finding significant differences from the plant mixes, they showed large inter array gaps were likely crucial in achieving overall benefits to pollinators, this partially aligns with findings by Graham et al. (2021) but gap size and degree of partial shade may negatively correlate, so further study is needed. Biesmeijer et al. (2020) also state that pollinators preferred sunlit areas, positing their need for sunlight to increase body temperature, they cite appropriate management as a crucial factor, but the practices used only partially align with recommendations by Blaydes et al. (2021) and appear to praise the site owned by the sponsors of the study.

These studies observe influences from panel presence, different management, and plant communities. But despite posited explanations, including panel spacing, floral availability and sunlight, none so far specifically examine pollinator behaviour under panels which may, by virtue of their design, differ in the type of canopy they create.

1.3 Knowledge gap

One of the differences in solar panel design which can influence under-canopy light conditions is the backing sheet. This is the outermost bottom layer which electrically insulates and protects photovoltaic components from external stresses.

A range of panel backings are available to manufacturers (Dunmore, 2021), specification is based on physical protective requirements, but also visual and light transmission requirements influencing aesthetics, efficiency, and heat regulation. The three most visually contrasting backings are compared in Table 1.1 below.

Colour	Common applications	Reasons for use
Black	Visible commercial and domestic	Improved aesthetics, more discrete, less contrast, often with black framing and black(mono crystalline) cells
White	Multi panel arrays/ solar parks	Residual light is reflected towards face of adjacent arrays. Efficiency gains. Better heat regulation.
Transparent	Bifacial panels	Cells can absorb light from both sides, giving efficiency gains if rear light is available (ground reflection etc.)

Table 1.1 Comparison of common solar backing sheets.

The inter cell gaps allow backings to be visible from the front and also allow light to pass through between cells when transparent or translucent backings are used. The environment below these differing backings will have differing conditions of illuminance due to both penetration and reflection.

The effect on pollinator foraging behaviour of these contrasting backings has not yet been investigated and may provide an avenue of research which enables greater understanding of how different pollinator species are influenced, allowing further optimisation of solar installations for the benefit of pollinators.

To partly address this knowledge gap a simple field-based method using standard count protocols was used to give a measure of pollinator-flower visit frequencies beneath differing simulated solar panels. Simulated solar panels, as used in some recent studies (Tanner et al., 2020; Hernandez et al., 2020) have control and access advantages.

1.4 Research question and hypotheses

Is pollinator-flower visit frequency affected by the differing shade cast over plots of wildflowers from simulated solar panels, (representing black-backed, white-backed, and bifacial panels). And do any observed effects differ between pollinator species or groups?

Investigating four treatments including three panel types and a control.

Hypotheses:

(H₁) = There is a difference in pollinator-flower visit frequency between treatments.

(H₂) = There is a difference in (specific species*) visit frequency between treatments.

* three *Bombus* species are analysed separately

The pollinators in this study were predominately common species in the genus *Bombus*, being the group most prevalent on the available observation plots of naturally occurring *Symphytum officinale*, and *Pentaglottis sempervirens*. It does not examine behaviour beyond the initial visit.

2. Methods.

2.1 Experimental set up.

The study was carried out in an arable area of Hertfordshire, UK (TL 4960 1925) in the margin of a fallow field adjacent to deciduous woodland and gardens between May 24th and July 13th, 2021. The study targeted the most abundant nectar sources on the site, particularly attractive to a range of bees (Foster et al., 2017; Goulson et al., 1998), including three plots of >95% *Symphytum officinale* and two plots of >80% *Pentaglottis sempervirens*, each $\approx 0.75 - 3 \text{ m}^2$ naturally occurring within a matrix of mixed grasses. Four treatments were applied to the study plots including three different panel types and a control treatment in full sun. Mobile simulated 1m x 0.7m solar panels were used (Figure 2.1), being an approximate half size version of a typical solar panel (Clements, 2019). Riveted 20mm x 20mm angle aluminium made up the panel frame, supported on wooden legs, 0.8m height at low end, and 35° elevation angle, being optimum for UK solar applications (Charles, 2019). This held interchangeable clear rigid twin wall polycarbonate sheets, covered with grids of 182mm x 182mm blue-chrome self-adhesive vinyl, spaced 5mm apart, representative of the latest size polycrystalline solar cells (Svarc, 2021). Three such sheets (Figure 2.2) simulated backings as in Table 1.1 with i. self-adhesive black vinyl, ii. self-adhesive white vinyl, iii. simulated cells facing downward.

For each observation session one of the four treatments was selected using Random Number Generator (2021). Panels were set up as shown in Figure 2.1, a strict 180° azimuth (as may be utilised for solar energy) was not considered essential as long as a suitable shadow was cast to fully encompass a 0.5m x 0.5m quadrat, deemed from a pilot study to be appropriate size to fit within the cast shadow and obtaining adequate pollinator counts.

2.2 Data collection, count protocols

Observation sessions occurred between 9am and 4.30pm, with no significant rain within preceding 12 hours, above 15°C, ensuring full sun during the observation period, (not attempted if moving cloud cover was significant), with no more than occasional light breeze defined by the Beaufort scale. The observer was 1m from the quadrat ensuring no interfering shadow. These conditions being deemed optimum and reasonably practical for pollinator observations, (Carvell, 2017; Fijen & Keijn, 2017).

To account for flower density the number of flower units within the quadrat was recorded before each session. The two plant species observed had differing flowers but similar clustered arrangement, each cluster being counted as one flower unit. This flower-unit count protocol and the following pollinator count protocols were guided by those described by the UK Pollinator Monitoring Scheme (Carvell, 2017); Hennig and Ghazoul, (2011), with adaptations, described below, recommended by Fijen and Keijn (2017).

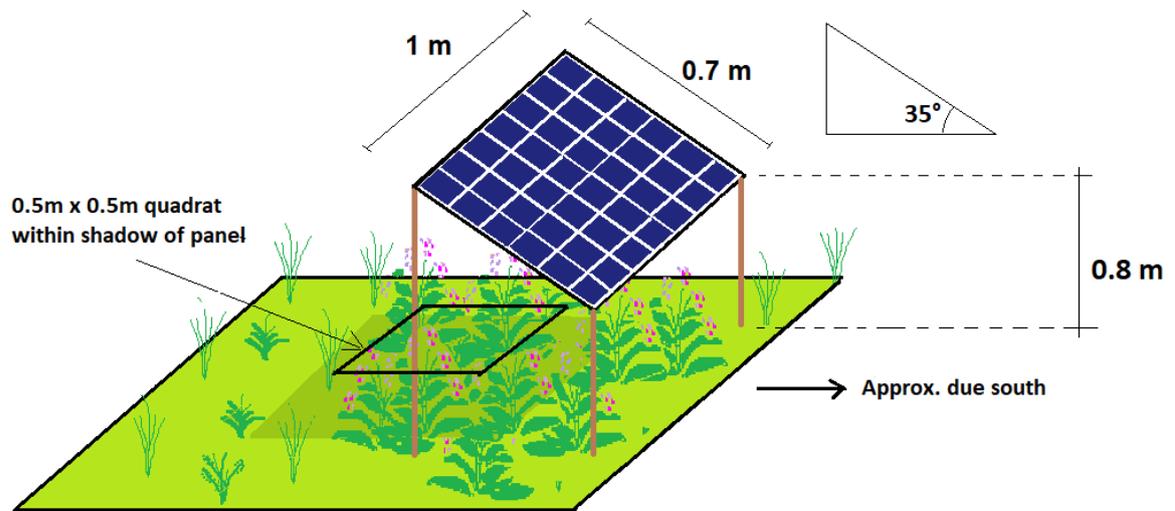


Figure 2.1 Diagram of simulated solar panel positioned over observation plot.



a.



b.



c.



d.

Figure 2.2 Three simulated solar panels mounted within support frame: a. top face imitation photovoltaic cells. b. underside of black backed panel. c. underside of white backed panel. d. underside of bifacial panel.

Pollinators were defined as insects actively searching for pollen/nectar and making contact with a flower. A pollinator visiting the quadrat was counted only once, as one pollinator-flower visit, not recounted if visiting more flowers in the quadrat or seen to leave and re-enter the quadrat.

A fixed count – variable time strategy was used, recommended by Fijen and Keijn (2017) to maintain a suitable level of visits for accurate estimates regardless of time, giving a ‘visit frequency’ of pollinator-flower visitors per flower per unit time (these units allow interchanging between differing counts or time periods). Time was recorded to reach 12 visits (a level established after initial five x 30 min. observation sessions), with a minimum observation time of 15 minutes and maximum of 1 hour, allowing some flexibility depending on circumstances.

Note that definitions of ‘visit frequency’ can differ amongst literature.

Pollinator type was recorded to species level where possible, otherwise to group level e.g. hoverfly, or ‘other pollinator’ and later arranged into groups which could be appropriately differentiated for analysis.

Consistent positive differentiation between *B. terrestris* (the most numerous), *B. lucorum* and *B. hortorum* was considered uncertain when in flight or rapidly feeding, so considered as one group, hereafter referred to as *B. terrestris*.

Identification was aided by field guides (Chinery, 2004; Moucha, 1993), online identity aids/keys (AES, 2021), and photography (Olympus OM-D E-M1 with 40-150mm lens).

For each observation session, suitable conditions (temperature, precipitation, windspeed, cloud-cover) were checked but not recorded, the following was recorded :

- Treatment type
- Flower unit count
- Pollinator visit count
- Session duration
- Temperature beneath panel, 5 minutes into observation session. (TFA Dostmann thermo-hygrometer no. 30.5005)
- Date and start time
- Illuminance of each treatment at beginning of observation (Lux Light Meter Free, android app, Sony Xperia D5503) sensor aimed upwards at backing panel (or open air for control)

2.3 Method of analysis

Visit frequencies were calculated for each observation session for all pollinators (supplementary worksheet 1), this data was analysed between the four treatments using one way ANOVA (Microsoft excel) with post hoc Tukey-Kramer analysis for pairwise comparison (supplementary worksheets 2,3,4).

Similar analysis was performed individually on the three most numerous species (supplementary worksheets 5,6,7,8).

Temperature and illuminance data between treatments were analysed with one way ANOVA and their association with visit frequency analysed with scatter plots (supplementary worksheets 9,10,11).

3. Results

3.1 Overview

26 hours of observations were made over 61 separate periods, recording 795 visiting pollinators, Figure 3.1 illustrates the relative proportions of the pollinator species/groups, 89% of which were from six species of the genus *Bombus*, the remaining approximately six species being *Apis mellifera*, 'Hoverfly' and 'Other' pollinators. The *B. terrestris* group can be considered mostly *B. terrestris*, the two associated species were identified in small numbers but not reliably. Observation time was split between *Symphytum officinale* (53%) and *Pentaglottis sempervirens* (47%), the two were not analysed separately.

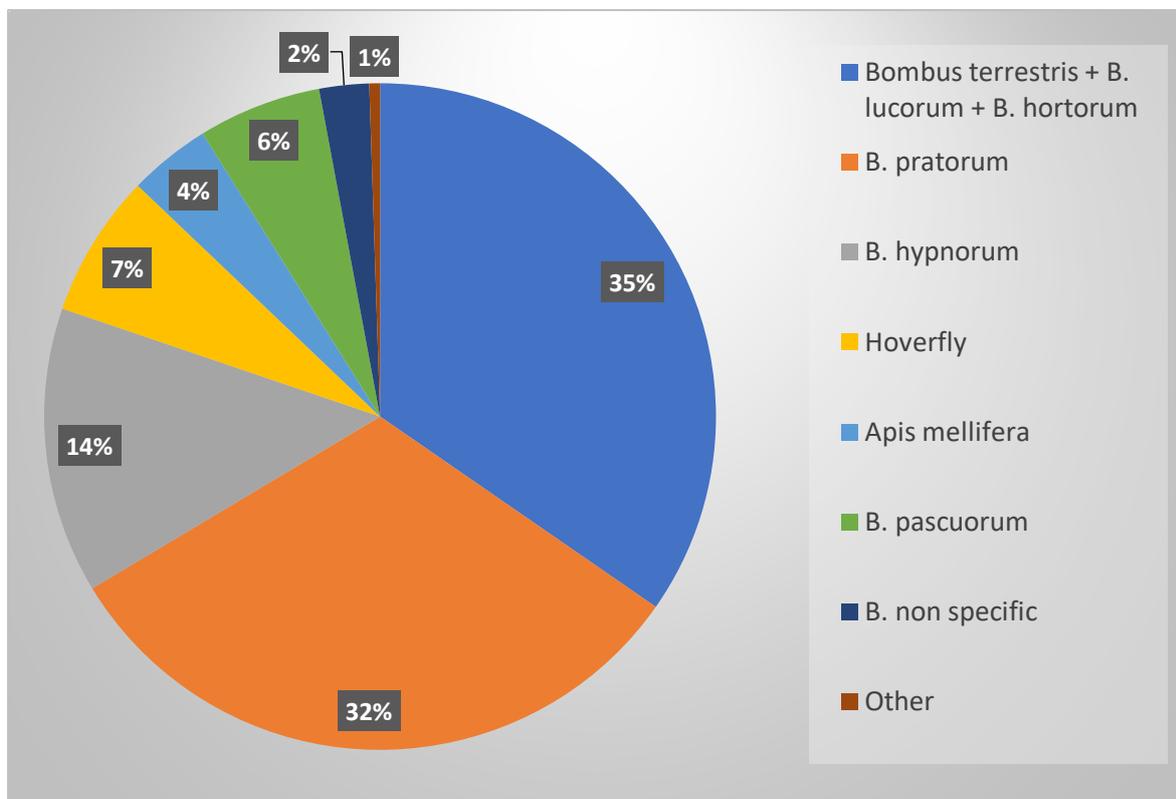


Figure 3.1. Pollinator species/groups observed, as a proportion of all visits.

3.2 Combined pollinator analysis

Figure 3.2 below illustrates the mean and standard deviation of all pollinator visit frequencies for each treatment. Mean visit frequencies appear to differ, from lowest to highest: 'black', 'bifacial', 'white' 'control', but there is considerable variability and overlap within the data.

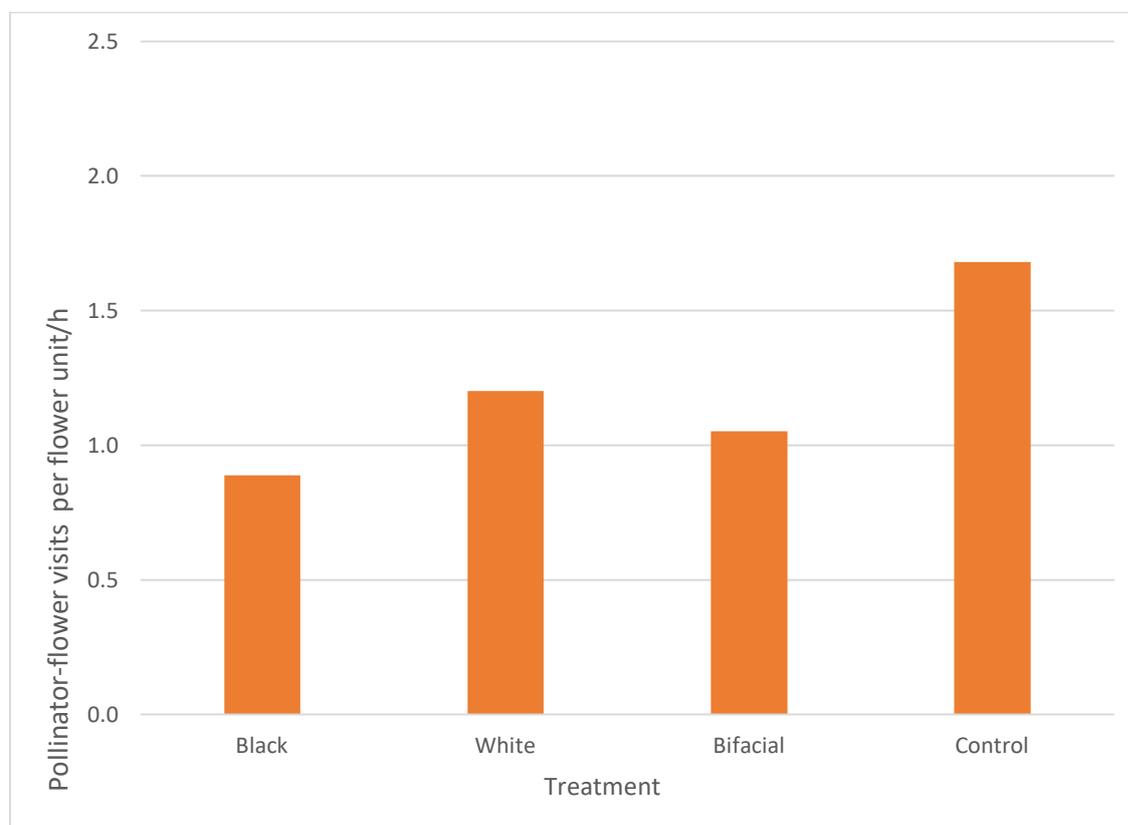


Figure 3.2 Mean and standard deviation of all pollinator-flower visit frequencies for each treatment.

Statistical analysis shows the mean visit frequency for the black backed panel ($M=0.89 \pm SD=0.60$ visits/flower unit/h), was significantly lower than the control ($M=1.7 \pm SD=0.81$ visits/flower unit/h) (One-way ANOVA: $F=3.55_{(3,57)} >$ critical value 2.77; $P<0.05$. Tukey-Kramer: $q = 4.28 > q_{critical} = 3.75$).

Rejecting the null hypothesis (H_{01}):

'There is no difference in mean pollinator-flower visit frequencies between the treatments: simulated black-backed panel, and control (no panel).'

Visit frequencies for the 'white' panel ($M=1.2 \pm SD=0.75$ visits/flower unit/h) appear slightly higher than the 'bifacial' ($M=1.1 \pm SD=0.75$ visits/flower unit/h), both slightly higher than for 'black' but approximately 2/3 that of the control. The null hypothesis (H_{01}) for these remaining treatments could not be rejected following pairwise comparisons using a Tukey-Kramer test (Table 3.1).

Pairwise comparison	Abs. mean difference	Q ($q_{critical} = 3.75$)	Significance
Black v white	0.3114	1.61	No
Black v bifacial	0.1628	0.83	No
Black v control	0.7920	4.28	Yes
White v bifacial	0.1486	0.77	No
White v control	0.4806	2.65	No
Bifacial v control	0.6292	3.40	No

Table 3.1 Tukey-Kramer test statistics for pairwise comparisons, all pollinators

3.3 Analysis of individual species.

Figure 3.3 below compares the treatments on a species by species basis, indicating possible variation in their response to treatments. All sample session data are used, including counts of zero visits. Actual number of each species is shown in Figure 3.3 and should be considered. Due to insufficient numbers to draw reliable conclusions *B. pascuorum*, *A. mellifera* and 'hoverflies' were not analysed further, although they show slight higher mean visit frequencies for 'white', 'control', 'white' respectively.

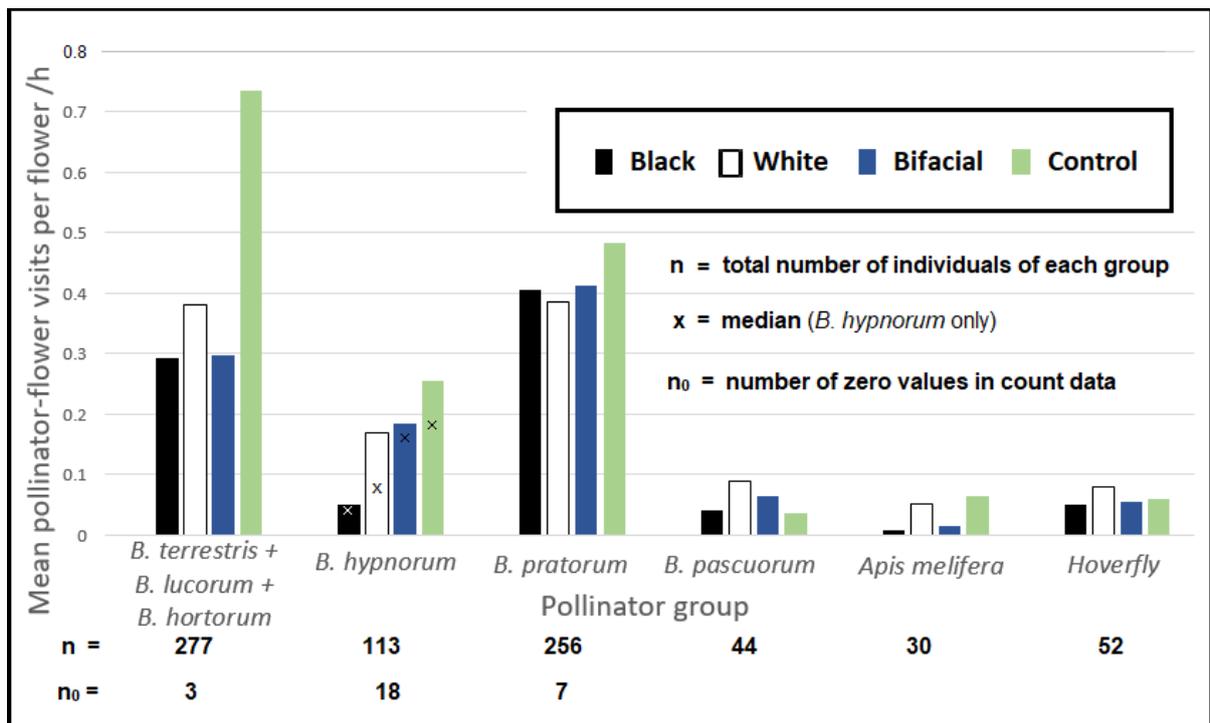


Figure 3.3 Mean visit frequencies for each treatment amongst main pollinator groups observed.

The mean (\pm SD) visit frequencies for *B. terrestris* were: 'black' 0.29 ± 0.30 ; 'white' 0.38 ± 0.34 ; 'bifacial' 0.30 ± 0.19 ; 'control' 0.74 ± 0.56 (visits/flower unit/h). Figure 3.3 indicates that any panel presence approximately halved the mean visit frequency, analysis shows mean visit frequency was significantly lower for 'black' and 'bifacial' panels relative to 'control' (ANOVA, Tukey-Kramer, Table 3.1). No other pairwise comparison showed significant differences:

Rejecting the null hypothesis:

'There is no difference in *B. terrestris* group mean visit frequencies between the treatments: simulated black-backed panel, and control (no panel), simulated bifacial panel, and control (no panel).'

B. hypnorum mean (\pm SD) visit frequencies were: 'black' 0.051 ± 0.056 ; 'white' 0.17 ± 0.24 ; 'bifacial' 0.18 ± 0.17 ; 'control' 0.26 ± 0.31 (visits/flower unit/h). Despite a particularly low visit frequency under the 'black' panel, no statistically significant difference between treatments could be shown using one-way ANOVA (Table 3.1). Note that only 113 individuals were observed, and the data set for *B. hypnorum* contained a relatively high number of zero values, thus distorting data distribution. A Kruskal-Wallis test (not assuming normal distribution) did show a statistical difference (Table 3.1, supplementary worksheet 7a). Comparing medians: 'black' mdn=0.040, IQR=0.098; 'white' mdn=0.077, IQR=0.18; 'bifacial' mdn=0.16, IQR=0.27; 'control' mdn=0.18, IQR= 0.19 (visits/flower unit/h), a Mann-Whitney U test comparing 'black' with 'control', shows the median visit frequency for 'black' is significantly lower than that of 'control' (Table 3.1, supplementary worksheet 7b).

Rejecting the null hypothesis:

'There is no difference in *B. hypnorum* median visit frequencies between the treatments : simulated black-backed panel, and control (no panel).'

For *B. pratorum* mean (\pm SD) visit frequencies were: 'black' 0.41 ± 0.41 ; 'white' 0.39 ± 0.48 ; 'bifacial' 0.41 ± 0.49 ; 'control' 0.48 ± 0.38 (visits/flower unit/h). Analysis showed no statistically significant differences between treatments (one-way ANOVA, Table 3.1)

The null hypothesis could not be rejected:

'There is no difference in *B. pratorum* mean visit frequencies between the treatments'

Species	Statistical analysis results	Comparison (post hoc)	Significance
<i>B. terrestris</i>	One-way ANOVA: $F=4.93_{(3,57)} > \text{critical value } 2.77; P < 0.05$ Tukey-Kramer: $q = 4.55 > q_{\text{critical}} = 3.75$	control – black	yes
	Tukey-Kramer: $q = 4.50 > q_{\text{critical}} = 3.75$	control - bifacial	yes
	Tukey-Kramer: $q < q_{\text{critical}}$	all other pairwise comparisons	no
<i>B. hypnorum</i>	One-way ANOVA: $F= 2.17_{(3,57)} < \text{critical value } 2.84; P > 0.05$	all treatments	no
	Kruskal-Wallis: $H = 8.88_{(3)}, p = 0.031$. mean rank: black 42 white 32, bifacial 27, control 24	n/a	yes
	Mann-Whitney U test: $U = 51 < \text{critical value } 74, \alpha = 0.05$	control – black (median)	yes
<i>B. pratorum</i>	One-way ANOVA: $F=0.154_{(3,57)} < \text{critical value } 2.77; P > 0.05$	all treatments	no

Table 3.2 Test statistics for individual species.

3.4 Analysis of illuminance.

Mean (\pm SD) illuminances below 'black', 'white', and 'bifacial' panels were 267 ± 189 lux, 1374 ± 212 lux, 1322 ± 109 lux respectively, all readings for control were recorded as minimum 15000lux due to an uncertainty from a limiting effect within the measuring device. All pairwise comparisons except for 'white' - 'bifacial' showed a statistically significant difference between mean illuminance (One-way ANOVA: $F=38089_{(3,57)} > \text{critical value } 2.77; P < 0.05$. Tukey-Kramer: 'White' - 'bifacial' $q = 0.788 < q_{\text{critical}} = 3.75$. All other comparisons: $q > q_{\text{critical}}$)

Figure 3.4 shows no strong trends relating illuminance and visit frequency *within* the treatments although the trend for increasing visit frequency across treatment type from 'black' to 'control' is evident.

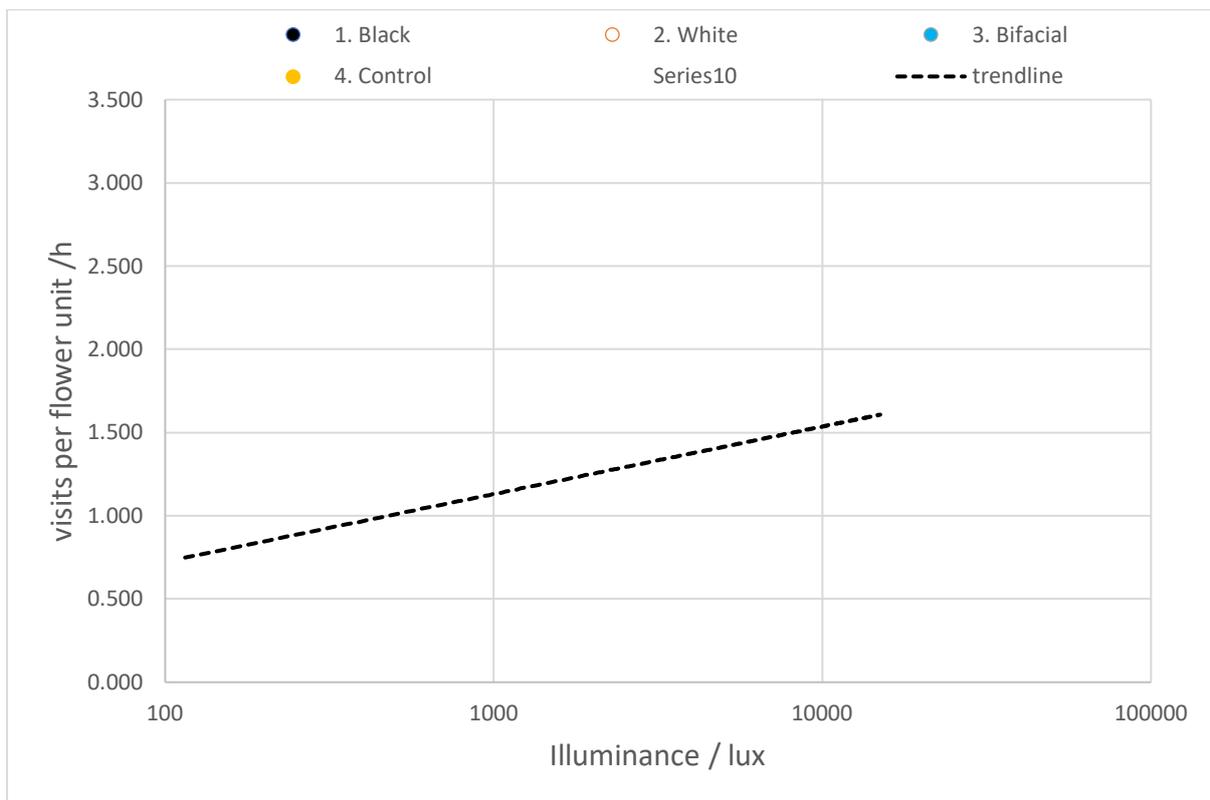


Figure 3.4 Visit frequency plotted against illuminance.

Note. logarithmic scale better represents perceived levels of brightness.

3.5 Analysis of temperature below panels.

Figure 3.5 shows general trends for higher visit frequency with higher temperature within the 'white', 'bifacial', and 'control' treatments, not evident for 'black'.

Mean (\pm SD) temperature measurements were 'black' $21 \pm 2.2^\circ\text{C}$, 'white' $22 \pm 2.1^\circ\text{C}$, 'bifacial' $22 \pm 1.7^\circ\text{C}$, and 'control' $23 \pm 3.3^\circ\text{C}$. These differences could not be shown to be statistically significant (One-way ANOVA: $F=1.68_{(3,57)} < \text{critical value} = 2.77; P>0.05$).

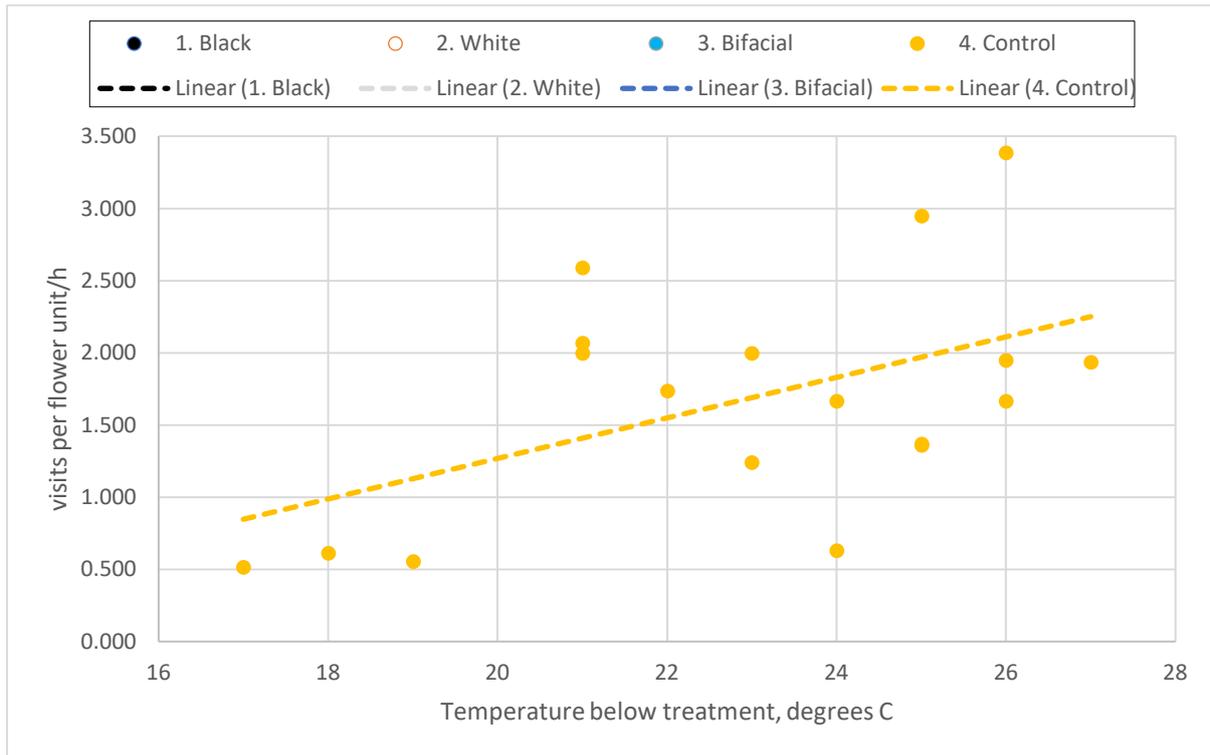


Figure 3.5 Visit frequency plotted against temperature, with trendline for each treatment.

4. Discussion

4.1 Observed pollinator diversity.

Low diversity of pollinators in this study restricts conclusions to just a few common species of bumblebees. The high proportion of bumblebees may be due to factors such as morphology, local scarcity of other pollinators, and competition. Most bees are polylectic, (utilise various plants), (Wood et al., 2016), so honeybee and solitary bee visits might be expected if locally present. Pollinator species will compete for resources, Balfour et al. (2021) found energetic efficiency (effort vs. reward trade-offs) as a significant influence on feeding preferences, studying 22 plant species in S.E England, 96% of observed visitors were bumblebees and honey bees, when limiting one they observed an increase in the other.

Other solar panel related pollinator studies cited in this report involved mixed flora, attracting more diverse visitors, polylectics and oligolectics (more specialised). However, use of fewer plant species can yield useful results; a study by Nichols et al. (2019) showed visitor richness varies with plant species but careful selection can target certain pollinators, identifying *Geranium pratense* and *Centaurea scabiosa* as attracting greater bumblebee richness.

Prepared mixed wildflower plots were attempted for this study, and included *C. scabiosa*, but poor growth and late flowering excluded their use. Fortunately both *S. officinale* and *P. sempervirens* were available growing naturally, likely particularly energetically efficient for foraging bumblebees. Data for the plants were not analysed separately. Further study may reveal differing effects of treatments between plant species, which might inform sowing plans for shade areas of solar park meadows.

4.2 Visit frequency differences.

In terms of all pollinators observed, results support the hypothesis (H_1) '*there is a difference in pollinator-flower visit frequency between treatments*', with a statistically significant lower mean visit frequency beneath black backed panels compared to the control. This alone implies a preference for open, sunlit foraging but as no statistically significant differences were found between the three panels it does not support a hypothesis that 'solar panel backing type effects visit frequency'. Differences seen in Figure 3.2 would still encourage an attempt at an improved study.

Examining individual species, improved identification would differentiate *B. hortorum*, but *B. lucorum* and *B. terrestris* workers are indistinguishable without capture. This group showed the greatest response to panel presence with a statistically significant lower mean visit frequency beneath both black backed and bifacial panels relative to control.

B. pratorum, the next most numerous, but smallest species, showed no statistically significant differences between treatments, suggesting least influence from panel presence.

Nectar robbing holes were evident at the bases of the majority of *S. officinale* flowers, these deep flowers are normally inaccessible to many short-tongued pollinators. According to Goulson et al. (1998) and Stout et al. (2020) these holes were likely caused by *B. terrestris* as primary nectar robber, facilitating secondary nectar robbing by *B. pratorum*. This facilitation may occur less with reduced visitation by *B. terrestris* beneath permanent 'black' or 'bifacial' panels. However, the use of temporary panels prevented any such effect, as flowers were unshaded most of the day. The degree of nectar robbing, whether primary or secondary, by other species, is uncertain.

B. hypnorum would appear to have an aversion to foraging beneath the 'black' panel. This is based on less rigorous, non-parametric tests, showing visit frequency to be significantly lower under 'black' than 'control'. The relatively high number of zero counts for *B. hypnorum* distorted the data distribution and was probably more problematic than their relatively low numbers. Sileshi (2006) examines this issue of excess zero values, common to insect count data, suggesting efficient statistical inferences require carefully selected models to fit the data distribution e.g. poisson, negative binomial or log-normal distribution, beyond the scope of this study. This brings into question the suitability of analysis methods used across subdivided count data.

Accepting non-normal *B. hypnorum* data, a Kruskal-Wallis test (a non-parametric equivalent of ANOVA) rejected H_0 the largest mean rank difference being between black and control. However, this test identifies shifts in distribution (more equivalent to medians) whereas ANOVA examines means. Mixing methods to test the same hypothesis is bad practice.

The hypothesis (H_2): 'There is a difference in (specific species) visit frequency between treatments', applied to each species in turn, is used because species data could not be directly tested against each other.

Testing this hypothesis can by weaker inference, examine the hypothesis 'effects on pollinator visit frequency, by different treatments, differs between pollinator groups/species' (H_3).

It was initially expected that unrelated groups may differ in response to treatments, but lack of data meant only the largest three *Bombus* species could be tested. Results support H_2 and by inference H_3 , albeit with caveats regarding suitability of the tests. This variation within genus is supported by Goulson et al. (1998), stating in relation to bumblebee visits and floral density on *S. officinale*: "from our data it appears that it may not be valid to treat bumblebee species as a behaviourally homogeneous group", despite many studies grouping bumblebee species together (e.g. Balfour et al. 2021). A larger study with more diverse or targeted pollinators may identify differences between unrelated groups.

Inter-species effects may occur, for example via nectar robbing or, if energetic efficiency of foraging differs, niche partitioning/competition. Such interactions may be affected by panel type/presence. The advantages and disadvantages of studying either individual species in isolation or studying communities is a large area of discussion.

4.3 Association with illuminance.

The uncertain 15000 lux figure for 'control' is likely an underestimate given a very bright summer day = 100,000 lux (ATP, 2021). Measurements under the bifacial panel were also uncertain in averaging the contrasting dark cells and bright inter-cell gaps. Readings were taken facing the panel underside, a better method may be to measure illuminance of a test sheet placed below treatments. Subjective judgement would classify the bifacial panel canopy as darker than the white, with patchy illumination, analogous to an overcast day versus a woodland sun-flecked canopy. In terms of illuminance as measured, there was no statistically significant difference between the 'bifacial' and 'control'. As expected, there was a significant reduction in illuminance below panels relative to the control, most extreme under the 'black' panel.

Illuminance may be a poor description of the light conditions experienced by pollinators. Considered subjectively in terms of the different light conditions, treatments may be placed in order of greatest to least 'interference of light': 'black' > 'bifacial' > 'white' > 'control'.

With visit frequency approximately negatively correlating with degree of light interference, it could be concluded that pollinators, particularly *B. terrestris* and *B. hypnorum*, prefer foraging in sunlit/well-lit areas. This preference for sunlight agrees with findings by Biesmeijer et al. (2020) and Graham et al. (2021) who both found a significant higher pollinator abundance in sunlight than panel shade.

Provision of sunlit patches alongside panel shading seems important to pollinators in solar parks, emphasised by Biesmeijer et al. (2020) suggesting an uncommonly large 3-4 meter spacing between arrays, and by Graham et al. (2021) who suggest the heterogeneity of shade, partial shade, and sunlight is of benefit.

4.4 Possible influence of patchy light.

The reduced visit frequencies of *B. terrestris* to the bifacial panel supports findings by Arnold and Chittka (2012) who examined *B. terrestris* preference for simulated leaf shade versus simulated daylight. They found that ability to discriminate colour when foraging in patchy illumination was hindered, furthermore switching between these conditions occurred less often than by chance, implying preference for familiar conditions. This impacts behaviour in woodland settings where conditions change in the short-term, but not experienced under permanent solar panels. This highlights problems with using temporary simulated panels for study purposes: these were swapped out between observation sessions in relatively short intervals, artificially altering conditions otherwise familiar to the bees.

4.5 Other influential factors.

Short-term placement of panels may have interrupted habitual flight paths. Thomson (1996) showed that species of the genus *Bombus* with foraging experience would persist in their flight paths. Some effects may also occur in permanent installations, Crall et al. (2015) showed that larger bumblebees move more slowly through structural clutter. Those apparently most affected by panel presence (Figure 3.3) *B. terrestris* (and *B. lucorum*, *B. hortorum*), and *B. hypnorum*, are all large, ≈12-18mm compared to *B. pratorum* and *B. pascuorum*, ≈10-13mm.

Trends for higher visit frequency with temperature were weak and unlikely to be a significant confounding variable. Reduced temperature beneath panels was not statistically significant but would likely become more apparent under larger panels. A cooling effect, if present, may

have advantages for microclimate diversity or shelter during extremes. Blaydes et al., (2021) list such microclimates amongst the advantages to pollinators.

4.6 Further shortcomings.

In using multiple observations of the same subjects, often with only short breaks before re-sampling, and with few plant plots and likely same bee colonies, the sampling of treatments amounted to pseudoreplication. This low statistical independence, with small spatial and temporal scales means the inferences of the ANOVA tests are weakened.

Simulated panels are not uncommon for study purposes (Tanner et al., 2020; Hernandez et al., 2020), they are more practical in size, but likely to have a more conservatively estimated effect. They should perhaps be closer in size to genuine panels as scale may influence microclimate effects and pollinator behaviour. Despite possible advantages in reducing variables from effects on flora, there are issues, as discussed, regarding temporary placement of panels introducing a confounding variable, resulting in possible disruption of flight paths, visual abilities, and nectar robbing facilitation.

Considering differences in floral abundance between different quadrats was deemed important. Units of visits per flower unit/hour is used in many pollinator count methods to account for greater attractions to higher density blooms, several studies have found that visitation rates increase with flower density (Akter et al., 2017; Vrdoljak et al., 2016). Floral abundance can also differ in permanent shade. Graham et al. (2021) explained lower pollinator abundance found in shade as due to lower floral abundance (but not finding reduced flower visitation rates) although Biesmeijer et al., (2020) suggest their plant mixes fared equally well in shade and sunlight. Comparisons are complicated, so it is useful to understand how much of an effect either floral abundance or panel presence each independently has on pollinator behaviour. The use of temporary simulated panels along with accounting for flower density was intended to reduce the influence of floral abundance.

Ohashi and Yahara, (2002) found bees may be more attracted to larger displays, but may visit proportionately fewer flowers, this suggests the measure of visit frequency used may be a problematic measure of pollinator behaviour, it ignores dwell time and further activity within the quadrat, which can be a measure of effectiveness of the pollinator and the quantity of resources utilised.

Dividing visit counts by flower density assumes a linear relationship between bloom density and pollinator attraction. Goulson et al. (1998) found otherwise, querying if larger blooms of *S. officinale* equates to more bumblebee visits per flower. They found relationships were neither perfectly linear or universal across species: visits by *B. terrestris* increased with flower density, *B. pratorum* favoured intermediate flower densities and *B. pascuorum* showed no preference.

Conclusions

Effects from panels seem to differ amongst species. There is insufficient evidence to differentiate between effects from different panel types, but the pollinators, particularly *B. terrestris* and *B. hypnorum*, showed a general preference for unobstructed sunlit areas.

Differing light conditions are likely a factor influencing at least some species, both intensity and uniformity of light. Confounding factors during the study include possible disruption of habitual flight paths and short-term lighting changes due to temporary study panels.

It should not be presumed that all pollinators respond equally to shade conditions.

An improved experimental design may use permanent panels, closer in size to conventional panels, placed on plots of flowering plants selected according to the study's target pollinators, with more genuine temporal and spatial replication. Higher panels may reduce effects of obstruction. A count protocol to also obtain data quantifying behaviour beyond the first visit would be valuable, and more accurate measures of light conditions.

Bumblebees clearly forage below panels although may be influenced by adjacent sunlit areas.

Solar park developers should consider limiting excessively dark shading and providing large sunlit corridors adjacent to panels. Further study should examine species specific effects, across a broader range of plant species.

[5000 words]

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Glossary

Mono-crystalline silicon cell . cut from single crystal 'grown' ingots, more efficient but costly cell, typically darker/uniform appearance.

Poly-crystalline silicon cell. Cut from cast multi crystal ingot, common type blueish grainy appearance.

Bifacial panel. Photovoltaic cells within the panel can absorb light from both sides.

Solar module. refers to a single unit composed of a group of interconnected photovoltaic cells. The module is sealed and framed to make up a panel. A solar panel may contain more than one module but generally the two terms are interchangeably with 'solar panel'.

Solar array. A larger system of power generation composed of a group or groups of solar modules/panels.

Illuminance. The total perceived power of light striking a unit area of surface.