ENVIRONMENTAL RESEARCH
LETTERS

Solar park management and design to boost bumble bee populations

H Blaydes[1,*] , E Gardner[2,3], J D Whyatt[1], S G Potts[2] and A Armstrong[1,4]

1 Lancaster Environment Centre, Library Avenue, Lancaster University, Lancaster LA1 4YQ, United Kingdom
2 Centre for Agri-Environmental Research, School of Agriculture, Policy and Development, University of Reading, Reading RG6 6AR, United Kingdom
3 UK Centre for Ecology and Hydrology, Wallingford OX10 8BB, United Kingdom
4 Energy Lancaster, Science & Technology Building, Lancaster University, Lancaster LA1 4YF, United Kingdom
* Author to whom any correspondence should be addressed.

E-mail: h.blaydes@lancaster.ac.uk

Abstract

Solar photovoltaics is projected to become the dominant renewable, with much capacity being installed as ground-mounted solar parks. Land use change for solar can affect ecosystems across spatial scales and solar parks offer a unique opportunity for ecological enhancement. One compelling potential benefit beginning to be deployed by the solar industry is management for insect pollinators. Specifically, solar parks can provide refuge for pollinators through the provision of suitable habitat, potentially contributing to halting and reversing widespread declines recorded in some pollinator groups. There is scope to both manage and design solar parks for pollinators, but understanding is limited. Using a geographic information system and a process-based pollinator model, we explore how solar park management, size, shape and landscape context might impact ground-nesting bumble bee density, nest density and nest productivity inside existing solar parks and surrounding landscapes in the UK. We show that bumble bee density and nest density is driven by solar park management, with twice as many bumble bees foraging and nesting inside solar parks managed as wildflower meadows, compared to those with only wildflower margins. In comparison, solar park size, shape and landscape context have a smaller impact on bumble bee response inside solar parks. However, large, elongated resource-rich solar parks were most effective at increasing bumble bee density in surrounding landscapes, with implications for local crop pollination. Specifically, there were double the number of foraging bumble bees surrounding large solar parks managed as meadows compared to smaller parks managed as turf grass. If designed and managed optimally, solar parks therefore have the potential to boost local bumble bee density and potentially pollination services to adjacent crops. Our results demonstrate how incorporating biodiversity into solar park management and design decisions could benefit groups such as pollinators and contribute to the wider environmental sustainability of solar parks.

1. Introduction

Globally, renewable energy development is projected to grow, with solar photovoltaics (PV) leading the way [1]. There are currently 633.7 GW of solar PV installed around the world [2] and ~13.5 GW in the UK [3]. At present, ~57% of the UK's PV capacity comes from ground mounted solar parks [3], occupying ~13 749 hectares of land [4]. Land use change for solar parks will increase as PV's contribution to the energy mix rises, but deployment is outpacing knowledge of the impacts on hosting ecosystems. Land use change for solar parks can have a range of ecosystem impacts [5, 6], but there is emerging evidence of the considerable benefits of managing solar parks for insect pollinators [7–10].

Pollinators contribute to food security, biodiversity maintenance, ecosystem stability and human

wellbeing [11]. Among the most important pollinators are bees and there are over 270 species in the UK, the majority of which are ground nesting [12]. Ground-nesting bumble bees (GNBBs) represent one of the most effective guilds for crop pollination in agricultural systems [13]. GNBB queens found nests in early spring and produce workers which forage up to 1 km from the nest, before producing new reproductive females at the end of the active season [14, 15]. New queens then disperse and overwinter (often underground) before founding their own nests the following spring. GNBBs require suitable sites for nesting and a continuous supply of pollen and nectar from foraging resources (flowering plants) [16]. However, many resources have disappeared as habitats have been lost and degraded [17], driving declines in GNBBs and other pollinators [18, 19]. Mitigation measures include re-establishing resources and in agroecosystems, have comprised of the creation of floral habitat [20, 21]. The UK solar industry are beginning to adopt these techniques [4] and a survey of 11 UK solar parks indicated greater bumble bee abundance in solar parks with higher floral diversity [22]. However, there is currently little evidence how the effectiveness of such interventions may depend on characteristics of the park itself and on the surrounding landscape context.

Characteristics, such as size and shape, of floral habitat provided on solar parks may influence pollinator response. In other contexts, habitat size impacts pollinators and increases in abundance, density and diversity have been reported with increasing flower patch area [23, 24]. Habitat shape can also have implications as edge length increases as habitats become more complex in shape [25, 26]. High edge to area ratios can increase exposure of pollinator populations to pesticides [27] and negative relationships between habitat patch complexity and pollinator visitation have been reported [28]. Conversely, edges themselves can be important pollinator habitats [29]. Whilst these principles are well explored in other contexts, to date there is no understanding of the specific impacts of solar park habitat size and shape on pollinators.

Further to habitat size and shape, characteristics such as landscape context could moderate pollinator response, as well as pollination to nearby crops. In the UK, solar parks are often located within agricultural landscapes where pollinator resources can be scarce, but pollination services are in demand [30, 31]. Landscape composition, including the proportion of semi-natural habitat, can drive landscape-level pollinator abundance via landscape-scale floral resource availability [32]. Thus, a good quality solar park in an otherwise poorly resourced landscape may have a greater impact on the landscape-level population size than the same park in a well-resourced landscape already supporting a large pollinator population. Pollinator response may in turn impact local crop

pollination. In agricultural systems, providing pollinator habitat can boost local pollinator abundance and pollination to nearby crops [33, 34]. Benefits could be greatest where solar parks are surrounded by pollinator-dependent crop types [8, 10], as pollinator visitation decreases with distance from semi-natural habitat [35, 36]. The benefits of pollinator habitat on solar parks may therefore be greater or lesser dependent on the characteristics of the surrounding landscape, although this remains unexplored.
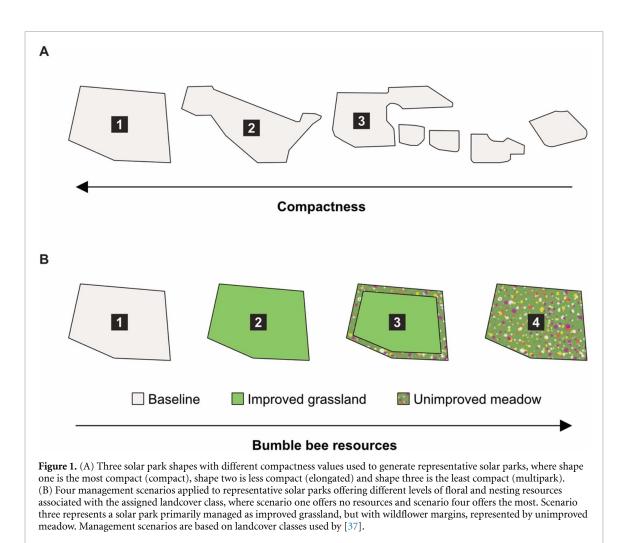
Understanding of pollinator response to habitat size, shape and landscape context in agroecosystems is relatively well developed and the potential to manage solar parks for pollinators has been highlighted. However, to date, the impact of solar park management, size, shape and location (with respect to surrounding landscape characteristics) on pollinator populations remains uninvestigated. Consequently, the aim of this study is to explore how solar park management and design can enhance GNBB density, whilst accounting for the effect of landscape context. This will be achieved by using a geographic information system (GIS) in combination with a validated process-based pollinator model to determine how solar park characteristics (management, size, shape and landscape context) affect foraging bumble bee density and nest density (a) inside solar parks and (b) in buffer zones surrounding solar parks.

2. Methods

A fully factorial design was used to investigate the impact of solar park management, size, shape and landscape context on foraging bumble bee density and nest density inside solar parks and surrounding buffer zones located in representative landscapes. This involved four steps: (a) generating representative solar parks, (b) selecting representative landscapes, (c) modelling and (d) statistical analysis of model outputs. Nest productivity was also investigated, with further details available in the supplementary information (SI) (available online at stacks.iop.org/ERL/17/044002/mmedia).

2.1. Generating representative solar parks
Three sizes of representative solar park were used (small, medium and large), based on the 5th median and 95th percentile area of 1032 real solar parks in the UK as of March 2020 (see the SI for further details). Solar park shape was defined using compactness (the ratio of a solar park's perimeter to the perimeter of a circle with the same area), where a circle takes the minimum value of one and more irregular shapes increase the measure. Three solar park footprints closest to the 5th median and 95th percentile compactness of 1032 real solar parks in the UK were used to determine the three shapes of representative solar park (compact, elongated,

Figure 1. (A) Three solar park shapes with different compactness values used to generate representative solar parks, where shape one is the most compact (compact), shape two is less compact (elongated) and shape three is the least compact (multipark). (B) Four management scenarios applied to representative solar parks offering different levels of floral and nesting resources associated with the assigned landcover class, where scenario one offers no resources and scenario four offers the most. Scenario three represents a solar park primarily managed as improved grassland, but with wildflower margins, represented by unimproved meadow. Management scenarios are based on landcover classes used by [37].

multipark; figure 1(a); table A, SI). Solar park sizes (*n* = 3) and shapes (*n* = 3) were then combined to create nine representative parks.

Four solar park management scenarios, providing different degrees of floral and nesting resources to GNBBs, were applied to each of the nine representative solar parks (figure 1(b)). Management scenarios were created by assigning different landcovers to solar parks, selected from those used by [37] (table B, SI). Firstly, a baseline scenario offering no floral or nesting resources to bumble bees was used as a control, representing a scenario where the park surface is gravelled or hardcore. Secondly, the 'improved grassland' landcover was used to represent a solar park managed entirely as turf grass, offering some bumble bee resources. Thirdly, 'improved grassland' was used in combination with the 'unimproved meadow' landcover (offering the most resources to bumble bees) to create a solar park managed as turf grass, but with floral margins (referred to as 'meadow margins'). Margins were distributed equally around the perimeter of the solar park and occupied 28.6% of solar park area (see the SI for further details). Lastly, the 'unimproved meadow' landcover was applied to the entire solar park to represent a management

scenario rich in floral and nesting resources. The estimated floral and nesting resource provision of each landcover was taken from [37] and is based on the results of a questionnaire sent to ten UK pollinator experts (tables C and D, SI).

Two buffer zones surrounding each solar park at distances of 0–500 m and 500–1000 m were generated, representing typical bumble bee foraging and dispersal zone, respectively. Distance values for buffer zones were based on the literature derived foraging/dispersal ranges used in [37] and [38].

2.2. Selecting representative landscapes

The 36 combinations of solar park size (*n* = 3), shape (*n* = 3) and management (*n* = 4) were then placed in ten real landscapes surrounding UK solar parks (figure 2). To select these landscapes, the national map produced by [37] was used, which is based on the UKCEH Landcover Map 2015 with Ordnance Survey orchard polygons overlaid on top and 2016 crop location information derived from rural payments agency databases. Square 10 × 10 km landscapes centred upon 1032 real solar parks in the UK were extracted using ArcGIS Pro version 2.5.0 [39] and the percentage covers of non-crop, crop and urban
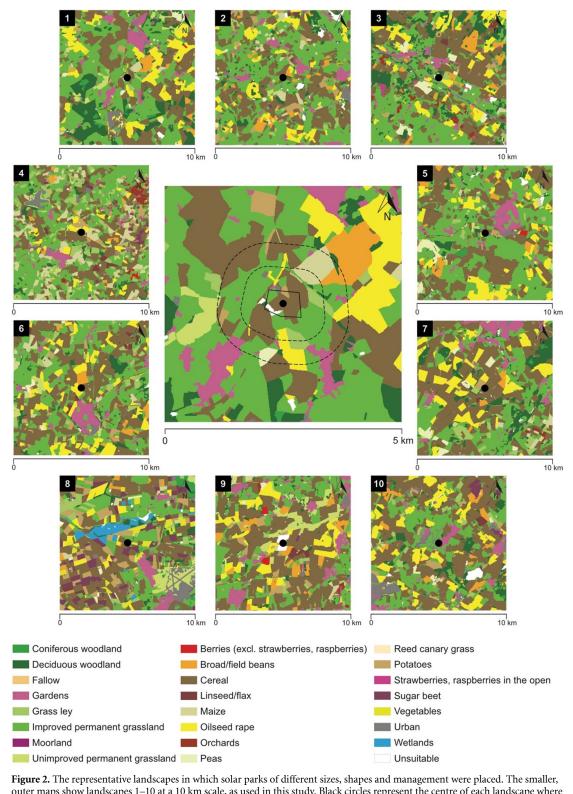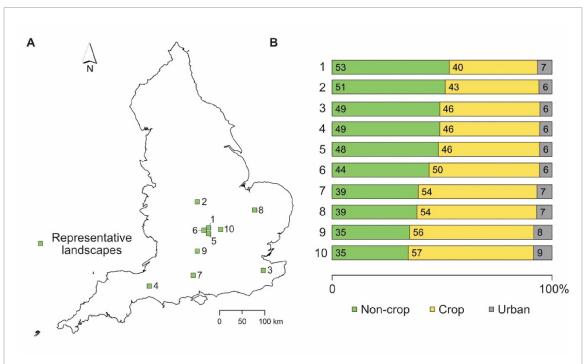
Figure 2. The representative landscapes in which solar parks of different sizes, shapes and management were placed. The smaller, outer maps show landscapes 1–10 at a 10 km scale, as used in this study. Black circles represent the centre of each landscape where solar parks were located. The larger, central map shows landscape one replicated at a 5 km scale with an example solar park (large, compact; solid line) and buffer zones at 500 m and 1000 m (dashed lines) in the centre. Landcovers are from the national map, as used in [37].

habitat (see the SI for further details) were calculated in each case (A_{noncrop}, A_{crop} and A_{urban}, see the SI). The mean percentage cover of non-crop, crop and urban habitat was then calculated across this landscape sample ($\bar{A}_{\text{noncrop}}$, $\bar{A}_{\text{crop}}$ and $\bar{A}_{\text{noncrop}}$, respectively) and the ten landscapes that lie closest to this

mean composition (i.e. $r^2 = \left(A_{\text{noncrop}} - \bar{A}_{\text{noncrop}}\right)^2 + \left(A_{\text{crop}} - \bar{A}_{\text{crop}}\right)^2 + \left(A_{\text{urban}} - \bar{A}_{\text{urban}}\right)^2$, closest to zero) were selected, with the additional constraint that these landscapes must not overlap (figure 3). Across the sample, the mean percentage cover of non-crop, crop and urban habitat was 59%, 31% and 11%,

Figure 3. (A) The locations of the ten representative landscapes in England, United Kingdom. Representative landscapes are real 10 × 10 km landscapes centred upon solar parks and are typical in terms of the percentage landcover of non-crop, crop and urban habitat they contain. Note that landscapes 1, 5 and 6 appear close together but do not overlap. (B) The percentage cover of non-crop, crop and urban landcover categories in the study landscapes 1–10. Black numbers inside bars represent the percentage of each category in a given landscape, rounded to the nearest whole number. Landscape 1 contains the highest percentage of non-crop habitat and landscape 10 contains the lowest.

Table 1. Poll4Pop model input parameters taken from literature data showing values for bumble bees. Reproduced from [37]. CC BY 4.0.

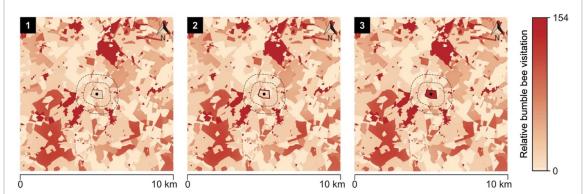| Parameter	Description	Unit	Value
n_{max}	Number of nests in a cell of maximum nesting quality	nests ha^{-1}	19
β	Mean dispersal distance for foraging	m	530
$\bar{\beta}$	Mean dispersal distance to new nesting sites	m	1000
a_w	Median of the growth rate for workers	—	100
b_w	Steepness of the growth rate for workers	—	200
a_q	Median of the growth rate for reproductive females	—	15 000
b_q	Steepness of the growth rate for reproductive females	—	30 000
w_{max}	Maximum number of workers produced by a reproductive female	—	600
q_{max}	Maximum number of new reproductive females produced	—	160
p_w	Fraction of foraging workers	—	0.5

respectively. Landscapes were then assigned numbers from 1 to 10, where landscape 1 contained the highest percentage of non-crop habitat and landscape 10 contained the lowest. Landscape one was chosen as the comparator.

All landscapes, solar parks and surrounding buffers were then rasterised at 10 × 10 m pixel resolution in ArcGIS Pro for input into the Poll4Pop model.

2.3. Modelling

Poll4Pop (derived from the Lonsdorf model [40] and developed via [38, 41]), is the only process-based model validated for the UK capable of predicting spatially explicit abundance of central-place-foraging pollinators, such as GNBBs, in a given landscape using input foraging and nesting habitat preferences and estimates of foraging distances

(table 1). The model accounts for colony growth over time, allows different ranges for foraging and dispersal and includes the preferential use of more rewarding floral resources. Using rasterised inputs (we use 10 × 10 m pixel resolution), the model accounts for the uneven delivery of pollination service across landscapes generated by habitat configuration and can reproduce source/sink population dynamics (figure 4). For further detail see the SI, for the full description of the model see [38] and for validation in Great Britain see [37].

The Poll4Pop model was run for all 360 combinations of solar park size ($n = 3$), shape ($n = 3$), management ($n = 4$) and landscape ($n = 10$) settings. GNBB abundance of foraging workers and nest abundance inside solar parks and surrounding buffer zones were predicted. The total floral and nesting

Figure 4. Examples of spatial outputs from the Poll4Pop model showing relative foraging bumble bee visitation per pixel in landscape one. There were 2160 spatial outputs from the model in total, but these examples show a large, compact solar park (solid line) and surrounding buffer zones at 500 m and 1000 m (dashed lines) under different solar park management scenarios, where (1) improved grassland, (2) meadow margins and (3) unimproved meadow. Black circles represent the centre point of each landscape. The spatial output is a continuous variable but appears discretised due to the landscape being divided into discrete fields of different attractiveness to bumble bees. Visitation rate changes within buffer zones are not visible because changes there are only of the order of doubling rates within an individual habitat type, whereas the whole scale necessarily spans two orders of magnitude in order to incorporate the large intrinsic differences between habitat types.

resources in each landscape and buffer zone were also calculated (see the SI for further information).

2.4. Statistical analysis

All analyses were undertaken in R 4.0.2 using the base R 'stats' package [42] and 'rstatix' package [43]. Bumble bee density and nest density values (per 100 m^2) were used in analyses to normalise for the effect of area (given the different solar park and buffer zone sizes). To allow the analysis of the additional bumble bees and nests compared to if the solar park offered no pollinator resources, relative values were used. Values in the baseline management scenarios ($n = 90$) were subtracted from values under other management scenarios (i.e. improved grassland, meadow margins and unimproved meadow) to calculate relative values ($n = 270$).

Mean foraging bumble bee density and nest density (per 100 m^2) inside solar parks and buffer zones was calculated for each solar park management, size, shape and landscape combination. Analysis of variance (ANOVA) was then performed to investigate if there were differences between means, followed by pairwise comparisons between groups using Tukey post-hoc tests [44].
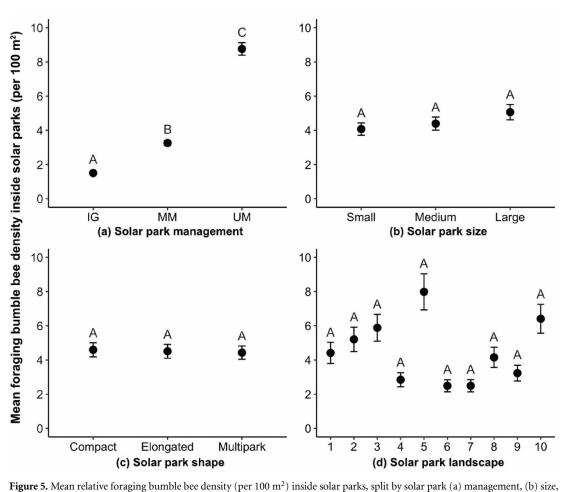
Linear regression (LR) was used to explain the variation in foraging bumble bee density and nest density inside solar parks and surrounding buffer zones. In all models, solar park management (factor), size (continuous), shape (continuous), landscape (factor), total floral resources in the landscape (continuous) and total nesting resources in the landscape (continuous) were used as explanatory variables. In LR where bumble bee density and nest density inside 0–500 m and 500–1000 m buffer zones were response variables, total floral resources in each

buffer (continuous) and total nesting resources in each buffer (continuous) were additional explanatory variables. Forward fitting using adjusted R^2 values was used to build each LR and variables were added as main effects to a model if the adjusted R^2 increased by at least 0.010. Only variables included as main effects were investigated for interactions.

For ANOVA and LR, assumptions of normality and equal variances were checked graphically and where necessary, response and explanatory variables were logged to improve model fit. Where there were negative values, an offset was applied to ensure all values were positive before log transforming.

3. Results

3.1. Foraging bumble bee density and nest density inside solar parks

Solar park management, landscape context and total nesting resources in the landscape explained more than 99% of variation in foraging bumble bee density per 100 m^2 inside solar parks ($P < 0.001$; table E, SI). Parks offering more resources were associated with higher densities of foraging bumble bees. On average (across all scenarios), there were more than twice as many bumble bees foraging per 100 m^2 inside solar parks managed as unimproved meadow, compared to those with meadow margins ($P < 0.001$; figure 5(a); table F, SI). Moreover, the mean change in relative foraging bumble bee density (across all scenarios) varied across study landscapes (figure 5(d); table F, SI). Landscapes contained different amounts of resources (figure A, SI) and the total landscape-level nesting resource was positively related to foraging bumble bee density inside parks ($P < 0.001$; table E, SI). Although greater numbers

Figure 5. Mean relative foraging bumble bee density (per 100 m²) inside solar parks, split by solar park (a) management, (b) size, (c) shape and (d) landscape context ($n = 270$). For solar park management, 'IG' refers to 'improved grassland', 'MM' to 'meadow margins' and 'UM' to 'unimproved meadow'. Error bars represent standard error and within each plot, points that share letters are not significantly different at the $P < 0.05$ level according to ANOVA and Tukey post-hoc analyses. For solar park landscape, there were 45 different combinations when comparing all landscapes to one another, therefore, letters indicate differences between landscape one (containing the highest proportion of non-crop habitat) and other landscapes only. Data used in analyses were log transformed to meet statistical test assumptions.
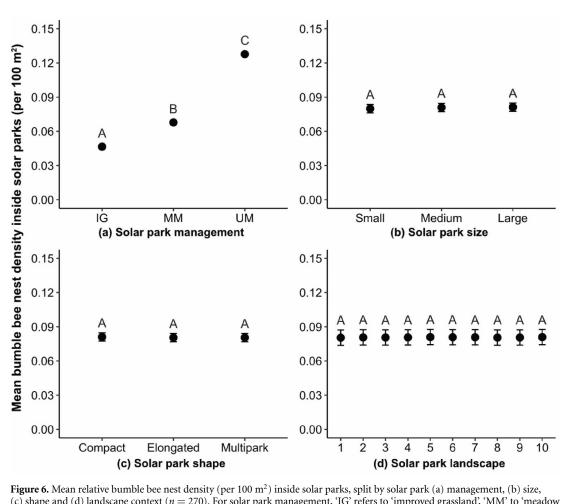
of bumble bees foraged inside larger parks, there was no difference in bumble bee density between solar parks of different shapes ($P = 0.97$; figure 5(c); table F, SI) or sizes ($P = 0.33$; figure 5(b); table F, SI), i.e. density remained constant as park size increased.

Solar park management alone explained more than 99% of the variation in nest density per 100 m² inside solar parks ($P < 0.001$; table G, SI). Parks offering more resources were predicted to contain higher nest densities (table G, SI) and on average (across all scenarios), there were approximately double the number of nests per 100 m² inside solar parks managed as unimproved meadow compared to those with meadow margins ($P < 0.001$; figure 6(a); table H, SI). Bumble bee nest density did not differ with park size ($P = 0.96$; figure 6(b); table H, SI), shape ($P = 0.99$; figure 6(c); table E, SI) or landscape ($P = 1$; figure 6(d); table H, SI). The larger number of nests in larger parks was a function of their larger area only, with nest density per unit area remaining constant as park size increases.

3.2. Foraging bumble bee density and nest density in buffer zones surrounding solar parks

Solar park management, size and landscape context explained >98% of variation in relative foraging bumble bee density (per 100 m²) in both foraging (0–500 m) and dispersal (500–1000 m) zones ($P < 0.001$; table I, SI). The change in foraging bumble bee density was almost always lower in dispersal zones than foraging zones. However, in both zones, solar parks offering more resources were associated with greater relative bumble bee density in the surroundings ($P < 0.001$; table I, SI). On average (across all scenarios) relative bumble bee density was three times greater in zones surrounding parks managed as unimproved meadow, compared to improved grassland ($P < 0.001$; figure 7(a); table J, SI). Predicted bumble bee density (per 100 m²) in both zones was also significantly higher when surrounding larger solar parks ($P < 0.001$; table I, SI) and when solar parks were placed in certain landscapes ($P < 0.05$; table I, SI).

Solar park management, shape and landscape explained 53% of variation in relative bumble bee nest

Figure 6. Mean relative bumble bee nest density (per 100 m^2) inside solar parks, split by solar park (a) management, (b) size, (c) shape and (d) landscape context ($n = 270$). For solar park management, 'IG' refers to 'improved grassland', 'MM' to 'meadow margins' and 'UM' to 'unimproved meadow'. Error bars on all plots represent standard error. Within each plot, points that share letters are not significantly different at the $P < 0.05$ level according to ANOVA and Tukey post-hoc analyses. Data used in analyses were log transformed to meet statistical test assumptions.
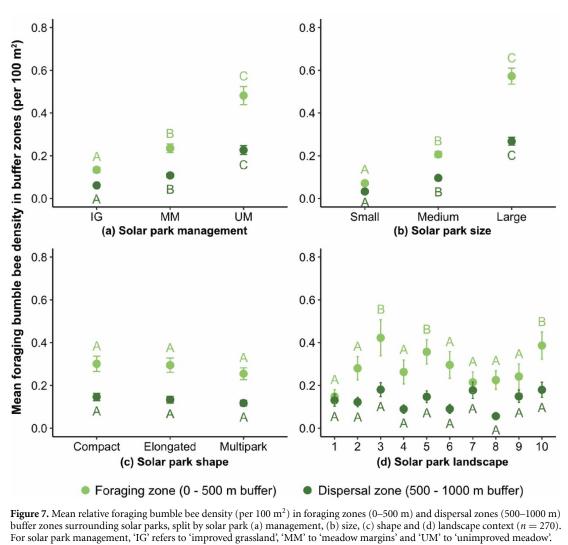
density (per 100 m^2) in foraging zones ($P < 0.001$; table K, SI). Across scenarios, mean relative nest density in foraging zones was higher when the park was managed with meadow margins or as unimproved meadow compared with improved grassland ($P < 0.001$; figure 8(a); table L, SI). Nest density per 100 m^2 was also higher in foraging zones surrounding elongated and multiparks compared to compact solar parks, on average (Tukey; $P < 0.001$; figure 8(c); table L, SI). The mean change in relative nest density within the foraging zone (across all scenarios) also varied across the study landscapes ($P < 0.001$; figure 8(d); table L, SI). In contrast, the solar parks were predicted to have no impact on bumble bee nest density in dispersal zones, where change in nest density was always zero (figure 8).

4. Discussion

This study used a GIS and process-based pollinator model to explore how solar park management, size, shape and landscape context might affect foraging bumble bee density and nest density inside solar parks

and surrounding buffer zones. Our findings suggest that management drives foraging bumble bee and nest density, whereas design and landscape context have a lesser influence. Modelling enabled solar park management and design combinations to be created that would not be possible with a real-world study and therefore allowed exploration of a wide range of park management and design options. However, model predictions are based on various assumptions and secondary data and so there is a need to collect data from the field to test the findings.

4.1. Foraging bumble bee density and nest density inside solar parks
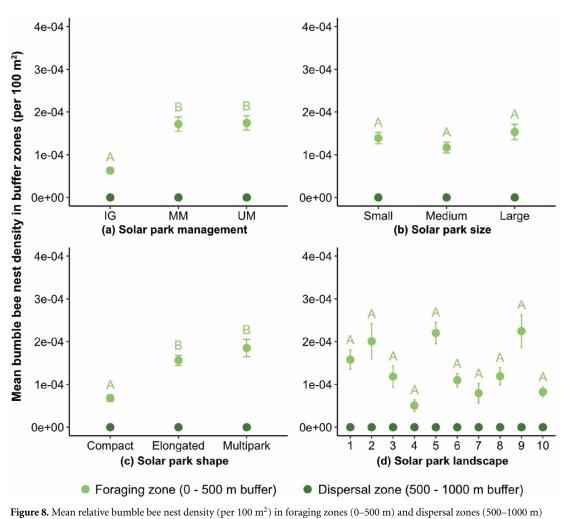Bumble bee nest density inside solar parks was explained solely by park management and increased as parks shifted from improved grassland to unimproved meadow, reflecting the increasing amounts of nesting resources provided by the different land cover types [37]. This implies that nest site provision is the limiting factor on nest abundance within solar parks and management to provide more resources can support greater nest densities, according to the model.

Figure 7. Mean relative foraging bumble bee density (per 100 m^2) in foraging zones (0–500 m) and dispersal zones (500–1000 m) buffer zones surrounding solar parks, split by solar park (a) management, (b) size, (c) shape and (d) landscape context ($n = 270$). For solar park management, 'IG' refers to 'improved grassland', 'MM' to 'meadow margins' and 'UM' to 'unimproved meadow'. Error bars represent standard error and within each plot, points that share letters are not significantly different at the $P < 0.05$ level according to ANOVA and Tukey post-hoc analyses. For solar park landscape, there were 45 different combinations when comparing all landscapes to one another, therefore, letters indicate differences between landscape one (containing the highest proportion of non-crop habitat) and other landscapes only. Data used in analyses were log transformed to meet statistical test assumptions.

Evidence from UK field studies suggests that bumble bee nest density varies with habitat type [29, 45], but this has never been explored in a solar park context. Additional research is therefore required to better understand the impacts of habitat management on bumble bee nest density.

Foraging bumble bee density also increased as parks shifted from improved grassland to unimproved meadow management, likely because of three factors. Firstly, nest density is greater inside resource-rich solar parks and this will result in a higher density of foraging bumble bees. Secondly, experts estimate that floral resources increase as solar park land cover changes from improved grassland to unimproved meadow [37]. Increasing floral resources provide more forage for the nests inside the solar park, resulting in nests producing more foraging bumble bee workers and therefore increasing foraging bumble bee density. Lastly, as floral resources inside the solar park increase, the park becomes a more attractive place for

bumble bees to forage. In the model, bumble bees preferentially spend more time in better quality foraging habitat. Consequently, those that nest inside the park will spend more time foraging inside it and external bumble bees will enter the park to forage. The positive relationship between foraging bumble bee density inside the solar park and nesting resources in the surrounding landscape also demonstrates this. Greater nesting resources in the surroundings result in more bumble bees in the landscape and therefore additional bumble bees crossing into the solar park to forage. Solar parks offering more foraging resources may therefore retain and attract more bumble bees, supporting evidence from field surveys suggesting pollinator abundance is greater on solar parks with higher botanical diversity and interventions in place to support biodiversity [22]. Our results also support the findings from a modelling study based on solar parks in the United States, where solar parks managed as native grassland (rich in forbs and pollinator

Figure 8. Mean relative bumble bee nest density (per 100 m²) in foraging zones (0–500 m) and dispersal zones (500–1000 m) surrounding solar parks, split by solar park (a) management, (b) size, (c) shape and (d) landscape context ($n = 270$). For solar park management, 'IG' refers to 'improved grassland', 'MM' to 'meadow margins' and 'UM' to 'unimproved meadow'. Error bars represent standard error and within each plot, points that share letters are not significantly different at the $P < 0.05$ level according to ANOVA and Tukey post-hoc analyses. ANOVA and Tukey post-hoc analyses were not performed on data in 500–1000 m buffer zones as all values were zero. For solar park landscape, there were 45 different combinations when comparing all landscapes to one another, therefore, letters indicate differences between landscape one (containing the highest proportion of non-crop habitat) and other landscapes only. Data used in analyses were log transformed to meet statistical test assumptions.

resources) increased pollinator supply by 30% compared to solar parks managed as turf grass [46].

Foraging bumble bee density inside the solar park varied with landscape context but there was little indication that variation was due to landscape characteristics, such as the cover of semi-natural habitat in the surroundings, measured at 10 km² scale. Greater bumble bee abundance inside resource-rich solar parks may have been expected when parks were placed in study landscapes with low cover of semi-natural habitat, as foraging habitat is more valuable in resource-depleted landscapes [32, 47]. In this case, study landscapes may have been too compositionally similar to affect bumble bee density inside solar parks. Furthermore, solar parks are small compared to bumble bee spatial scales and there is bumble bee movement across the boundary in each landscape such that variable resource provision in the immediate surroundings likely obscured the influence of larger-scale context.

Whilst the findings suggest that resource-rich solar parks are most likely to support greater bumble bee populations, other pollinator groups have not been considered. Groups such as solitary bees rely on similar resources to bumble bees but have a shorter range, so may respond differently to solar park and landscape characteristics. Groups such as butterflies and hoverflies were also not considered but rely on different resources to bumble bees and are not central-place-foragers, so an alternative modelling approach would have to be adopted. Further work could therefore be undertaken to test solar park management and design options for a wider range of pollinator groups.

4.2. Foraging bumble bee density and nest density in buffer zones surrounding solar parks
Solar park management and shape impacted bumble bee nest density inside foraging zones (0–500 m) surrounding solar parks. Foraging zone nest density

was greater surrounding solar parks managed with meadow margins or as unimproved meadow, suggesting that park resources sustain external nests that would otherwise be unviable. External nests were unaffected by the distribution of the solar park resources, as there were no differences in nest density around meadow margin and unimproved meadow parks. Distribution may have little impact as bumble bees from the foraging zone access resources from outside of the solar park, meaning they may not reach the centre of the park when foraging. However, solar park shape impacts nest density in the foraging zone and there were more nests surrounding elongated and multiparks. Shape may have an impact as the less compact (or more linear) the park, the greater the proportion of an external nests foraging circle will intersect with the solar park. In contrast, solar park characteristics had no impact on bumble bee nest density in the dispersal zone (500–1000 m). Nests in this zone are likely beyond the usual foraging range for bumble bees [48, 49]. Thus, the resources within the solar park are accessed by fewer individuals, make up a smaller part of their diet and are therefore unlikely to strongly influence whole nest viability.

Whilst the impact of solar park characteristics may not extend beyond the foraging zone for bumble bee nest density, solar park management and size impacted foraging bumble bee density in both the foraging and dispersal zones. Density of foraging bumble bees surrounding solar parks increased with solar park size and as the park was managed to provide more resources, likely because these parks host larger bumble bee populations. The increased nest density inside foraging zones surrounding resource-rich solar parks may also contribute to the increase in foraging bumble bees inside dispersal zones. Greater bumble bee density surrounding some solar parks signals potential benefits in terms of enhanced pollinator visitation to crops located within foraging and dispersal zones, up to 1 km from the park boundary. Co-location of solar and pollinator-dependent crops could have significant economic benefits [8, 10] but to date there has been no understanding of the impact of solar park management and design on such benefits. However, the results suggest that large, elongated and resource-rich solar parks are better placed in supporting the wider bumble bee population outside of the solar park. To quantify the economic pollination service benefit of managing and designing solar parks for wild pollinators, such as bumble bees, further research is required.

4.3. Uncertainties

There are a number of uncertainties involved in the model predictions, including those surrounding (a) the spatial configuration of different habitats around solar parks, (b) the floral and nesting attractiveness of individual habitats and (c) how well the landcovers

we used to represent solar park management reflect the quality of real solar park habitats.

We considered changes in bumble bee abundance/visitation at small spatial scales (within solar parks and buffer zones), where the dominant uncertainty is introduced through which habitats happen to be present within, and adjacent to, our area of interest (i.e. the spatial configuration of habitats). Where bumble bees choose to forage and nest in the modelled landscapes is a function of the relative attractiveness of different habitat types. Habitat types differ in their attractiveness and bumble bees (in real life and in the model) preferentially forage and nest in more attractive habitats. Consequently, exactly which habitat is adjacent to the solar park boundary will be the most important factor determining the movement of bumble bees across the park boundary. Our study was specifically designed to take into account this uncertainty, by repeating the simulations across ten real landscapes with a variety of habitat configurations typical of current UK solar park locations.

In addition, there are uncertainties in the exact values of the floral and nesting attractiveness parameters for individual habitats, which will affect exactly how many bumble bees forage and nest where. However, this within-habitat uncertainty is typically less than the uncertainty generated by a different habitat being present instead (c.f. standard errors on individual habitat attractiveness scores vs differences in scores between common habitats; table D, SI). A more significant uncertainty is how well the landcovers we used to represent solar park management translate to solar park habitats in real life. For example, we used floral attractiveness, nesting attractiveness and floral cover scores for improved grassland and unimproved meadow, rather than scores elicited for (or measured at) solar parks specifically, due to a lack of relevant data. Thus, it is uncertain how well these scores represent the actual quality of floral habitats that are created on solar parks, especially given they may have been established on a very different previous landcover. Pollinators have responded positively to habitat created in similar configurations. For example, increases in wild bee abundance have been reported with the creation of wildflower strips in agroecosystems [33, 34]. However, to improve future model predictions and better estimate biodiversity co-benefits from solar parks specifically, direct field evidence from solar parks is needed.

5. Conclusion

The increasing number of solar parks could represent an opportunity to help address drivers of pollinator decline. Pollinator habitat is increasingly being established on solar parks, but there is little understanding of the impacts of solar park characteristics on the habitat created and subsequently, pollinator response.

Focusing on GNBBs, our findings suggest that both foraging bumble bee density and nest density can be boosted under certain management and design scenarios. Specifically, management to provide bumble bee resources is critical to support the greatest densities of foraging bumble bees and nests inside solar parks. For example, solar parks managed entirely as a wildflower meadow could support twice as many foraging bumble bees and nests as a solar park with wildflowers established only in the margins. To support bumble bee populations in the surrounding landscape, large, elongated solar parks that are rich in resources may be the most effective. Our findings indicate that foraging bumble bee density surrounding large, resource rich parks could be double that of a small solar park providing fewer resources. Ultimately, modelling suggests that solar park management drives foraging bumble bee density and nest density inside the solar park and in the surroundings, but it is unknown if these findings are supported by empirical data from real-world solar parks. Field data are therefore required to better understand pollinator response to solar park characteristics, particularly management. This knowledge will help to maximise the value of solar parks to pollinators and contribute to ensuring their wider biodiversity benefits.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

ORCID iDs

H Blaydes ● https://orcid.org/0000-0002-7753-4938
A Armstrong ● https://orcid.org/0000-0001-8963-4621

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