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Honeybee pollination benefits could inform solar park business cases, planning decisions and environmental sustainability targets

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A B S T R A C T

Renewable energy deployment has accelerated exponentially, taking up a growing area of land at a time of increasing land use pressure and environmental degradation. Land use change for renewable energy can have positive and negative environmental consequences, but robustly quantifying the effects is challenging. Here, we evaluate the monetary benefits of pollination services from installing honeybee hives in solar parks and discuss how they could inform policy and practice. If honeybee hives were installed in all existing solar parks within England, we estimate that the pollination service benefits for pollinator dependent field crops, top fruits and soft fruit would have been £5.9 million in 2017. This is grounded in honeybee pollination crop values of £4.81–£75.04 ha^{-1} for field crops and £635–£10,644 ha^{-1} for fruit. However, given the greater field crop land areas the total associated economic benefits were greater than for fruit. Honeybee pollination service benefits could theoretically be as high as £80 million per year if the spatial distribution of crops was altered. However, the viability of this is uncertain given other factors that influence crop location and the potential trade-offs with wild pollinators. We outline how honeybee pollination service benefits could contribute to solar park business cases, inform the planning process, and be used as environmental sustainability indicators by industry. Such energy-economic-ecosystem wins demonstrate the potential of incorporating environmental co-benefits into energy decarbonisation policies and a means of addressing the land-energy-ecosystem nexus.

1. Introduction

As climate change progresses, increasing emphasis in policy, practice and research arenas is being placed on the importance of the environment and mitigating its degradation (Allen and et al., 2018; Figueres et al., 2017; IPBES, 2019). Within the renewable energy sector this has resulted in environment-focussed best practice guidance, for example within SolarPower Europe's Operation & Maintenance Best Practice Guidelines (SolarPower Europe, 2019). Moreover, energy specific and cognate policies are being developed to avoid detrimental and encourage beneficial impacts, such as pollinator habitat creation within US solar parks (Minnesota State, 2016). There is increasing emphasis on company social, environment and governance targets, partly in response to growing public awareness. Moreover, there has been a growth in sustainable mutual funds demonstrating demand for environmentally astute renewable energy investment opportunities (Busch et al., 2016). However, the challenge of quantifying environmental impacts often prevents their widespread and robust inclusion in decision making (Boerema et al., 2017; Dicks et al., 2014).

Taking the environmental impacts of ground-mounted photovoltaic solar parks into account is urgent given the high land take per unit of energy produced and exponential growth rates (Creutzig et al., 2017; McDonald et al., 2009; Moore-O'Leary et al., 2017). However, understanding of the environmental impacts of solar parks is only just emerging and must be generated for different ecosystems, climates and management practices given the differences in outcomes (Armstrong et al., 2014; Moore-O'Leary et al., 2017; Randle-Boggis et al., 2020). For example, vegetation diversity increased relative to previous land use but varied within the solar park due to differences in climate and management in the UK (Armstrong et al., 2016). In contrast, perennial plant cover and structure were lower at a solar park in a Californian desert, with differences in response related to construction technique (Grodsky and Hernandez, 2020). Moreover, understanding is not often framed in a manner suitable to inform solar park development, operation &

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maintenance and investment decisions. This is primarily due to the challenges of translating environmental effects into economic terms. For example, studies focus on the implications for the microclimate, greenhouse gas fluxes, vegetation, insects, and birds (Armstrong et al., 2016; Horváth et al., 2010; Visser et al., 2019). In cases where implications have been linked to ecosystem services, economic impacts are generally still neglected (Grodsky and Hernandez, 2020; Randle-Boggis et al., 2020).

Whilst most environmental impacts are challenging to monetise, impacts of solar parks on pollinators can be estimated through implications for crop yields and honey sales. In addition, the observed decline in pollinators across the world (Hanley et al., 2015; Klein et al., 2007; Potts et al., 2016a,b) provides a strong rationale for managing solar parks for pollinators. Moreover, solar parks are often located within intensively managed agricultural landscapes where pollinator habitats are commonly degraded and pollination service deficits are more likely

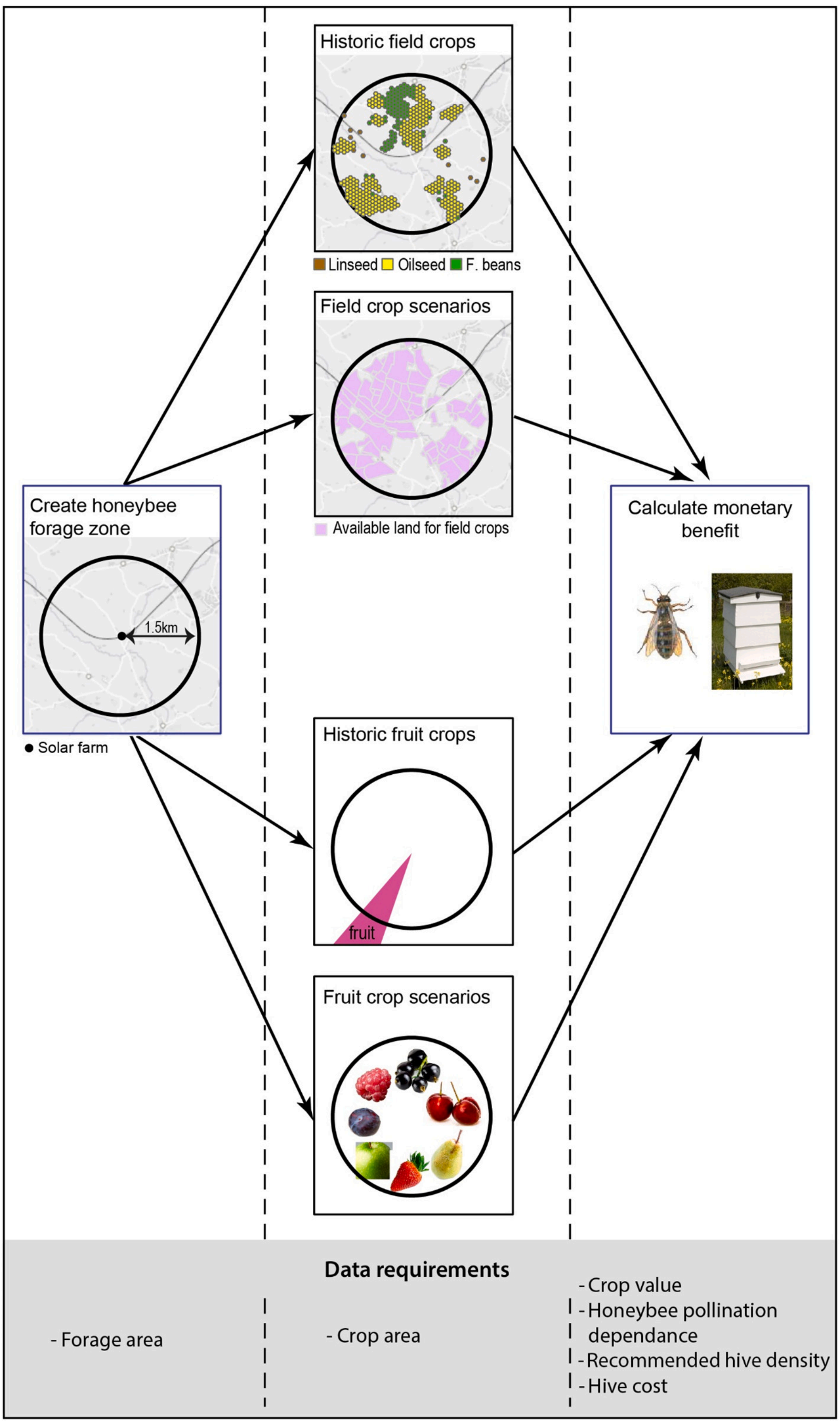

Fig. 1. Schematic of the methodology used to determine the pollination service benefit and honeybee hive costs of historic and crop scenarios for field and fruit crops. Spatially explicit land cover data were not available for individual fruit crops. Three scenarios were implemented: (1) to continue business as usual, (2) to maximise the dominant crop, and (3) to maximise economic value, all assuming five-year crop rotations. F. Beans = field beans. Contains Ordnance Survey (OS) data © Crown Copyright and database right 2018.

to occur (Aizen and Harder, 2009; Breeze et al., 2011). Solar parks are also relatively secure places where pollinator habitats and honeybee hives can be established without intentional or unintentional damage from humans. Moreover, there is little risk of land use change for 25–40 years and the climate niches provided by the solar panels (Armstrong et al., 2016) could mitigate climate change impacts on pollinators (Potts et al., 2016a; Rasmont et al., 2015).

The economic returns for managing solar parks for pollinators could be substantial. For example, managing 2888 US solar parks (2244 indicated as operational and 644 planned) for wild pollinators could result in an annual economic return of ~$6 M USD (Walston et al., 2018). This estimate was based on improved habitats for wild pollinators within the solar parks leading to a 1% increase in crop yields within 1.5 km of solar parks (Walston et al., 2018). Managed honeybees are widely used to supply pollination services, even when wild pollinators are the most effective pollinators, to provide extra insurance for crop production (Garibaldi et al., 2013). Honeybee hives have been used within solar parks but, to date, the potential costs and benefits have not been established (Wilson, 2015).

This paper aims to establish the economic pollination service benefit of managing solar parks for honeybees and how the practice could be embedded into solar park decisions. This will be achieved by addressing three objectives: (1) quantifying the pollination service benefits and costs of installing honeybee hives in existing solar parks using historic crop data and known pollination dependencies; (2) quantifying the potential pollination service benefits and costs of different crop distributions around solar parks with honeybee hives; and (3) reviewing how pollination services can be explicitly included in solar park business cases, planning applications and corporate social responsibility and sustainable investment fund targets. The analysis uses readily available data and is developed for England but is grounded in an approach and methodology that is readily applicable to other regions.

2. Methodology

The analysis uses existing national scale open access solar park location, land cover, crop distribution, crop value and honeybee hive data for England (Table S1). There were three key steps in the analysis, namely (1) quantification of crop areas, (2) assessment of pollination ecosystem service benefits, and (3) calculation of honeybee hive costs (Fig. 1). Analysis was undertaken for field crops (field beans, linseed and oilseed), top fruits (dessert apples, culinary apples, pears, cider apples & perry pears, plums and cherries) and soft fruits (strawberries, raspberries and blackcurrants). These crops were selected as they are pollinator dependent and national crop extent and production value data were available (Defra, 2017a,b).

2.1. *Crop area quantification*

ArcGIS Pro was used to map locations of existing solar parks, delineate honeybee foraging zones and assess crop areas. The UK Government's Renewable Energy Planning Database was used to locate all operational ground-mounted solar parks in England as of May 2018 (BEIS, 2018). The solar parks had a median area of 9.0 ha (25th percentile 8.1 ha, 75th percentile 16.1 ha). A 1.5 km buffer was generated around the centre point of each solar park to represent a typical honeybee foraging zone, as used by Walston et al. (2018); Honeybees routinely forage 1 or 2 km, although they can fly up to 10 km or more from their hives (Ratnieks et al., 2018). The buffers were not generated from the solar park boundaries as these data do not exist. Moreover, in practice the honeybee hives could be located anywhere within the solar park boundary. Individual buffers (foraging zones) were merged to avoid overlap and subsequent analysis was undertaken on the total area to avoid double counting. Given differences in crop data availability, different crop area methodologies were used for field and fruit crops (Fig. 1).

2.1.1. *Field crops*

To quantify the historic field crop distributions, the open access Crop Map of England (CROME, (RPA, 2016, 2017)) was intersected with the foraging zones. Areas of field beans, linseed, and oilseed (spring and winter crops) were quantified (Fig. 1 & Table 1) for each county/unitary authority area in England as defined by Defra (Defra, 2018b). Analysis was undertaken for both 2016 and 2017 but given the similarities in 2016 and 2017 data, the 2016 results are given in the supplementary information and the 2017 in the main text.

For the potential future scenarios, the total area of arable and horticultural land within solar park forage zones was quantified using the 2015 Centre for Ecology & Hydrology land cover map (Rowland et al., 2017) (Fig. 1). A five-year crop rotation was assumed, with one year oilseed or linseed, one year field beans and three years of pollination independent crops (Defra, 1996) (see SI Section 1.0 for further information). Three scenarios were then developed that maximised pollination dependent field crop cover on the arable and horticultural land within the solar park foraging zones: (1) *business as usual*, (2) *dominant crop maximisation*, and (3) *economic value maximisation* (Table 1). These three scenarios provide an indication of potential pollination service benefits, although it is recognised that crop market forces and farmer preference will strongly influence crop planting decisions.

2.1.2. *Fruit crops*

Spatially explicit land cover data were not available for individual fruit crops, precluding identification of fruit crop fields within solar park foraging zones (Defra, 2018b). Therefore, to quantify the historic crop distributions, we calculated the proportion of field crop land area within foraging zones (using the 2017 CROME data) then assumed the same percentage of fruits were grown within the foraging zones (Table 1, see SI Section 2.0). For the crop redistribution scenarios, we assumed that all fruit crops were relocated within solar park foraging zones (Table 1); the total arable and horticultural land area within the foraging zones was notably greater than the total land area used to grow fruit crops (Table S2).

Table 1
Summary of the historic and scenario analysis. The scenarios exploit all arable and horticultural land within solar park foraging zones.

	Analyses	Description
Field crops	Historic	Used spatially explicit crop location data from 2016 or 2017
	Business as usual	Assumed that the proportions of linseed, oilseed and field beans grown on the arable and horticultural land within the solar park foraging zones for each county/unitary authority area were the same as those grown in the solar park foraging area in 2017.
	Dominant crop maximisation	Assumed that only the dominant crop found within the county/unitary authority area was grown on the arable and horticultural land within the solar park foraging zones in that county/unitary authority area.
	Economic value maximisation	Assumed that all arable and horticultural land within the solar park foraging zones was used to grow the field crop with the highest honeybee pollination service benefit per hectare, as defined by the crop market value (C, £ ha^{-1}; derived by dividing the annual value of production of that crop in England by the total area of that crop in England (Defra, 2017a,b)), *and* honeybee pollination dependence (H, %), $C = \frac{V_E}{A_E}$ (Eq. 1)
Fruit	Historic	Used regional fruit location data from 2016 or 2017. Assumed the same proportion of fruit crops were grown in solar park forage zones as for field crops.
	Scenario	All fruit crops were relocated to within solar park foraging zones.

2.2. Pollination ecosystem service benefit

The economic pollination service benefit of managed honeybee colonies in the foraging zones was calculated using the established proportional total production approach (Gallai et al., 2009). This approach is advantageous as it capitalises on available open access data, including honeybee pollination dependencies (that are very expensive to measure) synthesised from existing studies. Briefly, the pollination service benefit (P_B, £) for each crop was derived from the area of each crop within the forage zones (A, ha), multiplied by the crop market value (C, £ ha^{-1}; see Eq. (1)), and the honeybee pollination dependence (H, %):

$$P_B = (A\ C\ H) \tag{2}$$

Honeybee pollination dependence (H, %) is the extent to which honeybee pollination is required to increase the quantity and/or the quality of fruits or seeds. Honeybee pollination dependencies for each of the crops were synthesised from existing studies (Table 2, see SI Section 3.0). There are no nation-wide data on crop pollination deficits, wild pollinator densities or honeybee hive locations. Consequently, we assumed that there was no over-pollination or competition with wild pollinators and that all honeybee pollination was derived from hives located within solar parks. However, wild pollinators, naturalised honeybee populations or managed honeybee hives near solar parks could provide some pollination services. This approach therefore estimates the maximum benefit, however, any adjustment would be arbitrary given the pollination deficit, wild pollinator density and existing honeybee hive location knowledge gaps. To quantify the potential economic gains for historic crop distributions, the honeybee pollination value of each crop per hectare (V, £ ha^{-1}) was calculated for 2016 and 2017. Specifically, the crop market values (C) were multiplied by the honeybee pollination dependencies (H) (Tables 2 and S3). The cost of land was not considered as only existing arable and horticultural land areas were included in the analysis. For the field crops, the honeybee crop production values per hectare (V, £ ha^{-1}) were multiplied by the land area of each crop within the foraging zones. These values were then aggregated for each region, namely North East, North West & Merseyside, Yorkshire & the Humber, East Midlands, West Midlands, Eastern, South East, and South West (Defra, 2018b). The same approach was used for the fruit crops. However, the pollination ecosystem service value for each crop was only produced at the national scale given the lack of spatially explicit fruit crop cover data (Defra, 2017b).

To quantify the potential pollination ecosystem service benefits of crop distribution scenarios, the same approach was used as for historic crops. However, inter-annual changes in crop yields and prices were taken into account. Specifically, the median, 5th and 95th percentile honeybee crop production values per hectare (V) were derived from the 2008 to 2017 Defra data (Defra, 2017a,b) (Table S3).

2.3. Honeybee hive costs

We calculated the costs of maintaining honeybee hives in solar parks for both the historic crop distributions and the crop redistribution scenarios. For each crop type we multiplied the cost of maintaining a hive by the recommended hive stocking densities, following Delaplane and Mayer (2000), and the area of crop land. Given the high variability in net hive costs we used three measures: the 25th percentile (−£11.59), median (£11.87), and 75th percentile (£35.00) costs across all beekeepers from Breeze et al. (2017). The net costs include the costs of queens, equipment, swarming and disease costs less the value of honey produced. It was assumed that the hives remained in the solar parks and labour costs omitted as median costs were reported as zero by Breeze et al. (2017). Given the high variability in recommended hive densities, we calculated hive costs using both lower and upper densities derived by Delaplane and Mayer (2000) (Table 2). We calculated the hive density per m^2 to ensure the number of hives was realistic for each solar park; the median, 25th and 75th percentile solar park areas were estimated using their capacities (BEIS, 2018) and assuming a power density of 1 MW per 1.8 ha (STA, 2019).

3. Results

3.1. Historic crop distributions

Across England in 2017, field crops covered approximately 38,000 ha of land within solar park foraging zones (Fig. 2 & Table 3, see Table S4 for 2016 data). In addition, a further 850 ha was estimated to be covered with top and soft fruits (Fig. 2 & Table 3, see Table S4 for 2016 data). The increase in pollination service benefit due to honeybee pollination was estimated at £5.9 M (Table 3, see Table S4 for 2016 data). This comprised £2.6, £1.3 and £1.9 M from field crops, top fruits and soft fruits, respectively (Table 3, see Table S4 for 2016 data). However, the honeybee pollination crop values per ha were two orders of magnitude greater for fruit crops, and in particular for strawberries and raspberries (Fig. 2 & Table 3, see Table S4 for 2016 data). In terms of regional patterns for the field crops, values were highest in the east and the south, driven by the area of crop land (Fig. 3). The pollination service benefit from soft fruits was second greatest and approximately 1.5 times that from top fruits, despite taking up half the land area (Fig. 2 & Table 3, see Table S4 for 2016 data). In terms of individual crops, the pollination service benefits associated with honeybee pollination were an order of magnitude greater for oilseed and strawberries compared to the other crops. These higher benefits were associated with high land areas for oilseed and high crop values for strawberries (Fig. 2 & Table 3, see Table S4 for 2016 data).

The cost efficiency of hive installation was highly dependent on the

Table 2
Honeybee pollination dependence (H, %), and minimum and maximum recommended hive stocking densities (Delaplane and Mayer, 2000) and costs per hectare of crop using the 25th, median and 75th percentiles.

	Crop	H, %	Hive numbers per ha		Hive costs, £ ha^{-1}					
					Median		25th percentile		75th percentile	
			Min	Max	Min	Max	Min	Max	Min	Max
Field	Field beans	2	2.5	5.0	29.68	59.35	−28.98	−57.95	87.50	175.00
	Linseed	1	2.0	15.0	23.74	178.05	−23.18	−173.85	70.00	525.00
	Oilseed	8	2.3	10.0	27.30	118.70	−26.66	−115.90	80.50	350.00
Top fruit	Dessert apples	14	1.0	12.5	11.87	148.38	−11.59	−144.88	35.00	437.50
	Culinary apples	14	1.0	12.5	11.87	148.38	−11.59	−144.88	35.00	437.50
	Pears	15	1.0	5.0	11.87	59.35	−11.59	−57.95	35.00	175.00
	Cider & perry	14	1.0	12.5	11.87	148.38	−11.59	−144.88	35.00	437.50
	Plums	14	2.0	5.0	23.74	59.35	−23.18	−57.95	70.00	175.00
	Cherries	19	1.0	3.5	11.87	41.55	−11.59	−40.57	35.00	122.50
Soft fruit	Strawberries	16	1.2	25.0	14.24	296.75	−13.91	−289.75	42.00	875.00
	Raspberries	13	0.5	2.5	5.94	29.68	−5.80	−28.98	17.50	87.50
	Blackcurrants	19	3.0	8.0	35.61	94.96	−34.77	−92.72	105.00	280.00

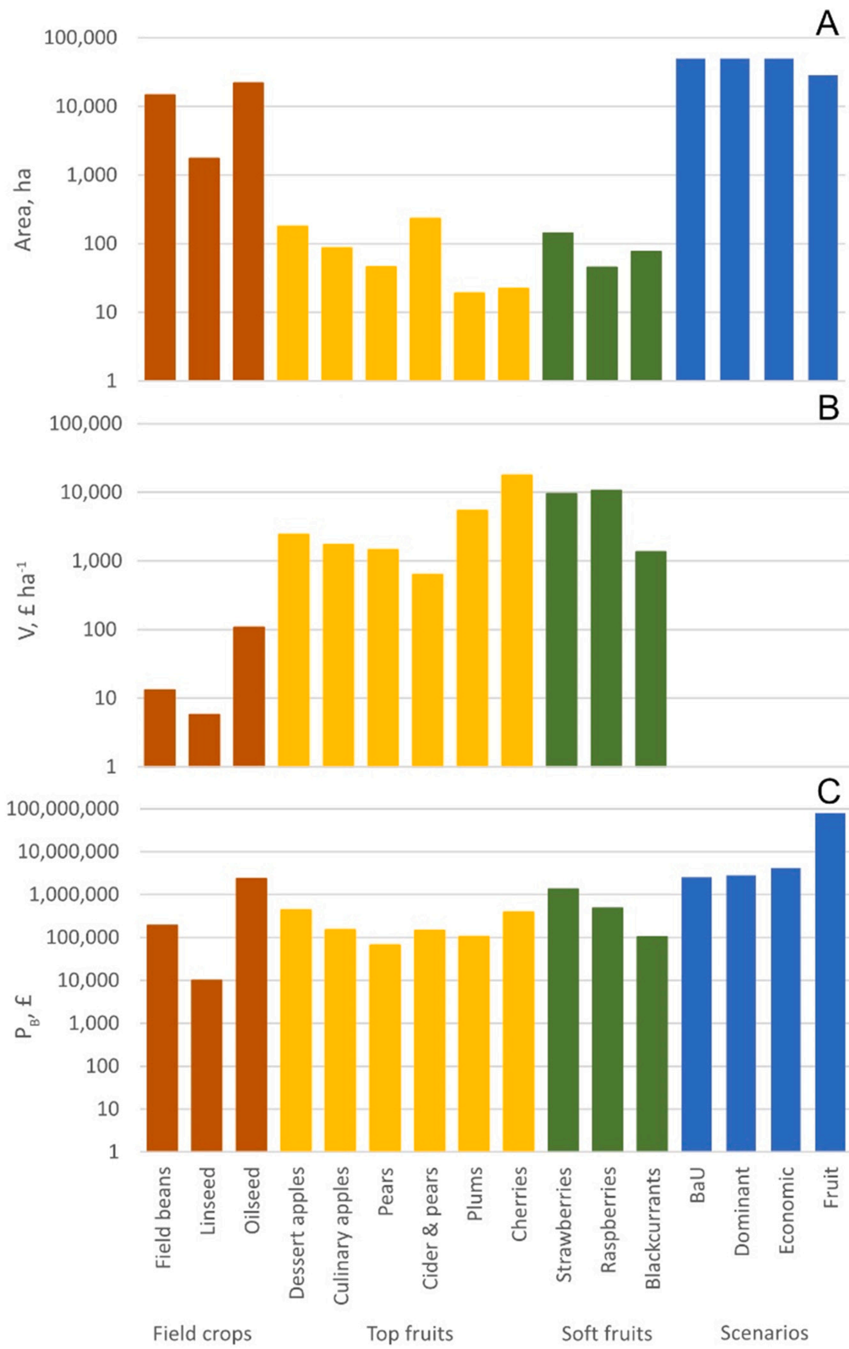

Fig. 2. Land area (A), honeybee pollination crop values per ha (B) and total honeybee pollination service benefit (C) for all crops in 2017. Field crops, top fruits, soft fruits are represented by red, yellow, green bars respectively whilst scenarios are represented by blue bars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

net cost used. For field crops the median net cost of maintaining hives was only lower than the pollination service benefits for oilseed at the lower hive stocking densities (Table 3). If the 25th percentile of hive costs was used the net cost was negative as the value of honey produced was greater than the costs (Table 3). Alternatively, if the 75th percentile net hive cost was used, hive installation was not economically viable for any of the field crops (Table 3). In contrast, the hive costs were economically viable for fruit regardless of whether the net median, 25th percentile or 75th percentile cost was used (Table 3). If the median net hive costs were used, the pollination service benefit was at least an order of magnitude higher for all fruit crops (Table 2). For example, the honeybee pollination value was £434 K for dessert apples and the hive costs £2 K and £27 K at the lower and higher densities, respectively (Table 3). The density of hives within the solar parks varied between 5.7 and 11.3 hives per ha for the lower advised density. At the higher advised density there were between 29 and 57 hives per ha (Table S5).

3.2. Crop distribution scenarios

Distributing field crops across all the arable and horticultural land in solar park foraging zones, assuming a five-year crop rotation, increased pollination service benefits (Table 4). The pollination service benefits were £2.5 M, £2.8 M and £4.2 M for the business as usual, dominant crop and economic maximisation scenarios, respectively (Fig. 2 & Table 4). The economic maximisation scenario pollination service benefit (Table 4) was 1.6 times the 2017 value (Table 3). Spatially, the

Table 3
Total crop areas in solar park foraging zones (ha), honeybee pollination crop value per ha in 2017 (V, £ ha^{-1}), total honeybee pollination service benefit (P_B, £), upper and lower estimates for hive numbers and net cost of hives (£) for field crops, top fruit and soft fruits grown in England in 2017.

Crop	Area, ha	V - 2017, £ ha^{-1}	P_B, £	No. of hives		Median hive cost, £		25th pc hive cost, £		75th pc hive cost, £	
				Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Field beans	14,589	13.09	190,966	36,473	72,946	432,933	865,866	−422,720	−845,441	1,276,550	2,553,100
Linseed	1746	5.77	10,076	3929	17,463	46,640	207,289	−45,540	−202,399	137,523	611,213
Oilseed	21,888	107.92	2,362,138	43,776	328,318	519,618	3,897,134	−507,361	−3,805,205	1,532,150	11,491,128
Field crop total	38,223		2,563,181	84,178	418,727	999,191	4,970,288	−975,621	−4,853,045	2,946,223	14,655,441
Dessert apples	179	2421	434,389	179	2243	2130	26,622	−2080	−25,994	6280	78,499
Culinary apples	87	1721	149,920	87	1089	1034	12,926	−1010	−12,621	3049	38,113
Pears	46	1448	66,868	46	231	548	2740	−535	−2676	1616	8080
Cider & pears	232	635	147,102	232	2895	2749	34,364	−2684	−33,553	8106	101,325
Plums	19	5427	104,204	38	96	456	1140	−445	−1113	1344	3360
Cherries	22	17,701	388.186	22	77	260	911	−254	−890	768	2686
Top fruit total	585		1,290,670	605	6630	7177	78,702	−7008	−76,846	21,162	232,063
Strawberries	142	9480	1344,726	170	3546	2021	42,094	−1973	−41,101	5958	124,118
Raspberries	45	10,644	482,878	23	113	269	1346	−263	−1314	794	3969
Blackcurrants	77	1351	103,443	230	613	2727	7271	−2662	−7100	8040	21,439
Soft fruit total	264		1,931,047	423	4272	5016	50,711	−4898	−49,515	14,791	149,527
Grand total	39,072		5,784,898	85,205	429,630	1,011,384	5,099,702	−987,527	−4,979,406	2,982,177	15,037,031

economic maximisation scenarios returned the greatest benefits, or were approximately equal to the dominant crop scenario. This is due to the dominance of oilseed (the crop with the highest pollination service benefit per ha), and thus similarity between the two scenarios (Figs. 2 & 3). The business as usual scenario only returned greater benefits than the dominant crop scenario in the South West region (Fig. 4).

There was sufficient land within solar park foraging zones to relocate all fruits; there was 248,412 ha of arable and horticultural land and in 2017 fruit was grown on 28,307 ha (Tables 3 & S2). Distributing all fruit crops within solar park foraging zones would result in a total pollination service benefit of £80 M, with a third of this attributable to top fruit and two thirds to soft fruits (Table 4). The pollination service benefit was an order of magnitude higher for dessert apples, strawberries and raspberries compared with the other crops (Fig. 2 & Table 4).

For all field crop scenarios, assuming the lower recommended hive stocking densities and median or 25th percentile net hive costs, honeybee hives were economically viable (Table 4). If the upper recommended hive numbers or the 75th percentile hive costs were used, hive costs were two to forty times higher than the pollination service benefit (Table 4). For the fruit scenario, the pollination service benefit was consistently greater than the net hive cost (Table 4). With the exception of cider apples and pears, the median hive cost was less than 10% of the pollination service benefit for the upper hive densities (Table 4). If the lower recommended hive densities were used, the costs were less than 5% for all fruit crops (Table 4). For field crops hive densities within the solar parks varied from 6.7 to 14.4 hives ha^{-1} assuming lower recommended hive densities (Table S5). If the higher recommended hive densities were used, this increased to between 36 and 99 hives ha^{-1} (Table S5). The densities for the fruit scenarios were lower: 2.3 to 4.5 and 24 to 48 hives ha^{-1} for the lower and higher recommended hive densities, respectively (Table S5).

4. Discussion

Embedding environmental co-benefits into solar parks is attractive given the accelerating use of land for low carbon energy and the degraded state of many ecosystems. Solar parks offer an opportunity to boost pollination services in agricultural landscapes, mitigating shortfalls in supply of these services. Our results show, for the first time, the potential monetary benefits of pollination services if honeybee hives are located in solar parks. Across England the estimated economic benefit would have been £5.9 M in 2017 and could *theoretically* increase to £80 M if all fruits were grown within solar park foraging zones. The cost effectiveness of honeybee hives ranged from negative costs (indicating that the value of the honey was greater than the hive costs) to greater than the pollination benefits, depending on the crop and net hive cost used. For fruit crops, hive costs were consistently less than the honeybee pollination services benefits, suggesting honeybee hives could be a cost-effective solar park management option. However, uncertainties in how the number of hives required would be managed, and the associated labour costs which vary significantly (Breeze et al., 2017), need to be resolved. Moreover, the broader implications of the change in the landscape, for pollinators and broader ecosystem function, remain uncertain. Moreover, it is likely that, where possible, encouraging wild pollinators would be preferable over honeybee hive installation (Mallinger et al., 2017).

Below we discuss the implications of crop type, spatial and temporal variations in honeybee pollination service benefits, and the potential interactions with wild pollinators. Finally, we review the implications of, and means by which, pollination service benefits could be embedded within solar park decisions. In particular, we focus on including potential pollination service benefits in solar energy business cases, planning applications, sustainable investment funds, and corporate social responsibility strategies.

4.1. Crop type variation in honeybee pollination

Several factors should be considered when selecting which crops to grow in solar park foraging zones, or at which solar parks to locate hives. Crop types and varieties differ in their honeybee pollination dependencies and yields. Therefore, honeybee pollination service benefits per unit land area can vary significantly and thus our findings cannot be generalised between crops or varieties (Breeze et al., 2011; Free, 1993). For England the highest honeybee pollination service benefit was for oilseed. However, soft fruits, especially strawberries, had the highest pollination service benefits per unit land area given their high market value and relatively high honeybee pollination dependence. If aiming to maximise the economic pollination service benefits, crops with the highest honeybee pollination value per ha should be grown within solar park foraging zones. Consequently, strategies in England (and likely other countries) should target soft fruits. Field crops should be given the lowest priority given their low pollination values per unit area and need for crop rotation with pollinator independent crops (Defra, 1996).

It is important to consider site-specific factors, such as soil type and climate, to ensure location suitability for crop types (Redman, 2019). Within England, site-specific factors are especially important for fruit crops as they are only grown in particular regions. For example, almost half of all top fruits are grown in the south east. Field crops, in contrast,

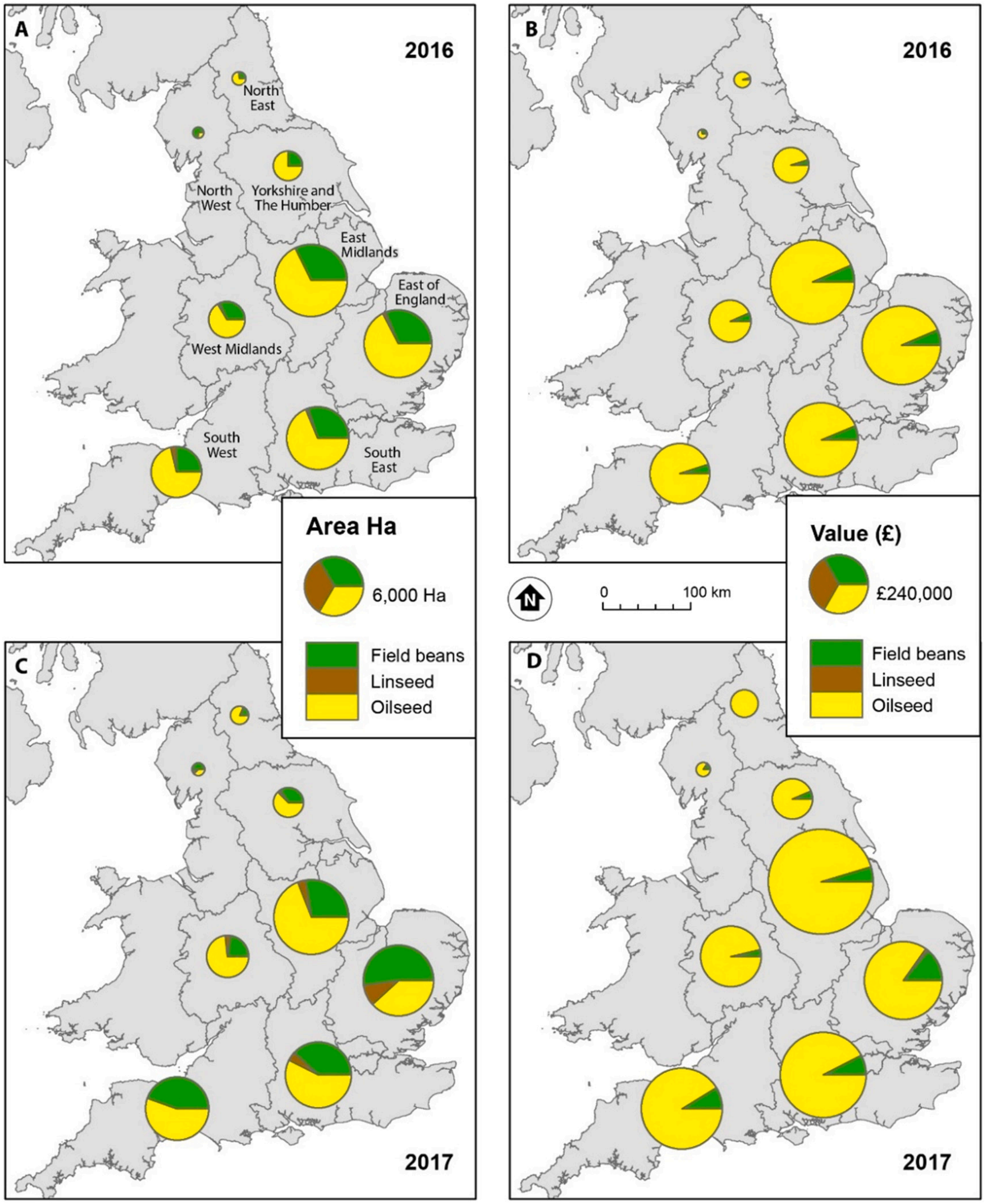

Fig. 3. Land areas (A, C) and honeybee pollination service benefits (B, D) of field beans, linseed and oilseed across regions in England in 2016 (A, B) and 2017 (C, D). Note: no spatially explicit data exists for fruit crops in England.

are grown across England on a wide variety of soils (Berry et al., 2014; Crops, 2018; PGRO, 2016). If fruit is not grown, honeybee hives should be installed in solar parks surrounded by crop rotations with high proportions of oilseed in order to provide the greatest economic returns. This is because oilseed has a significantly higher market value and honeybee pollination dependence than field beans or linseed. In addition to the environmental conditions, socio-economic factors, such as farmer preferences, profitability, and supply and demand dynamics are pivotal and will influence crop decisions.

In terms of site selection, solar parks surrounded by crops with known pollination deficits should be prioritised, as benefits are likely to be higher. For example, deficits in apple fruit yield and quality (using seed number as a proxy) were estimated to be up to 75% and 56%, respectively, within the UK (Garratt et al., 2013). This deficit relates to a predicted pollination service benefit of £21.4 M per year (Garratt et al., 2016). However, to target crops with pollination deficits, improved understanding of site-specific pollination deficits is required for most crops. Crops that also benefit from improvements in quality (i.e. shape and size) and nutritional value, as well as yields, should be prioritised (Potts et al., 2016a). For example, honeybee pollination can increase the weight, commercial grade and shelf life of strawberries (Klatt et al., 2014). In contrast, excessive honeybee hive densities may result in over-pollination with detrimental effects for some top fruits and strawberries (Shahee et al., 2017). For example, excessive pollination in apple orchards can necessitate thinning of set fruit – an additional cost – to ensure apples attain desirable sizes (Garratt et al., 2016). Determining

Table 4
Total crop areas within solar park foraging zones in England (ha), honeybee pollination service benefits (P_B, £) derived using the ten-year median honeybee pollination values per ha, upper and lower estimates for hive numbers, and net median, 25th and 75th percentile cost of hives (£) for each scenario. A 5-year crop rotation was assumed for each of the three field crop distribution scenarios, using the 2017 actual crop data to inform the business as usual and dominant crop scenarios. For soft fruits it was assumed that all, based on the 2017 data, were relocated within solar park foraging zones.

	Crop	Area, ha	P_B, £	No of hives		Median hive cost, £		25th pc hive cost, £		75th pc hive cost, £	
				Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Field crops	Business as usual										
	Field beans	20,456	260,407	51,140	102,279	607,026	1,214,052	−2,963,527	−5,927,054	8,949,392	17,898,784
	Linseed	2202	13,204	4954	22,016	58,799	261,330	−287,073	−1,275,879	866,915	3,852,955
	Oilseed	27,022	2,275,283	54,044	405,327	641,498	4,811,231	−3,131,833	−23,488,748	9,457,650	70,932,372
	Total	49,679	2,548,852	110,137	529,622	1,307,323	6,286,613	−6,382,433	−30,691,681	19,273,956	92,684,111
	Dominant										
	Field beans	19,130	243,527	47,826	95,652	567,695	1,135,389	−2,771,505	−5,543,011	8,369,516	16,739,032
	Oilseed	30,549	2,572,260	61,098	458,235	725,233	5,439,249	−3,540,625	−26,554,688	10,692,138	80,191,034
	Total	49,679	2,815,752	108,924	553,887	1,292,928	6,574,639	−6,312,131	−32,097,699	19,061,654	96,930,066
	Economic										
	Oilseed (total)	49,682	4,183,260	99,365	745,236	1,179,460	8,845,951	−5,758,190	−43,186,426	17,388,840	130,416,300
Top fruits	Dessert apples	5981	10,866,721	5981	74,761	70,994	887,413	−69,320	−866,480	209,335	2,616,635
	Culinary apples	2904	5,297,193	2904	36,298	34,470	430,857	−33,657	−420,694	101,640	1,270,430
	Pears	1539	1,963,412	1539	7695	18,268	91,340	−17,837	−89,185	53,865	269,325
	Cider & perry	7720	1,879,054	7720	96,500	91,636	1,145,455	−89,475	−1,118,435	270,200	3,377,500
	Plums	640	3,728,360	1280	3200	15,194	37,984	−14,835	−37,088	44,800	112,000
	Cherries	731	2,795,861	731	2559	8677	30,375	−8472	−29,659	25,585	89,565
	Top fruit total	19,515	26,530,601	20,155	221,012	239,240	2,623,424	−233,596	−2,561,541	705,425	7,735,455
Soft fruits	Strawberries	4728	38,695,977	5674	118,208	67,350	1,403,129	−65,762	−1,370,031	198,590	4,137,280
	Raspberries	1512	11,783,261	756	3780	8974	44,869	−8762	−43,810	26,460	132,300
	Blackcurrants	2552	2,903,758	7657	20,418	90,889	242,362	−88,745	−236,645	267,995	714,630
	Soft fruit total	8792	53,382,997	14,087	142,407	167,213	1,690,359	−163,268	−1,650,486	493,045	4,984,210
	Fruit total	28,307	79,913,598	34,242	363,419	406,453	4,313,784	−396,865	−4,212,026	1,198,470	12,719,665

the risk of over-pollination is challenging. This is because of the dependence on the abundance of wild pollinators, which is determined by factors such as weather, disease, and floral and nesting resource availabilities (Murray et al., 2009). Moreover, pollination demand within the landscape, in response to crop types and areas, also affects over-pollination risk. Other considerations include the implications of relocation and establishment costs, although relocation costs for field crops will be limited. In comparison, relocation costs will be higher for perennial crops (i.e. fruits), although the benefits of enhanced pollination services for perennial crops could extend for several decades.

4.2. Spatial and temporal variation in honeybee pollination

The economic return of honeybee pollination varies between years. We quantified the pollination benefits across England for two years and comparison of our results for 2016 and 2017 provides some insight into temporal variability. The honeybee pollination benefit of oilseed was greater in 2017 than 2016, whereas the benefit for plums and culinary apples was higher in 2016. Further, whilst our analysis was conducted at the national scale, and therefore produces an 'average' response, differences will occur between sites (Jongman, 2002). Consequently, it will be necessary gain a better understanding of the spatial and temporal variations to provide robust economic input into specific solar park decisions. Further, as well as ensuring there are sufficient honeybees to provide the required pollination services, there must be sufficient resources to sustain the populations. Consequently, if hives remain in solar parks throughout the year, as we assumed, it may be necessary to offset timings of mass flowering crops. Alternatively, the impacts of mass flowering could be mitigated by establishing forage resources in boundaries or uncultivated areas. Finally, if not possible to provide sufficient nectar and pollen for the honeybees, the hives could be moved, incurring additional labour costs (Breeze et al., 2017).

Longer term temporal changes will also influence the impact of solar park honeybee hive pollination benefits in several ways. Crop choice may change through time due to dietary choice, global supplies, response to climate change and advances in agronomy. Given the variation in pollination dependence between crops, these temporal changes could result in increases or decreases in honeybee pollination benefits (Aizen et al., 2008; Bedoya-Perales et al., 2018; Knapp et al., 2017; Moniruzzaman, 2015). Moreover, the relative dependence of crops on honeybees may increase in response to further declines in wild pollinators, or decrease if wild pollinator populations recover (Venturini et al., 2017). Further, whilst solar is anticipated to grow, means of deployment (i.e. building-, water- or ground-mounted), may change (IRENA, 2019). If solar parks proliferate, there may also be increased foraging zone overlaps, reducing the per solar park impact of the installed honeybee hives.

4.3. Interactions with wild pollinators

Our analysis focused on quantifying the impact of installing honeybee hives at solar parks; a current industry practice (Wilson, 2015). However, there is evidence that honeybee hives can potentially have detrimental impacts on wild pollinators, due to competition for resources and disease spread (Cane and Tepedino, 2017; Mallinger et al., 2017; Wojcik et al., 2018). Moreover, several studies demonstrate that honeybees do not enhance pollination if wild pollinators are present. However, in years when wild populations are low (i.e. due to weather) the contributions of honeybees can be critical (Garibaldi et al., 2013). Further, some landscapes, with high proportions of mass flowering crops can result in local declines in pollinator diversity and pollination services (Bartomeus et al., 2014; Eeraerts et al., 2017; Holzschuh et al., 2016). Consequently, honeybee hives can provide a degree of 'insurance' in heavily managed landscapes. Using honeybee hives to increase pollination is attractive because hive numbers can be annually adjusted to match crop demands. In contrast, managing solar parks for wild pollinators, especially in nutrient rich ex-arable fields, can be challenging. Dual wild and honeybee strategies are possible and are generally seen as a sustainable strategy to reconcile reliable crop production with wild pollinator conservation (Kleijn et al., 2018) (Mallinger et al., 2017).

Whilst using honeybee hives to ensure pollination services is attractive, managing sites for wild pollinators offers a range of co-benefits for other wildlife and ecosystems services (Pywell et al., 2002). For example, managing for wild pollinators can contribute to biodiversity conservation through habitat provision for other

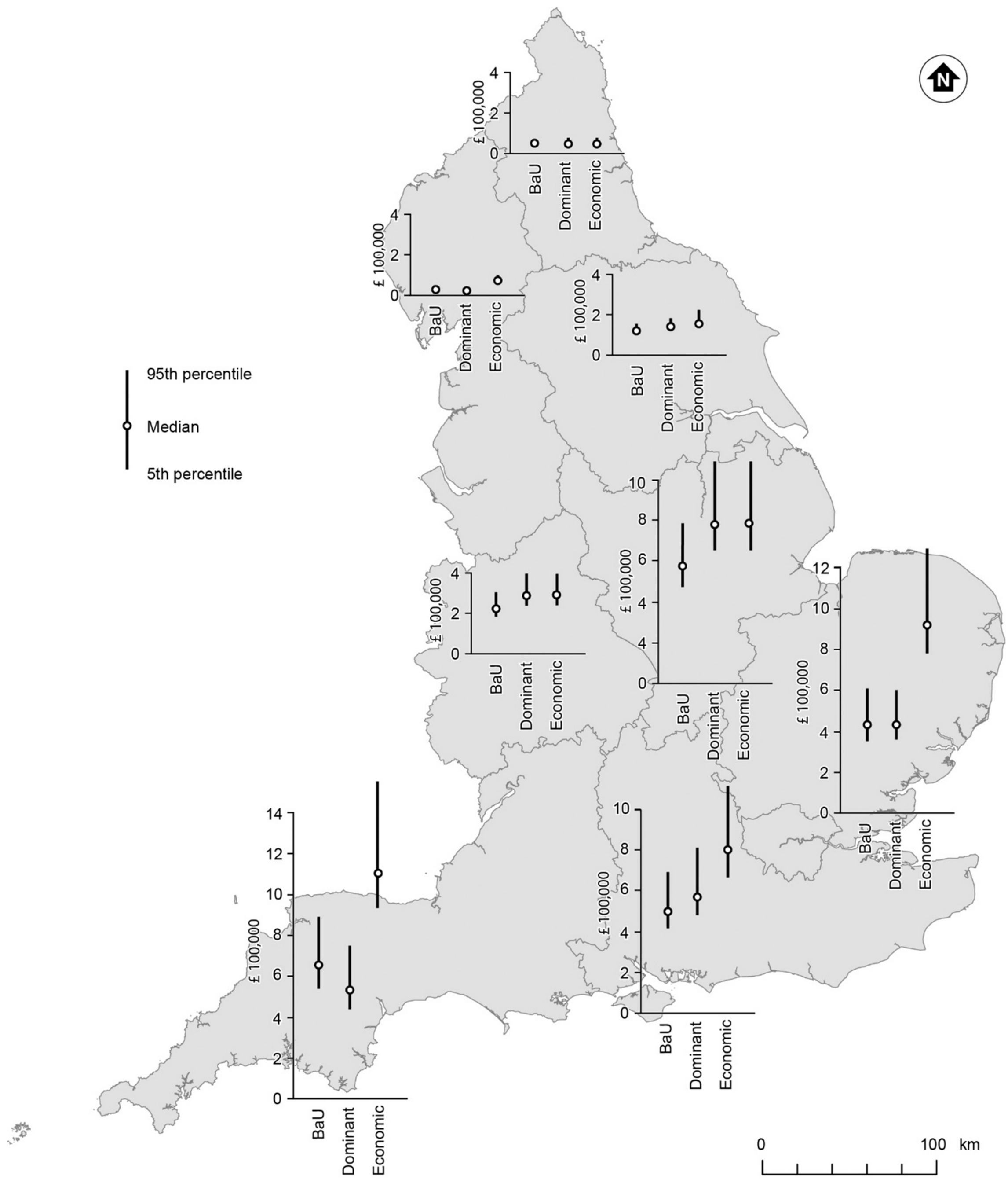

Fig. 4. Regional variation in honeybee pollination service benefits under business as usual (BaU), dominant crop and economic maximisation scenarios assuming a five-crop rotation. Circles represent the median and bars the 5th and 95th percentiles.

invertebrates, birds and mammals; enhanced biological control of pests; reduced soil erosion and runoff of nutrients, reduced fertiliser need; and improved soil structure; supressed weeds; and improved aesthetics and tourism (Morandin et al., 2016; Wratten et al., 2012). Moreover, wild pollinators offer important opportunities for wild plant pollination (Garibaldi et al., 2013) and are often more efficient than honeybees (Brittain et al., 2013; EY, 2017; Vicens and Bosch, 2000; Willmer et al., 1994; Winfree et al., 2007). Wild pollinator habitat management costs and the time required (one to several years) for habitats to develop will be critical when comparing with honeybees hive installation.

4.4. Embedding pollination services into policy and practice within the solar park industry

The economic quantification of pollination service benefits from increased crop yields offers significant potential to explicitly include pollination service provision in solar park decisions. Moreover, policy makers and industry are showing willingness to embed environmental enhancements into solar park development, operation and maintenance (SolarPower Europe, 2019; MHCLG, 2018). Indeed, pollinators are increasingly included as elements of Corporate Social Responsibility commitments (UNEP-WCMC, 2018). Here, we review means by which to include the economic value of installing honeybee hives in solar parks into public and industry policies. We focus on inclusion in economic business cases, the planning process, sustainable investment funds and corporate social responsibility strategies. However, whilst we focus on the economic case of installing honeybees, concomitant impacts on ecosystems and agriculture should be considered, for example, the implications for wild pollinators and landscape structure (Gámez-Virués et al., 2015; Pywell et al., 2002). Moreover, the same mechanisms outlined below could be used if wild pollinator populations were enhanced in solar parks.

4.4.1. Business case

Depending on the market model for installing honeybee hives within solar parks, an economic case may need to be made. Pollination services are generally considered a 'public good' in as much as they are non-rival and non-excludable, which limits 'private' efforts to enhance their availability. However, given the limited flight distances of honeybees, their pollination services could be re-cast as a 'private good' and thus included in business cases. The mechanism will depend on solar park and agricultural land ownership and rights structures. If both the solar park and surrounding cropland were owned by the same person, the economic returns could be incorporated as an income stream. Alternatively, if the solar park developer rented the land, the economic benefits could, theoretically, be used to negotiate a commensurate reduction in land rent. Given the outcomes of our analysis, this possibility likely only exists for fruit crops.

4.4.2. Policy and the planning process

The increasing need for environmental protection and enhancement may preclude the requirement for net economic returns from locating honeybee hives in solar parks (Defra, 2018a). Direct inclusion of the pollination service value of honeybees or wild pollinators into national level renewable energy policy is unlikely. However, it could be incorporated through national environment policies that support landowners to protect pollinators (Defra, 2014) and to improve the environment more broadly (Defra, 2018a). In addition, the pollination benefits could be included within local or state policies. For example, there is a voluntary standard stating that solar park owners will provide habitat suitable for pollinators, amongst other things in Minnesota (Minnesota State, 2016). Economic pollination service estimates could deliver directly to local authority policy requirements. For example, the estimates could contribute to the net environmental gain requirements in the UK's National Planning Policy Framework (MHCLG, 2018). Moreover, at the local scale, environmental management plans, which could include pollination benefits, are often a statutory requirement for solar parks.

Explicit inclusion of pollination service benefits could also reduce community resistance to solar park applications given the societal benefits, including enhanced food security (Potts et al., 2010). Indeed, pollination benefits could be offered as a community environmental improvement benefit within the planning application, as is common practice in solar park developments (Cass et al., 2010). This may reduce the time and costs associated with extended planning procedures resulting from community resistance to solar park developments.

4.4.3. Sustainable investment funds & corporate social responsibility strategies

Stipulating pollination services could deliver much needed robust indicators of environmental sustainability for sustainable investment fund and corporate social responsibility policies and targets. Access to sustainable investment funds for solar park financing and corporate social responsibility targets require robust indicators to avoid criticisms of 'greenwashing' (Busch et al., 2016). Consequently, robust pollination service benefit quantification methodologies could unlock more attractive finance offers, and more central inclusion of environmental impacts into corporate social responsibility strategies.

4.5. Key future knowledge needs

Further understanding is required to robustly embed pollination service benefits into practice. Firstly, it is critical, given the potential implications, to resolve the relative costs and benefits of managing solar parks for wild pollinators and honeybees. Secondly, depending on the acceptable level of uncertainty in the economic benefits, improved knowledge of pollination, both spatially and temporally, may be required. Several regulating factors, including weather conditions, floral resources, habitat provision, existing pollinator populations, and market drivers that determine crop prices would need to be considered (Garibaldi et al., 2011; Garratt et al., 2016; Kleijn et al., 2015; Senapathi et al., 2021). Such understanding would ideally be developed for specific locales over several years, given the spatial and temporal variability in pollination service benefits. If honeybee hives are installed, the implications of the relatively high hive densities within solar parks, including implications for management, need to be better understood. Apiary sizes can exceed 100 hives with no detrimental impact on honey yield (Popesci, 2013). However, the consequences of high hive densities within solar parks (i.e. foraging behaviour and efficiency, hive health and contributions to pollination), as opposed to distributed throughout the landscape, remains unknown. Further, the potential for hives to be moved, and the implications for costs, would be pivotal to ensure sufficient season-long resources for the honeybees and to maximise the economic returns.

5. Conclusion

As low carbon energy demands and land use pressures increase, identifying synergistic benefits between renewable energy and environmental goals will become increasingly important. Moreover, policies to enable and encourage uptake of such integrated approaches will be required. Enhancing pollinator populations in solar parks offers potential land use, ecosystem service and economic co-benefits, applicable across the world. Our analysis suggests that benefits could extend across the honeybee, agricultural and solar park industries, with implications for energy specific and cognate policies. Consequently, the potential to exploit solar parks to boost pollination services through changes in both policy and practice should be pursued. Advances in understanding of pollination deficits, the relative merits of managing solar parks for wild pollinators and honeybees, and site-specific studies are required. This knowledge will contribute to ensuring energy system decarbonisation delivers significant, and necessary, environmental enhancements.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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