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Pollinator monitoring more than pays for itself

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Abstract

1. Resilient pollination services depend on sufficient abundance of pollinating insects over time. Currently, however, most knowledge about the status and trends of pollinators is based on changes in pollinator species richness and distribution only.
2. Systematic, long-term monitoring of pollinators is urgently needed to provide baseline information on their status, to identify the drivers of declines and to inform suitable response measures.
3. Power analysis was used to determine the number of sites required to detect a 30% change in pollinator populations over 10 years. We then evaluated the full economic costs of implementing four national monitoring schemes in the UK: (a) professional pollinator monitoring, (b) professional pollination service monitoring, (c) volunteer collected pan traps and (d) volunteer focal floral observations. These costs were compared to (a) the costs of implementing separate, expert-designed research and monitoring networks and (b) the economic benefits of pollination services threatened by pollinator loss.
4. Estimated scheme costs ranged from £6,159/year for a 75-site volunteer focal flower observation scheme to £2.7 M/year for an 800-site professional pollination service monitoring network. The estimated research costs saved using the site network as research infrastructure range from £1.46–4.17 M/year. The economic

value of UK crop yield lost following a 30% decline in pollinators was estimated at ~£188 M/year.

5. *Synthesis and applications*. We evaluated the full costs of running pollinator monitoring schemes against the economic benefits to research and society they provide. The annual costs of monitoring are <0.02% of the economic value of pollination services that would be lost after a 30% decline in pollination services. Furthermore, by providing high-quality scientific data, monitoring schemes would save at least £1.5 on data collection per £1 spent. Our findings demonstrate that long-term systematic monitoring can be a cost-effective tool for both answering key research questions and setting action points for policymakers. Careful consideration must be given to scheme design, the logistics of national-scale implementation and resulting data quality when selecting the most appropriate combination of surveyors, methods and site networks to deliver a successful scheme.

KEYWORDS

biodiversity monitoring, biodiversity policy, cost–benefit analysis, ecological economics, pollination services, pollinators, power analysis, science policy

1 | INTRODUCTION

The abundance and diversity of pollinating insects, such as bees and flies, is critical to ecosystem functioning, crop productivity, farm income and access to nutritious food (Garibaldi et al., 2020; Genung et al., 2017; IPBES, 2016). Concerns over pollinator declines have resulted in major national (e.g. DEFRA, 2015) and international (e.g. CBD, 2016; IPBES, 2016) policy demands for information on pollinator status and trends to develop appropriate conservation and management strategies.

Recent research suggests that the occupancy of bee and hoverfly species has declined by an average of 25% across Britain since 1980, particularly among specialist species (Powney et al., 2019), resulting in homogeneous pollinator communities (Carvalheiro et al., 2013) and disrupting plant–pollinator networks (Redhead et al., 2018). These and other key studies of pollinator trends (e.g. Kerr et al., 2015) are based solely upon species records collected opportunistically by volunteer recorders rather than through repeated, standardised surveys. Consequently, it is not possible to reliably estimate changes in pollinator abundance (a major driver of pollination services; Garibaldi et al., 2020) at a local or national scale, or to identify areas of pollination service deficit (Garibaldi et al., 2020; Garratt et al., 2014).

While drivers of pollinator decline (e.g. land use, climate change and pesticide exposure) have been inferred through field research and statistical modelling of opportunistic records (Kerr et al., 2015; Senapathi et al., 2017; Sponsler et al., 2019), without long-term abundance data we cannot reliably estimate their relative importance in driving declines at multiple scales. Furthermore, in the United Kingdom (and elsewhere), management for wild pollinators is only partially targeted, mostly comprising of agri-environment subsidies paid to farmers for implementing agri-environment measures, such as maintaining hedgerows and flower-rich field margins (e.g. DEFRA, 2020). Although these measures have been observed to effectively increase pollinator activity, diversity and pollination services at local scales (Garratt, Senepathi, Coston, Mortimer, & Potts, 2017; Scheper et al., 2013), this more likely reflects short-term ‘sinks’ for flower visitors rather than true population changes (Scheper et al., 2013), with real population changes taking years to fully establish (Blaauw and Isaacs, 2014; but see Carvell et al., 2017; Morandin, Long, & Kremen, 2016).

Understanding how land management affects pollinator abundance and diversity in combination with other drivers is necessary to design more targeted, adaptive management strategies at national scales (Garibaldi et al., 2020; Lyons et al., 2008). To this end, systematic monitoring of pollinators and pollination services has been identified in the United Kingdom (DEFRA, 2015) and internationally (IPBES, 2016), as vital to obtaining a more complete picture of pollinator status and trends, identifying the importance of different pressures, and to inform suitable response measures.

Approaches to biodiversity monitoring are diverse (Pocock et al., 2018). Large-scale and long-term surveillance monitoring (e.g. reporting of species occurrence by volunteers) provides broad, spatiotemporal baseline data that can allow early detection of issues and assessment of species trends over time (Lindenmayer et al., 2013), but that can be difficult to integrate into specific conservation management due to the nature of the data it provides (Nicholas & Williams, 2006). In contrast, targeted monitoring with a specific question or focus may be more efficient at addressing specific management issues and developing adaptive management responses (Nicholas & Williams, 2006), but may be less effective at establishing baseline data or discovering ‘unknown unknowns’ (Wintle et al., 2010). These potential trade-offs mean there is growing interest in the relative costs and benefits of different monitoring approaches and their outcomes (McDonald-Madden et al., 2010; Nicholas & Williams, 2006). Integrating research and monitoring could potentially provide baseline information for more targeted conservation management and save costs on essential discovery science. There is evidence to support the potential for active hypothesis testing through careful, stratified sampling of a sufficiently large network (Staley et al., 2016).

As data on the state of wild pollinator populations at national scales are limited, well-designed monitoring will have inherent value in providing the consistent baseline data necessary to transition towards more targeted assessments or specific management decisions (McDonald-Madden et al., 2010; Nygard et al., 2016). However, only Lebuhn et al. (2013) to date have explored the costs of a dedicated pollinator monitoring network, finding that a global network of 200 sites, each sampled fortnightly for 2 years within a 5-year window would cost $1.7 M. However, this study did not place these costs in the broader context of the benefits of pollinator monitoring, or the conservation of pollination services which add $235–577 bn/year to global agricultural productivity (IPBES, 2016), several orders of magnitude greater than the scheme costs.

Biodiversity monitoring is often conducted through citizen science schemes, where volunteer members of the public collect data following a standardised protocol (e.g. the UK Butterfly Monitoring Scheme; Roy et al., 2015). Although citizen science projects have returned scientifically valuable data on pollinators (e.g. Le Feon et al., 2018) and pollination services (Birkin & Goulson, 2015), significant expertise and microscopic examination are often required to identify many pollinator species. Consequently, observation-based volunteer data are often less accurate (O'Connor et al., 2019; Roy et al., 2016), or of lower taxonomic resolution (e.g. Mason & Arathi, 2019) than would be collected by professional staff with training in invertebrate taxonomy (but see Ratneiks et al., 2016). By contrast, professionally led monitoring can take advantage of existing capacity to return higher-quality data in a much shorter time-span, but is more expensive (Fox et al., 2017).

Here, a partnership of stakeholders developed four potential, monitoring schemes, designed to identify national-scale trends in the abundance of insect pollinators (at different levels of taxonomic resolution) and/or pollination services to crops. These schemes are as follows: (a) professional pollinator monitoring, (b) professional pollination service monitoring, (c) volunteer collected pan traps and (d) volunteer focal floral observations. They represent a spectrum in data quality and annual financial investment, combining different sampling methods and levels of participant expertise to deliver defined outputs (Supporting Information Annex 1). Estimated scheme costs, based on existing pilot work, are contrasted against the economic benefits of each network (a) for research funders, by designing the network to address scientific questions and (b) for society, by offsetting the risks from failing to respond to pollinator declines that impact on biodiversity, crop pollination services and human well-being.

2 | MATERIALS AND METHODS

2.1 | Scheme designs

Four hypothetical national-scale monitoring schemes were developed, based on combinations of participants (whether data were collected and/or identified by volunteers or professionals, non-experts or experts), methods (how pollinators or crop pollination were sampled and samples processed) and metrics (what data were generated e.g. species abundance) with a focus on wild bees and hoverflies as key insect pollinator groups. Each 'Recorder–Sampling Method–Metric' combination was given a score based on feasibility and the degree of training required. This exercise considered 15 different methods, related research and using expert opinion across the partnership of authors (Garratt et al., 2019; O'Connor et al., 2019) to reach consensus (by simple majority agreement, following group discussion) on the assigned scores. Scores and means across each method are provided in Supporting Information Annex 1. Pan traps, transect walks and timed focal flower observations were identified as the methods most effective at delivering suitable metrics (Carvell et al., 2016) and serve as the basis of the four schemes (summarised in Table 1):

- Scheme 1—*Professional pollinator monitoring*: This scheme aims to monitor national trends in the abundance of specific species (including key crop pollinators), using mixed methods to cover a wide range of taxa. Institutes each allocate technical staff time to monitoring part of a site network (5 sites/person/institution) using pan traps, transect walks and 10-min focal floral observations. Bee and hoverfly specimens from the pan traps and transects are identified to species level by expert taxonomists, apart from those readily identified in situ during transects, and stored at a central institute. Other insects sampled in pan traps, and all flower visitors during the focal floral observations would be identified to broad group level (e.g. beetles).
- Scheme 2—*Professional pollination service monitoring*: This scheme aims to monitor the abundance of key crop pollinator species and the delivery of pollination services in four major UK crops (apples, strawberries, field beans and oilseed rape, representing the main orchard, soft fruit, protein and arable crops). This includes observations of species groups and easy-to-identify species on transects in and around crop fields three times/year corresponding to crop flowering periods (Scheme 2a), requiring only one staff member/10 sites. Scheme 2b uses crop bagging and hand pollination to directly assess the level of pollination service provided to the crop (see Garratt et al., 2014).
- Scheme 3—*Volunteer collected pan traps*: This scheme aims to monitor national trends in the abundance of specific pollinators, rather than guilds through a hybrid of volunteer data collection and expert identification. Volunteers use pan traps and focal floral observations to sample insects and collect flower visitation data at specified locations. They are supplied with the necessary information, materials and training and send their samples to a central

TABLE 1 Overview of scheme design, structure and outputs

Scheme		Methods	Staff			Training	Output metrics[a]
			Collection	Identification	Administration		
1	Professional pollinator monitoring	Pan traps (5/replicate), transect (5/replicate), 10-min focal observations (2/replicate)	Professional (1 per 5 sites)	Professional taxonomist	Full time: Postdoctoral staff	Staff training in years 1, 4, 7 and 10	Species-level abundance, group-level abundance of flower visitors, habitat and flower cover
2a	Professional pollination service monitoring	Transects (5/replicate),	Professional (1 per 10 sites)	N/A	Full time: Postdoctoral staff	Staff training in years 1, 4, 7 and 10	Easy to identify and morpho-species-level abundance of crop visitors
2b	Professional pollination service monitoring (with hand pollination)	Transects (5/replicate), hand pollination (1 round/replicate)	Professional (1 per 8 sites)	Professional technician (fruits only)	Full time: Postdoctoral staff	Staff training in years 1, 4, 7 and 10	Easy to identify and morpho-species-level records of crop visitors. Measures of crop pollination service levels.
3a	Volunteer pan traps (traditional ID)	Pan traps (5/replicate), 10-min focal observations (2/replicate)	Volunteer	Professional taxonomist	Full time: Postdoctoral staff	Volunteer training (1 day per volunteer)	Species-level abundance. Group-level abundance of flower visitors.
3b	Volunteer pan traps (DNA barcoding)	Pan traps (5/replicate), 10-min focal observations (2/replicate)	Volunteer	Professional taxonomist (DNA barcoding)	Full time: Postdoctoral staff	Volunteer training events: (1 day per volunteer)	Group-level records of flower visitors. Species-level abundance. DNA barcode data.
4a	Volunteer focal floral observations	10-min focal observations (2/replicate)	Volunteer	Professional technician (photo verification @2/min)	Part time: extension of current NGO staff	Annual instruction and identification materials	Group or morpho-species-level records of flower visitors
4b	Volunteer focal floral observations	10-min focal observations (2/replicate)	Volunteer	Crowd-sourced identification	Full time: NGO staff	Annual instruction and identification materials	Group or morpho-species-level records of flower visitors

[a]Where outputs include species-level abundance, this refers to bees and hoverflies only, and would include measures of species richness and diversity for these groups. A ‘replicate’ represents one survey at a site.

administrating organisation at a cost to the project. Specimens are identified by expert taxonomic consultants either traditionally (Scheme 3a) or via individual-based DNA barcoding (Scheme 3b), which has been demonstrated to accurately measure species identity from specimens collected in pan traps (Creedy et al., 2019).

- Scheme 4—*Volunteer focal floral observations*: This citizen science-led scheme aims to meet the minimum requirements of monitoring trends in pollinator abundance at broad taxonomic group level. Volunteers record the number of flower visitors, to a 50 × 50 cm patch of flowering plants from a suggested list of 'target' species, over a 10-min period. Recorders are asked to take photographs of representative individuals of each observed insect group which are then verified either by an expert professional (Scheme 4a) or by crowd sourcing using a specially established portal (Scheme 4b). The scheme is managed either as an extension of an existing monitoring scheme (e.g. the UK Butterfly Monitoring Scheme), requiring part of the time (15% full time) of an existing administrator (4a) or as a stand-alone web portal with a dedicated, full-time administrator (4b). As it does not identify specific species, this scheme is not suited to evaluating changes in specific crop pollinators, but may provide an indication of changes in plant visitation across different insect taxa, and could be targeted towards recording on specific crop plants.

2.2 | Power analysis

To develop credible scheme structures for national-scale assessments, statistical power analyses were conducted using available datasets from systematic surveys measuring pollinators and pollination services to UK crops and simulating a range of potential scenarios of change over a 10-year period. This aimed to estimate the minimum levels of replication (number of sites) required to achieve power greater than 80% to detect national-scale changes of a given size in the relevant output metrics. The 10-year period was selected to detecting long-term trends and matched the expert-derived estimate of time over which regular sampling would be required for a monitoring scheme (see Results).

Four large-scale systematic datasets were used to examine the likely range of initial count values and variance parameters, assuming that sites differ by their initial count (random effects intercept) and rate of change over time (random effects slope). The datasets represented pollinator abundance from pan traps and transects over 2 years (W. E. Kunin, M. Gillespie, S. G. Potts, S. Roberts, J. Memmott, & M. Baude, unpubl. data); bumblebee abundance on transects over 4 years (Carvell et al., 2011); butterfly abundance from transects over 10 years (Roy et al., 2015) and crop visitor observations, transects and direct measures of crop pollination service and deficit in UK oilseed rape, beans and apples (Garratt et al., 2014; Garratt et al., 2014; O'Connor et al., 2019). Poisson GLMMs were run on each pollinator response measure and for the crop pollination service data, using Poisson GLMMs, in both cases with random intercepts and slopes across years, and site as a random effect (see model details in Supporting Information Annex 2).

The simulated scenarios differed in (a) initial pollinator abundance (counts per site, from 1 to 200) or levels of pollination service and deficit (from 5% to 30% depending on crop), (b) % decline in pollinator populations over 10 years to be detected (0%, 1%, 5%, 10%, 30% and 50%) and (c) number of sites monitored annually (from 10 to 1,000 sites for pollinators or up to 100 sites per crop for pollination service measures) (see Supporting Information Annex 2, Table A2a for pollinator abundance simulations). These were modelled as with the empirical data under a Poisson GLMM with a random effects intercept *SD* of 0.5 and random effects slope (across years) *SD* of 0.1 (values selected to most closely reflect those from the modelled empirical data while still giving realistic count values across 10 years), with site as a random effect. This model assumes a single total pollinator count per year, which may be achieved via multiple sampling visits to a site, here assumed to be four per year, to cover activity periods of the majority of UK pollinators. Crop pollination service measures were modelled under the Poisson GLMM with a random effects variance intercept *SD* of 0.5 and random effects slope (across years) *SD* of 0.01, with site as a random effect. All scenarios were run with 1,000 Monte Carlo simulations (see estimated power in Supporting Information Annex 2, Table A2a). The statistical power was estimated as the percentage of simulations that gave a statistically significant result (5% alpha). From these, a detection level of 30% national-scale decline over 10 years (equating to a 3.5% annual decline) was selected as sufficiently sensitive to detect overall population declines, provide sufficient replication to identify plausible drivers of these declines (using additional environmental data such as weather records) and trigger response measures. This was more sensitive than the ideal detection levels recommended across most output measures in the expert survey (see below).

2.3 | Costs of monitoring schemes

Costs estimated for each scheme covered (a) staff salaries to undertake field work, identify specimens and administer the scheme; (b) material costs for field equipment, specimen storage, travelling to and from sampling sites and postage of specimens to be identified; (c) training staff/volunteers and (d) maintaining digital records and publicly available data. These costs (Supporting Information Annex 3) were based on the observed costs of a recent pollinator monitoring pilot study (O'Connor et al., 2019) and implementation of the existing UK Pollinator Monitoring Scheme (UKCEH, 2019). We assumed costs to be static for all 10 years, not accounting for inflation. However, as inflation affects both the schemes and the estimated costs saved, it is unlikely to affect the conclusions.

2.4 | Benefits of monitoring schemes: Research costs saved

Although developed as surveillance monitoring schemes, given the scale of the networks, it is possible to test numerous hypotheses through each scheme by carefully stratifying site selection to capture variance in landscape, climate and management. These potential monetary costs to research funders from using a monitoring scheme as the basis for UK research data collection were estimated by conducting a survey of experts in 2015 to determine the size of the site network and sampling intensity required to address each of eight key pollinator research questions through independent research projects (Table 2).

Research questions were selected from academic literature and policy reports reviewing the key knowledge gaps in pollinator research (Dicks et al., 2013; Vanbergen et al., 2012) and approved through discussions with policymakers from the Department for Environment Food and Rural Affairs (DEFRA) to ensure their relevance to wider policy.

In all, 36 experts (Supporting Information Annex 4) were selected on the basis that they had either (a) at least five publications on pollinator field research in northern or Western Europe or (b) prior expertise in invertebrate population monitoring. Experts were divided into four groups based on their specific expertise, each of which was given a different selection of three research questions relevant to their expertise (Supporting Information Annex 4). Question 8 was posed to all four groups (Table 2). In total, 28 experts (78%) completed the questionnaire in full. To avoid biasing their answers, experts were not given any details of the proposed monitoring schemes or the power analysis.

For each research question, experts were asked to give their opinion on the minimum and ideal site network attributes (number, scale and variation of sites sampled, regularity of sampling and years of sampling) and detectable rate of change in metrics of pollinators and pollination service to crops (e.g. abundance of pollinators) required to answer each question. Experts were also asked to state their confidence in their answers to capture uncertainty. The questionnaire (Supporting Information Annex 5) was refined through a short pilot with members of the authorship team who were not involved in the survey drafting, resulting in only minor language changes.

Given variation in expert responses and low sample size, the median response for each attribute was then used to determine the final minimum and ideal 'research networks' for each question (see Supporting Information Annex 6 for mean values). The costs of implementing research networks was estimated in two ways (i) using the same cost structure as scheme 1—reflecting standard research costs or (ii) using the cost structure of the scheme it was compared to (e.g. Scheme 3a) to give a more direct comparison.

To assess how well each proposed monitoring scheme fitted the structure of the research networks, an overlap index was created (Supporting Information Annex 7). This involved dividing the number of sites, replicates and years (always 10) in each scheme network by the respective median responses that experts gave these attributes for each research question (minimum and ideal standards). If the sum of these three divisions is 3 or greater (i.e. the monitoring network matches 1 for 1 or better on all aspects of the research network), the site network was deemed able to address this question. Scheme 2 was not deemed appropriate for research question 3 (urban interventions) because of limited agriculture in urban areas, and thus pollination services, in UK cities. The total estimated costs of implementing all the overlapping research networks were compared with the estimated costs of the schemes to provide a cost:benefit ratio.

TABLE 2 Key research questions used in the expert survey

Number	Question
1	How does **climate change** influence changes in pollinator populations and pollination services?
2	How do **habitat-based interventions** affect the status and trends of pollinator populations and pollination services in **agricultural** landscapes?
3	How do **habitat-based interventions** affect the status and trends of pollinator populations and pollination services in **urban** landscapes?
4	How do changes in the **abundance and diversity** of pollinator populations affect **pollination services to crops** in the United Kingdom?
5	How do changes in the **abundance and diversity** of pollinator populations affect **pollination services to wildflowers** in the United Kingdom?
6	How does **changing landscape complexity** influence changes in pollinator populations and pollination services?
7	How does **agrochemical** use influence changes in pollinator populations and pollination services?
8	How is the **abundance and diversity of pollinator populations changing** within the United Kingdom?

2.5 | Benefits of monitoring schemes: Economic impacts of pollination

By providing a measure of change in pollinator populations, nationwide monitoring can support specific management to halt or reverse losses in pollination services, providing direct economic benefits to producers and consumers (IPBES, 2016). To illustrate the economic benefits of pollination services to the United Kingdom, which a monitoring scheme could help safeguard, we employed (a) dependence ratio and (b) consumer surplus methods. Dependence ratio methods are expressed as:

$$\mathrm{IPO}_{it} = \mathrm{O}_{it} \times \mathrm{DR}_i, \quad (1)$$

where IP is the economic benefits of insect pollination to crop i in year t, O_{it} is the total market price of all UK production of crop i (from DEFRA, 2019a, 2019b, 2019c) and DR_i is the insect pollinator dependence ratio of crop i; a metric of the proportion of crop production lost in the absence of insect pollination. To compensate for inter-annual variations in productivity and prices, an average of the last 3 years of available, verified data (2014–2016) was used, with some additional modifications to more accurately estimate average crop prices (see Supporting Information Annex 8). Where available, dependence ratios were based on appropriate UK studies into pollination service benefits for particular crops (e.g. Garratt et al., 2016), otherwise generalisations from global literature were used (Supporting Information Annex 8).

A complete loss of pollination service is unlikely as at least some of the services can be provided by managed pollinators (but see Breeze et al., 2014). The study therefore presents these economic estimates following a 30% loss of pollination, reflecting the cumulative change in nationwide pollinator abundance detectable by the monitoring schemes proposed here. By assuming that pollination services are approximately linear and additive, a 30% loss of pollination services would result in an estimated $DR_i \times 0.3$ loss of yield. This provides a more realistic estimate of possible losses from inaction. For comparison, results for 100% pollinator loss are in Supporting Information Annex 9.

If pollination services decline, then prices for insect-pollinated crops will rise. This will result in a loss of economic welfare as people are forced to pay more to obtain the same quantity of these crops, limiting their capacity to spend their money on other goods and services. Consumer surplus loss is a measure of the total value of this loss of economic welfare across the whole country (see IPBES, 2016 for a complete discussion). Here, consumer surplus is estimated as (see Supporting Information Annex 10 for proofs):

$$\mathrm{CSLoss} = \frac{P_i Q_{it}}{1+\varepsilon}\left(\phi_i^{\frac{1}{\varepsilon}+1} - 1\right), \tag{2}$$

where P_{it} is the price/tonne of crop I in year t, Q_{it} is the total quantity of crop production and ε is the price elasticity of demand; a theoretical metric of the percentage change of price/tonne in relation to a 1% change in total crop production. Φ_i is a value equivalent to one minus the dependence ratio (DR) of each crop multiplied by the proportion of pollination service loss (here: 0.3). As there is insufficient data to estimate the price elasticities for all 18 crops, following Gallai et al. (2009), elasticities are set between a low of −0.5 and high of −1.5.

3 | RESULTS

Based on the range of initial annual counts per site from the empirical data, the estimated number of sites needed to detect 30% declines with 80% power is either 75 sites where the initial pollinator count per site for a given metric (e.g. bee or hoverfly abundance) is 10 individuals, 145 sites where the initial annual count per site is 1 individual, or 200 sites per crop where initial levels of pollination service and deficit average around 10% (Table 3).

3.1 | Costs of monitoring schemes

The estimated 10-year costs of the four potential monitoring schemes varied considerably, ranging from £61,588 for a 75-site volunteer focal floral observation scheme (Scheme 4a) to £26.4 M for an 800-site professional pollination service monitoring scheme (Scheme 2b, Table 3). A professional pollinator monitoring scheme (Scheme 1) that would return the highest quality data (species-level abundance of bees and hoverflies) was found to range from £5.3 M to £9.1 M in total, due to the high number of sites required. Professional research staff account for 66%–88% of the total scheme costs in Schemes 1 and 2 (Supporting Information Annex 11), while administrative staff accounted for 36%–57% of the costs of a volunteer pan trap scheme (Schemes 3a/b). The costs of DNA barcoding of pan trap catches (3b) were marginally higher than the costs of traditional identification (3a) due to the staff time required to perform the molecular analysis (e.g. sequencing) but are likely to fall in future. The volunteer pan trap scheme had the highest material, training and postage costs because of the large number of recorders required and specimens generated. By contrast, Scheme 4 has no fuel or postage costs. Scheme

TABLE 3 Summary of costs for each scheme

Scheme	Sites	Years	Replicates	Year 1 costs	Years 2–10 annual costs	Total costs (10 years)	Costs/site (10 years)	Costs/replicate (10 years)
1	75	10	4	£539,157	£532,825	£5,334,584	£71,128	£17,782
	145	10	4	£917,145	£905,671	£9,068,187	£62,539	£15,635
2a	200	10	4	£865,699	£863,971	£8,641,438	£28,805	£9,602
2b	800	10	4	£2,669,541	£2,657,004	£26,582,579	£33,228	£11,076
3a	75	10	4	£222,724	£181,133	£1,852,921	£24,706	£6,176
	145	10	4	£305,246	£225,770	£2,337,173	£16,118	£4,030
3b	75	10	4	£253,222	£211,630	£2,157,895	£28,772	£7,193
	145	10	4	£363,274	£283,798	£2,917,456	£20,120	£5,030
4a	75	10	4	£6,159	£6,159	£61,588	£821	£205
	145	10	4	£7,551	£7,551	£75,514	£521	£130
4b	75	10	4	£43,400	£33,400	£344,002	£4,587	£1,147
	145	10	4	£43,400	£33,400	£344,002	£2,372	£593

TABLE 4 Median size and time-span of expert suggested research networks

Research question	Standard	Sites	Regularity	Years	Confidence
1: Climate change	Min	30	4	10	8
	Ideal	300	21	30	7
2: Agricultural interventions	Min	10	3	3	8
	Ideal	20	8	5	8
3: Urban interventions	Min	15	3	3	8
	Ideal	21	5	8	8
4: Crop pollination services	Min	10	3	3	7
	Ideal	25	11	11	8
5: Wildflower pollination	Min	30	5	4	6
	Ideal	65	10	8	5.5
6: Landscape complexity	Min	30	5	5	7
	Ideal	100	10	15	7
7: Pesticide use	Min	25	5	3	7.5
	Ideal	100	15	8	8
8: Status and trends of pollinators	Min	50	5	8	7
	Ideal	200	10	11	8

4b has constant ongoing costs due to identification being entirely online. Across all schemes, costs per site and per replicate fall with a greater number of sites sampled (Table 3).

3.2 | Benefits of monitoring schemes: Research costs saved

Responses to the expert survey showed variation in median size and regularity of sampling depending on the research question (Table 4). In general, research questions focusing on interventions tended to have smaller site networks than questions regarding pressures on pollinators (landscape, pesticides, climate change), which had ideal networks in excess of 100 sites. Experts generally proposed sampling at greater regularity than the four sampling visits per year that were proposed within the costed schemes in this study. This suggests that the proposed schemes may not adequately record certain species with limited flight periods. However, most wild bee and hoverfly species typically have flight periods lasting 2 months (Falk & Lewington, 2018) and the largest proposed networks are designed to detect changes in species with very low counts, suggesting that this remains a reasonable sampling intensity. Over a long enough time period, statistical methods for accounting for seasonality could be implemented to further correct for this (Dennis et al., 2016). Except for landscape complexity and climate change, ideal durations were within 1 year of the 10-year duration used for the four candidate monitoring schemes. Expert minimum standards for a network to monitor pollinator status and trends were very similar to the networks proposed in this study; however, networks for assessing pollination services were much smaller. Confidence of the experts in their assigned scores was mid-high for most questions, with the exception of wild flower pollination where confidence was towards the middle of the scale.

The estimated costs of each scheme were compared with the estimated costs of funding up to eight separate research projects based on the recommended structures provided by expert opinions to illustrate the economic value monitoring can provide to wider research. Compared with fully professional research, a pollinator monitoring network will always save at least £1.53 per £1 invested in running the scheme (Table 5). Comparing the costs of each scheme to running each overlapping research project with the same methods indicates that savings are only <£1:£1 in the case of Scheme 2b, as the sum total of sites and sampling required to address all seven applicable research questions is lower than the total sampling effort of 600 or 800 sites sampled three times a year for 10 years. Otherwise, all schemes, including a fully professional pollinator monitoring scheme (Scheme 1), provide substantial cost savings compared to running separate site networks focused on individual research questions.

3.3 | Economic benefits of pollination services

Dependence ratio analysis indicates that pollination services in the United Kingdom increase productivity by ~£630 M per year based on an average of 2014–2016 data across crops (Supporting Information Annex 9). A 30% loss of these services therefore equates to £188 M/year (Table 6), ~71 times the annual costs of the most expensive scheme described (Scheme 2b, 800 sites, Supporting Information Annex 12). Just over 50% of these benefits stem from two crops: oilseed rape, which is very widely grown despite having only moderate pollinator dependence, and strawberries, where pollination is essential to good quality fruits (e.g. Wietzke et al., 2018) and which produce a large output of high price/tonne fruit per hectare. Estimating the economic surplus value of pollinator losses indicates that a 30% loss of pollination services would result in a loss of between £131.8

TABLE 5 Research cost–benefit analysis

Scheme	Sites	Costs (total, 10 years)	Research costs (professional)	Cost:benefits (professional)	Research costs (reflective)	Cost:benefits (reflective)
1	75	£5.3 M	£14.6 M	£2.74	£14.6 M	£2.75
	145	£9.1 M	£17.7 M	£1.96	£17.7 M	£1.96
2a	300	£8.5 M	£15.6 M	£1.80	£10.5 M	£1.22
2b	800	£26.4 M	£41.2 M	£1.55	£22.1 M	£0.83
3a	75	£1.9 M	£14.6 M	£7.90	£9.8 M	£5.27
	145	£2.3 M	£17.7 M	£7.59	£10.9 M	£4.68
3b	75	£2.1 M	£14.6 M	£6.78	£9.5 M	£4.40
	145	£2.6 M	£17.7 M	£6.08	£10.5 M	£3.60
4a	75	£0.06 M	£14.6 M	£237.68	£0.4 M	£6.50
	145	£0.08 M	£17.7 M	£234.88	£0.4 M	£5.87
4b	75	£0.3 M	£14.6 M	£42.55	£2.8 M	£8.00
	145	£0.3 M	£17.7 M	£51.56	£2.8 M	£8.00

Note: Research costs/costs:benefits (professional) = the costs/costs:benefits of funding eight (seven in the case of Schemes 2a and 2b) overlapping research projects (Supporting Information Annex 5) using the methods and costing structure of Scheme 1. Research Costs/costs:benefits (reflective) = the costs/costs:benefits of funding up to eight overlapping research projects (Supporting Information Annex 5) using the methods and costing structure of the scheme in the same row.

TABLE 6 Summary of the economic benefits of pollination services in the United Kingdom (2014–2016 average)

Crop	Pollinator dependence	Total production (2014–2016 av)	Pollination benefits (30% loss of service)	Consumer surplus change (30% loss of service)	
				Elasticity − 0.5	Elasticity − 1.5
Dessert apples	60%+	£108.1 M	£19.5 M	−£47.50	−£13.85
Culinary apples	69%+	£60.8 M	£12.6 M	−£31.76	−£9.05
Cider apples	57%+	£31.3 M	£5.4 M	−£12.97	−£3.81
Pears	65%	£15.5 M	£3.0 M	−£7.50	−£2.16
Plums	65%	£12.2 M	£2.4 M	−£5.92	−£1.70
Sweet cherries	85%	£11.4 M	£2.9 M	−£7.83	−£2.14
Other top fruit	65%	£5.6 M	£1.1 M	−£2.73	−£0.79
Strawberry	45%	£334.4 M	£45.1 M	−£104.36	−£31.56
Raspberry	45%	£112.3 M	£15.2 M	−£35.07	−£10.60
Blackcurrant	45%	£14.8 M	£2.0 M	−£4.62	−£1.40
Other soft fruit	45%	£28.3 M	£3.8 M	−£8.83	−£2.67
Oilseed rape	25%	£662.0 M	£49.6 M	−£107.35	−£33.96
Field bean	25%	£90.8 M	£6.8 M	−£14.72	−£4.66
Broad bean	25%	£6.7 M	£0.5 M	−£1.08	−£0.34
Runner Bean	85%	£15.6 M	£4.0 M	−£10.65	−£2.91
Courgette	60%+	£19.8 M	£3.6 M	−£8.70	−£2.54
Tomato	25%	£128.3 M	£9.6 M	−£20.80	−£6.58
Sweet pepper	25%	£21.6 M	£1.6 M	−£3.51	−£1.11
Total		£1,692.3 M	£188.7 M	−£435.90	−£131.83

Note: Pollinator dependence = the proportion of yield lost in the absence of pollination. + = taken from a specific UK case study, see Supporting Information Annex 5. Total production = the total market sale price of all UK production of the crop. Pollination benefits = the monetary benefits of crop production theoretically lost with a 30% loss of pollination services. Consumer surplus change = the sum value of consumer welfare changes from rising crop prices, this was performed under assumptions of −0.5 and −1.5 supply elasticity of demand (the % change in prices following a 1% increase in supply).

M and £435.9 M in annual consumer welfare, 50–164 times the annual costs of the most expensive scheme described (Scheme 2b, 800 sites, Supporting Information Annex 12).

4 | DISCUSSION

This study is the first to evaluate the full economic costs and benefits of a range of national-level monitoring schemes for insect pollinators and crop pollination services, spanning professional and volunteer-led citizen science approaches. The results demonstrate that a well-designed pollinator monitoring scheme could be a highly cost-effective means of addressing key research questions, compared to the costs of implementing separate research projects. A fully professional monitoring network that monitors trends in species-level abundance was estimated to save at least £1.96 per £1 spent (Table 6: Scheme 1). The study also illustrates the value of pollinator monitoring as part of efforts to maintain the stability of pollination services to food production. The annual costs of monitoring were estimated at ≤0.006% of the market price of pollinator-dependent crop production and ≤0.02% of the annual economic value of pollination services to consumers lost with a 30% decline in insect pollinators. Although based on the best available data, these estimates are still subject to a number of assumptions that may affect the values estimated but these are unlikely to influence the results overall (see Supporting Information Annex 13 for a review).

4.1 | Challenges in implementing nationwide monitoring

Our results are consistent with other work comparing different monitoring scheme structures, with volunteer recorders reducing costs significantly compared with professionals (Fox et al., 2017; Targetti et al., 2016). However, it is important to consider differences in data quality and taxonomic resolution resulting from different monitoring approaches and how they influence the utility for subsequent management or policy responses (Wintle et al., 2010).

As different species within taxonomic groups provide pollination services to different crops (e.g. Garratt et al., 2016), group-level data (Scheme 4: Volunteer focal floral observations) may have little value in projecting pollination service stability, overlook important trends driven by changes in key species (e.g. Le Feon et al., 2016), and neither detect species loss nor help develop management for specialist species beyond what can be achieved with existing occupancy data (Carvalheiro et al., 2013). Furthermore, although validation of photographic records collected by citizen scientists can improve accuracy (Roy et al., 2016), many pollinator species cannot be identified consistently from photographs even by experts (Falk et al., 2019; Morris et al., 2016), although advances in machine learning could theoretically make this more viable in the near future. The only scheme providing a direct measurement of pollination service (Scheme 2: Professional pollination service monitoring) has the potential to detect areas with economically significant deficits (Garratt et al., 2014). However, the trade-off is that non-crop pollinators, which make up the bulk of pollinator biodiversity (Kleijn et al., 2015) are underrepresented in the data, making it unsuitable for biodiversity-oriented objectives (e.g. CBD, 2016; DEFRA, 2015; Protect Pollinators, 2019). In contrast, Scheme 3 (Volunteer collected pan traps) produces species-level diversity data, but if focussed on pan traps and focal observations alone, risks under-representing certain pollinator species due to biases in the species caught (Fijen & Kleijn, 2017; O'Connor et al., 2019). Scheme 1 (Professional pollinator monitoring) would provide the most comprehensive data for baseline surveillance of pollinator biodiversity and (depending on site stratification) enough data on key crop pollinators to potentially act as a valid surrogate for overall pollination services, at the cost of being more expensive to implement. Consequently, although each scheme is capable of answering multiple questions, only Schemes 1 and 3 are likely to deliver a high enough taxonomic resolution for meeting wider biodiversity goals.

Working with inexperienced volunteer recorders also brings additional challenges and opportunities. Volunteers require engagement, including feedback, and training to maintain quality data collection retain them over time (Domrose & Johnson, 2017; Kremen et al., 2011; Mason & Arathi, 2019), they often select sites based on aesthetics or their perceived probability of seeing the focal organisms (Tulloch et al., 2013) and may be unwilling to undertake prescribed methods (Garratt et al., 2019). Consequently, volunteers may be unsuited to surveying across a stratified, randomly distributed monitoring network, especially in homogeneous agricultural landscapes (Tulloch et al., 2013). We did not explicitly consider the use of expert consultant entomologists as the main data providers because the number of UK consultants with sufficient taxonomic expertise remains below the scale required for the proposed schemes. This, in turn, highlights the value that a well-designed surveillance monitoring scheme can have in building capacity, particularly among citizen scientists (Birkin & Goulson, 2015; Fox et al., 2017; Gustaffson et al., 2017). As political willingness to act is often driven by public demands (Cardaso, Erwin, Borges, & New, 2011), deepening public involvement and understanding around pollinators, and particularly the role they play in sustaining biodiversity and ecosystems (IPBES, 2016) represents an important leverage point to drive lasting changes in attitudes towards biodiversity conservation (Abson et al., 2017). Further research into volunteer motivations and perceptions (e.g. Domrose & Johnson, 2017) could therefore yield benefits to future invertebrate conservation. A scheme combining professional and volunteer-monitored sites would require forward planning to identify site distributions (e.g. Tulloch et al., 2013) and retain volunteers (Mason & Arathi, 2019) but could yield the best of both approaches. Based on the 75-site network costs estimated for Schemes 1 and 3a, minus the cost of one full-time administrator to avoid double counting, a 150-site network, evenly divided between professional and volunteer recorders, would cost £7.1 M, ~£2 M less than a 145-site professional pollinator monitoring network while retaining a similar research and monitoring power.

4.2 | Long-term research benefits

This study is the first to directly evaluate the value of running a monitoring scheme as a form of research infrastructure by comparing the costs of running the scheme to the costs of equivalent primary research. Limited availability of long-term, systematically generated data remain one of the biggest challenges in advancing ecological research (Lindenmayer et al., 2012). Presently, there are only a few long-term ecological projects in the United Kingdom run by research organisations (e.g. Silvertown et al., 2006) or NGO–government–research partnerships (Greenwood, 2003) collecting continuous data, most of which receive little guaranteed public funding. Over 95% of ecological research projects funded by UK research councils since 2010 have had a duration of under 5 years (UKRI, 2019). Even if such research were funded, a paradigm of encouraging regular publications, rather than waiting years for more substantial outputs will make it difficult to recruiting qualified staff to lead monitoring work (Lindenmayer et al., 2013).

Key to the success of any monitoring scheme as a research network will be data accessibility, which should be mandatory for publicly funded schemes. Openly accessible long-term ecological data can allow researchers to supplement their own research networks (Fischer et al., 2010), develop cross-disciplinary work (Robertson et al., 2014) and address challenges in theoretical ecology (Lindenmayer et al., 2012). This study illustrates that a sufficiently large monitoring network can act as cost-effective research infrastructure. In reality, separate power analyses would be required to determine how monitoring networks overlap of with research networks (Buckland & Johnston, 2017); however, the data required for such power analyses would require initial monitoring to establish. Furthermore, the eight research questions considered by the experts are merely an illustrative example, there are many alternative and questions that could be developed within such a future network (Le Feon et al., 2018; Silvertown et al., 2006; Wintle et al., 2010) particularly if integrated into international efforts such as the Long-Term Ecological Research network (LTER Network, 2020). The cost savings presented here are thus likely to be an under-estimate. The methods used in this study could also be expanded to monitor wider insect taxa, particularly when using pan traps which collect non-target invertebrates as by-catch, although care should be taken to avoid an inappropriate 'one-size-fits-all' approach (Lindenmayer & Likens, 2009).

Finally, effective monitoring should aim to underpin a more targeted approach to measuring the impacts of management interventions on pollinator diversity, pollination services and community resilience at a national level (IPBES, 2016; Staley et al., 2016). With better insights into the effects of pressures and management, the question of how much monitoring should be undertaken can be revisited using Value of Information analysis, whereby the costs of monitoring are compared with the likely improvement in management objectives arising from the additional information (Benett et al., 2018). As there are major deficits in the knowledge base necessary to develop national-scale adaptive management practices for pollinators, monitoring as proposed in this study is valuable in itself (Nygard et al., 2016). However, as more targeted management becomes possible, there will be resource trade-offs between monitoring and management itself which should be addressed. Nonetheless, such costs are still likely to be far below the value of such monitoring to pollination services and research expertise. Most Value of Information analysis has focused solely on the direct value of monitoring to the management benefits (Bolan et al., 2019). By demonstrating the added value of monitoring as a research tool, our study highlights the potential of monitoring to provide scientific infrastructure that could be funded by research funders while adding value to natural resource management.

5 | CONCLUSIONS

Policy for supporting pollinators is a matter of international concern (CBD, 2016; IPBES, 2016), yet the systematic data on pollinator abundance and diversity required to determine the impacts of pressures and appropriate responses remains lacking (Garibaldi et al., 2020). This study demonstrates that even expensive, systematic professional monitoring schemes that deliver the highest quality data can more than pay for themselves. By providing a long-term site network, they can underpin cost-effective research into key questions in a manner not supported by existing research funding, yet which is vital to meeting the UKs international commitments to support pollinator and wider biodiversity conservation (CBD, 2016; Promote Pollinators, 2019). More fundamentally, by tracking pollinator populations in agricultural landscapes, monitoring potentially allows more targeted and immediate interventions to avoid or reverse economically damaging losses of pollination services (Lindenmayer et al., 2013). This study provides a strong economic and scientific argument that monitoring is both affordable and highly beneficial for ecological research, decision-making, conservation action and ultimately underpinning the transformative change required to sustain nature (Abson et al., 2017).

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AUTHORS' CONTRIBUTIONS

T.D.B., C.C., H.E.R., S.G.P. and M.P.G. designed the study; C.C., T.B., R.C., R.S.O., M.E., M.P.G., M.H., C.H., C.M.J., W.E.K., P.L., R.K.A.M., A.M., D.B.R., H.E.R. and C.Q.T. developed the monitoring schemes; M.J., N.I., H.E.R. and C.C. undertook the power analysis; C.C., T.B., R.C., M.E., M.P.G., M.H., C.H., C.M.J., W.E.K., P.L., R.K.A.M., A.M., R.S.O., J.P., S.G.P., S.P.M.R., D.B.R., H.E.R., C.Q.T. and A.J.V. all supplied data used in the cost assessments; T.D.B., C.C. and S.G.P. designed, disseminated and analysed the expert survey; T.D.B., A.P.B. and K.G.B. conducted the Economic analyses. All authors contributed to the manuscript and its annexes and approved the publication of the manuscript in this form. T.B. copy edited the paper.

DATA AVAILABILITY STATEMENT

All original data used in this study are available in the Supporting Information Annexes 1, 3, 6 and 8, copies of which are available via the Dryad Digital Repository https://doi.org/10.5061/dryad.2547d7wnx (Breeze et al., 2020). Other economic data are publicly available where indicated (DEFRA, 2019a, 2019b, 2019c). Primary cost data on staff wages is confidential and cannot be shared because of commercial confidentiality; however, averages are presented in Supporting Information Annex 3. Primary expert survey responses cannot be shared due to confidentiality agreements at the time of dissemination.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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