METHOD

Rapid assessment of insect pollination services to inform decision-making

Fabrizia Ratto¹,² | Tom D. Breeze³ | Lorna J. Cole⁴ | Michael P. D. Garratt³ | David Kleijn⁵ | Bill Kunin² | Denis Michez⁶ | Rory O’Connor³ | Jeff Ollerton⁷ | Robert J. Paxton⁸,⁹ | Guy M. Poppy¹ | Simon G. Potts³ | Deepa Senapathi⁵ | Rosalind Shaw¹⁰ | Lynn V. Dicks¹¹,¹² | Kelvin S.-H. Peh¹¹,¹¹

¹School of Biological Sciences, University of Southampton, Southampton, UK
²School of Biology, Faculty of Biological Sciences, University of Leeds, Leeds, UK
³Centre for Agri-Environmental Research, School of Agriculture, Policy and Development, University of Reading, Reading, UK
⁴Integrated Land Management, Environment & Society, SRUC, Ayr, UK
⁵Resource Ecology Group, Wageningen University and Research, Wageningen, The Netherlands
⁶Laboratoire de Zoologie, Université de Mons, Mons, Belgium
⁷Faculty of Arts, Science and Technology, University of Northampton, Northampton, UK
⁸General Zoology, Martin Luther University Halle-Wittenberg, Halle, Germany
⁹German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany
¹⁰Environment and Sustainability Institute, University of Exeter, Penryn, UK
¹¹Conservation Science Group, Department of Zoology, University of Cambridge, Cambridge, UK
¹²School of Biological Sciences, University of East Anglia, Norwich, UK

Correspondence
Fabrizia Ratto, School of Biology, Faculty of Biological Sciences, University of Leeds, Mall Building, Leeds LS2 9JT, UK.
Email: fabrizia.ratto@gmail.com

Abstract
Pollinator declines have prompted efforts to assess how land-use change affects insect pollinators and pollination services in agricultural landscapes. Yet many tools to measure insect pollination services require substantial landscape-scale data and technical expertise. In expert workshops, 3 straightforward methods (desk-based method, field survey, and empirical manipulation with exclusion experiments) for rapid insect pollination assessment at site scale were developed to provide an adaptable framework that is accessible to non-specialist with limited resources. These methods were designed for TESSA (Toolkit for Ecosystem Service Site-Based Assessment) and allow comparative assessment of pollination services at a site of conservation interest and in its most plausible alternative state (e.g., converted to agricultural land). We applied the methods at a nature reserve in the United Kingdom to estimate the value of insect pollination services provided by the reserve. The economic value of pollination services provided by the reserve ranged from US$6163 to US$11,546/year. The conversion of the reserve to arable land would provide no insect pollination services and a net annual benefit from insect-pollinated crop production of approximately $1542/year (US$24⋅ha⁻¹⋅year⁻¹). The methods had wide applicability and were readily adapted to different insect-pollinated crops: rape (Brassica napus) and beans (Vicia faba) crops. All methods were rapidly employed under a low budget. The relatively less robust methods that required fewer resources yielded higher estimates of annual insect pollination benefit.

KEYWORDS
dependency ratio, ecosystem services, exclusion experiment, field beans, insect pollinators, oilseed rape, TESSA, visitation frequency

Diversidad y Conservación de Gasterópodos Subterráneos de Agua Dulce en los Estados Unidos y en México

Resumen: Las declinaciones de los polinizadores han impulsado los esfuerzos por evaluar cómo el cambio del uso de suelo afecta a los insectos polinizadores y los servicios de polinización en los paisajes agrícolas. Aun así, muchas de las herramientas para medir los servicios de los insectos polinizadores requieren datos sustanciales a escala de paisaje y el conocimiento de expertos. Desarrollamos tres métodos sencillos (método de gabinete, censo de campo y manipulación empírica con experimentos de exclusión) durante algunos talleres de expertos para la evaluación rápida de la polinización por insectos a escala de sitio con el objetivo de proporcionar un marco de trabajo adaptable y accesible para quienes no son especialistas y cuentan con recursos limitados. Estos métodos
fueron diseñados para TESSA (Toolkit for Ecosystem Service Site-Based Assessment, en inglés) y permiten la evaluación comparativa de los servicios de polinización en los sitios de interés para la conservación y su estado alternativo más plausible (p. ej: convertido a suelo agrícola). Aplicamos los métodos en una reserva natural del Reino Unido para estimar el valor de los servicios de polinización por insectos que proporcione la reserva. El valor económico de los servicios de polinización que proporciona la reserva varió desde US$6,163 a US$11,546 al año \(^{1}\). La conversión de la reserva a suelo arable no proporcionaría servicios de polinización por insectos, pero sí un beneficio anual neto a partir de la producción de cultivos polinizados por insectos de aproximadamente $1,542 al año \(^{1}\) (US$24 ha\(^{-1}\) año \(^{-1}\)). Los métodos tuvieron una aplicabilidad generalizada y estaban ya adaptados a los diferentes cultivos polinizados por insectos: cultivos de colza (Brassica napus) y habas (Vicia faba). Todos los métodos pudieron usarse con bajo presupuesto. Los métodos relativamente menos robustos que requirieron menos recursos produjeron estimados más elevados del beneficio anual de la polinización por insectos.

**INTRODUCTION**

The information resulting from ecosystem service assessments is useful to a wide range of stakeholders, decision makers, and nongovernmental organizations to highlight the importance of ecosystem services for humans and biodiversity (Neugarten et al., 2018). Biotic pollination plays a key role in enhancing yield and quality in three-quarters of major food crops globally (Klein et al., 2007) and contributes an annual market value of US$235–577 billion worldwide (Potts et al., 2016). Pollination by at least 350,000 species of animals is responsible for maintaining reproduction in over 300,000 flowering plants (Ollerton, 2017).

The majority of pollinators are insects that require foraging and nesting resources in natural, seminatural, and managed areas across agricultural landscapes (Kennedy et al., 2015). Insect pollinator richness and visitation to crop flowers declines as isolation from natural areas increases (Garibaldi et al., 2011). Some management decisions, such as conversion of natural areas to agricultural uses, result in reduced pollination services in agricultural fields (e.g., Ricketts & Lonsdorf, 2013), adversely affecting crop production (Dainese et al., 2019).

Assessing ecosystem services can support advocacy for site conservation or restoration. Guidance on how to incorporate pollination services assessment in ecosystem services tools, such as ARIES and InVEST, often requires detailed land-cover information and substantial technical expertise (Neugarten et al., 2018). For example, ARIES models use a collaborative software in which artificial intelligence pairs spatial data with ecosystem services models (Neugarten et al., 2018). Simple methods that quantify pollination services and their economic value at a local scale would elucidate the consequences of land-use changes to pollination service provision based on locally relevant data.
(Peh et al., 2013). This would enable conservation practitioners to assess a wide set of counterfactuals and provide simple instructions to staff and volunteers on how to collect or collate data needed to measure services at individual sites. Low-budget methods can provide service estimates that are robust enough for effective advocacy, without expending considerable resources or technical knowledge. To ensure accessibility to practitioners in low-income countries, such methods should be freely available and adaptable to a range of financial and technical resources.

**METHODS**

We developed practical methods for assessing insect pollination services for the Toolkit for Ecosystem Service Site-Based Assessment version 2.0 (TESSA; Peh et al., 2017) (background on TESSA project in Appendix S1). These methods were designed to include key TESSA features (Peh et al., 2013). Hence, they had to be straightforward and low cost; usable by nonexperts lacking technical knowledge; enable cost–benefit analyses between the focal site and a counterfactual (i.e., the most plausible alternative state); and generate data to inform local decisions on land use.

We examined 3 different methods for the assessment of insect pollination services: use of existing data sets (desk-based approach) and 2 methods that also include local field data. Including locally relevant field data, if resources permit, is important because it allows for consideration of local insect pollinators with different levels of sensitivity to land-use change at a site and accounts for their foraging range. To our knowledge, these methods have not been used in rapid ecosystem service assessments. We applied the 3 methods, separately, to value pollination services provided by a nature reserve. We examined their usability at the reserve and compared estimates among methods.

**Expert workshop**

An expert elicitation process (2-day workshop) was used to develop practical methods of valuing insect pollination services provided by natural or seminatural areas (e.g., a nature reserve) for TESSA (Peh et al., 2013). Twelve insect pollination scientists based in the United Kingdom or continental Europe participated (Appendix S2).

**TESSA methods for insect pollination service assessment**

Following the TESSA framework (Appendix S1) (Peh et al., 2013), the experts proposed 3 site-based protocols—suitable for nonspecialists with varying degrees of financial and time constraints—to estimate the economic value of insect pollination services contributed by a seminatural site of conservation interest: desk-based methods for users with low budget (method a1, a2, a3); field surveys for users with medium budget (method b1, b2, b3); and empirical manipulation with exclusion experiments for users with high budget (method c1, c2, c3) (Figure 1).

These methods allow users to determine the economic effects of losing insect pollination services due to a change in land use (with varying degrees of accuracy and reliability depending on the resource availability) on economically important crops and harvested wild goods (e.g., food, energy). Economic values can be calculated for pollinator-dependent crops or harvested wild goods at a site under current conditions and within 1 km of the site for up to 5 crops. The methods also allow a comparative assessment between a site in its current state and the same area an alternative state (e.g., converted to agricultural land). Guidance on how to determine the alternative state of a site is in Appendix S1.

An insect pollination service assessment, regardless of the method used, broadly follows the same steps (Figure 1). The flow diagram in Figure 1 is a guide for choosing the appropriate method based on availability of resources (budget, workforce, and time). Costs and time requirements are in Table 1. Details for each method are in Appendix S3 and guidance on identification and field observation of insect pollinators and common dependency-ratio estimates is in Appendix S4.

**Low-budget desk-based method**

The low-budget method is the simplest. Time-consuming and resource-intensive field work is not needed (Figure 1 & Table 1). This desk-based approach uses dependency ratios (proportion of yield due to animal pollination [Klein et al., 2007]) from databases and the estimated decay rate of pollinator visitation from peer-reviewed scientific studies. It is therefore rapid and inexpensive. When there are no pollinator-dependent crops growing within 1 km of the site, the value of pollination for the site itself is calculated using Equation (1) (Table 2) (method a1).

The rate many pollinators visit crop flowers decays with distance from seminatural habitat, giving rise to an estimated decay curve (Ricketts et al., 2008). To assess the value of pollination services to crops within 1 km of the site (buffer zone), one must establish what crops are growing in this area and the distance of the crops from the site. The buffer is therefore divided into 3 distinct concentric zones, each approximately 300 m wide. The innermost zone is adjacent to the focal site and the outermost zone ≤1 km from the perimeter of the site. Visitation frequencies in each zone are calculated at the distance at which the crop occurs with Equation (2) (Table 2), which incorporates decay rate in pollinator visitation to crop flowers from Ricketts et al. (2008).

Visitation frequencies obtained from Equation (2) for each buffer zone are converted to a monetary value (U.S. dollars) with Equation (3) (Table 2). This includes the deduction of the estimated pollination value at 3 km, which is done to exclude the baseline pollination services provided by those pollinators that persist in the agricultural matrix independent of the pollination services provided by a natural or seminatural area (e.g., nature reserves) (method a2).
1. Obtain information from stakeholders (e.g., farmers) on:
- Insect-pollinated crops or wild goods cultivated or harvested at and around the focal site
- Crops grown inside and around focal site
- Cultivated area, maximum yield achievable, farmgate price, production costs
2. Perform protocol for the focal site and 1 km buffer zone under current state
   See below to choose the most suitable methods (a1, b1, c1, d1)
3. Repeat the protocol at the completion site as a surrogate for the alternative state of the focal site
   Methods a3, b3, c3.
4. Summarize the results on a single table or graph

FIGURE 1 Flowchart detailing the steps to follow to perform the insect pollination service protocol and guiding the selection of the most appropriate method. Dependency ratio is defined as the proportional increase in yield directly attributable to pollinators. The buffer is the area within 1-km radius from the focal site.

Medium-budget field-observation survey

The medium-budget method is based on the existing data used in the desk-based approach, but considers data obtained in field surveys. Such locally relevant and real-time data on insect-pollinator visitation frequency to crop and wild-goods flowers are used as a proxy for insect pollination services provided by the focal site.

When calculating the pollination services of crops growing inside the focal site, it is assumed pollination services are optimized and crops reach their highest yield. Thus, it is not necessary to collect visitation frequency data in the focal site. The value of pollination is calculated with Equation (5) (Table 2) (method b1).

When pollinator-dependent crops are grown in the buffer zone, pollinator surveys should be carried out in the focal site (to establish a baseline visitation rate for optimal pollination services) and buffer zones to enable estimation of service decay (method b2).

In the focal site, for each important pollinator-dependent crop or harvested wild goods, 9 (where possible) evenly distributed sampling locations are identified in the site, preferably at least 500 m apart, to increase the chances of independence of sampled flower visitors. At each sampling location, three 1 m plots are established (9 sampling locations and 27 plots for each crop type). The plot size is adapted to the target crop. All insects visiting crop flowers inside each plot are recorded for 15 min. Guidance on carrying out surveys, flower morphology, pollinators, and flower visitors is in the toolkit (Appendix S4). The number of open crop flowers in each plot is counted to determine visitation frequencies (number of visits per flower per minute). For each crop, average pollinator visitation frequency is calculated across the 9 plots in each buffer zone.

In the buffer, to determine the actual decay rate from the focal site, the area around that site is divided into 3 distinct

If the alternative state is agriculture that involves pollinator-dependent crops, the pollination value for the focal site under the alternative state is calculated with Equation (4) (Table 2). Visitation frequency of insect pollinators for each important pollinator-dependent crops or wild good is calculated at >1 km from the site as a measure of background pollination services attributed to the agricultural matrix (i.e., the alternative state). At this distance, one assumes that the site does not provide significant additional pollination services beyond those delivered by the agricultural landscape. If the focal site is degraded under the alternative state but retains its basic structure (e.g., logged forest), its total pollination value is the same as that of its current state (method a3).
TABLE 1 Comparison of estimated time and costs among 3 practical methods for assessing insect pollination services

| Method                                      | Desk-based (low budget) | Field-observation surveys (medium budget) | Empirical manipulations (high budget) |
|---------------------------------------------|-------------------------|------------------------------------------|---------------------------------------|
| Estimated time required                     | In the site and in the buffer<sup>a</sup>; Gather the data: 1 person-day. Carry out the desk-based analysis: 1 person-day. Total (per crop): 2 person-days. Maximum time (assuming 5 crops): 10 person-days. | In the site: Visitation frequency per crop: 2–3 person-days. In the buffer: Visitation frequency per crop: 6 person-days (2 days at each distance). Total (per crop): 8–9 person-days. Maximum time (assuming 5 crops): 45 person-days. | In the site: Make exclusion bags: 2 person-days. Bagging plants per crop: 1 person-day. Unbag and collect yield data: 2 person-days. In the buffer: Bagging plants per crop: 3 person-days. Remove bags: 1 person-day. Checking and adjusting bags in site and buffer: 2–3 person-days. Collect yield data: 2 person-days. Total (per crop): 13–20 person-days. Maximum time (assuming 5 crops): 60 person-days. |
| Estimated costs (per crop)                  | Materials: £0. Total estimate: £0. | Materials: Pen, Paper: <£10. Total estimate: <£10. | Materials: Mosquito net/gauze: up to £25–50. Plant labels and thread: £5. Sewing material: £10. Freezer bags: £10–20 (to store seeds/pods). Total estimate: ca £150. |
| Notes                                       | Although this is a desk-based method, you may want to allow a day for a "ground truth" site visit. | Knowledge of crops and flowering time. | - Costs will vary depending on the size of the plants and if you are bagging the whole plant or only 1 stem/branch. - Some crop types (e.g., perennial plants with branches) will require a more durable material (e.g., netting material that needs sealing), which will increase costs. - Prices will also vary across countries. The time required for the experiment varies considerably depending on the crop type, flowering system, and habitat. We strongly recommend that you assess the specific logistical requirements of your crop before choosing this method, for example, working with tall trees might require help of professional tree climbers, and/or require more time between bagging and yield assessment. |

<sup>a</sup>Estimated time required for a task is based on the number of days 1 person needs to work on 1 type of crop (person-day).

<sup>b</sup>Area within 1-km radius of the focal site.

zones as described in the desk-based method. For each important pollinator-dependent crop or wild good, 3 sampling locations within each buffer zone are randomly chosen. Where possible, these sampling locations avoid proximity to other natural or seminatural areas to minimize their influence. At each sampling location, three 1 × 1 m random plots are established (9 sampling locations and 27 plots across the distance gradient for each crop). The mean observed visitation frequency, \(vf(d)\), for each zone is obtained and converted to a monetary value with Equation (6) (Table 2, method b2).

To estimate the value of insect pollination services provided by the focal site under the alternative state, visitation frequency of insect pollinators for each pollinator-dependent crop or wild good is collected >1 km from the site. If possible, data are collected 3 km from the focal site, which exceeds the average foraging range for the majority of bee species (Greenleaf et al., 2007). The pollination value for the site under the alternative state is calculated with Equation (7) (method b3).

**High-budget empirical manipulation with exclusion experiments**

We consider pollinator exclusion techniques the most robust means of estimating pollination services. Using this method, nonspecialists can directly derive the actual dependency ratios of the crops and wild goods at a site in its current and alternative states and those in the buffer.

For each pollinator-dependent crop and wild good at the site, 15 pairs of plants at similar preflowering stage are randomly selected at the site for the exclusion experiment to estimate yield and pollination dependency ratio. Each pair is randomly assigned to floral units manipulated by being enclosed in mesh bags to prevent access by insect pollinators or unmanipulated floral units where flowers are accessible to wind and insect pollination (control). If resources do not permit use of whole plants, on each of 15 plants, 2 floral units (flower or inflorescence) at similar preflowering stage are selected and assigned to either bagged or control treatments.
## TABLE 2  Equations used to carry out practical methods for assessing insect pollination services provided by a site of conservation interest

| Method | Equations | Worked example for oilseed rape at Noar Hill |
|--------|-----------|---------------------------------------------|
| **Desk-based methods** | | |
| Method a1  
Value of pollination services at the focal site | **Equation (1)**  \[ V_{\text{site}} = \sum_{i} \left( Y_{\text{max}} \times DR_{i} \times P_{i} \times A_{i} \right) \]  
Ymax = maximum yield (ha\(^{-1}\)\(\times\)year\(^{-1}\)) for crop or wild good \(i\)  
DR = dependency ratio of crop or wild good \(i\)  
P = farmgate price of crop or wild good \(i\) (US\$\(^{-1}\))  
A = total area (ha) of crop or wild good \(i\) harvested at the site  
\[
\begin{align*}
V_{\text{alternative}} &= \sum_{i} \left( Y_{\text{max}} \times DR_{i} \times P_{i} \times A_{i} \right) \times e^{3000a} \\
Y_{\text{max}} &= \text{maximum yield (ha}^{-1}\times\text{year}^{-1}) \text{ for crop } i \\
DR &= \text{dependency ratio obtained from existing database for crop } i \\
P &= \text{farmgate price of crop } i \text{ (US$}^{-1}) \\
A &= \text{total area (ha) of crop } i \text{ harvested at the site under the alternative state} \\
e &= \text{overall decay rate for pollinator visitation (}=-0.00104; \text{see Appendix S3, but use value for tropics or temperate climate domain if appropriate)}
\end{align*}
\]  
No crops cultivated or wild goods harvested at reserve  
| a = 1  
d = 59 m (innermost)  
d = 439 m (medium)  
d = 1000 m (outermost)  
e\(_{0} = 0.00104 \times 59 = 0.94 \text{ (innermost)}\)  
e\(_{0} = 0.00104 \times 439 = 0.63 \text{ (medium)}\)  
e\(_{0} = 0.00104 \times 1000 = 0.35 \text{ (outermost)}\)  
\[
\begin{align*}
Y_{\text{max}} &= 3.75 \\
DR &= 0.25 \\
P &= $423 \\
A &= 43.1 \\
\end{align*}
\]  
\[
\begin{align*}
V_{\text{buffer}} \text{ (inner)} &= (3.75 \times 423 \times 0.25 \times 0.94) \times 83 = $289\text{ha}^{-1}\text{year}^{-1} \\
V_{\text{buffer}} \text{ (medium)} &= (3.75 \times 423 \times 0.25 \times 0.63) \times 83 = $166\text{ha}^{-1}\text{year}^{-1} \\
V_{\text{buffer}} \text{ (outer)} &= (3.75 \times 423 \times 0.25 \times 0.35) \times 83 = $55\text{ha}^{-1}\text{year}^{-1} \\
V_{\text{buffer}} \text{ (average)} &= (289 + 166 + 55)/3 = $170\text{ha}^{-1}\text{year}^{-1} \\
V_{\text{buffer}} \text{ (total)} &= (170 \times 43.1) = $7327/\text{year}
\end{align*}
\]  
(Continues)
### Table 2 (Continued)

| Method | Equations | Worked example for oilseed rape at Noar Hill |
|--------|-----------|--------------------------------------------|
| **Field observation** | | |
| **Method b1** | Value of pollination services at the focal site | |
| **Equation (5)** | $V_{site} = \sum_{i} (Y_{max} \times DR_{i} \times P_{i} \times A_{i}) \times v_f(d = 0)$ | No crops cultivated or wild goods harvested at reserve |
| | $v_f(d = 0)$ = visitation frequency parameter at the focal site where $d$ is the distance from the focal site $= 0$ (set at the default maximum value = 1) | Maximum visitation set at same visitation frequency as innermost, which was recorder at boundaries of the site $v_f(d = 0) = 0.0058$ |
| | The rest of the parameters are the same as those in Equation (1). | |
| | Functionally, Equation (5) provides the same estimate as Equation (1) from the desk-based method. | |
| **Method b2** | Value of pollination services in a 1-km buffer zone | |
| **Equation (6)** | $V_{buffer} = \sum_{i} \left( \frac{(Y_{max} \times P \times DR_{i}) \times v_f(d)}{v_f(d > 1000)} \right) \times A_{i}$ | $v_f(d = 0)$ = 0.0058 (innermost) |
| | $Y_{max} =$ maximum yield ($\text{t} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$) for crop $i$ in buffer zone $n$ | $v_f(d = 0)$ = $0.0017$ (medium) |
| | $v_f(d)$ = observed visitation frequency at distance, $d$, from the focal site | $v_f(d = 0)$ = $0.0016$ (outermost) |
| | $P =$ farmgate price of crop $i$ ($\text{tf} \cdot \text{ha}^{-1}$) | $v_f(d = 0)$ = from the focal site | |
| | $A_{i} =$ total area (ha) of crop $i$ in buffer zone $n$ | This equation—similar to Equation (3)—excludes baseline pollination services provided by those pollinators that persist in the agricultural matrix. This baseline pollination is estimated by using observed visitation frequency, $v_f(d > 1000)$, at a distance over 1000 m from the focal site. | |
| | This equation—similar to Equation (3)—excludes baseline pollination services provided by those pollinators that persist in the agricultural matrix. This baseline pollination is estimated by using observed visitation frequency, $v_f(d > 1000)$, at a distance over 1000 m from the focal site. | |
| **Method b3** | Value of pollination services in the alternative state | |
| **Equation (7)** | $V_{alternative} = \sum_{i} \left( \frac{(Y_{max} \times P \times DR_{i}) \times v_f(d > 1000)}{v_f(d > 1000)} \right)$ | $Y_{max} = 3.75$ |
| | $Y_{max} =$ maximum yield ($\text{t} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$) for crop $i$ | $DR_{i} = 3.75$ |
| | $v_f(d)$ = observed visitation frequency at distance, $d$, from the focal site | $P = 0.25$ |
| | $P =$ farmgate price of crop $i$ ($\text{tf} \cdot \text{ha}^{-1}$) | $A_{i} = 9.5$ |
| | $A_{i} =$ total area (ha) of crop $i$ in buffer zone $n$ | $v_f(d > 1000) = 0.0012$ (2000 m) |
| **Empirical manipulation** | | |
| **Method c1** | Value of pollination services at the focal site | No crops cultivated or wild goods harvested at reserve |
| **Equation (8)** | $V_{site} = \sum_{i} (Y_{max} \times DR_{EE,i} \times P_{i} \times A_{i})$ | |
At harvest, the yield of seeds or fruit is quantified for both treatments. The yield of bagged flowers—the yield of unbagged flowers—the resulting ratio is the estimate of the proportion of yield due to wind and autopollination. The dependency ratio (DR), 1 − proportion of yield due to wind and autopollination, is calculated for each plant. These values are averaged to obtain a pollination contribution value for each crop in the site.

When there are no pollinator-dependent crops growing in the buffer, the average dependency ratio (obtained from the 15 pairs of plants) is used to estimate the value of pollination services provided by the site with Equation (8) (method c1, Table 2).

When there are pollinator-dependent crops growing in the buffer, exclusion experiments are repeated in each zone with 5 pairs of randomly chosen preflowering plants of each pollinator-dependent crop or wild good. The average DR from all plants across the buffer is used to estimate the value of pollination services to crops and wild goods in the buffer with Equation (9) (Table 2, method c2).

For the alternative state, exclusion experiments are conducted outside the buffer (methods a3, b3) to determine the DR of each crop and wild good. The DR is used to estimate the pollination value of the site under the alternative state with Equation (10) (Table 2, method c3).

Application

We applied the 3 methods to a 63-ha nature reserve in the United Kingdom, Noar Hill. We used the methods to quantify the economic value of insect pollination services the reserve provides to the adjacent agricultural crops. Noar Hill (hereafter reserve) (Appendix S5) is primarily calcareous grassland (19.5 ha) and broadleaf woodland (43.5 ha). It is a site of special scientific interest. There are no crops cultivated or wild goods harvested at the reserve.

The hypothetical alternative state of the reserve is agricultural land. This alternative state reflects the same proportion of crop types occurring in the wider landscape, which in the focal site results in 18.9 ha of cereal (30%), 9.5 ha oilseed rape (15%), 9.5 ha field beans (15%), and 6.3 ha uncultivated land (10%).

In the agricultural land adjacent to the reserve, there were 2 insect-pollinated crops: oilseed rape (Brassica napus) and field beans (Vicia faba). Both are grown widely as part of arable rotations in the region (Garratt, Breeze, et al., 2014). We interviewed (Appendix S6) with the local farmers to obtain information on the highest locally achievable yield in the area and cultivation locations. We used these data to estimate total area of each crop in the buffer; farmgate prices (market value minus selling costs); and annual production costs (costs attributable to crop production). Annual management costs for the reserve were obtained from the reserve manager at Hampshire and Isle of White Wildlife Trust.

For the desk-based method, we derived the DR of each crop from the literature (Appendix S4) and estimated the pollinator visitation frequency parameter (Equation 2) along a distance gradient where both crops were cultivated (oilseed rape: 60,
RESULTS

The total area of oilseed rape and field beans growing in the 1-km buffer around the reserve was 43.1 and 48.5 ha, respectively. Maximum locally achievable yields at the study site were 3.75 t ha⁻¹ year⁻¹ for oilseed rape and 3.88 t ha⁻¹ year⁻¹ for field beans. Farmgate prices for oilseed rape and field beans were $423 and $199/t, respectively. Farming cost was estimated at 1098 ha⁻¹ year⁻¹ for both crops and the management cost of the reserve was estimated at $6566/year.

Desk-based method

The exponential decay curve, based on the desk-based assessment, showed a decrease in the value of insect pollination services to oilseed rape from the innermost buffer (nearest to the reserve) to the outermost buffer (Figure 2a). The value of baseline insect pollination for oilseed rape (derived at 1.5 km from the reserve for consistency with the other methods)—which equates to the value of insect pollination services to this crop provided by the reserve under its alternative state—was estimated at $83 ha⁻¹ year⁻¹ ($788/year) (Figure 2a & Table 2). After deducting this baseline value, the additional value of insect pollination services attributed to the reserve ranged from $289 ha⁻¹ year⁻¹ in the innermost buffer to $35 ha⁻¹ year⁻¹ in the outermost buffer, with an estimated average value of $170 ha⁻¹ year⁻¹.

Similarly, insect pollination services for field beans declined along the distance gradient from the reserve (Figure 2b). After deducting the baseline value estimated of $40 ha⁻¹ year⁻¹ ($380/year) (equal to the alternative state), the additional value of insect pollination services to field beans provided by the reserve ranged from $139 ha⁻¹ year⁻¹ in the innermost buffer to $35 ha⁻¹ year⁻¹ in the outermost buffer, for an average value of $87 ha⁻¹ year⁻¹ (Figure 2b). Total value of insect pollination services to both crops provided by the reserve under the current and alternative state was estimated at $257 and $123 ha⁻¹ year⁻¹, respectively (Table 3).

Field survey

The observed visitation frequency of insect pollinators to flowers of oilseed rape declined sharply along the buffer (nearest to the reserve 0.0058 visits flower⁻¹ min⁻¹; outermost buffer 0.0016 visits flower⁻¹ min⁻¹). Based on the observed visitation frequency and dependency ratio of oilseed rape (0.25; Klein et al., 2007), and after deducting the baseline value of insect pollination (estimated at $82 ha⁻¹ year⁻¹, $779/year also equal to value of the alternative state of the reserve), the additional insect pollination value provided by the reserve ranged from $314 ha⁻¹ year⁻¹ in the buffer nearest to the reserve to $27 ha⁻¹ year⁻¹ in the outermost buffer (Figure 2c). The average estimated value estimated was $125 ha⁻¹ year⁻¹.
The observed visitation frequency of insect pollinator to field bean flowers declined from 0.0028 visits\(\text{flower}^{-1}\text{min}^{-1}\) in the buffer nearest to the reserve to 0.0009 visits\(\text{flower}^{-1}\text{min}^{-1}\) in the outermost buffer, dropping by half at approximately 500 m from the reserve (Figure 2d). After deducting the baseline value (estimated at $55\text{ha}^{-1}\text{year}^{-1}$, $525$/year, which also equated to the value of insect pollination services provided by the alternative state), the value of additional pollination services provided by the reserve ranged from $138\text{ha}^{-1}\text{year}^{-1}$ in the innermost buffer to $7\text{ha}^{-1}\text{year}^{-1}$ in the outermost buffer, giving an average estimate of $56\text{ha}^{-1}\text{year}^{-1}$. Total value of insect pollination services to both crops provided by the reserve under the current and alternative state was estimated at $181$ and $137\text{ha}^{-1}\text{year}^{-1}$, respectively (Table 3).

**Empirical manipulation with exclusion experiment**

The relative contribution of insects to pollination of oilseed rape (DR) decreased from 0.36 in the buffer nearest to the reserve to 0.04 in the buffer furthest from the reserve (Figure 2e). Hence, the mean DR of oilseed rape was 0.19. After deducting the baseline value, the value of additional pollination services for oilseed rape production within the 1-km buffer from the reserve was estimated at $143\text{ha}^{-1}\text{year}^{-1}$. Beyond 1 km from the reserve, the mean DR of oilseed rape was 0.10. The value of pollination services under the alternative state is the baseline value of $158\text{ha}^{-1}\text{year}^{-1}$. 

---

**FIGURE 2**  Economic values of pollination services (means SE) to (a, c, e) oilseed rape and (b, d, f) field beans at increasing distance from the reserve under the current state estimated with desk-based method, field survey method, and exclusion experiments method (points, economic value of pollination services in the 3 areas described in Appendix S6 prior to deducting the baseline value [≥ 1 km]; horizontal lines, value of pollination provided by pollinators that inhabit agricultural matrix [i.e., baseline pollination]).
Alternative state

The insect pollination service values and management costs from the reserve (63 ha) and of the same land if the reserve were converted into arable land (63 ha)

| Nature reserve (63 ha) | Arable land (63 ha) |
|------------------------|---------------------|
| **Service (flow)** ($/year) | **Management cost ($/year)** |
| Insect-pollinated crop production | 0 | 22,404 |
| Insect pollination | 6120 | 3040 |
| **Net annual benefit ($/year)** | **Net annual benefit ($/ha$–1$\cdot$year$^{-1}$)** |
| –446 | –7 |
| 1542 | 24 |

Note: Values in bold indicate that the values were obtained by multiplying the value of pollination services provided by the reserve to each insect-dependent crop by the mean DR of each crop within the 1-km buffer from the reserve. The value of pollination services was then estimated by dividing the product of the DR and the service value by the area of the reserve.

The mean DR of field beans ranged between 0.12 and 0.18 within the 1-km buffer from the reserve without clear decay curve with distance from the site (Figure 21). Beyond 1 km from the reserve, the mean DR for field beans was 0.21, with an estimated pollination value of $162/ha$–1$\cdot$year$^{-1}$. This indicated that there was no pollination service for field beans provided by the reserve (Table 3). Total value of insect pollination services to both crops provided by the reserve under the current and alternative state was estimated at $143 and $320/ha$–1$\cdot$year$^{-1}$, respectively (Table 3).

Overall, we estimated that the economic value of pollination services provided by the reserve (to the crops outside the reserve) ranged from $6163 to $11,546/year, depending on the method adopted (Table 3). Our results showed that the conversion of the reserve to arable land would provide no insect pollination services to the adjacent cropland. However, this alternative state of the reserve would have a net annual benefit from insect-pollinated crop production estimated at $1542/year ($24/ha$–1$\cdot$year$^{-1}$) (Table 4).

**DISCUSSION**

The methods we tested aim to enable nonspecialists with limited expertise and resources to estimate the value of insect pollination services provided by a site. The 3 methods were practical and effective and provided a comparison between the estimate of the insect pollination services provided by a site of conservation interest and that provided by the same area under an alternative state. For oilseed rape, the estimates of the insect pollination value to the crops outside the reserve based on the most robust exclusion experiment method were lower than the estimate obtained from the desk-based method by 16% and greater than the estimate obtained from field survey methods by 12%. The estimate of the insect pollination service value provided by the agricultural matrix in the exclusion experiment method was almost double that of the other 2 methods. For field beans, the exclusion experiments showed that the reserve...
did not provide any insect pollination services. Hence, the
desk-based and field survey methods overestimated the insect
pollination services to the crop outside the reserve by 87% and
56%, respectively. The value of insect pollination provided by
the agricultural matrix was again underestimated by the desk-
and field survey methods by 75% and 66%, respectively.
The 3 methods varied in degree of accuracy (Table 2), showing
that there is a trade-off between simplicity (associated with
speed and low cost) and accuracy.

A number of assumptions underpinning each method
present limitations. The simpler methods had more associated
assumptions, which may present limitations. The desk-based
method, which uses the best available published estimate of dis-
tance decay rate (Ricketts et al., 2008), inevitably generalized
the relationship between pollinator visitation frequency and dis-
tance from natural habitat, providing a less accurate estimate of
the value of pollination to yield of a focal crop. In fact, the field
survey methods in our application detected a steeper distance
decay rate for both crops than that found in Ricketts (2008). The
effect of distance on crop flower visitation frequency depends
on the crop’s key pollinators and their foraging ranges, which
vary among taxonomic groups and body sizes (Greenleaf et al.,
2007). The estimate would have a higher level of confidence if
dependency ratios (from existing databases) were derived from
similar habitat near the focal site. The dependency ratios we
used could be derived from areas that do not provide a good sur-
rogate of the Noar Hill site or from moderately different crops
and wild goods (i.e., different varieties). Users could increase
accuracy by using local pollinator visitation data where available
and adjusting the buffer radius based on information on the
mobility of known crop visitors. Furthermore, variety-specific
values of DR should be used if available to reduce the varietal
differences observed for some crops (Bishop et al., 2020; Stan-
ley et al., 2013). If the varieties planted in the area vary between
years, it may still be appropriate to use an average for that par-
ticular crop species.

The field survey method in field beans produced an over-
estimation of the pollination service value compared with the
exclusion experiment method. The effectiveness of visitation
rate as a proxy for pollination services is dependent on the crop,
taxa of visiting insects (Andrikopoulos & Cane, 2018) and their
behavior (Monzón et al., 2004), and the frequency of visits with,
in some circumstances, very high visitation rates even leading
to a reduction in crop yield (Sáez et al., 2014). The overesti-
mation by this method might be due to robbing bumblebee
species, which are the predominant flower visitors of field beans
(Garratt, Coston, et al., 2014), being counted as legitimate vis-
itors. Also, there could be considerable variation in pollinator
visitation rate between days, seasons, and years, which could
potentially affect the results of field surveys with 1-day observa-
tions (Fijen & Kleijn, 2017). To improve accuracy, the sampling
effort could be increased (e.g., repeating observation across 3 or
more days), visitation time could be reduced, or sampling points
increased to account for variation in visitation within the crop to
provide a more robust estimate of visitation rate. Furthermore,
using visitation rate as a proxy assumes equal effectiveness of
all pollinators; thus, users may consider using only the visitation
rate of the most effective pollinators for a given crop, if this information is known.

The exclusion experiment method provides the most accu-
rate measure of the contribution of insects to crop pollina-
tion. Nonscientists can be trained to use this method (Garratt
et al., 2019). However, the time required to carry out exclusion
experiments varies considerably among crop types. A skilled
researcher in this study who implemented this method used 20
and 13 person-days for oilseed rape and field beans, respectively.
This resource requirement may challenge the rapid assessment
framework, especially when there are several insect-pollinated
crops grown at the site of interest and in its adjacent buffer. Fur-
thermore, the time delay between bagging and the actual mea-
surement of pollination service contribution may be a limiting
factor in adopting this method. Nevertheless, where resources
are limited, users could adapt this method to their circum-
stances, for example, by focusing on the few crops that are most
relevant to the local economy or crops with the highest depen-
dency on insect pollination.

The results of our field application showed that the conver-
sion to arable land would be economically more profitable than
maintaining the site in its current state due to the maintenance
costs exceeding the economic benefits of pollination services.
Indeed, an economic valuation of pollination to crop alone
does not capture the intrinsic and aesthetic values attached to
pollinators existence. Furthermore, less-dominant pollinator
species that do not contribute substantially to crop pollina-
tion provide a stabilizing effect on the services over time or
space and resilience in the face of environmental change. This
highlights the importance of applying an integrated ecosystem
service approach when assessing the value of a protected site
to provide a more holistic estimate of its value and more
robust argument for site conservation. Furthermore, the ben-
et and cost calculated are not equally distributed among
stakeholder because some may benefit from conversion to
agriculture (e.g., farmers) and others from site conservation
(e.g., recreational users). Our methods can potentially reveal the
synergies and trade-offs that may provide insight into ensuring
an equitable distribution of benefits and costs while conserving
biodiversity.

Our practical methods necessarily simplify some facets of
pollination service provision. Estimating whether the yield of a
crop or wild good is under- versus overpollination is beyond the
scope of our approach (Garibaldi et al., 2020) and, in most mod-
ified landscapes, underpollination is likely the norm (Reilly et al.,
2020). Nevertheless, our methods could be a useful addition to a
range of existing pollination service assessment and monitoring
tools. Other computer-based approaches (e.g., InVEST pollina-
tion model) can be unsuitable in many developing parts of the
world, where there is a lack of locally relevant data and techni-
cal expertise. These are also the poorer areas where there is a
heavy reliance on locally grown produce and yet insect pollina-
tors are threatened due to habitat loss or degradation (Ashworth
et al., 2009). We found that our methods can be implemented
readily by nonexperts; enable low-cost comparative assessment of
a protected area to illustrate the economic consequences of
loss of insect pollination services provided by the area; and yield
straightforward results that can be easily interpreted to inform decision-making or management.

ACKNOWLEDGMENTS

We thank the staff at the Selborne Landscape Partnership for granting access to their farms. We are grateful to E.A-T., R.M.-C., and A.P-D. for their field assistance. This study was part of F.R.'s PhD project, funded by the Institute for Life Sciences and School Biological Sciences, University of Southampton, and K.S.H.P.'s starting grant. L.C. received funding from Scottish Government Rural Affairs, the Environment Strategic Research Programme 2016-2021, and SRUC Research Excellence Grant. L.V.D. is funded by the Natural Environment Research Council (grant NE/N014472/1).

ORCID

Fabricia Ratto https://orcid.org/0000-0001-8411-4379

REFERENCES

Andrikopoulos, C., & Cane, J. (2018). Comparative pollination efficiencies of five bee species on raspberry. *Journal of Economic Entomology*, 111(6), 2513–2519.

Ashworth, L., Quesada, M., Casas, A., Aguilar, R., & Oyama, K. (2009). Pollinator-dependent food production in Mexico. *Biological Conservation*, 142, 1050–1057.

Bishop, J., Garratt, M. P. D., & Breeze, T. D. (2020). Yield benefits of additional pollination to faba bean vary with cultivar, scale, yield parameter and experimental method. *Scientific Reports*, 10, 1–11.

Dainese, M., Martin, E. A., Aizen, M. A., Albrecht, M., & Bartomeus, I. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances*, 5, eaax0211.

Fijen, T. P. M., & Kleijn, D. (2017). How to efficiently obtain accurate estimates of flower visitation rates by pollinators. *Basic and Applied Ecology*, 19, 11–18.

Garibaldi, L. A., Steffan-Dewenter, I., Kremen, C., Morales, J. M., Bommarco, R., Cunningham, S. A., Carvalheiro, L. G., Chacoff, N. P., Dudenhofer, J. H., Greenleaf, S. S., Holzschuh, A., Isaacs, R., Krewenka, K., Mandelik, Y., Mayfield, M. H., Morandin, L. A., Potts, S. G., Ricketts, T. H., Szentgyorgyi, H., … Winfree, R. (2011). Stability of pollination services decreases with isolation from natural areas despite honey bee visits. *Ecology Letters*, 14, 1062–1072.

Garibaldi, L. A., Sáez, A., Aizen, M. A., Fijen, T., & Bartomeus, I. (2020). Crop pollination management needs flower visitor monitoring and target values. *Journal of Applied Ecology*, 57, 664–670.

Garratt, M. P. D., Breeze, T. D., Jenner, N., Polce, C., Biesmeijer, J. C., & Potts, S. G. (2014). Avoiding a bad apple: Insect pollination enhances fruit quality and economic value. *Agriculture Ecosystems & Environment*, 184, 34–40.

Garratt, M. P. D., Coston, D. J., Truslove, C. L., Lappage, M. G., Polce, C., Dean, R., Biesmeijer, J. C., & Potts, S. G. (2014). The identity of crop pollinators helps target conservation for improved ecosystem services. *Biological Conservation*, 169, 128–135.

Garratt, M. P. D., Potts, S. G., Banks, G., Hawes, C., Breeze, T. D., O’Connor, R. S., & Carvell, C. (2019). Capacity and willingness of farmers and citizen scientists to monitor crop pollinators and pollination services. *Global Ecology and Conservation*, 20, e00781.

Greenleaf, S. S., Williams, N. M., Winfree, R., & Kremen, C. (2007). Bee foraging ranges and their relationship to body size. *Oecologia*, 153, 589–596.

Kennedy, C. M., Lonsdorf, E., Neel, M. C., Williams, N. M., Ricketts, T. H., Winfree, R., Bommarco, R., Brittain, C., Burley, A. L., Cariveau, D., Carvalheiro, L. G., Chacoff, N. P., Cunningham, S. A., Danforth, B. N., Dudenhofer, J. H., Eilie, E., Gaines, H. R., Garibaldi, L. A., Gratton, C., & Holzschuh, A. (2015). A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecology Letters*, 16, 584–599.

Klein, A.-M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, 274, 95–96, 191.

Monzón, V. H., Bosch, J., & Retana, J. (2004). Foraging behavior and pollinating effectiveness of *Osmia cornuta* (Hymenoptera: Megachilidae) and *Apis mellifera* (Hymenoptera: Apidae) on “Comice” pear. *Apidologie*, 35, 575–585.

Neugarten, R. A., Langhammer, P. F., Osipova, E., Bagstad, K. J., Bhagabati, N., Butchart, S. H. M., Dudley, N., Elliott, V., Gerber, L. R., Gutierrez Arrellano, C., Ivaní, K.-Z., Kettunen, M., Mandle, L., Merriman, J. C., Mulligan, M., Peh, K. S.-H., Raussepp-Hearne, C., Semmens, D. J., Stolton, S., … Groves, C. (2018). *Tools for measuring, modelling, and valuing ecosystem services provided by Key Biodiversity Areas, natural World Heritage sites, and protected areas*. IUCN.

Ollerton, J. (2017). Pollinator diversity: Distribution, ecological function, and conservation. *Annual Review of Ecology, Evolution, and Systematics*, 48, 353–376.

Peh, K. S.-H., Balmford, A., Bradbury, R. B., Brown, C., Butchart, S. H. M., Hughes, F. M. R., Stattersfield, A., Thomas, D. H. L., Walpole, M., Bayliss, J., Gowling, D., Jones, J. P. G., Lewis, S. L., Mulligan, M., Pandeya, B., Stratford, C., Thompson, J. R., Turner, K., Vira, B., … Birch, J. C. (2013). TESSA: A toolkit for rapid assessment of ecosystem services at sites of biodiversity conservation importance. *Ecosystem Services*, 3, 51–57.

Peh, K. S.-H., Balmford, A. P., Bradbury, R. B., Brown, C., Butchart, S. H. M., Hughes, F. M. R., MacDonald, A. M., Stattersfield, A. J., Thomas, D. H. L., Trevelyan, R. J., Walpole, M., & Merriman, J. C. (2017). *Toolkit for Ecosystem Service Site-based Assessment (TESSA)*. Version 2.0.

Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Aizen, M. A., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J., & Vanbergen, A. J. (2016). The assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services on pollinators, pollination and food production. *Nature*, 540, 220–229.

Reilly, J. R., Artz, D. R., Biddinger, D., Bobiwash, K., Boyle, N. K., Brittain, C., Brokaw, J., Campbell, J. W., Daniels, J., Elle, E., Ellis, J. D., Fletcher, S. J., Gibbs, J., Gillespie, R. L., Gundersen, K. B., Gut, L., Hoffman, G., Joshi, N., Lundin, O., Mason, K., & McGrady, C. M. (2020). Crop production in the USA is frequently limited by a lack of pollinators. *Proceedings of the Royal Society B: Biological Sciences*, 287, 20200922.

Ricketts, T. H., Regetz, J., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., Bogdanski, A., Gemmill-Herren, B., Greenleaf, S. S., Klein, A. M., Mayfield, M. M., Morandin, L. A., Ochieng’, A., Potts, S. G., & Viana, B. F. (2008). Landscape effects on crop pollination services: Are there general patterns? *Ecology Letters*, 11, 499–515.

Ricketts, T. H., & Lonsdorf, E. (2013). Mapping the margin: Comparing marginal values of tropical forest remnants for pollination services. *Ecological Applications*, 23, 1113–1123.

Sáez, A., Morales, C. L., Ramos, L. Y., & Aizen, M. A. (2014). Extremely frequent bee visits increase pollen deposition but reduce drupelet set in raspberry. *Journal of Applied Ecology*, 51, 1603–1612.

Stanley, D. A., Gunnung, D., & Stout, J. C. (2013). Pollinators and pollination of oilseed rape crops (*Brassica napus L.*) in Ireland: Ecological and economic incentives for pollinator conservation. *Journal of Insect Conservation*, 17, 1181–1189.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher’s website.