Widespread losses of pollinating insects in Britain

Gary D. Powney\textsuperscript{1}, Claire Carvell\textsuperscript{1}, Mike Edwards\textsuperscript{2}, Roger K. A. Morris\textsuperscript{3}, Helen E. Roy\textsuperscript{1}, Ben A. Woodcock\textsuperscript{1} & Nick J. B. Isaac\textsuperscript{1}

Pollination is a critical ecosystem service underpinning the productivity of agricultural systems across the world. Wild insect populations provide a substantial contribution to the productivity of many crops and seed set of wild flowers. However, large-scale evidence on species-specific trends among wild pollinators are lacking. Here we show substantial inter-specific variation in pollinator trends, based on occupancy models for 353 wild bee and hoverfly species in Great Britain between 1980 and 2013. Furthermore, we estimate a net loss of over 2.7 million occupied 1 km\textsuperscript{2} grid cells across all species. Declines in pollinator evenness suggest that losses were concentrated in rare species. In addition, losses linked to specific habitats were identified, with a 55\% decline among species associated with uplands. This contrasts with dominant crop pollinators, which increased by 12\%, potentially in response agri-environment measures. The general declines highlight a fundamental deterioration in both wider biodiversity and non-crop pollination services.
Insect pollinators are vital for the maintenance of ecosystem health and for global food security, with 75% of crop species, 35% of global crop production, and up to 88% of flowering plant species being dependent on insect pollinators to some extent. However, substantial concern exists over their current and future conservation status. Key threats to pollinators include agricultural intensification (particularly habitat loss and pesticide use), climate change and the spread of alien species. Despite their importance, there is a critical absence of robust large-scale, species-specific estimates of distribution change for pollinating insects, in particular bees and hoverflies, which are considered some of the most important pollinators. Published data on species-specific trends are currently only available from field-scale experiments typically spanning short time periods (<5 years) and spatially restricted to a limited number of sites. Evidence at the large-scale comes from trends in aggregate metrics such as species richness and turnover. Although useful, such metrics are insufficiently sensitive to identify pollination deficits nor are they suitable for developing International Strategic Goals. Evidence at the large-scale comes from trends in aggregate metrics such as species richness and turnover. Although useful, such metrics are insufficiently sensitive to identify pollination deficits nor are they suitable for developing International Strategic Goals.

Biological records, defined as a record of a species at a given time and place, are a valuable but under-utilized source of data for estimating species trends. The vast volume of these records, especially in western Europe and in particular Britain, allows the estimation of national-scale species-specific trend metrics spanning multiple decades. However, as biological records tend to be collected by large networks of volunteer recorders, they lack a standardized protocol and thus contain sampling bias. Considerable statistical issues need to be overcome if they are to be used for detecting genuine signals of change.

Here we take advantage of recent analytical developments to construct hierarchical Bayesian occupancy detection models for 353 hoverfly and bee species, based on 715,392 biological records collected by the UK Hoverfly Recording Scheme and the Bees, Wasps and Ants Recording Society. We use these models to estimate national-scale species-level trends for Great Britain between 1980 and 2013. Our models estimate the proportion of occupied 1 km grid squares (henceforth occupancy) each year and are designed to account for incomplete and biased sampling in the raw data.

**Results**

**Overall trends in pollinators.** We found widespread variation in the trends of wild pollinators in Britain, with individual species experiencing a range of trajectories between 1980 and 2013 (Fig. 1 and Supplementary Figure 1). Species-level trends, calculated as the annual growth rate in occupancy (percent change per year between the first and last year), reveal that a third of wild pollinator species (33%) have decreased over this period, approximately a tenth have increased, with the remaining species showing no clear trend (Supplementary Table 1 and Supplementary Figure 1). The balance of decreasing and increasing species was similar between bees and hoverflies (Supplementary Table 1). The direction and magnitude of the species-specific trend estimates, equate to a loss (net change) of 11 pollinator species (4 bees and 7 hoverflies) per 1 km grid cell between 1980 and 2013. Extrapolating these patterns to the whole of Great Britain (~240,000 1 km grid cells), our results estimate a net loss of over 2.7 million occupied 1 km grid cells for pollinator species between 1980 and 2013 (net change in the number of unique species by occupied 1 km grid cells). The magnitude of these changes highlights significant risks not just for regional pollinator communities, but also for the net provision of pollination services.

**Patterns of change among pollinator assemblages.** Contribution to pollination service is known to vary between species according to...
to their life history and ecological characteristics\textsuperscript{22,23}. We therefore assessed long-term changes in mean occupancy for various trait-based subsets of pollinating insects. We found similar overall declines for bees (25% decline; 95% credible interval (CI): 21% to 30% decline; \( n = 139 \) species) and hoverflies (24% decline; 95% CI: 20% to 28% decline; \( n = 214 \)), although there are marked differences between these two groups in the temporal pattern of declines (Fig. 2 and Supplementary Figure 2). Virtually all severe declines observed for overall bee occupancy occurred post 2007. By contrast, hoverflies declined steadily from 1987 to 2012. There are several key functional and ecological differences between bees and hoverflies, which could explain this pattern. Notably, most bees are fixed-place foragers whose early life stages are sheltered and actively provisioned by adults, whereas hoverflies move freely across landscapes and have juvenile stages filling a range of niches (e.g., aphidophagous, phytophagous, and detritivore) that are not directly cared for by adults. Understanding the contribution of these factors and their interaction with environmental change in explaining the contrasting trends of bees and hoverflies should be a priority for future research. Although most bee species declined, this was not the case for the subset of species identified as being key pollinators of a range of economically important European crops\textsuperscript{14} (Supplementary Figure 3). On average, occupancy increased for these dominant crop pollinators by 12% (95% CI: 1% to 23%) from 1980 to 2013. In addition, we found notable changes in the eusocial bee species (including the bumblebees) (Supplementary Figure 4), for whom average occupancy increased by 38% (95% CI: 20% to 58%) compared with a decline of 32% (95% CI: 27% to 36% decline) for solitary bees (bees classified as non-eusocial in Supplementary Data 1). These increasing trends may be attributed to the widespread implementation of agri-environmental schemes specifically designed to support bumblebees in arable farming systems\textsuperscript{24}. Furthermore, we found striking differences according to the species’ geographic distributions. In particular, upland species showed declines of 55% (95% CI: 47% to 62% decline), whereas the average decline among southern species was 25% (19% to 30% decline), with the majority of this change occurring since 2006 (Supplementary Figure 5). The apparent vulnerability of upland species may reflect retractions of the trailing (southern) range edges in response to climatic warming\textsuperscript{25}.

To further understand changes in pollinator assemblages, we used Simpson’s evenness metric to assess the extent to which communities become dominated by a small number of wide-spread species\textsuperscript{26}. We found little temporal variation in hoverfly evenness, but bees showed strong declines in evenness in the late 2000s (Fig. 3). The decline in bee evenness parallels the decline in mean occupancy of bees, suggesting losses in the late 2000s were concentrated among species with already small distributions. This result raises concerns around the fate of pollination services to wild flowers, given that more diverse communities are more effective in pollinating a wide range of wild flowers\textsuperscript{2}.

**Discussion**

Our findings fill an important gap in the evidence base on the status of wild pollinators. By providing species-level, national-scale estimates of change, our study found evidence of declines across a large proportion of pollinator species in Britain between 1980 and 2013. These overall declines are in addition to the losses that occurred before 1980, noted in previous studies\textsuperscript{10}, and are likely driven by a host of pressures known to act upon pollinators, including habitat loss, climate change, and pesticides\textsuperscript{2,6,7,27}. In terms of conservation, it appears that current investment in agri-environmental schemes may have been effective in promoting pollinator populations on farmland, especially among the wide-spread common species responsible for crop pollination. However, as yields of pollinator-dependent crops are related to abundance as well as diversity of pollinators\textsuperscript{28}, the lack of standardized monitoring data limits our understanding of the link between change in species occupancy, local abundance, and in turn pollination deficit\textsuperscript{28}. Although current conservation efforts...
Statistical analysis. Much of these data were collected by volunteer recorders without specific sampling design. Therefore, the data contain a variety of forms of bias that inhibit the ability to extract robust trends from them. For example, the occurrence data suffered from temporal bias, with greater numbers of records in recent years. A host of techniques have been proposed to account for such bias while estimating trends, with recent studies suggesting hierarchical occupancy, models fitted within a Bayesian framework perform particularly well[15-17]. In this study, we used a Bayesian occupancy of modelling approach based on the models of refs. 17 and 31, to estimate occupancy (the proportion of occupied 1 km grid cells) each year between 1980 and 2013 for each species. By using two hierarchically coupled sub-models (1 and 2, below), the occupancy model simultaneously estimates and accounts for variation in detectability, while estimating species presence for a given site, year combination.

\[ z_i \sim \text{Bernoulli}(\psi_i) \]
\[ logit(\psi_i) = b_i + u_i \]

where, \( z_i \) and \( \psi_i \) are the true (unknown) occupancy and probability of occupancy of site \( i \) in year \( t \), respectively. \( b_i \) and \( u_i \) are categorical fixed and random effects for year and site (1 km grid cell), respectively. \( Y_{ijt} \) represents the observed data, this is a 1 or 0 based on whether the species was detected or not at site, \( i \), in year \( t \), visit \( v \). \( p_{itv} \) is the probability of detection at site \( i \) in year \( t \) on visit \( v \) and is conditional upon \( z_{it} = 1 \). Probability of detection was modelled as a function of \( a_i \) a random year level effect (accounting for variation in detectability over time), and \( \delta_1 \) and \( \delta_2 \) the effects of list categories 2 and 3, relative to category 1. For most species, we expect detectability to be lower on shorter lists, we therefore included list category (L) as a covariate in the detection model to account for variation in detectability.

Fig. 3 Annual estimates of change in assemblage evenness (first derivative of evenness). a Bee and b hoverfly assemblages. Points represent the median estimate of the posterior, with uncertainty presented as the limits of the credible intervals (thin = 95% CI, thick = 80% CI)

Methods

Distribution data. Trends were estimated from occurrence records of hoverflies and bees extracted from the Hoverfly Recording Scheme (http://www.hoverfly.org.uk/) and the Bees, Wasps and Ants Recording Society (BWARS: http://www.bwars.org). Combined, the dataset used in this study consisted of 715,392 (Hoverfly = 417,856, Bee = 297,536) records, defined as a unique combination of 1 km grid cell, date, and species. By excluding records pre-1980 and post-2013, we focussed on a core period of recording activity for both taxonomic groups. We excluded grid cells with <2 years of data, removing the most poorly sampled regions. These observations constitute presence-only data, so we inferred non-detections from records of other species within the taxonomic group on the same grid cell and date (henceforth visit)[37,38]. The analysis was based on 12,849 and 12,076 unique 1 km grid cells for hoverflies and bees, respectively. The 1 km grid was chosen to reflect the scale at which hoverfly and bee populations use the landscape. Species with taxonomic issues during the time frame of the study and species not considered to be pollinators (following expert guidance from BWARS) were excluded from the analysis. In addition, we follow the species exclusion criteria of ref. 31, dropping species with fewer than 50 records. The final dataset was based on 139 bee and 214 hoverfly species (covering ~75% of the British bee and hoverfly fauna).
as seen in Fig. 2 and Supplementary Figures 3, 4, and 5). Occupancy estimates were logged and fed into a linear model with year and species treated as categorial explanatory variables. Sum contrasts were used to ensure the composite trend reflects the average species response. The parameter estimates for the year effects were converted back to the occupancy scale and used as our composite trend metric, effectively a geometric mean occupancy estimate each year across species.

In addition to calculating geometric mean occupancy, we examined temporal patterns in the balance between rare and common species, defined in terms of low and high occupancy, and measured using Simpson's evenness (the \( \log(D) \) formulation\(^{26} \)). Decreases in evenness are indicative of diversity loss and can be considered a signal of biotic homogenization, i.e., communities becoming dominated by a small number of widespread species. Again, using 1000 sampled values from the posterior distribution allowed full propagation of uncertainty. We extracted the first derivatives (i.e., the difference between adjacent years) of geometric mean occupancy and evenness to highlight notable years of change.

**Trait and assemblage classification.** We examined change across five grouping variables aimed at improving our insight into the key drivers of change and potential implications for pollination services. First, we divided species into their broad taxonomic group (splitting bees and hoverflies). This reflects fundamental differences in breeding ecology, with bees being potential contributors to pollination services. First, we divided species into their

**Data availability**

Data are available from the corresponding author upon request. The occupancy models in this study were run using \texttt{R2jags}\(^{27} \) via the \texttt{occDetFunc} function, which is freely available as part of the R package \texttt{Sparta}\(^{28} \).

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**References**

1. Ollerton, J., Winfree, R. & Tarrant, S. How many flowering plants are pollinated by animals? *Oikos* 120, 321–326 (2011).

2. Potts, S. G. et al. Global pollinator declines: trends, impacts and drivers. *Trends Ecol. Evol.* 25, 345–353 (2010).

3. Goulson, D., Nicholls, E., Botias, C. & Rotheray, E. L. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347, 1255957 (2015).

4. Garratt, M. P. D. et al. Pollination deficits in UK apple orchards. *J. Pollinat. Ecol.* 12, 9–14 (2014).

5. Ollerton, J., Edwards, M. & Crockett, R. Extinctions of aculeate pollinators in Britain and the role of large-scale agricultural changes. *Science* 346, 1360–1362 (2014).

6. Vanbergen, A. J., The Insect Pollinators Initiative. Threats to an ecosystem service: pressures on pollinators. *Front. Ecol. Environ.* 11, 251–259 (2013).

7. Baude, M. et al. Historical nectar assessment reveals the fall and rise of floral resources in Britain. *Nature* 530, 85–88 (2016).

8. Biesmeijer, J. C. et al. Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science* 313, 351–354 (2006).

9. Carvell, C. et al. Bumble bee species’ responses to a targeted conservation measure depend on landscape context and habitat quality. *Ecol. Appl.* 21, 1760–1771 (2011).

10. Carvalheiro, L. G. et al. Species richness declines and biotic homogenisation have slowed down for NW-European pollinators and plants. *Ecol. Lett.* 16, 870–878 (2013).

11. Senapathi, D. et al. The impact of over 80 years of land cover changes on bee and wasp pollinator communities in England. *Proc. R. Soc. B Biol. Sci.* 282, 20152094–20152094 (2015).

12. Bommarco, R., Lundin, O., Smith, H. G. & Rundlöf, M. Drastic historic shifts in bee–flower–bee community composition in Sweden. *Proc. Biol. Sci.* 279, 309–315 (2012).

13. Rader, R. et al. Non-bee insects are important contributors to global crop pollination. *Proc. Natl Acad. Sci. USA* 113, 146–151 (2016).

14. Klein, D. et al. Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nat. Commun.* 6, 7414 (2015).

15. Powney, G. D. & Isaac, M. J. B. Beyond maps: a review of the applications of biological records. *J. Linn. Soc.* 115, 532–542 (2015).

16. Hill, M. O. Local frequency as a key to interpreting species occurrence data when recording effort is not known. *Methods Ecol. Evol.* 3, 195–202 (2012).

17. Isaac, N. J. B., van Strien, A. J., August, T. A., de Zeeuw, M. P. & Roy, D. B. Statistics for citizen science: extracting signals of change from noisy ecological data. *Methods Ecol. Evol.* 5, 1052–1060 (2014).

18. van Strien, A. J., van Swaay, C. A. M. & Termaat, E. Opportunistic citizen science data of animal species produce reliable estimates of distribution trends if analysed with occupancy models. *J. Appl. Ecol.* 50, 1450–1458 (2013).

19. Royle, J. A. & Kery, M. A Bayesian state-space formulation of dynamic occupancy models. *Ecol. Appl.* 23, 1813–1823 (2013).

20. Britain, C., Kreemen, C. & Klein, A. M. Biodiversity buffers pollination from changes in environmental conditions. * Glob. Chang. Biol.* 19, 540–547 (2013).

21. Hoehn, P., Tscharntke, T., Tylianakis, J. M. & Stefan-Dewenter, I. Functional group diversity of bee pollinators increases crop yield. *Proc. R. Soc. B Biol. Sci.* 278, 2283–2291 (2011).

22. Breeze, T. D., Bailey, A. P., Balcombe, K. G. & Potts, S. G. Pollination services in the UK: How important are honeybees? *Agric. Ecosys. Environ.* 142, 137–143 (2011).

23. Woodcock, B. A. et al. Crop flower visitation by honeybees, bumblebees and solitary bees: Behavioural differences and diversity responses to landscape. *Agric. Ecosys. Environ.* 171, 1–8 (2013).

24. Carvell, C. et al. Bumblebee family lineage survival is enhanced in high-quality landscapes. *Nature* 543, 547–549 (2017).

25. Thomas, C. D., Franco, A. M. A. & Hill, J. K. Range retractions and extinction in the face of climate warming. *Trends Ecol. Evol.* 21, 415–416 (2006).

26. Buckland, S. T., Magurran, A. E., Green, R. E. & Freest, R. M. Monitoring change in biodiversity through composite indices. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 360, 243–254 (2005).

27. Vanbergen, A. J., Heard, M. S., Breeze, T. D., Potts, S. G. & Hanley, N. Status and Value of Pollinators and Pollination Services (Defra, UK, 2014).

28. Carvell, C. et al. Design and Testing of a National Pollinator and Pollination Monitoring Framework (WC1101): A Report to the Department for Environment, Food and Rural Affairs (Defra) Scottish Government and Welsh Government (Defra, UK, 2016).

29. Pywell, R. F. et al. Wildlife-friendly farming increases crop yield: evidence for ecological intensification. *Proc. R. Soc. B Biol. Sci.* 282, 20151740 (2015).

30. Carvell, C., Meek, W. R., Pywell, R. F., Goulson, D. & Nowakowski, M. Comparing the efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. *J. Appl. Ecol.* 44, 29–40 (2007).

31. Outhwaite, C. L. et al. Prior specification in Bayesian occupancy modelling improves analysis of species occurrence data. *Ecol. Ind.* 93, 333–343 (2018).

32. Su, Y. & Yajima, M. Package “R2jags”. https://cran.r-project.org/web/packages/R2jags/ (2015).

33. Klein, A. M. et al. Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B Biol. Sci.* 274, 303–313 (2007).

34. Preston, C. D., Harrower, C. A. & Hill, M. O. Distribution patterns in British and Irish liverworts and hornworts. *J. Bryol.* 33, 3–17 (2011).

35. De Palma, A. et al. Ecological traits affect the sensitivity of bees to land-use pressures in European agricultural landscapes. *J. Appl. Ecol.* 52, 1567–1577 (2015).

36. August, T. A. et al. Sparta: Trend Analysis for Unstructured Data. R package version 0.1.44. https://github.com/BiologicalRecordsCentre/sparta (2018).

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G.D.P., C.C., M.E., R.K.A.M., H.E.R., B.A.W., and N.J.B.I. designed the study and contributed to the writing of the manuscript. G.D.P. performed the analysis and led the writing of the manuscript.

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