




Using citizen science butterfly counts to predict species population trends

Emily B. Dennis ^{1,2*} Byron J.T. Morgan,¹ Tom M. Brereton,² David B. Roy,³ and Richard Fox²

¹School of Mathematics, Statistics and Actuarial Science, University of Kent, Canterbury, CT2 7FS, U.K.

²Butterfly Conservation, Manor Yard, East Lulworth, Wareham, BH20 5QP, U.K.

³Centre for Ecology & Hydrology, Benson Lane, Crowmarsh Gifford, Wallingford, OX10 8BB, U.K.

Abstract: Citizen scientists are increasingly engaged in gathering biodiversity information, but trade-offs are often required between public engagement goals and reliable data collection. We compared population estimates for 18 widespread butterfly species derived from the first 4 years (2011–2014) of a short-duration citizen science project (Big Butterfly Count [BBC]) with those from long-running, standardized monitoring data collected by experienced observers (U.K. Butterfly Monitoring Scheme [UKBMS]). BBC data are gathered during an annual 3-week period, whereas UKBMS sampling takes place over 6 months each year. An initial comparison with UKBMS data restricted to the 3-week BBC period revealed that species population changes were significantly correlated between the 2 sources. The short-duration sampling season rendered BBC counts susceptible to bias caused by interannual phenological variation in the timing of species' flight periods. The BBC counts were positively related to butterfly phenology and sampling effort. Annual estimates of species abundance and population trends predicted from models including BBC data and weather covariates as a proxy for phenology correlated significantly with those derived from UKBMS data. Overall, citizen science data obtained using a simple sampling protocol produced comparable estimates of butterfly species abundance to data collected through standardized monitoring methods. Although caution is urged in extrapolating from this U.K. study of a small number of common, conspicuous insects, we found that mass-participation citizen science can simultaneously contribute to public engagement and biodiversity monitoring. Mass-participation citizen science is not an adequate replacement for standardized biodiversity monitoring but may extend and complement it (e.g., through sampling different land-use types), as well as serving to reconnect an increasingly urban human population with nature.

Keywords: Big Butterfly Count, butterfly abundance, gardens, generalized abundance index, phenology, species trends, UK Butterfly Monitoring Scheme

El Uso de Conteos de Ciencia Ciudadana de Mariposas para Predecir las Tendencias Poblacionales de las Especies

Resumen: Los ciudadanos científicos cada vez participan más en la recopilación de información sobre la biodiversidad, pero comúnmente se requieren compensaciones entre los objetivos de participación pública y la recolección confiable de datos. Comparamos las estimaciones poblacionales para 18 especies de mariposas de extensión amplia derivados de los primeros cuatro años (2011–2014) de un proyecto de ciencia ciudadana de corta duración (Gran Conteo de Mariposas [GCM]) con aquellos estimados de datos de largo plazo y monitoreo estandarizado recolectados por observadores experimentados (Esquema de Monitoreo de Mariposas del Reino Unido [EMMRU]). Los datos del GCM son recopilados durante un periodo anual de tres semanas, mientras que los muestreos del EMMRU se realizan durante seis meses cada año. Una comparación inicial con los datos del EMMRU restringida al periodo de tres semanas del GCM reveló que los cambios en la población de las especies

*Address for correspondence: School of Mathematics, Statistics and Actuarial Science, University of Kent, Canterbury, CT2 7FS, U.K. email e.b.dennis@kent.ac.uk

Paper submitted September 2, 2016; revised manuscript accepted April 26, 2017.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

estuvieron correlacionados significativamente entre las dos fuentes. La corta duración de la temporada de muestreo dejó a los conteos del GCM susceptibles al sesgo causado por la variación fenológica interanual en la cadencia de los periodos de vuelo de las especies. Los conteos del GCM estuvieron relacionados positivamente con la fenología de las mariposas y el esfuerzo del muestro. Los estimados anuales de la abundancia de especies y las tendencias poblacionales pronosticadas a partir de modelos que incluían datos del GCM y covarianzas del clima como sustitutos de la fenología se correlacionaron significativamente con aquellos derivados de los datos del EMMRU. En general, los datos de la ciencia ciudadana obtenidos utilizando un protocolo simple de muestreo produjeron estimaciones de la abundancia de especies de mariposas comparables con los datos recolectados por medio de métodos estandarizados de monitoreo. Aunque se recomienda precaución en la extrapolación a partir de este estudio del Reino Unido de un número pequeño de insectos comunes y conspicuos, encontramos que la participación masiva en la ciencia ciudadana puede contribuir simultáneamente a la participación pública y al monitoreo de la biodiversidad. La ciencia ciudadana con participación masiva no es un remplazo adecuado para el monitoreo estandarizado de la biodiversidad pero puede extenderla y complementarla (p. ej.: por medio del muestreo de diferentes tipos de uso de suelo).

Palabras Clave abundancia de mariposas, Esquema de Monitoreo de Mariposas del Reino Unido, fenología, Gran Cuento de Mariposas, jardines, índice de abundancia generalizada, tendencias de las especies

Introduction

Citizen science, the participation of members of the public in gathering research and monitoring data, is increasing rapidly across many scientific disciplines, including biodiversity conservation (Dickinson et al. 2012; Follett & Strezov 2015). Public involvement in biodiversity recording and monitoring has a long history in some countries (Miller-Rushing et al. 2012; Pocock et al. 2015). Distinction can be made, however, between citizen science projects in which standardized protocols are used to conduct systematic, repeatable sampling in long-term studies (e.g., the Breeding Bird Survey [Gregory & Baillie 1998]) or for hypothesis-driven enquiry (e.g., Conker Tree Science [Pocock & Evans 2014]) and schemes reliant on opportunistic sampling undertaken with relatively unstructured protocols (e.g., eBird [Sullivan et al. 2009]). Opportunistic schemes with simple sampling protocols reduce barriers to participation (e.g. time commitment, prior knowledge) and may thus engage large numbers of new, inexperienced citizen scientists. Although these increase sample size and public outreach, the data gathered may lack credibility (Riesch & Potter 2014; Lewandowski & Specht 2015). Standardized schemes may have much greater barriers to participation and therefore rely on fewer dedicated, skilled volunteers. However, the abilities of these participants to undertake biodiversity monitoring may be comparable with those of professional scientists (Chase & Levine 2016). Biodiversity citizen science projects often involve trade-offs between the goals of public engagement and education (counteracting the extinction of experience; Soga & Gaston 2016) and the collection of reliable data for research (Chase & Levine 2016; Lakeman-Fraser et al. 2016).

Many aspects of citizen science biodiversity research have been examined, including the quality of observations (Lewandowski & Specht 2015), participants' motivations (Hobbs & White 2012), and the development

of new data-analysis techniques (Bird et al. 2014). However, few studies have compared population trends based on relatively unstructured sampling undertaken by mass-participation citizen science with those derived from long-term systematic monitoring and none, to our knowledge, involving terrestrial invertebrates. We derived and compared species population trends from 2 contrasting citizen science projects in the United Kingdom—the Big Butterfly Count (BBC) and U.K. Butterfly Monitoring Scheme (UKBMS).

The BBC is an annual survey of widespread butterfly species launched in 2010 that encourages participation by members of the general public (www.bigbutterflycount.org). It seeks to engage people with little or no experience with biodiversity monitoring and aims to enhance public awareness and interaction with nature and to gather species-abundance data. To minimize barriers to participation, the sampling protocol is simple: 15-minute counts of 18 butterfly species and 2 diurnal moths over 3 weeks in the summer. Consequently, and thanks to a high media profile, BBC has met its aims of mass-participation (mean = 47,636 people involved per year 2013–2015) and raising awareness but, given the target audience, likelihood of identification mistakes, and simple method, counts may not provide a meaningful indication of butterfly population change.

The UKBMS, initiated in 1976, has a robust, standardized recording protocol in which weekly fixed-route counts are conducted over 6 months each year at >1000 sites. High levels of commitment and identification skills are required so participants tend to be experienced amateur butterfly observers or professional conservationists, and the high-quality data generated are used to produce population trend estimates for 56 of 59 regularly breeding U.K. butterfly species, as biodiversity indicators by government (Brereton et al. 2011a; Eaton et al. 2015), and in scientific research (e.g., Dennis et al. 2013; Oliver et al. 2015b; Thackeray et al. 2016). We tested the validity

of BBC data for estimating species trends by determining whether population changes derived from BBC data were comparable with those from UKBMS.

Butterfly abundance differs throughout the year as one or more broods emerge. These phenological patterns vary year to year in response to the weather (Sparks & Yates 1997) and show long-term trends due to climate change (Roy & Sparks 2000). Because the BBC runs for just 3 weeks each summer, interannual variation in counts for each species may result from differing phenology rather than real population changes. We assessed temporal variation in phenology with respect to the BBC survey period to determine its influence on estimates of annual change. Furthermore, we investigated whether population-change estimates from the BBC, in conjunction with weather covariates, can provide an accurate indicator of how populations are faring. In the rapidly expanding field of citizen science, we sought to provide a rare test of the validity of a mass-participation approach to biodiversity monitoring.

Methods

Big Butterfly Count

The BBC runs annually in late July and early August during the peak overall abundance of butterflies. In 2010, the scheme ran for 9 days. Since 2011, the BBC occurs over a period of up to 24 days each year (Supporting Information), although participants can additionally submit counts taken throughout July and August. Due to this difference, we excluded 2010 data from analyses and used BBC data from 2011 to 2014. Participants count 18 widespread butterflies (Supporting Information) and 2 day-flying moths for 15 minutes during bright weather. No training is provided, sightings are submitted online, and minimal verification of sightings is undertaken. Counts can be undertaken anywhere in the United Kingdom. If counting from a fixed position, the maximum number of each species seen at any time is recorded rather than an additive total so as to reduce double counting. BBC data are summarized in Supporting Information and show the scheme's rapid growth. Sightings are spatially referenced and land-use type is recorded by the participant. The majority of counts are taken in gardens (65% on average [Supporting Information]). An average of 12%, 11%, and 4% are taken in fields, other rural, and woodland sites, respectively, and a small number are taken in other land-use types.

UK Butterfly Monitoring Scheme

The UKBMS counts are undertaken along line transects, typically 2–4 km, with systematic, standardized methods (Pollard & Yates 1993). In 2014, 1223 UKBMS transects were monitored (Brereton et al. 2015). Counts can be

made throughout the main season for U.K. butterfly activity; the core period is April–September. A 5-m-wide fixed transect route is walked weekly at specified times of the day and weather conditions, and all butterflies seen are identified and counted. In practice approximately 30% of core-season weekly counts are missed (Dennis et al. 2013). Transect counts are used to generate annual indices of relative abundance from which population trends can be calculated.

Comparisons of BBC and UKBMS Data

We compared species abundance estimates from the 2 schemes in 3 ways. First, we examined agreement through direct comparison of annual growth rates. Second, we investigated the effects of sampling effort and phenology. Finally, we tested whether UKBMS trends may be predicted over 36 years (1980–2015) and 10 years (2006–2015) based on BBC data and an appropriate weather variable acting as a proxy for butterfly phenology.

The BBC and UKBMS are inherently different, independent data sets, and although sample locations are self-selected by participants in both schemes, the representation of habitats may differ. Overall U.K. coverage of each scheme is shown in Supporting Information. Most BBC counts are undertaken in gardens, whereas UKBMS locations are biased toward seminatural habitats that are often managed to benefit biodiversity (Brereton et al. 2011b). We compared the habitats covered by the schemes by summarizing land-cover data from 2007 (Morton et al. 2014) in the 1-km squares sampled in each scheme. For each UKBMS transect, the central 1 × 1 km grid square was used to characterize the habitat.

Comparison of Annual Growth Rates

To make an initial direct comparison between the 2 schemes, we limited the UKBMS data to counts made within the BBC survey period each year and restricted the analysis to the 18 butterfly species counted by the BBC (Supporting Information). Because BBC data are available for only a 3-week period, by initially restricting the UKBMS data to the same period we could directly compare the 2 schemes in the absence of seasonal differences, for example due to multiple broods (which are sampled by the UKBMS).

Following Roy et al. (2015), we determined annual population growth rates for each species from the 2 data sets. In brief, we defined $\mu_{i,t}$ as the expected total count of a species at site i in year t across $v_{i,t}$ visits, and regarded this as the realisation of a Poisson random variable. Annual proportional changes in abundance were assumed to be the same across sites, such that we estimated annual growth rate (R_t) as

$$R_t = \log \left(\frac{\mu_{i,t+1}/v_{i,t+1}}{\mu_{i,t}/v_{i,t}} \right), \quad (1)$$

which leads to

$$\log(\mu_{i,t}) = \sum_{j=1}^{t-1} R_j + \log(\mu'_{i,1}) + \log(v_{i,t}), \quad (2)$$

where $\mu'_{i,t} = \mu_{i,t}/v_{i,t}$. Standard generalized linear model (GLM) software, for example in R (R Core Team 2016), may be used to fit this model. However, the many sites represented in the BBC data each require the estimation of a site parameter each year; hence, the model described is computationally challenging to fit to BBC data with standard GLM software because of the amount of computer memory required. Therefore, we adopted a concentrated (or profile) likelihood approach (Morgan 2008; Pawitan 2013) that reduces the number of parameters to estimate and results in efficient model fitting (Dennis et al. 2016).

With the notation $S_i = \log(\mu'_{i,1})$, apart from an additive constant, the log-likelihood may be written as

$$l = \log(L) = \sum_{i=1}^S \sum_{t=1}^T \left[-\exp \left\{ \sum_{j=1}^{t-1} R_j + S_i + \log(v_{i,t}) \right\} + y_{i,t} \left\{ \sum_{j=1}^{t-1} R_j + S_i + \log(v_{i,t}) \right\} \right]. \quad (3)$$

Then for site i we obtain

$$\frac{\partial l}{\partial S_i} = \sum_{t=1}^T \left[-\exp \left\{ \sum_{j=1}^{t-1} R_j + S_i + \log(v_{i,t}) \right\} + y_{i,t} \right], \quad (4)$$

and equating to zero gives

$$S_i = \log \left\{ \frac{\sum_{t=1}^T y_{i,t}}{\sum_{t=1}^T v_{i,t} \exp \left(\sum_{j=1}^{t-1} R_j \right)} \right\}. \quad (5)$$

Substituting Eq. (5) into Eq. (3) results in a concentrated likelihood that can be maximized simply with respect to $\{R_j\}$. We maximized the likelihood with the optim function in R and the BFGS algorithm (Nocedal & Wright 1999).

We estimated the net change, N , over T years for each survey with

$$\hat{N} = \sum_{t=1}^T \hat{R}_t, \quad (6)$$

where the variance of \hat{N} is the sum of all the entries of the covariance matrix for the growth rates. We adjusted for overdispersion by scaling standard errors with the square root of the ratio of the Pearson chi-square statistic to its degrees of freedom.

Effects of Phenology and Effort

Seasonality of life-cycle phenology results in differences in counts of adult butterflies throughout the year and complicates the analysis of population data (Rothery & Roy 2001; Dennis et al. 2013, 2016). We used UKBMS data to establish how the BBC data were influenced by changes in flight-period phenology. Seasonal abundance patterns for each species in each year were estimated by fitting an appropriate generalized abundance index model (GAI) (Dennis et al. 2016) to the UKBMS data (without date restriction, in contrast to the comparison of annual population growth rates). For univoltine and bivoltine species, a phenomenological GAI is based on the assumption that the flight period of each brood follows a normal distribution (μ , mean flight date; σ , standard deviation). For species with complex seasonal flight patterns, which are difficult to model parametrically, a GAI was fitted using a spline to describe the seasonal variation. The approach used for each species is in Supporting Information.

For each univoltine and bivoltine species, we plotted the total BBC count per day and the estimated annual seasonal pattern from the UKBMS GAI. The BBC counts from all dates were used, rather than only the official 3-week sampling period. We explored the relationship between BBC data and sampling effort and phenology. For each species, a negative-binomial model with log link was fitted using the glm.nb function from the MASS package (Venables & Ripley 2002) in R. The response was the total BBC count per day, and measures of effort (log[number of counts per day]) and phenology based on the estimated seasonal pattern from the UKBMS were covariates. We also modeled the number of counts per day (rather than the total BBC count); however, this measure was right skewed and therefore less satisfactory. The estimated seasonal pattern from the GAI (which sums to unity across the season) formed the measure of phenology for a given day and year. This is in anticipation of positive associations between BBC count and both sampling effort and the timing of sampling coinciding with the peak in species' seasonal patterns.

Predicting UKBMS Species Trends from BBC Data

We assessed whether UKBMS species' population trends were described by the BBC data with weather covariates as a proxy for phenology. We used a simple linear model to regress UKBMS abundance indices for 2011–2014 on BBC data and weather covariates and the index for the previous year (autoregression) to account for potential density dependence.

We used a GAI to estimate UKBMS indices. In a given year, the GAI produces a relative abundance, N_i , for each site i (Dennis et al. 2016). Given the variation

in UKBMS sites between years, we fitted a Poisson GLM with year and site factors and used scaled predicted year effects as indices of abundance (Dennis et al. 2013).

We used BBC data from the official 3 weeks of sampling as a covariate in the linear model; the sum of the total counts per day was scaled by daily effort (defined as the log of the number of counts for all species for that day). However, scaling by the numbers of counts produced similar results.

Average monthly mean temperatures (Parker et al. 1992) and total rainfall (Alexander & Jones 2000) for central England for spring (March–May) and summer (June–August) were used as weather covariates. All weather covariates were standardized to have zero mean and unit variance. The maximum correlation between weather covariates was 0.67.

Potential longer-term (rather than for 2011–2014 only) effects of weather and density dependence were accounted for by fitting a linear model to the GAI index values for 1980–2014; the index values in the previous year and the 4 weather covariates were explanatory variables. The products of the slope coefficients and covariates from each model were included as optional offsets in the linear models to allow for potential longer-term effects than those for 2011–2014 only.

We used the dredge function in the MuMIn package (Barton 2016) in R to select models based on the Akaike information criterion (AIC). Given the few years for which BBC data were available, we allowed up to 2 variables only and only one weather covariate (either as a covariate for 2011–2014 or as an offset for weather from 1980 to 2014). The relative importance of the BBC and weather covariates was assessed using the relaimpo package (Grömping 2006) in R.

Each year UKBMS data are collated (from online and hard copy sources) and verified. Unverified UKBMS data were available for 2015 online; hence, a GAI was fitted to incorporate these data and estimate an index of abundance for 2015. We compared this 2015 index, estimated from observed UKBMS data, with the abundance index predicted from the BBC linear model with the lowest AIC. An abundance index for 2015 was also predicted for each of the candidate models, and we assessed the model with the prediction closest to the index from the observed UKBMS data.

Population trends were compared by fitting linear models to the index of abundance, where the index for 2015 had either been estimated from UKBMS data or predicted from the best linear model. We estimated percent change over 2 periods (long-term for 1980–2015 and short term for 2006–2015) and calculated percent change with respect to the previous year. In doing so we assessed whether predicting the 2015 index from the BBC affected the overall UKBMS trend estimates.

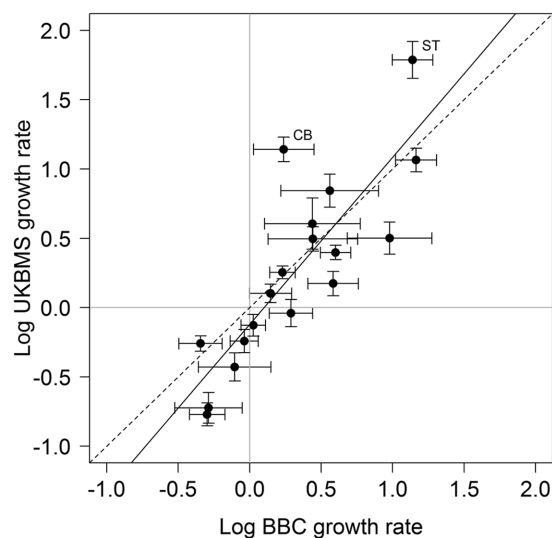


Figure 1. Comparison of estimated log growth rates of populations of 18 butterfly species from Big Butterfly Count (BBC) and U.K. Butterfly Monitoring Scheme (UKBMS) counts for 2011–2014 (error bars, 95% confidence intervals; solid gray lines, zero growth; dashed line, equal growth rates between the data sets; solid black line, fitted linear regression between the growth rates based on BBC and UKBMS data). The small tortoiseshell (ST) and common blue (CB) have the greatest differences.

Results

Comparison of BBC and UKBMS Data

A greater proportion of 1-km squares sampled in the BBC were classified as urban than were transects in the UKBMS (Supporting Information). This was expected given that most BBC counts were undertaken in gardens. The UKBMS squares contained a greater proportion of broadleaf woodland than the BBC, but the 2 schemes showed similar coverage of arable farmland and improved grassland.

Comparison of Annual Growth Rates

There was a significant correlation between net species population changes from the 2 schemes for 2011–2014 ($\rho = 0.84$, $p < 0.001$) (Fig. 1). There was also a significant correlation ($p < 0.01$) between each of the year-to-year changes (Supporting Information). From 2011 to 2014, 11 of the 18 species had significantly positive and 3 had significantly negative change in abundance in the BBC, whereas 11 species had significantly positive and 6 had significantly negative change in the UKBMS. The remainder showed nonsignificant trends (Supporting Information). Population changes estimated from the 2 schemes were similar, although the BBC growth rates were less precise and tended to underestimate UKBMS

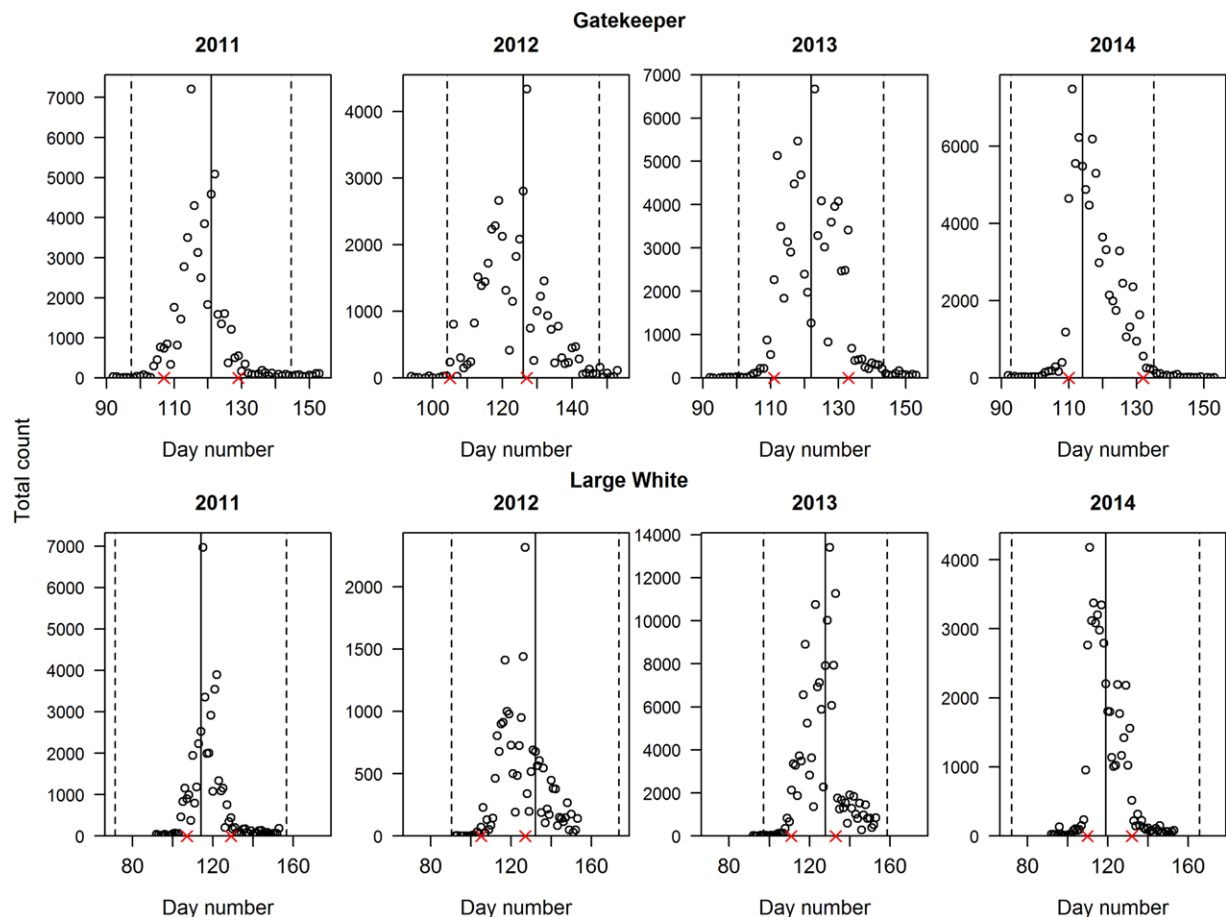


Figure 2. Total counts of gatekeeper and large white from Big Butterfly Count (BBC) data per day in each year, where day 1 is 1 April (vertical lines, mean flight dates estimated from a generalized abundance index model; dashed lines, twice the SD; top, 1st brood; bottom, 2nd brood; red crosses, official BBC survey period for each year).

growth rates. Changes were generally of a similar magnitude and were always of the same sign, with the exception of comma (*Polytonia c-album*) and small white (*Pieris rapae*), and in no cases were the changes significantly different from zero and in opposite directions (Supporting Information). Nevertheless, there were significant differences in net change 2011–2014 between the 2 schemes for 11 species, and confidence intervals for BBC results were on average twice the width of the UKBMS results (0.38 and 0.19 respectively). Estimates of overdispersion were greater than unity for both schemes (Supporting Information). The BBC confidence intervals narrowed in 2013–2014 (average width 0.18) relative to 2012–2013 (0.38) because of the increasing number of counts (Supporting Information).

Effects of Phenology and Effort

Overlaying total daily abundance of each species from BBC counts with phenology information from the UKBMS, revealed how BBC population estimates may be influenced by interannual variation in the timing of

species' flight periods (examples in Fig. 2 & Supporting Information). For gatekeeper (*Pyronia tithonus*) the peak flight period was fairly central in the BBC recording period in 2011 and 2013 but fell at the end of period in 2012 and near the beginning in 2014. For large white (*Pieris brassicae*) timing of the second brood varied; in 2012 in particular, the peak fell outside the BBC period.

Regressing the BBC counts on measures for effort and phenology showed good agreement between the counts and expected values, given the simplicity of the model used (Fig. 3 & Supporting Information). Residual deviance values suggested a good fit for the negative-binomial model compared with the Poisson model (Supporting Information).

Predicting UKBMS Species Trends from BBC Data

The BBC was a covariate in the best model (in terms of AIC) for 13 of 18 species (Table 1), in conjunction with summer rainfall, spring temperature, and spring rainfall each for 3 species; summer temperature for 2; and

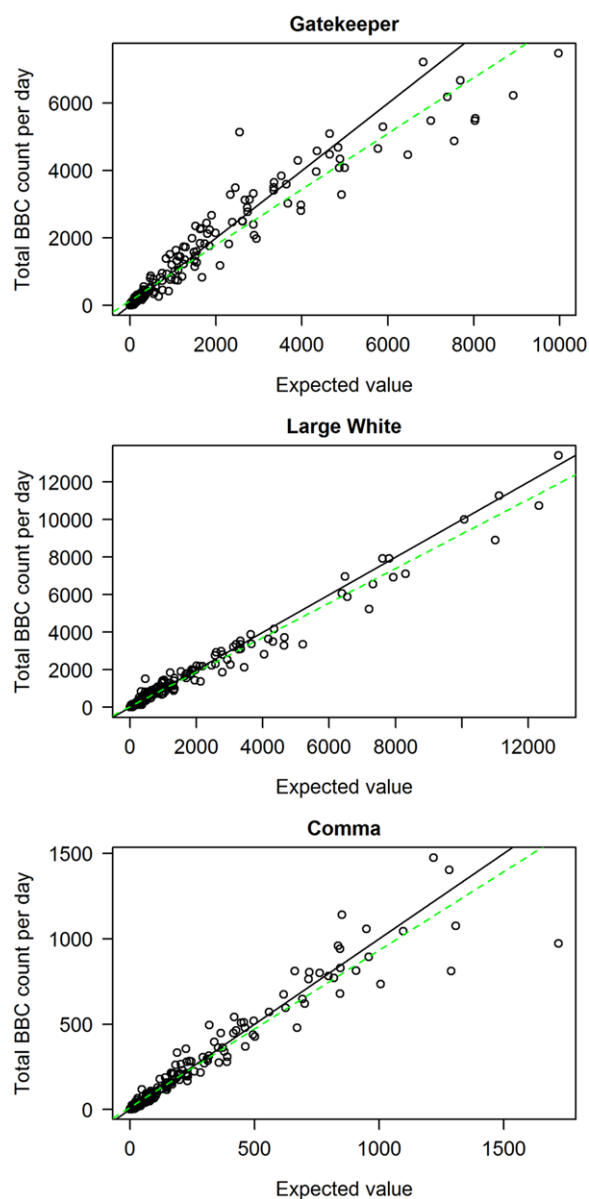


Figure 3. Total counts of 3 butterfly species (gatekeeper, univoltine; large white, bivoltine; comma, multivoltine) from Big Butterfly Count (BBC) data per day versus the expected value from a negative-binomial model with log-link in which the response variable is the total count per day and measures of effort (log number of counts made) and phenology (from the corresponding generalized abundance index model curve) are covariates (black line, equal expected values and total counts; green dashed line, fitted linear regression through the points).

offset long-term spring rainfall and autoregression for 1 species each. Of the 11 species where BBC and a weather covariate were in the best model, the relative importance of BBC exceeded the weather covariate for 8 species (Supporting Information). For 5 species BBC

was not included in the best model, but autoregression was important. The observed 2015 index of abundance was within the 95% confidence interval of the best model for 10 out of 18 species, and only 4 species showed major discrepancies (Fig. 4).

There were significant correlations between estimated population trends (Fig. 5), where the values for 2015 were from the observed data or predicted from the best model: $\rho = 0.99$ for 1980–2015, $\rho = 0.95$ for 2006–2015, $\rho = 0.75$ for 2014–2015, where all $p < 0.001$. For 1980–2015, the difference between the 2 trends was $< 5\%$ for all species. For 2006–2015 and 2014–2015, the difference was $< 5\%$ for 13 and 10 species, respectively, out of 18. Significant trends were correctly identified for the 7 species with significant UKBMS trends for 1980–2015, although 2 further species were predicted to have significant trends. There was greater correlation between the trends when the model with the best 2015 prediction was used (Supporting Information).

Discussion

Citizen science appears to offer opportunities for large-scale, cost-effective biodiversity monitoring. However, the reliability of species trends may be compromised in citizen science projects that prioritize public outreach goals because there is often a trade-off between mass participation and scientific rigor.

This reliability has rarely been tested empirically by comparing opportunistic citizen science data with standardized sampling data. Munson et al. (2010) found that eBird transect checklists predict bird species occurrence almost as accurately as highly standardized North American Breeding Bird Survey data. In contrast, Snäll et al. (2011) reported only weak overall correlation between opportunistic bird reports in Sweden and annual count data from a standardized transect-style survey. In the only terrestrial invertebrate examples we are aware of, Warren et al. (2001) and Oliver et al. (2015a) found correlations between U.K. butterfly species' occurrence trends assessed with opportunistic recording-scheme data and UKBMS population trends.

Population change estimates from the BBC and UKBMS using only counts from the official 3-week BBC period were significantly correlated ($\rho = 0.84$). This compares favorably with the value of 0.75 obtained by Roy et al. (2015) when they compared population trends from the UKBMS with the Wider Countryside Butterfly Survey, in which a reduced-effort UKBMS sampling protocol is used in randomly selected locations (Brereton et al. 2011b).

The temporal distribution of BBC counts showed a potential mismatch with annual phenological variation, and the BBC data were well described by measures of recording effort and phenology. Simple annual proportional changes in abundance calculated from the BBC

Table 1. Estimated population trends (percent changes) in relative abundance for 18 U.K. butterfly species for the best models and selected covariates in terms of Akaike information criterion (AIC) or predicted index closest to the observed 2015 UKBMS index, relative to observed UKBMS populations trends estimated from the generalized abundance index model.

Species	Best fit ^a		1980-2015		2006-2015	
	AIC	2015 prediction	observed	best AIC	observed	best AIC
Brimstone	bbc+SPRt	SUMr+of(auto)	35.9	35.1	-0.5	-2.2
Comma	bbc+SUMr	bbc+SUMr	10.9 ^b	10.9 ^b	-5.4	-5.5
Common blue	bbc+SUMr	bbc+SUMr	-9.0	-8.9	5.2	5.5
Gatekeeper	bbc+SPRt	bbc+SUMr	-12.5 ^b	-12.4 ^b	-1.7	-1.3
Green-veined white	auto+SUMr	bbc+SPRt	-4.1	-2.8	6.6	11.2
Holly blue	bbc+of(auto)	bbc+of(SUMr)	4.1	1.4	-6.1	-14.1
Large skipper	auto+SPRt	auto+SPRt	-12.9 ^b	-13.5 ^b	-13.5	-15.6
Large white	bbc+SPRr	SPRt	-7.5	-7.0	-3.9	-2.3
Marbled white	auto+SUMr	auto+SUMt	-0.7	1.3	10.2	17.3
Meadow brown	bbc+SPRt	SUMt+of(auto)	-4.7	-4.9 ^b	2.4	1.7
Painted lady	bbc+SUMr	bbc+SUMt	-0.3	-4.3	-36.9	-46.0
Peacock	auto+SPRt	auto+of(SPRt)	-1.0	3.0	6.5	20.3
Red admiral	auto+SPRt	auto+bbc	13.9	14.9 ^b	-11.9	-9.3
Ringlet	bbc+SUMt	of(SPRr)	12.3 ^b	11.3 ^b	7.9	5.2
Small copper	bbc+of(SPRr)	SUMt+of(auto)	-14.2 ^b	-12.6 ^b	-11.8	-6.1
Small tortoiseshell	bbc+SPRr	of(SPRr)	-27.0 ^b	-27.4 ^b	30.2	27.7
Small white	bbc+SPRr	bbc+of(auto)	-7.2	-6.2	0.1	3.3
Speckled wood	bbc+SUMt	bbc+of(SPRr)	8.2 ^b	8.0 ^b	0.6	0

^aAbbreviations: SPRt, spring temperature; SPRr, spring rainfall; SUMt, summer temperature; SUMr, summer rainfall; auto, autoregression; of, offset variable.

^bSignificance: $p < 0.01$.

could result from varying phenology and effort rather than true population changes and may mask or falsely predict declines and increases. This demonstrates that the results of snap-shot citizen science biodiversity projects, which often take place at fixed points during the year, are vulnerable to bias from temporal factors that are not normally measured in such projects, as well as from variation in participation.

Despite the limited number of years and lack of standardization or verification, linear models based on BBC data and simple weather covariates were surprisingly successful at predicting the UKBMS abundance index for 2015 and consequently correcting for the effects of changing phenology. The BBC was an important variable for 13 out of 18 butterfly species, and the difference between the 2 trends was <5% for all species in 1980–2015. Predictions of population trends were good even for species that are not straightforward to identify for inexperienced participants (e.g., 3 *Pieris* species: large, small, and green-veined white). The significant correlation and similar estimates of population trends between the 2 schemes validates the use of BBC data in assessing abundance change for these U.K. butterfly species. We used only 4 years of BBC data; over time one would expect even better predictions from BBC.

Species with the poorest model predictions of the 2015 abundance index, and consequently greatest differences in trend estimates relative to the UKBMS, tended to be those recorded in fewer locations by the BBC (Supporting

Information). Wider confidence intervals for the prediction of the 2015 index were also associated with species recorded in fewer BBC locations. Species may be less well recorded by the BBC due to reduced population densities in locations such as gardens, where most counts are undertaken. This may be addressed by encouraging BBC observers to sample other land-use types. Population trends for some species may also be better described by alternative climatic covariates. For example, trends for migratory painted lady (*Vanessa cardui*) and red admiral (*V. atalanta*) may be better explained by weather from parts of their ranges outside the United Kingdom.

This study concerns only 18 widespread butterfly species in the United Kingdom; therefore, caution should be applied in extrapolating our conclusions to other taxa and areas. Relative to many invertebrate taxa, butterflies are conspicuous and popular, and, in the context of butterfly monitoring, the United Kingdom benefits from low species richness, high human population density, and a tradition of amateur natural history recording.

From a biodiversity conservation perspective, the limitations of BBC relative to the UKBMS are clear. The UKBMS provides population trends for all but one of the threatened butterfly species on the British Red List (18 of 19 species), whereas BBC primarily counts just 18 common butterfly species (all also monitored by the UKBMS). Even in the United Kingdom, mass-participation citizen science is unlikely to provide reliable data on the large number of threatened, habitat-specialist invertebrates.

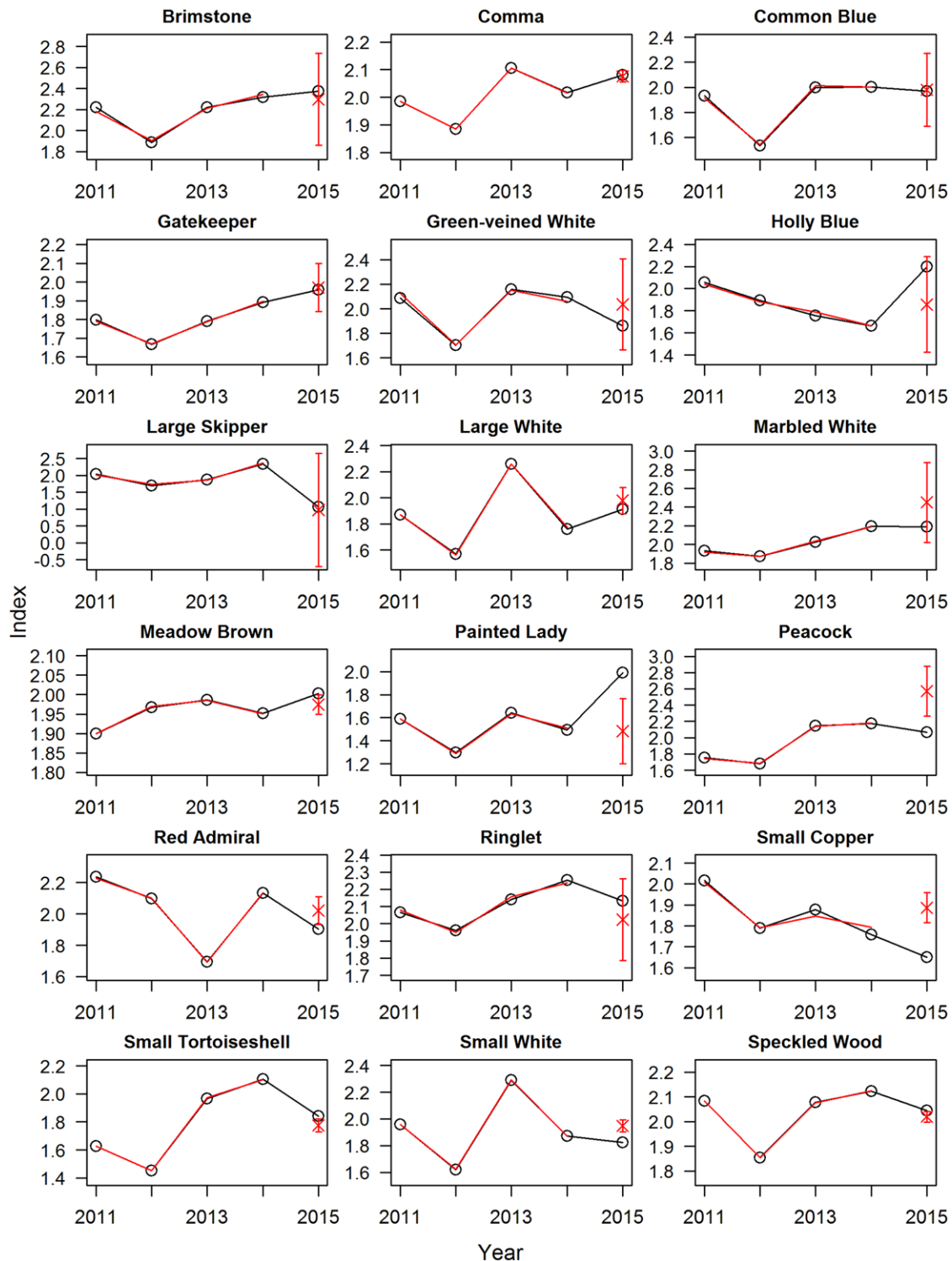


Figure 4. Comparison of the generalized abundance index from U.K. Butterfly Monitoring Scheme (UKBMS) data (black) and predicted butterfly abundance indices from the best model in terms of Akaike information criterion (red) (vertical line, 95% confidence intervals for the 2015 prediction).

Nevertheless, the BBC data, as validated by our results, provide the potential for additional or improved assessments of biodiversity change. For example, there is increasing interest in the biodiversity of urban areas, both

as potential refuges for species whose habitats have been degraded in intensively farmed countryside and for the opportunities it affords for human-wildlife interactions and associated human well-being (Goddard et al. 2010;

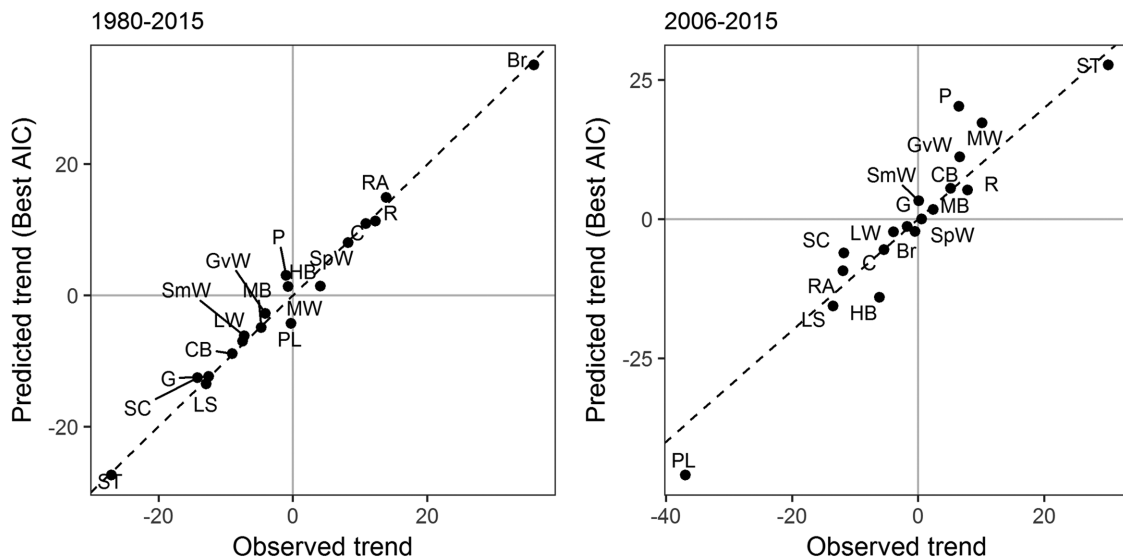


Figure 5. Comparison of linear trends in relative butterfly abundance from the generalized abundance index model. The indices for 2015 are from observed data or predicted from the best model in terms of Akaike information criterion (solid grey lines, 0% change in relative abundance; dashed line, equal population trends). Abbreviations are for species common names (see Supporting Information).

Shanahan et al. 2015). Sampling protocols developed for use in seminatural habitat or open countryside may not be easily implemented in built areas and private gardens. The BBC samples more urban habitat than the UKBMS, and the majority of counts are undertaken in private gardens; hence, the BBC could provide a new biodiversity indicator for the performance of butterfly populations in gardens and parks, providing a valuable tool to engage the public and managers of urban greenspace.

The sampling of private gardens and urban areas as part of BBC also provides potentially useful population data for common butterfly species to complement UKBMS sampling of seminatural habitat and the farmed landscape. While not of highest conservation priority, trends of common species are, nevertheless, of considerable interest due to the significance of such species to ecosystem function (Gaston & Fuller 2008). In the United Kingdom, the overall abundance of widespread butterflies decreased by 25% over 40 years (Fox et al. 2015), and many widespread species have significant negative population trends in the United Kingdom and the Netherlands (Van Dyck et al. 2009). Currently, the drivers of these declines are poorly understood. The BBC and UKBMS data could be combined in an integrated analysis (Pagel et al. 2014) representative of a wider range of land-use types, although variation in the scale and accuracy of the 2 surveys would need to be addressed, for example, by weighting different likelihood components (Francis 2011).

In practice, the financial costs of mass-participation citizen science versus standardized monitoring are an important factor, particularly where a new scheme is to be implemented. Both schemes incur considerable

annual expenditure due to the essential involvement of professional staff, but the cost of running BBC is about a quarter that of the UKBMS. Aside from minor coordination, the primary cost of BBC arises from the need for media promotion to engage the public. Despite a larger overall cost due to greater coordination needs, it could be argued that the UKBMS is more cost-effective because data are collected for many more species, including those that are the main focus of conservation. Both schemes also require an online data system, however, as the primary monitoring method for U.K. butterflies, the UKBMS incurs additional costs associated with data validation, which is not undertaken in the BBC.

The UKBMS operating costs are contingent on the assumption that an adequate network of skilled, trained volunteers already exists or can be mobilized quickly. Without this, the start-up costs and lead-in time for a monitoring scheme would be substantially greater than for mass-participation citizen science, for example, if paid professionals were required (Carvell et al. 2016). As we have shown with BBC, mass-participation citizen science may, in some instances and with suitable adjustments (e.g., for effort and phenology), provide meaningful estimates of population trends for common, easily identifiable species. Even if this is not the case (or cannot be tested), by raising awareness and providing informal education, citizen science projects may provide a means to develop the necessary pool of skilled, engaged volunteers to enable the establishment of standardized biodiversity monitoring of additional areas and of taxa that are not currently well-monitored.

Despite relatively simplistic modeling and only a few years of available data, and contrary to the scepticism

with which mass-participation citizen science is sometimes viewed, we found that BBC can produce population change estimates for common butterflies comparable to standardized monitoring data collected by skilled recorders. These results establish BBC as an example of a citizen science win win (Chase & Levine 2016; Lakeman-Fraser et al. 2016); a project focused on outreach and public engagement that generates meaningful scientific output.

Acknowledgments

We are extremely grateful to all the citizen scientists who gathered data for BBC and UKBMS. The BBC is run by Butterfly Conservation and received funding from Marks & Spencer. The UKBMS is operated by the Centre for Ecology & Hydrology, the Butterfly Conservation and the British Trust for Ornithology and funded by a multi-agency consortium including Defra, Joint Nature Conservation Committee, Forestry Commission, Natural England, Natural Resources Wales, Natural Environment Research Council, and Scottish Natural Heritage. We thank S. Freeman for helpful advice and M. Kéry and an anonymous reviewer for constructive comments.

Supporting Information

Additional information describing the data (Appendix S1), comparisons of UKBMS and BBC population growth rates (Appendix S2), effects of phenology and effort (Appendix S3), and comparisons of trend estimates from BBC and UKBMS (Appendix S4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

- Alexander L, Jones P. 2000. Updated precipitation series for the UK and discussion of recent extremes. *Atmospheric Science Letters* **1**: 142–150.
- Barton K. 2016. MuMIn: multi-model inference. R package. Version, 1.15.6. R Foundation, Vienna. Available from <https://CRAN.R-project.org/package=MuMIn> (accessed December 2015).
- Bird TJ, et al. 2014. Statistical solutions for error and bias in global citizen science datasets. *Biological Conservation* **173**:144–154.
- Brereton TM, Botham MS, Middlebrook I, Randle Z, Roy DB. 2015. United Kingdom butterfly monitoring scheme report for 2014. Centre for Ecology & Hydrology and Butterfly Conservation, Wallingford, Oxfordshire.
- Brereton TM, Cruickshanks KL, Risely K, Noble DG, Roy DB. 2011b. Developing and launching a wider countryside butterfly survey across the United Kingdom. *Journal of Insect Conservation* **15**:279–290.
- Brereton TM, Roy DB, Middlebrook I, Botham MS, Warren MS. 2011a. The development of butterfly indicators in the United Kingdom and assessments in 2010. *Journal of Insect Conservation* **15**:139–151.
- Carvell C, et al. 2016. Design and testing of a national pollinator and pollination monitoring framework. Final summary report to the Department for Environment, Food and Rural Affairs, Scottish Government and Welsh Government: project WC1101. Centre for Ecology & Hydrology, Wallingford, Oxfordshire.
- Chase SK, Levine A. 2016. A framework for evaluating and designing citizen science programs for natural resources monitoring. *Conservation Biology* **30**:456–466.
- Dennis EB, Freeman SN, Brereton T, Roy DB. 2013. Indexing butterfly abundance whilst accounting for missing counts and variability in seasonal pattern. *Methods in Ecology & Evolution* **4**:637–645.
- Dennis EB, Morgan BJT, Freeman SN, Brereton TM, Roy DB. 2016. A generalised abundance index for seasonal invertebrates. *Biometrics* **72**:1305–1314.
- Dickinson JL, Shirk J, Bonter D, Bonney R, Crain RL, Martin J, Phillips T, Purcell K. 2012. The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment* **10**:291–297.
- Eaton MA, et al. 2015. The priority species indicator: measuring the trends in threatened species in the UK. *Biodiversity* **16**:108–119.
- Follett R, Strežov V. 2015. An analysis of citizen science based research: usage and publication patterns. *PLOS ONE* **10**:e0143687. <https://doi.org/10.1371/journal.pone.0143687>.
- Fox R, et al. 2015. The state of the UK's butterflies 2015. Butterfly Conservation and the Centre for Ecology & Hydrology, Wareham, Dorset.
- Francis RICC. 2011. Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* **68**:1124–1138.
- Gaston KJ, Fuller RA. 2008. Commonness, population depletion and conservation biology. *Trends in Ecology & Evolution* **23**:14–19.
- Goddard MA, Dougill AJ, Benton TG. 2010. Scaling up from gardens: biodiversity conservation in urban environments. *Trends in Ecology & Evolution* **25**:90–98.
- Gregory RD, Baillie SR. 1998. Large-scale habitat use of some declining British birds. *Journal of Applied Ecology* **35**:785–799.
- Grömping U. 2006. Relative importance for linear regression in R: The Package relaimpo. *Journal of Statistical Software* **17**:1–27.
- Hobbs SJ, White PCL. 2012. Motivations and barriers in relation to community participation in biodiversity recording. *Journal for Nature Conservation* **20**:364–373.
- Lakeman-Fraser P, Gosling L, Moffat AJ, West SE, Fradera R, Davies L, Ayamba MA, van der Wal R. 2016. To have your citizen science cake and eat it? Delivering research and outreach through Open Air Laboratories (OPAL). *BMC Ecology* **16**(Suppl 1):57–70.
- Lewandowski E, Specht H. 2015. Influence of volunteer and project characteristics on data quality of biological surveys. *Conservation Biology* **29**:713–723.
- Miller-Rushing A, Primack R, Bonney R. 2012. The history of public participation in ecological research. *Frontiers in Ecology and the Environment* **10**:285–290.
- Morgan BJT. 2008. *Applied Stochastic Modelling*. 2nd edition. CRC, Chapman & Hall, Boca Raton, Florida.
- Morton RD, Rowland CS, Wood CM, Meek L, Marston CG, Smith GM. 2014. Land Cover Map 2007 (1km percentage aggregate class, GB). Version 1.2. NERC-Environmental Information Data Centre.
- Munson MA, et al. 2010. A method for measuring the relative information content of data from different monitoring protocols. *Methods in Ecology and Evolution* **1**:263–273.
- Nocedal J, Wright SJ. 1999. *Numerical optimization*. Springer, New York.
- Oliver TH, Isaac NJB, August TA, Woodcock BA, Roy DB, Bullock JM. 2015a. Declining resilience of ecosystem functions under biodiversity loss. *Nature Communications* **6**:10122.
- Oliver TH, Marshall HH, Morecroft MD, Brereton T, Prudhomme C, Huntingford C. 2015b. Interacting effects of climate change and habitat fragmentation on drought-sensitive butterflies. *Nature Climate Change* **5**:941–945.
- Pagel J, Anderson BJ, O'Hara RB, Cramer W, Fox R, Jeltsch F, Roy DB, Thomas CD, Schurr FM. 2014. Quantifying range-wide variation in

- population trends from local abundance surveys and widespread opportunistic occurrence records. *Methods in Ecology and Evolution* **5**:751–760.
- Parker DE, Legg TP, Folland CK. 1992. A new daily central England temperature series, 1772–1991. *International Journal of Climatology* **12**:317–342.
- Pawitan Y. 2013. In all likelihood: statistical modelling and inference using likelihood. Oxford University Press, Oxford.
- Pocock MJO, Evans DM. 2014. The success of the Horse-Chestnut Leaf-Miner, *Cameraria obridella*, in the UK revealed with hypothesised citizen science. *PLOS ONE* **9**:(e86226) <https://doi.org/10.1371/journal.pone.0086226>.
- Pocock MJO, Roy HE, Preston CD, Roy DB. 2015. The Biological Records Centre: a pioneer of citizen science. *Biological Journal of the Linnean Society* **115**:475–493.
- Pollard E, Yates TJ. 1993. Monitoring butterflies for ecology and conservation. Chapman & Hall, London.
- R Core Team. 2016. R: A language and environment for statistical computing. R Foundation, Vienna.
- Riesch H, Potter C. 2014. Citizen science as seen by scientists: Methodological, epistemological and ethical dimensions. *Public Understanding of Science* **23**:107–120.
- Rothery P, Roy DB. 2001. Application of generalized additive models to butterfly transect count data. *Journal of Applied Statistics* **28**: 897–909.
- Roy DB, Sparks TH. 2000. Phenology of British butterflies and climate change. *Global Change Biology* **6**:407–416.
- Roy DB, et al. 2015. Comparison of trends in butterfly populations between monitoring schemes. *Journal of Insect Conservation* **19**: 313–325.
- Shanahan DF, Fuller RA, Bush R, Lin BB, Gaston KJ. 2015. The health benefits of urban nature: How much do we need? *BioScience* **65**:476–485.
- Snäll T, Kindvall O, Nilsson J, Pärt T. 2011. Evaluating citizen-based presence data for bird monitoring. *Biological Conservation* **144**: 804–810.
- Soga M, Gaston KJ. 2016. Extinction of experience: evidence, consequences and challenges of loss of human-nature interactions. *Frontiers in Ecology and the Environment* **14**:94–101.
- Sparks TH, Yates TJ. 1997. The effect of spring temperature on the appearance dates of British butterflies 1883–1993. *Ecography* **20**: 368–374.
- Sullivan BL, Wood CL, Iliff MJ, Bonney RE, Fink D, Kelling S. 2009. eBird: a citizen-based bird observation network in the biological sciences. *Biological Conservation* **142**:2282–2292.
- Thackeray SJ, et al. 2016. Phenological sensitivity to climate across taxa and trophic levels. *Nature* **535**:241–245.
- Van Dyck H, van Strien AJ, Maes D, van Swaay CAM. 2009. Declines in common, widespread butterflies in a landscape under intense human use. *Conservation Biology* **23**:957–965.
- Venables WN, Ripley BD. 2002. Modern applied statistics with S. 4th edition. Springer, New York.
- Warren MS, et al. 2001. Rapid responses of British butterflies to opposing forces of climate and habitat change. *Nature* **414**:65–69.

