Realising the full potential of citizen science monitoring programs

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Abstract

Citizen science is on the rise. Aided by the internet, the popularity and scope of citizen science appears almost limitless. For citizens the motivation is to contribute to "real" science, public information and conservation. For scientists, citizen science offers a way to collect information that would otherwise not be affordable. The longest running and largest of these citizen science programs are broad-scale bird monitoring projects. There are two basic types of protocols possible: a) cross-sectional schemes such as Atlases – collections of surveys of many species contributed by volunteers over a set period of time, and b) longitudinal schemes such as Breeding Bird Surveys (BBS) – on-going stratified monitoring of sites that require more coordination. We review recent applications of these citizen science programs to determine their influence in the scientific literature. We use return-on-investment thinking to identify the minimum investment needed for different citizen science programs, and the point at which investing more in citizen science programs has diminishing benefits. Atlas and BBS datasets are used to achieve different objectives, with more knowledge-focused applications for Atlases compared with more management applications for BBS. Estimates of volunteer investment in these datasets show that compared to cross-sectional schemes, longitudinal schemes are more cost-effective, with increased BBS investment correlated with more applications, which have higher impact in the scientific literature, as measured by citation rates. This is most likely because BBS focus on measuring change, allowing the impact of management and policy to be quantified. To ensure both types of data are used to their full potential we recommend the following: elements of BBS protocols (fixed sites, long-term monitoring) are incorporated into Atlases; regional coordinators are in place to maintain data quality; communication between researchers and the organisations coordinating volunteer monitoring is enhanced, with monitoring targeted to meet specific needs and objectives; application of data to under-explored objectives is encouraged, and data are made freely and easily accessible.

1. Introduction

Citizen science, the involvement of citizens from the non-scientific community in academic research, has become increasingly important in conservation science, as resources for monitoring fail to match the scale of the questions at hand. For citizens, the motivation is to contribute to scientific understanding and conservation decisions. For scientists, citizen science provides an opportunity to gather information that would be impossible to collect because of limitations in time and resources (Dickinson et al. 2010). The field of ornithology has the longest history of citizen science (Greenwood 2007), with thousands of amateur and professional ornithologists worldwide. The National Audubon Society's Christmas Bird Count in the United States, started in 1900, is the longest-running citizen science project with over 110 years of data collected so far. Advances in technology have led to new citizen science internet applications that use crowd-sourcing to invite large numbers of the public to monitor biodiversity over broad geographic regions, and allow volunteers to access and interpret the data they collect (Howe 2006).This has resulted in datasets that are often very large and readily accessible. To respond to the many and varied needs of biodiversity management, many conservation agencies rely on these volunteer-compiled datasets to inform their management strategies. Citizen science is often the only practical way to achieve the geographic extent required to document ecological patterns and address ecological questions at scales relevant to species range shifts, migration patterns, disease spread, broad-scale population trends, changes in national and state policy, and impacts of environmental processes like climate change. The varied uses of these data mean that quality assurance and control is critical. At least one comparative analysis suggests that citizen science data can provide similar information to professionally collected and designed monitoring programs (Szabo et al. 2012). A century on since the first citizen science program, it is timely to examine what makes citizen science programs effective at achieving high quality datasets that are useful for answering pure and applied questions (Mackechnie et al. 2011).

The largest citizen science programs are broad-scale bird monitoring schemes that can be categorised as one of two protocols: cross-sectional surveying (e.g. Atlases) and longitudinal surveying (e.g. Breeding Bird Surveys). Atlases are collections of species occurrences contributed by volunteers over a set time period, with volunteers generally free to choose where they survey. As of 2012, more than 400 Bird Atlases have been developed. The spatial sampling units of these programs are variable (0.02 – 3092km^2), and the spatial extent can be anything from local areas (21km^2) to entire continents (10,390,000km^2). As much as 68% of Atlases are ‘repeat’ Atlases, covering the same areas as those covered by a previous Atlas (Dunn and Weston 2008). The number and density of contributors is highly variable over space, and the data collected are often uneven through the year (Dunn and Weston 2008; Gibbons et al. 2007). Due to the often unstructured or undirected nature of sampling in Atlases (with volunteers usually allowed to conduct surveys wherever and whenever they want), data quality issues caused by volunteer bias in survey effort (Botts et al. 2010; Dennis and Thomas 2000; Reddy and Dávalos 2003), survey inconsistencies over time (Szabo et al. 2010), errors in records (Cohn 2008; Robertson et al. 2010), and issues of scale (Araujo et al. 2005), must be dealt with when using these data. In contrast, Breeding

Bird Surveys are based on a network of sampling locations at which species occurrence and relative abundance are collected at given time steps to document temporal trends (Brotons et al. 2007; Robertson et al. 2010). These on-going programs are less common than purely cross-sectional schemes, as they generally require more institutional coordination of stratified surveys and provide datasets that are more representative and less biased by volunteer behaviour. Despite limitations, both types of programs have the potential for high volunteer involvement, and can provide numerous direct and indirect benefits to conservation.

We review recent applications in the scientific literature of citizen science bird-monitoring programs to explore lessons learned. In doing so, we examine whether we are making the most of the considerable efforts of the volunteers and data coordinators. Past reviews have highlighted various applications of citizen science monitoring programs, often related to learning about ecological systems and their management (Table 1; Donald and Fuller 1998; Dunn and Weston 2008; Underhill et al. 1991). A substantial focus of the literature has been on the methodology of volunteer-monitoring programs (usually Atlases or Breeding Bird Surveys), and the issues that need to be dealt with when using and analysing the data (e.g. Dickinson et al. 2010; Donald and Fuller 1998; Dunn and Weston 2008; Gibbons et al. 2007; Pomeroy et al. 2008; Robertson et al. 2010; Schmeller et al. 2012; Thomas 1996; Underhill et al. 1991). This emphasis has potentially overshadowed the many benefits these datasets have to offer. There has been little discussion about which programs are best for achieving particular objectives or whether additional objectives could be met using these same datasets. We investigate the range of potential objectives of using volunteer monitoring data, and compare the ability of different volunteer-monitoring schemes to achieve them. We examine the level of stakeholder investment in these programs and ask if broad-scale citizen science bird monitoring has been a cost-effective investment, by relating the quality and quantity of inputs to the scientific outcomes. We aim to inform two investment questions: a) What is the minimum amount of investment needed for different citizen science programs, and b) At what point would spending more money on citizen science programs deliver little additional benefit? Finally, we explore how we can make volunteer-monitoring datasets more useful for informing research or management, to optimally use resources spent on supporting these projects.

2. Objectives of volunteer monitoring data

Various authors have summarised objectives of long-term monitoring (Nichols and Williams 2006; Possingham et al. 2012; Salzer and Salafsky 2006). Building on these, we identify eight unique objectives for gathering and using volunteer-collected monitoring data (Table 1). Not all of these objectives have direct conservation or management-related outcomes, but they can often lead to indirect benefits to nature conservation:

1) Management: monitoring the state of a system to inform management actions (state-dependent management), or to learn how the ecological system works and responds to management as part of the adaptive management cycle (passive or active adaptive management).

2) Awareness: to educate the public and policy makers about long-term ecological changes and planning (e.g. for urban development, policy development for threatened species, and conservation planning).

3) Education: to increase public knowledge as opposed to scientific knowledge (e.g. informing where birds occur or the location of birdwatching hotspots, demonstrating new techniques or skills), or to engage the public in ecological issues thereby leveraging effort and support.

4) Serendipity: to uncover unexpected events (Lindenmayer and Likens 2010a; Wintle et al. 2010).

5) Recreation: the involvement of the community for recreation and well-being, for example psychological and health outcomes such as creating a community bond through shared interests and activities (Clayton and Myers 2009; Prior and Schaffner 2011; Thomsen 2008).

6) Social and economic research: to study human behaviour (e.g. travel-cost method, valuing natural assets by quantifying birdwatcher time investment, understanding motivations for actions) (e.g. Booth et al. 2011; Knight et al. 2010).

7) Ecological knowledge: for knowledge's sake (pure scientific learning), to know more about a system, species, or theory, e.g. species-environment associations.

8) Improving methods: learning to improve methods of monitoring and evaluation (e.g. selecting the best monitoring method, changing the sampling protocol or design), or to develop new analytical approaches.

Reviews of papers using volunteer-monitoring data suggest applications have focused largely on three of the eight objectives: knowledge gain, increasing awareness and improving methods (Table 1). Applications such as exploring human behaviour (Booth et al. 2011; Jordan et al. 2011; Tulloch and Szabo 2012; Weston et al. 2006) are rare but increasing because of a new emphasis on interdisciplinary approaches and the role of social research in conservation planning and natural resource management (Bodin and Crona 2009; Knight et al. 2010).

3. Review of citizen science bird-monitoring literature

To determine the use of cross-sectional datasets, we used Bird Atlases as a case study and searched the literature for applications of these schemes by querying the words "bird*" and "Atlas*" anywhere in the title, keywords or abstract of journal articles in Web of Science, published between 2005 and 2010 (20/8/2011). We chose this period to encompass and follow on from Atlas reviews in recent years, but did not include 2011 as there would not be enough time for these papers to be cited yet and we were interested in citation data. We removed any articles not specifically using Bird Atlas data to answer a research question (e.g. reviews, Atlases for other taxa). An Atlas was defined as any program enlisting the efforts of volunteers to collect surveys of all bird species at a broad-scale and without direct requirements for the volunteers to return to certain areas over a period of time (94 papers). To compare these applications with those for an alternative longitudinal citizen science protocol, we looked at the use and influence of Breeding Bird Surveys (BBS) from 2005 to 2010 by searching for the words “breeding” and “bird*” and “survey*” in Web of Science, and again refining the list to those papers that used BBS data to answer a research question (136 papers). A BBS was defined as a standardised longitudinal scheme requiring repeat visits by volunteers to a specified site to survey all bird species. To explore the various applications of bird monitoring programs, we assigned each paper to one (or more) objectives (examples in Table 1).

One way to assess the scientific benefits of a monitoring program is through the influence of applications that utilise the monitoring data in the scientific literature. We investigated how influential each application of Atlas and BBS data was using its citation rate (average citations per year). We first calculated the average overall citation rate for all Atlas papers compared with all BBS papers. We used Analysis of Variance (ANOVA) to determine if the citation rates for each of the ascribed objectives were significantly different between each volunteer dataset type.

We developed a database of all the Atlases and BBS datasets cited in these papers, which we used to calculate the average number of studies per dataset, a second indication of how influential the dataset has been on research in recent years. To explore the factors influencing the frequency of Atlas use in the scientific literature, we reviewed in detail each Atlas paper and its associated Atlas, and developed a database of general characteristics related to the spatial and temporal extent of the Atlas, its sampling design and dataset completeness, and methods used to analyse the Atlas data (Appendix A). We developed hypotheses describing potential factors influencing the number of papers using a particular Atlas (Table A.1), and used generalised linear modelling to fit 20 models. Hypotheses were compared in an information-theoretic framework using AICc model selection (Burnham and Anderson 2002) to find the most influential factors. We collected similar data for BBS programs, but modelling was not repeated as the sample size was too small (n = 11).

To calculate the return on investment of a monitoring scheme, we need information not only on the benefits but also on the costs involved in data collection and coordination. We estimated volunteer investment in monetary terms into collecting data for all the BBS schemes and the top 20 cited Atlases in our review using a replacement cost method (e.g. Levrel et al. 2010).The valuation is based on what an organisation would have paid employees to do the work that they benefitted from at no cost as a result of volunteer activity. The total number of survey records, number of volunteer hours, and/or number of routes (for BBS) were determined from searching the websites of the coordinating institutions, scanning publications from the monitoring programs or their applications, or contacting data custodians directly. We were unable to obtain data for 6 of the top 20 Atlases, resulting in 14 estimates. The total investment in the monitoring program was calculated using a simple equation that multiplied the number of hours volunteers spent collecting data by an average single field survey cost of US$50/hr. We realise this is probably an under-estimate of the total investment as we did not take into account additional factors such as travelling time (some volunteers travel many hundreds of kilometres to see certain birds; Tulloch and Szabo 2012), but we wanted a simple metric that could be calculated with minimal data requirements, and compared across schemes where data on travelling times by volunteers are not always available. We also gathered information on the number of paid staff members or coordinators allocated to each monitoring program. We found that there was usually the equivalent of one full-time staff member on Atlases, and an average of two full-time staff members on BBS datasets. We therefore estimated the total cost of coordinating data compilation by multiplying the number of years the program ran by the annual cost of one full-time staff (US$100,000) for Atlases, and two full-time staff (US$200,000) for BBS programs. The annual monetary investment in each monitoring program was estimated by adding the total volunteer investment to the coordination investment, then dividing this value by the number of years the program ran. We then defined the program 'benefits' – here the number of papers published between 2005 and 2010, found using a keyword search (as described above) in both Web of Science and Google Scholar, which mention the use of Bird Atlases or Breeding Bird Surveys to achieve a given objective. Finally, we calculated a cost-effectiveness metric that divided the benefits by the annual investment in data collection and coordination.

4. Citizen science programs with different protocols are used differently

Our review showed that bird monitoring data from Atlas and BBS programs are used in different ways (Table 2). Knowledge-gain was the most common objective for both types of citizen science program between 2005 and 2010, and the fraction of total applications was higher for Atlas studies than for BBS (90% vs. 65%). The majority of knowledge-gain objectives were spatial analyses that focused on understanding and modelling species-environment relationships and distributions (e.g. Araujo et al. 2005; Bahn and McGill 2007), or testing the predictions of theories (e.g. the species-energy relationship; Rowhani et al. 2008; Storch et al. 2005; Whittaker et al. 2007)(Appendices C and D). One in five BBS studies focused on management outcomes, which were a rare outcome for Atlas applications (Table 2).Gaining knowledge about management usually requires ancillary information about that management, e.g. grazing or fire or logging. This is rarely a part of citizen science. The data requirements to understand the consequences of management compared with knowledge objectives like species distribution models or biogeography can be large, with space and time components needed to demonstrate change. Most Atlases do not include temporal replication requirements, compared with BBS programs where this is implicit in the monitoring protocol. In addition, abundance data (such as that generally collected by BBS volunteers) are more useful for monitoring change in management regimes than species lists of occurrence that are the usual format of most Atlases. The rare application of Atlases to evaluating management outcomes could also be due to scale issues (e.g. the scale of data aggregation is too large to link with on-ground management or land use data), or a lack of data on whether birds were breeding, making it difficult to make inferences about habitat quality or population processes. In some management cases, neither types of citizen science dataset will be useful. For example if the aim of monitoring is to trigger action or stop an activity (e.g. harvesting of species), citizen science data might not be collected regularly enough (or along with the appropriate ancillary information, e.g. number harvested) to be responsive, and the answers to these questions might require professional monitoring (or monitoring by the people that are harvesting the resource; Månsson et al. 2011).

About a third of Atlas and BBS papers focused on improving monitoring and analysis methods (Table 2), which is important for quality control and optimising survey design (Field et al. 2005).These studies were often linked with knowledge gain. Both Atlas and BBS monitoring protocols are useful for answering these questions because both have the ability to collect enough short-term data on observer effort, to allow the efficiency of different sampling regimes or survey protocols to be compared between seasons, methods or areas (e.g. Munson et al. 2010). The high volume and broad scale of data and variability within these datasets is also useful for improving the performance of spatial analysis methods such as species distribution modelling (e.g. Araujo et al. 2005; Bahn and McGill 2007; Brotons et al. 2007; Luoto et al. 2007), and estimation of species richness (Kery and Royle 2008).The addition of temporal replication by BBS datasets allows for the development of new trend analysis techniques that incorporate variability and imperfect detection (Lele 2006; Royle et al. 2005). Accurate trend analysis and abundance estimation is crucial to enable effective conservation decisions for declining species, with interest in predicting the impacts of management and climate change increasing in recent years (Fujisaki et al. 2008; Wilson et al. 2011). Long-term BBS programs with repeated sampling were more highly cited for both knowledge-gain (F = 4.64, d.f. = 1,172, p = 0.03; Fig. 1, Appendix B) and for methods improvement (F = 3.22, d.f. = 1,80, p = 0.07), as they could link their study to being directly useful for conservation and/or planning (e.g. Buckland et al. 2005; Devictor et al. 2008).

Similar proportions of Atlas and BBS applications focused on informing conservation policy and planning (Table 2), but BBS applications with this objective had significantly higher citation rates than Atlas applications (F = 7.57, d.f. = 1,66, p = 0.01; Fig. 1), most likely due to the stratified long-term and fine-scale nature of BBS schemes. Data for this objective must also be linked to land use and/or climatic changes at local or regional-scales. The study with the highest influence on the scientific literature (21.5 citations per year on average) investigated the emergence of West Nile Virus (LaDeau et al. 2007), requiring long-term abundance data that allowed the impacts of this introduced disease to be distinguished from other forces that influence population dynamics. Many Atlas studies required additional data (e.g. from field surveys, the literature, or BBS datasets; Appendix C) to achieve similar objectives (e.g. Blancher et al. 2009; Schulte et al. 2005; Van Turnhout et al. 2007). Longitudinal datasets such as Breeding Bird Surveys are crucial for answering questions (e.g. about system modifications) that require a significant amount of before and after data, as they can inform early detection and on-going monitoring (Crosbie et al. 2008). Use of BBS data in this way is a form of serendipity. Although no studies in our review explicitly presented serendipity as an objective, it is something that occurs only when there is sufficient data to detect an unexpected occurrence or disturbance event that might otherwise have been missed (Lindenmayer and Likens 2010a, b). There are several instances in which surveillance monitoring similar to that in citizen science datasets has led to the corroboration of change, in particular for diseases or declines, e.g. the discovery of Devil Facial Tumour Disease in Tasmanian Devils (*Sarcophilus harrisii*) through a state-wide roadside spotlight survey dataset in Tasmania, Australia (Hawkins et al. 2006). Events like the uncovering of a never-before seen behaviour are probably more likely to be reported in local ornithological journals (e.g. Martin et al. 2003), newsletters or other informal communications rather than international publications.

Only Atlases were applied to social research or recreation objectives, and only a few Atlas and BBS applications focused on education (Table 2). 'Human-focused' objectives have low data requirements, as they concentrate on the citizen scientists rather than species that might require rigorous sampling protocols to cover space and time needs, but they have the potential for high impact (Fig. 1). Social research suits the data collection protocols of Atlases rather than BBS programs, with the undirected nature of sampling in many Atlases providing information about observer behaviour that can be mined and analysed (Tulloch et al. 2013; Tulloch and Szabo 2012). Social research, recreation and education objectives may feature poorly relative to management and knowledge outcomes because there are alternative ways to achieve education objectives than through scientific publication, for instance through online information pages (e.g. BirdLife Australia's Bird Finder: http://www.birdsinbackyards.net/finder (accessed October 2012)), or providing resources for participants to gain essential skills (e.g. North American BBS Methodology Training Program: http://137.227.245.162/bbs/participate/(accessed October 2012)).

5. Features of useful volunteer monitoring datasets

Citizen science projects must cope with trade-offs between data quality and quantity, standardisation of sampling methods, quantification of sampling effort, and mismatches in skills and expectations between data collectors and data users (Robertson et al. 2010). The results of our GLMs showed that the more spatial coverage an Atlas has (in both resolution and extent), the more it is used for research (Table A.3). Atlases with increased spatial resolution (i.e. smaller size of minimum and major spatial units) were also used more than those that collected data at a coarse scale (Table A.4). Many past Atlas projects (e.g. South African Bird Atlas Project 1 (SABAP1), First Australian Bird Atlas) collected data at a resolution too coarse to be used for species distribution modelling and most conservation planning (Mills et al. 2010), because the sampling units were too heterogeneous to be linked with spatial covariates (Araujo et al. 2005; Rouget 2003). Another focus that limited the usefulness of many previous Atlases was to achieve 'completeness', i.e. to fill in all the gaps. This is not necessarily useful, and in fact could direct valuable volunteer attention away from where it is most needed. We showed that Atlas 'completeness' had no statistically significant impact on how often the Atlas was used (Table A.3).

Many authors have discussed the relative merits of increased temporal resolution of data collection (Lindenmayer and Likens 2010a; Robertson et al. 2010). The length of Atlases ranged from 1 to 34 years (mean (SE) = 5.68 (0.85)), compared with a range of 9 to 111 years (mean (SE) = 26.18 (8.99)) for BBS datasets. We found no impact of increased temporal resolution of Atlas data on the number of times an Atlas was used for a scientific publication (Table A.3). However, Atlases that included spatially and temporally structured aspects similar to BBS protocols (increasing temporal resolution through either length of or replication within Atlas), were used more than those that did not (Tables A.3 and A.4). BBS programs had on average five times more publications (mean 12.2 papers/BBS) than Atlases (mean 2.3 papers/Atlas), which provides evidence that longitudinal datasets such as BBS are more useful than purely cross-sectional schemes (e.g. many Atlases), at least for time-dependent questions. Furthermore, the citation rates of all BBS applications (mean (SE) = 3.14 (0.29), max 21.5 per year) were significantly higher than those of Atlases (mean (SE) = 1.93 (0.22), max 10.6 per year; $F = 9.88$, d.f. = 1,228, $p = 0.002$), suggesting that longitudinal monitoring is also more influential in the scientific literature (Appendix B). It should also be noted that many covariates are compounded here, including the country of origin of the dataset, institution coordinating the dataset, and survey methodology, all of which might also impact the influence of the dataset in the scientific literature. For example, some Atlases have taken a more structured methodology that directs volunteers to cover a representative sample of all environments or habitats, which might result in greater applicability to multiple objectives (Appendix D). Examples of these are the Atlas II of Breeding Birds in Britain and Ireland, and the New Catalan Breeding Bird Atlas 1999-2002, which have citation rates higher than the average for all Atlases (mean (SE) = 3.28 (1.40) and mean (SE) = 2.35 (0.49) respectively).

Low citation rates might indicate a lack of confidence or a lack of scientific interest in a publication. A lack of confidence in the scientific community in the results of a publication could be attributed to weak inferences due to a failure to model the sampling processes that give rise to the data, hence ignoring such issues as detection probabilities that are less than one and variable across space or time, or misclassification due to incorrect species identification. One problem unique to Atlas datasets and their analysis is fuzzy temporal resolution. Atlas data may represent multiple years of surveys, but are typically treated as snapshots in time. Analyses that deal with these issues are likely to be more robust than those that ignore them.

6. Investment in citizen science monitoring programs

The costs of coordinating citizen science programs with different monitoring protocols differ, with the structured nature of BBS sampling requiring more planning and coordination compared with Atlases (Appendices E and F).The main costs for the coordinating agency of a volunteer dataset are data compilation, coordination of sampling and volunteer communication. We found 82 Bird Atlases applied to scientific publications in 2005–2010 (mean (SE) = 2.3 (0.3) papers per dataset; Appendix C), almost eight times more than the number of BBS datasets used (mean (SE) = 12.2 (7.6) papers per dataset; Appendix D). The New Atlas of Australian Birds was the Atlas that inspired the most publications (15), whereas the Atlas with the highest investment was the EBCC Atlas of European Breeding Birds (Appendix E). The North American Breeding Bird Survey was used in the most papers (94), and the Christmas Bird Count had the most investment (Appendix F). The total number of hours volunteers spent collecting data for Atlases (mean (SE) =186,500 (70,300)) was similar to the overall hours contributed to BBS programs (mean (SE) = 147,900 (86,600); $F = 0.12$, d.f. = 1,23, $p = 0.73$). The total investment by volunteers and coordinators in collecting the data for each Atlas dataset (mean (SE) = US$10,133,500 (3,564,600)) was also similar on average to that of BBS programs (mean (SE) = US$10,014,200 (5,165,400); $F = 0.14$, d.f. = 1, 23, $p = 0.73$). However, there was a significant difference in the number of hours invested by volunteers annually in each type of citizen science ($F = 23.83$, d.f. = 1,23, $P < 0.001$), with significantly lower annual investments in BBS programs (mean (SE) = US$431,100 (65,600)) compared with Atlases (mean (SE) = US$1,097,300 (279,800)). This translated to significantly lower volunteer investments per publication output for BBS relative to Atlas programs ($F = 5.60$, d.f.= 1,230, $p = 0.03$; Fig. 2). Taken together this means that the cost per paper in terms of volunteer effort is much cheaper for BBS than Atlas programs.

There was no strong evidence to suggest that increasing total and annual investment in Atlases increases scientific publications (Fig. 3), meaning that more hours spent by volunteers providing surveys do not result in significantly more publications. The cost-effectiveness of Atlases for informing science (measured by scientific publications/annual investment) was highest for small investments (<US$500,000 annual investment by volunteers and coordinators; Appendix E). In contrast with Atlases, the benefit of BBS schemes increased rapidly with investment (Fig. 3), due to a combination of more scientific publications and lower annual volunteer investment (Appendix F, Fig. 2). This means increasing data quantity in BBS schemes (through higher levels of volunteer effort), will positively impact the number of possible applications, as longer time-series sets open up more possibilities, e.g. unexpected changes and changes over a long time frame such as invasive alien organisms and climate change.

We determined the benefit threshold of a citizen science program strategy (here Atlases or BBS schemes), which is the area on the return on investment curve where there are few gains in benefits with increased investment (i.e. diminishing returns). The benefit threshold was considerably higher for BBS schemes compared with Atlases even when the outlier of the North American BBS was removed (Fig. 3). As expected, with increasing investment in coordination there was an increase in the benefits accrued from Atlases (this was a linear relationship; Fig. 4), meaning that the longer an Atlas runs, the more papers there are likely to be published from the data collected. Clearly, benefits will not increase forever, but up to around US$2 million, there is no sign of a reduced rate of return. There was no evidence that the number of applications produced from BBS schemes was higher for higher levels of coordination (i.e. more years running; Fig. 4), indicating that it is the combined efforts of the coordinators and the volunteers that lead to the beneficial outcomes of BBS investment (Fig. 3).

Despite the higher investment by volunteers in many Atlases compared with BBS programs, Atlases in general had a lower impact on the scientific literature (in particular for investments of below US$1.5 million; Fig. 5). Our evidence suggests that levels of investment over approximately US$2 million in BBS schemes result in little increase in benefit in either number of papers (Fig. 3) or citation rates (Fig. 5).In contrast, very high investments in Atlas programs (i.e. >US$2 million) eventually resulted in higher citation rates (Fig. 5). This is probably because use of Atlas data where there is low investment is usually restricted to simple methodological or educational applications with low data requirements, with the more highly cited applications using larger more extensive datasets that allow the focus to switch to objectives with higher impact. The average citation rate of BBS programs remained relatively high regardless of the amount of effort invested (Fig. 5). BBS data are richer (e.g. providing abundances and covariates), so they can be used to investigate more complex methodological questions.

7. A cost-effectiveness approach to guide planning of volunteer monitoring

Citizen science datasets are extremely valuable if judged by the size of the investment in them (Appendices E and F). However, these data come with a cost that includes coordination, communication with volunteers, and data checking and compilation. If datasets are on-going, these costs can quickly mount into the millions. The way in which a volunteer monitoring program is planned and undertaken is therefore a trade-off between spending resources to achieve different objectives that have different data requirements (Chadès et al. 2011; McDonald-Madden et al. 2010).

Organisations wishing to set up a volunteer monitoring scheme should first determine what the relative costs (e.g. long-term coordination and other elements) and benefits (e.g. potential usefulness of the dataset for achieving different research objectives) of such a scheme would be. These can be weighed against each other to determine if the benefits (e.g. publications advancing our scientific knowledge, increased public education and happiness) outweigh the costs. Our estimated average ‘investment’ in producing a scientific publication using a BBS dataset ranged from as low as US$12,000 (Puerto Rican Breeding Bird Survey) to US$840,000 (Catalan Common Bird Survey). The mean of US$253,866 per BBS was considerably lower than the average of over US$2 million of volunteer effort per Atlas publication, although BBS programs were more expensive to coordinate (Appendices E and F). It should be noted that our approach to calculate the benefits of a citizen science scheme is just one of many. Other approaches might include exploring the impact of a scheme on the ‘grey’ literature (e.g. government reports and conservation agency planning documents), or to search more widely for non-scientific publications (e.g. using a different search engine such as Google Scholar; see Appendix G for an example), rather than investigating only the scientific impact of data. Our review was not comprehensive – it was biased towards publications that explicitly name their dataset either in their keywords or abstract (for papers found using Web of Science search criteria), or in the main body of their text (for papers retrieved using Google Scholar). Because of this, a number of papers published in high-rank journals were not reviewed, as the citizen science datasets these papers use are not reported in the main text of the publication, but rather in the Supplementary Material. For example, publications by Araujo et al. (2009) and Beale et al. (2008) in the *Proceedings of the National Academy of Sciences of the U.S.A.* used, but did not report, the name of the dataset (European Breeding Bird Atlas). Publications such as these were not found by the traditional searching methods used here (i.e. Web of Science), and changing the search methodology (to either search for a particular program or all programs in google scholar) also failed to detect these and other more recent high-impact publications. Notably, papers by Thuiller et al. (2011) in *Nature* and Devictor et al. (2012) in *Nature Climate Change* have mean citation rates of 34/year. Such papers, when known, reveal that it is hard to ever comprehensively grasp a fully comprehensive realisation of the contribution of citizen science. Our study has shown how diverse these benefits might be from a sample of the scientific literature. Further, the definition of benefits will ultimately relate to the kinds of objectives that the data are intended to inform.

Increasing our investment in a volunteer-monitoring program does not necessarily lead to higher quality data and more publications. Businesses typically conduct a scoping analysis to investigate the level of potential funding available for a particular investment. Citizen science programs can do the same. If an initial scoping analysis for investment suggests low investment by volunteers (or funding bodies), then a cross-sectional scheme with low institutional input (i.e. little structure or direction of volunteers) provides more 'bang for your buck' in terms of scientific outputs (Fig. 3). However, the data collection protocols of unstructured cross-sectional schemes (such as many Bird Atlases) mean that they are not always able to answer the more sophisticated or management-oriented high-impact questions that more structured schemes are able to answer (Fig. 2 and 4). If we believe there will be a large and sustained volunteer effort, the repeated sampling protocol of a longitudinal scheme such as a BBS is more cost-effective in terms of scientific output (Fig. 3).

8. Future of citizen science datasets

With limited resources for monitoring, there is a growing need to devise programs that are both cost-effective and capable of fulfilling multiple objectives. We have shown that volunteer-collected data from different volunteer-monitoring protocols are useful for multiple objectives. However, the spatial extent and resolution of data, as well as the structure of the program (e.g. coordination of volunteers, replicated sampling), limits the questions that can be addressed. Although large data collections are amassed through different monitoring protocols, the higher impact of applications using longitudinal data such as BBS in the scientific world suggests that cross-sectional data such as Atlases are less useful for answering pressing topics, perhaps because of methodological or analysis issues (e.g. volunteer bias, coarse-scale sampling). However, this will most likely depend on whether the objective has a space- and time-aspect, and the level of structure in the Atlas sampling design. Undirected monitoring (i.e. without a clear objective or sampling design) can use up considerable resources and time yet achieve very little, resulting in inadequate datasets that fail to inform decisions (McNie 2007; Sarewitz and Pielkejr 2007), and might be used for the wrong purposes if they create the illusion that sufficient monitoring has been carried out (Legg and Nagy 2006). We therefore make the following recommendations to ensure citizen science datasets are used to their full potential:

1. Incorporate elements of BBS protocols into Atlases, and emphasise:

   a) fine-scale data collection,

   b) temporal replication that covers the full range of habitats or land use types (Schmeller et al. 2012), and

   c) communication of data needs with volunteers.

   Repeated sampling will allow more flexibility in applications for achieving alternative objectives. Many volunteers are already doing this (e.g. the new fixed route surveys in the New Atlas of Australian Birds). Communication with volunteers could be through a newsletter informing them of recent activity and data gaps, or an online site that allows users to update their own lists, compare with others' lists, and access information about an area of interest in a readily usable format (e.g. eBird; Marris 2010; Sullivan et al. 2009).

2. Regional coordinators are in place to maintain data quality and iteratively assess the value of additional information. Increased quantity of data does not necessarily equate to increased quality or usefulness for today's research questions (Mackechnie et al. 2011).

3. Under-explored applications with lower data requirements but high impact (e.g. social research) are encouraged in the scientific community, particularly for Atlases with a less structured design, which are ideal for answering these questions due to the untargeted nature of sampling. Rather than struggling with how to account for data issues and waiting for datasets to be 'completed' before use, researchers could now use data limitations such as sampling bias to focus studies on the people collecting the data. These social research studies could range from explorations of human behaviour, to the science of 'conservation psychology', to investigating the reasons and motivations behind volunteering and public involvement in conservation. Atlases therefore have the potential to fulfil important political, social and scientific needs that cannot be answered by BBS datasets.

4. Coordination and communication between researchers and the organisations carrying out volunteer monitoring is enhanced, by setting up and paying attention to scientific advisory boards. Scientists and those planning or coordinating citizen science programs need to talk more about the objectives, benefits and costs of the program to ensure that the data are useable for the research questions of today and the future. Program developers and coordinators should be clear about the primary uses of the resulting data, rather than providing often vague lists of benefits (e.g., conservation) without

guidance as to how data might be used for specific purposes and issues. Program coordinators can identify one or more primary uses of the monitoring dataset, identify the characteristics of a monitoring program that would answer their questions (e.g., cross-sectional vs. longitudinal data), then ensure that the monitoring program can meet these needs. Data should be made freely available to scientists by the custodians of citizen science programs to maximise the use of these data to inform scientific research. In return, it is important for scientists and data-users to clarify the objectives to which data are to be put when obtaining data from custodians, and to clearly acknowledge datasets that have contributed to learning or management decisions in publications. If the authors of applications of volunteer-monitoring data do not acknowledge the considerable efforts of citizen science programs to collect data useful for scientific research, it is difficult to understand and communicate the true benefits of these data to the public and policy-makers.

We are just beginning to see the multiple benefits of using data from citizen science programs to monitor changes in the environment (Freeman et al. 2007; Jiguet et al. 2005; Link et al. 2008; Zuckerberg et al. 2009). Citizen science is not perfect, but no data are (Szabo et al. 2012). This should not preclude use of this vital resource. We reiterate calls for the need to learn from examples where volunteers are used effectively (Mackechnie et al. 2011), and the need for quality assurance and quality control (without this, quantity of data increases but perhaps only a proportion of it is useable, and this proportion is usually unknown). In particular, future research should learn from the strengths of these datasets as opposed to focusing on their shortfalls. Used appropriately, both Atlas and BBS programs can be a vital tool for informing not only management, methods and ecology, but also human behaviour, policy and planning, and resource allocation to conservation.

Acknowledgements

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Supporting Information

Results of models describing Atlas characteristics (Appendix A), ANOVA analyses (Appendix B), the list of Atlas applications (Appendix C) and BBS applications (Appendix D), estimated costs of Atlases (Appendix E) and Breeding Bird Surveys (Appendix F) from our review, and sensitivity analyses of the search method (Appendix G), 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.

References

Araujo, M.B., Thuiller, W., Williams, P.H., Reginster, I., 2005. Downscaling European species atlas distributions to a finer resolution: implications for conservation planning. Global Ecology and Biogeography 14, 17-30.
Araújo, M.B., Thuiller, W., Yoccoz, N.G., 2009. Reopening the climate envelope reveals macroscale associations with climate in European birds. Proceedings of the National Academy of Sciences 106, E45-E46.
Bahn, V., McGill, B.J., 2007. Can niche-based distribution models outperform spatial interpolation? Global Ecology and Biogeography 16, 733-742.
Beale, C.M., Lennon, J.J., Gimona, A., 2008. Opening the climate envelope reveals no macroscale associations with climate in European birds. Proc Natl Acad Sci U S A 105, 14908-14912.
Blancher, P.J., Phoenix, R.D., Badzinski, D.S., Cadman, M.D., Crewe, T.L., Downes, C.M., Fillman, D., Francis, C.M., Hughes, J., Hussell, D.J.T., Lepage, D., McCracken, J.D., McNicol, D.K., Pond, B.A., Ross, R.K., Russells, R., Venier, L.A., Weeber, R.C., 2009. Population trend status of Ontario's forest birds. Forestry Chronicle 85, 184-201.
Bodin, O., Crona, B.I., 2009. The role of social networks in natural resource governance: What relational patterns make a difference? Global Environmental Change-Human and Policy Dimensions 19, 366-374.
Booth, J.E., Gaston, K.J., Evans, K.L., Armsworth, P.R., 2011. The value of species rarity in biodiversity recreation: A birdwatching example. Biological Conservation 144, 2728-2732.
Botts, E.A., Erasmus, B.F.N., Alexander, G.J., 2010. Geographic sampling bias in the South African Frog Atlas Project: implications for conservation planning. Biodiversity and Conservation 20, 119-139.
Brotons, L., Herrando, S., Pla, M., 2007. Updating bird species distribution at large spatial scales: applications of habitat modelling to data from long-term monitoring programs. Diversity and Distributions 13, 276-288.
Buckland, S.T., Magurran, A.E., Green, R.E., Fewster, R.M., 2005. Monitoring change in biodiversity through composite indices. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 243-254.
Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach, 2nd edn. Springer-Verlag, New York.
Chadès, I., Martin, T.G., Nicol, S., Burgman, M., Possingham, H.P., Buckley, Y.M., 2011. General rules for managing and surveying networks of pests, diseases, and endangered species. Proceedings of the National Academy of Sciences 108, 8323-8328.
Clayton, S., Myers, G., 2009. Conservation Psychology: understanding and promoting human care for nature. Wiley-Blackwell, Chichester, UK.
Cohn, J.P., 2008. Citizen science: Can volunteers do real research? BioScience 58, 192-197.
Crosbie, S.P., Koenig, W.D., Reisen, W.K., Kramer, V.L., Marcus, L., Carney, R., Pandolfino, E., Bolen, G.M., Crosbie, L.R., Bell, D.A., Ernest, H.B., 2008. Early Impact of West Nile Virus on the Yellow-Billed Magpie (*Pica nuttalli*). The Auk 125, 542-550.
Dennis, R.L.H., Thomas, C.D., 2000. Bias in Butterfly Distribution Maps: The Influence of Hot Spots and Recorder's Home Range. Journal of Insect Conservation 4, 73-77.
Devictor, V., Julliard, R., Couvet, D., Jiguet, F., 2008. Birds are tracking climate warming, but not fast enough. Proceedings of the Royal Society B: Biological Sciences 275, 2743-2748.
Devictor, V., van Swaay, C., Brereton, T., Brotons, L., Chamberlain, D., Heliola, J., Herrando, S., Julliard, R., Kuussaari, M., Lindstrom, A., Reif, J., Roy, D.B., Schweiger, O., Settele, J., Stefanescu, C., Van Strien, A., Van Turnhout, C., Vermouzek, Z., WallisDeVries, M., Wynhoff, I., Jiguet, F., 2012. Differences in the climatic debts of birds and butterflies at a continental scale. Nature Clim. Change 2, 121-124.
Dickinson, J.L., Zuckerberg, B., Bonter, D.N., 2010. Citizen Science as an Ecological Research Tool: Challenges and Benefits. Annual Review of Ecology, Evolution, and Systematics 41, 149-172.
Donald, P.F., Fuller, R.J., 1998. Ornithological atlas data: a review of uses and limitations. Bird Study 45, 129-145.
Dunn, A.M., Weston, M.A., 2008. A review of terrestrial bird atlases of the world and their application. Emu 108, 42-67.
Field, S.A., Tyre, A.J., Possingham, H.P., 2005. Optimizing allocation of monitoring effort under economic and observational constraints. Journal of Wildlife Management 69, 473-482.
Freeman, S.N., Noble, D.G., Newson, S.E., Baillie, S.R., 2007. Modelling population changes using data from different surveys: the Common Birds Census and the Breeding Bird Survey:CapsuleA method for producing and

validating long-term population indices using data from the Common Birds Census and its successor, the Breeding Bird Survey, is described. Bird Study 54, 61-72.
Fujisaki, I., Pearlstine, E.V., Miller, M., 2008. Detecting population decline of birds using long-term monitoring data. Population Ecology 50, 275-284.
Gibbons, D.W., Donald, P.F., Bauer, H.-G., Fornasari, L., Dawson, I.K., 2007. Mapping avian distributions: the evolution of bird atlases. Bird Study 54, 324 - 334.
Greenwood, J.J.D., 2007. Citizens, science and bird conservation. Journal of Ornithology 148, S77-S124.
Hawkins, C.E., Baars, C., Hesterman, H., Hocking, G.J., Jones, M.E., Lazenby, B., Mann, D., Mooney, N., Pemberton, D., Pyecroft, S., Restani, M., Wiersma, J., 2006. Emerging disease and population decline of an island endemic, the Tasmanian devil *Sarcophilus harrisii*. Biological Conservation 131, 307-324.
Howe, J., 2006. The rise of crowdsourcing. Wired 14, 06.
Jiguet, F., Julliard, R., Couvet, D., Petiau, A., 2005. Modeling spatial trends in estimated species richness using breeding bird survey data: A valuable tool in biodiversity assessment. Biodiversity and Conservation 14, 3305-3324.
Jordan, R.C., Gray, S.A., Howe, D.V., Brooks, W.R., Ehrenfeld, J.G., 2011. Knowledge Gain and Behavioral Change in Citizen-Science Programs. Conservation Biology 25, 1148-1154.
Kery, M., Royle, J.A., 2008. Hierarchical Bayes estimation of species richness and occupancy in spatially replicated surveys. Journal of Applied Ecology 45, 589-598.
Knight, A.T., Cowling, R.M., Difford, M., Campbell, B.M., 2010. Mapping Human and Social Dimensions of Conservation Opportunity for the Scheduling of Conservation Action on Private Land. Conservation Biology 24, 1348-1358.
LaDeau, S.L., Kilpatrick, A.M., Marra, P.P., 2007. West Nile virus emergence and large-scale declines of North American bird populations. Nature 447, 710-713.
Legg, C.J., Nagy, L., 2006. Why most conservation monitoring is, but need not be, a waste of time. Journal of Environmental Management 78, 194-199.
Lele, S.R., 2006. Sampling Variability and Estimates of Density Dependence: A Composite-Likelihood Approach. Ecology 87, 189-202.
Levrel, H., Fontaine, B., Henry, P.-Y., Jiguet, F., Julliard, R., Kerbiriou, C., Couvet, D., 2010. Balancing state and volunteer investment in biodiversity monitoring for the implementation of CBD indicators: A French example. Ecological Economics 69, 1580-1586.
Lindenmayer, D.B., Likens, G.E., 2010a. Effective Ecological Monitoring. CSIRO Publishing, Collingwood, VIC.
Lindenmayer, D.B., Likens, G.E., 2010b. The science and application of ecological monitoring. Biological Conservation 143, 1317-1328.
Link, W.A., Sauer, J.R., Niven, D.K., 2008. Combining Breeding Bird Survey and Christmas Bird Count Data to Evaluate Seasonal Components of Population Change in Northern Bobwhite. Journal of Wildlife Management 72, 44-51.
Luoto, M., Virkkala, R., Heikkinen, R.K., 2007. The role of land cover in bioclimatic models depends on spatial resolution. Global Ecology and Biogeography 16, 34-42.
Mackechnie, C., Maskell, L., Norton, L., Roy, D., 2011. The role of 'Big Society' in monitoring the state of the natural environment. Journal of Environmental Monitoring 13, 2687.
Månsson, J., Hauser, C.E., Andren, H., Possingham, H.P., 2011. Survey method choice for wildlife management: the case of moose *Alces alces* in Sweden. Wildlife Biology 17, 176-190.
Marris, E., 2010. Birds flock online: Supercomputer time will help ornithologists make ecological sense of millions of records of bird sightings. Nature Published online 10 August 2010, http://www.nature.com/news/2010/100810/full/news.102010.100395.html.
Martin, T.G., Joseph, L.N., Possingham, H.P., 2003. Black-chinned Honeyeaters (*Meliphreptus gularis gularis*) stealing koala (*Phascolartos cinereus*) fur to build a nest. Sunbird 33, 16-19.
McDonald-Madden, E., Baxter, P.W.J., Fuller, R.A., Martin, T.G., Game, E.T., Montambault, J., Possingham, H.P., 2010. Monitoring does not always count. Trends in Ecology & Evolution 25, 547-550.
McNie, E., 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environmental Science & Policy 10, 17-38.
Mills, M., Pressey, R.L., Weeks, R., Foale, S., Ban, N.C., 2010. A mismatch of scales: challenges in planning for implementation of marine protected areas in the Coral Triangle. Conservation Letters 3, 291-303.

Munson, M.A., Caruana, R., Fink, D., Hochachka, W.M., Iliff, M., Rosenberg, K.V., Sheldon, D., Sullivan, B.L., Wood, C., Kelling, S., 2010. A method for measuring the relative information content of data from different monitoring protocols. Methods in Ecology and Evolution 1, 263–273.

Nichols, J.D., Williams, B.K., 2006. Monitoring for conservation. Trends in Ecology & Evolution 21, 668-673.

Pomeroy, D., Tushabe, H., Cowser, R., 2008. Bird atlases - how useful are they for conservation? Bird Conservation International 18, S211-S222.

Possingham, H.P., Wintle, B.A., Fuller, R.A., Joseph, L.N., 2012. The conservation return on investment from ecological monitoring, In Biodiversity Monitoring in Australia. eds D. Lindenmayer, P. Gibbons, pp. 49-61. CSIRO Publishing, Melbourne.

Prior, P., Schaffner, S., 2011. Bird Identification as a Family of Activities: Motives, Mediating Artifacts, and Laminated Assemblages. Ethos 39, 51-70.

Reddy, S., Dávalos, L.M., 2003. Geographical sampling bias and its implications for conservation priorities in Africa. Journal of Biogeography 30, 1719-1727.

Robertson, M.P., Cumming, G.S., Erasmus, B.F.N., 2010. Getting the most out of atlas data. Diversity and Distributions 16, 363-375.

Rouget, M., 2003. Measuring conservation value at fine and broad scales: implications for a diverse and fragmented region, the Agulhas Plain. Biological Conservation 112, 217-232.

Rowhani, P., Lepczyk, C.A., Linderman, M.A., Pidgeon, A.M., Radeloff, V.C., Culbert, P.D., Lambin, E.F., 2008. Variability in Energy Influences Avian Distribution Patterns Across the USA. Ecosystems 11, 854-867.

Royle, J.A., Nichols, J.D., Kery, M., 2005. Modelling occurrence and abundance of species when detection is imperfect. OIKOS 110, 353-359.

Salzer, D., Salafsky, N., 2006. Allocating resources between taking action, assessing status, and measuring effectiveness of conservation actions. Natural Areas Journal 26, 310-316.

Sarewitz, D., Pielkejr, R., 2007. The neglected heart of science policy: reconciling supply of and demand for science. Environmental Science & Policy 10, 5-16.

Schmeller, D., Henle, K., Loyau, A., Besnard, A., Henry, P.-Y., 2012. Bird-monitoring in Europe – a first overview of practices, motivations and aims. Nature Conservation 2, 41-57.

Schulte, L.A., Pidgeon, A.M., Mladenoff, D.J., 2005. One hundred fifty years of change in forest bird breeding habitat: Estimates of species distributions. Conservation Biology 19, 1944-1956.

Storch, D., Evans, K.L., Gaston, K.J., 2005. The species-area-energy relationship. Ecology Letters 8, 487-492.

Sullivan, B.L., Wood, C.L., Iliff, M.J., Bonney, R.E., Fink, D., Kelling, S., 2009. eBird: A citizen-based bird observation network in the biological sciences. Biological Conservation 142, 2282-2292.

Szabo, J., Vesk, P., Baxter, P., Possingham, H., 2010. Regional avian species declines estimated from volunteer-collected long-term data using List Length Analysis. Ecological Applications 20, 2157-2169.

Szabo, J.K., Fuller, R.A., Possingham, H.P., 2012. A comparison of estimates of relative abundance from a weakly structured mass-participation bird atlas survey and a robustly designed monitoring scheme. Ibis 154, 468-479.

Thomas, L., 1996. Monitoring long-term population change: Why are there so many analysis methods? Ecology 77, 49-58.

Thomsen, D.C., 2008. Community-based research: facilitating sustainability learning. Australasian Journal of Environmental Management 15, 222-230.

Thuiller, W., Lavergne, S., Roquet, C., Boulangeat, I., Lafourcade, B., Araujo, M.B., 2011. Consequences of climate change on the tree of life in Europe. Nature 470, 531-534.

Tulloch, A.I.T., Mustin, K., Possingham, H.P., Szabo, J.K., Wilson, K.A., 2013. To boldly go where no volunteer has gone before: predicting volunteer activity to prioritise surveys at the landscape scale. Diversity and Distributions 19, 465-480.

Tulloch, A.I.T., Szabo, J.K., 2012. A behavioural ecology approach to understand volunteer surveying for citizen science datasets. Emu 112, 313-325.

Underhill, L.G., Oatley, T.B., Harrison, J.A., 1991. The role of large scale data collection projects in the study of southern African birds. Ostrich 62, 124–148.

Van Turnhout, C.A.M., Foppen, R.P.B., Leuven, R.S.E.W., Siepel, H., Esselink, H., 2007. Scale-dependent homogenization: Changes in breeding bird diversity in the Netherlands over a 25-year period. Biological Conservation 134, 505-516.

Weston, M.A., Silcocks, A., Tzaros, C.L., Ingwersen, D., 2006. A survey of contributors to an Australian bird atlassing project: demography, skills and motivation. Australian Journal on Volunteering 11, 51-58.

Whittaker, R.J., Nogues-Bravo, D., Araujo, M.B., 2007. Geographical gradients of species richness: a test of the water-energy conjecture of Hawkins et al. (2003) using European data for five taxa. Global Ecology and Biogeography 16, 76-89.
Wilson, H.B., Kendall, B.E., Fuller, R.A., Milton, D.A., Possingham, H.P., 2011. Analyzing Variability and the Rate of Decline of Migratory Shorebirds in Moreton Bay, Australia. Conservation Biology 25, 758-766.
Wintle, B.A., Runge, M.C., Bekessy, S.A., 2010. Allocating monitoring effort in the face of unknown unknowns. Ecology Letters 13, 1325-1337.
Zuckerberg, B., Woods, A.M., Porter, W.F., 2009. Poleward shifts in breeding bird distributions in New York State. Global Change Biology 15, 1866-1883.

Table 1. Applications of citizen science monitoring data highlighted in past reviews and how they relate to our eight objectives.

Objectives	Underhill et al. 1991	Donald and Fuller 1998	Greenwood 2007	Gibbons 2007	Dunn and Weston 2008	Pomeroy 2008	Robertson 2010	Dickinson et al. 2010
Management		- Generate hypotheses about causes of range change			- Generate hypotheses about causes of range change			
Awareness to inform policy and planning	- Land-use planning - Changes in bird distribution/ abundance in relation to explanatory variables - Historic changes in distribution -Environmental Impact Assessments	- Document distribution and population for conservation and research purposes - Document range and population changes	- Changes in bird distribution/ abundance in relation to explanatory variables		- Document range and population changes - Land-use planning - Conservation planning - Pest-control planning - Risk assessment for introduced species - Disease-control planning - Environmental Impact Assessments	- Conservation planning - Changes in bird distribution/ abundance in relation to explanatory variables	- Assess anthropogenic impacts (climate change, urbanisation) - Conservation planning - Environmental Impact Assessments	- Landscape ecology: habitat loss and fragmentation - Global climate-change effects on birds - Biocontaminants, biogeochemistry, and ecosystem ecology
Education and engagement for leverage		- Education and recreation	- Education		- Education and recreation - Commercial applications			
Serendipity								- Find new invasive organisms
Recreation		- Education and recreation			- Education and recreation			
Social research								
Ecological research	- Distribution - Phenology - Movement	- Bird-environment associations - Test ecological theory	- Migration - Distribution and habitat - Population studies	- Distribution	- Bird-environment associations - Test ecological theory - Phenology - Movement patterns	- Distribution	- Ecological explorations (e.g. biogeography, niche modelling) - Test ecological theory	- Global climate-change effects on birds - Macroecology - Population and community ecology
Improving methods		- Provide a framework for survey design		- Improve survey methods	- Provide a framework for survey design		- Test new modelling techniques	- Develop tools to deal with observer error - Sampling bias - Methods for improving data analysis

Table 2. Summary of the eight different objectives of applications of volunteer bird monitoring data from Atlases and Breeding Bird Surveys between 2005 and 2010 (Papers could be assigned to more than one objective, so percentages do not add up to 100%)

Objective	Description	Percentage of Atlas papers (total number)	Percentage of BBS papers (total number)
1	Management	3 (3)	14 (19)
2	Awareness	31 (30)	28 (38)
3	Public education	4 (4)	4 (6)
4	Serendipity	0	0
5	Recreation	1 (1)	0
6	Social research	5 (5)	0
7	Ecological knowledge	90 (85)	65 (89)
8	Improving methods	34 (32)	37 (50)

Figure legends

Figure 1. Comparison of influence in the scientific literature of each objective for Atlas (light bars) and BBS (dark bars) applications, showing mean (SE) citation rate per paper.

Figure 2. Mean (SE) annual investment by volunteers and with coordinators added relative to publication output, in Atlas (light bars) and BBS (dark bars) programs.

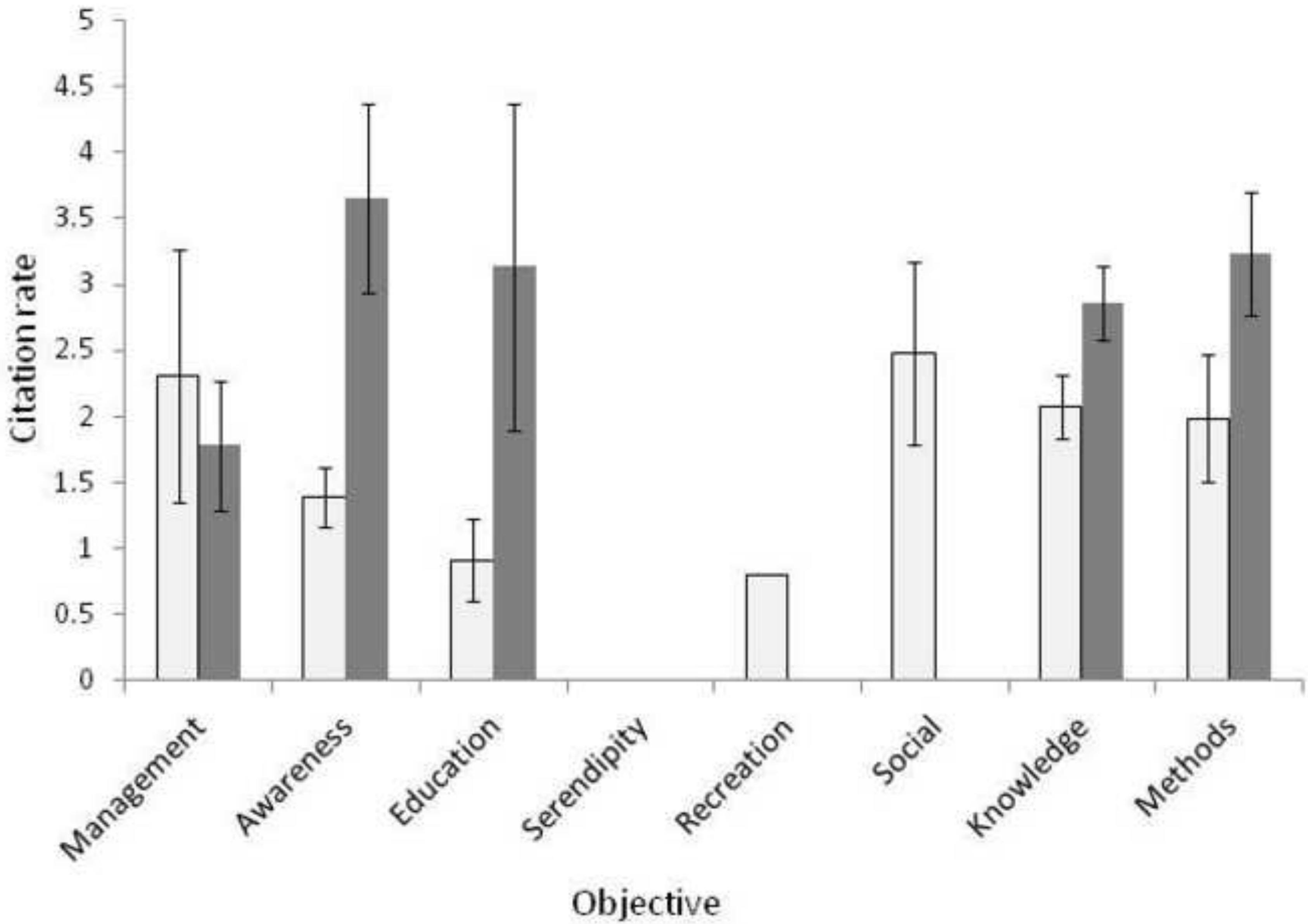
Figure 3. The return on investment in the most-cited Atlases (open circles) and Breeding Bird Surveys (crosses), measured as benefit (i.e. number of papers published in both Web of Science and Google Scholar), compared with average annual monetary investment (by volunteers and coordinators). The diminishing returns curve of best fit for Atlases (dashed line) is *Benefit* = 0.39ln(*investment*) + 0.61(R^2 = 0.01: no relationship), and for BBS (solid line, outlier of North American BBS removed) is *Benefit* = 10.35ln(*investment*) – 126.88 (R^2 = 0.62).

Figure 4. The return on investment in the most-cited Atlases (open circles) and Breeding Bird Surveys (crosses), measured as benefit (i.e. number of papers published), compared with total monetary investment in coordination. The curve of best fit for Atlases (dashed line) is *Benefit*= ($7x10^{-6}$)(*investment*) – 0.49(R^2 = 0.31), and for BBS (solid line) is *Benefit* = –0.94ln(*investment*) + 19.38 (R^2 = 0.02: no relationship).

Figure 5. The return on investment in the most-cited Atlases (open circles) and Breeding Bird Surveys (crosses), measured as benefit (i.e. average annual citation rate), compared with average annual monetary investment (by volunteers and coordinators). The curve of best fit for Atlases (dashed line) is *Benefit* = ($4x10^{-13}$)($investment)^2$ – ($2x10^{-7}$)(*investment*) + 1.35(R^2 = 0.63), and for BBS (solid line) is *Benefit* = 0.13$investment^{0.24}$ (R^2 = 0.07: no relationship).

Supplementary Material

Figure 1



5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Citation rate
Management
Awareness
Education
Serendipity
Recreation
Social
Knowledge
Methods
Objective

Figure 2

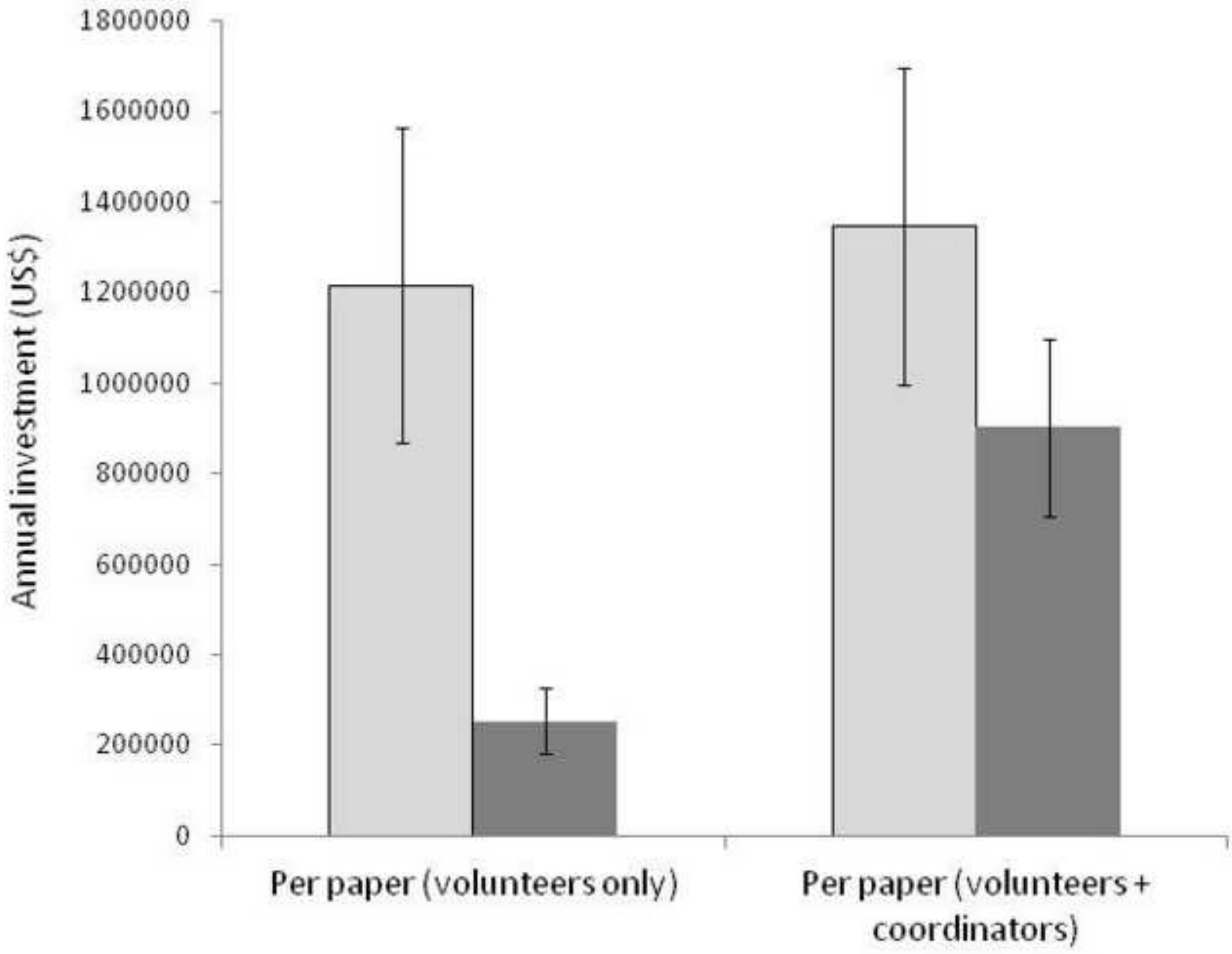

Annual investment (US$)
1800000
1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
Per paper (volunteers only)
Per paper (volunteers + coordinators)

Figure 3

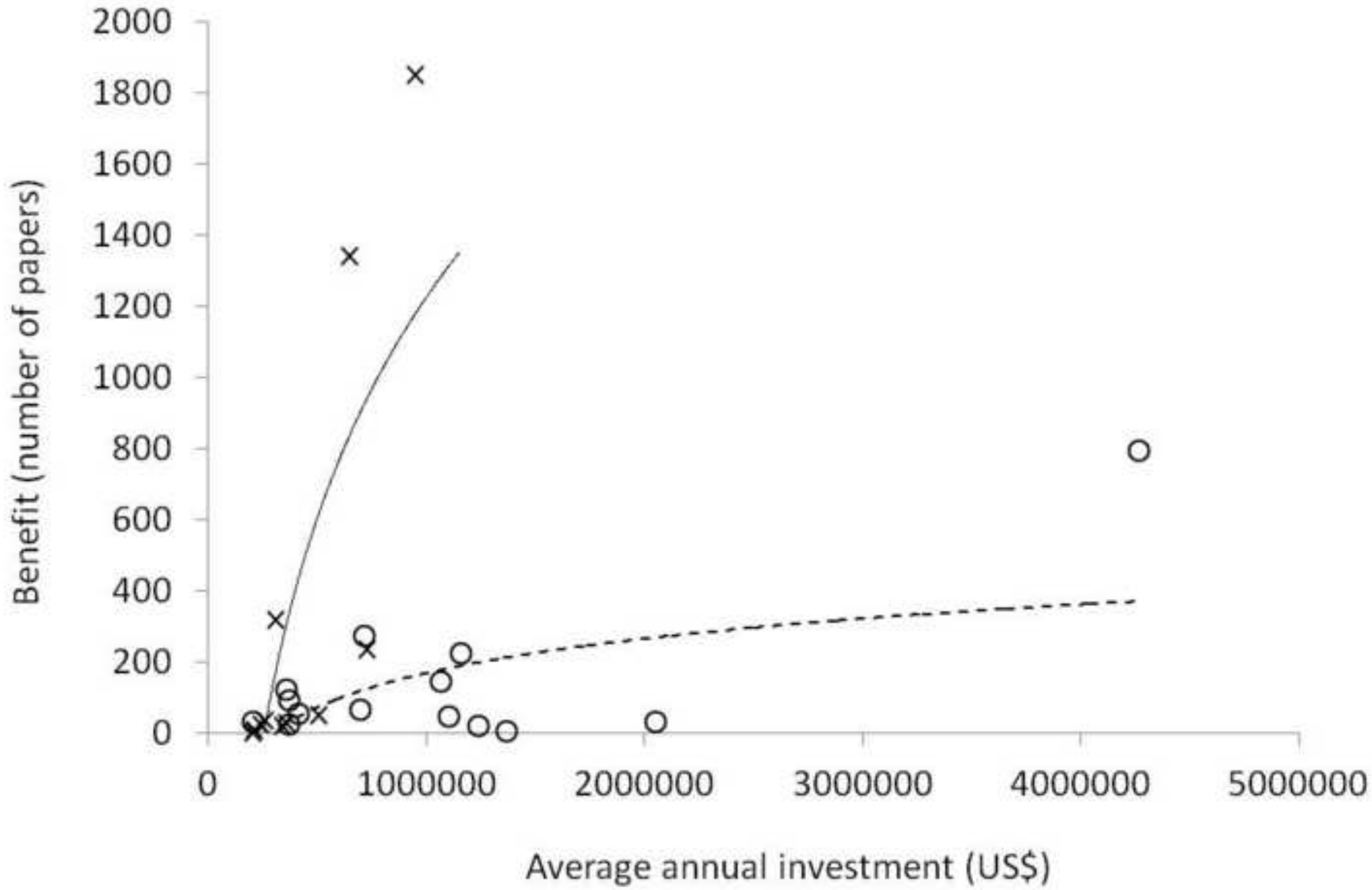

2000
1800
1600
1400
1200
1000
800
600
400
200
0
Benefit (number of papers)
0
1000000
2000000
3000000
4000000
5000000
Average annual investment (US$)

Figure 4

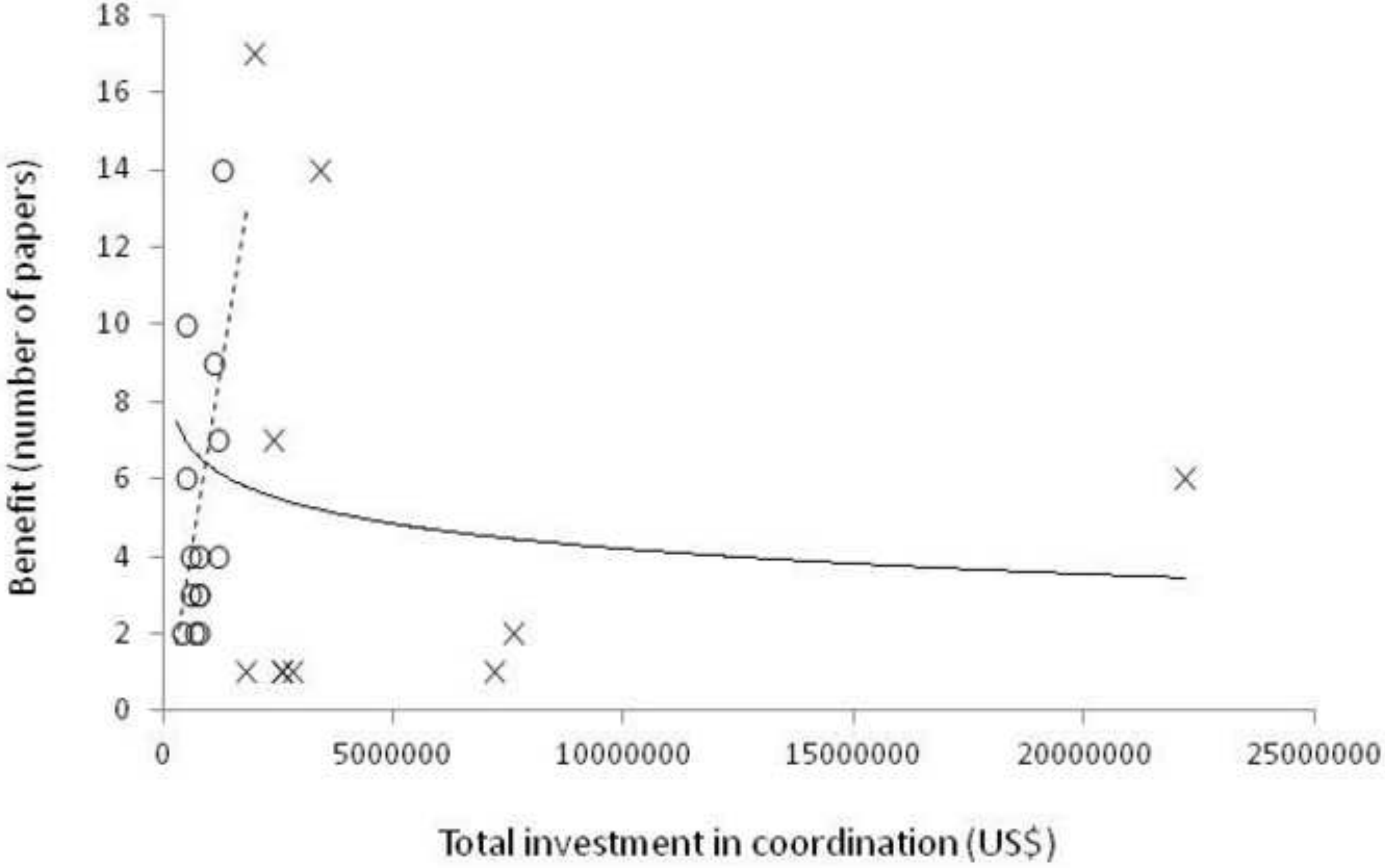
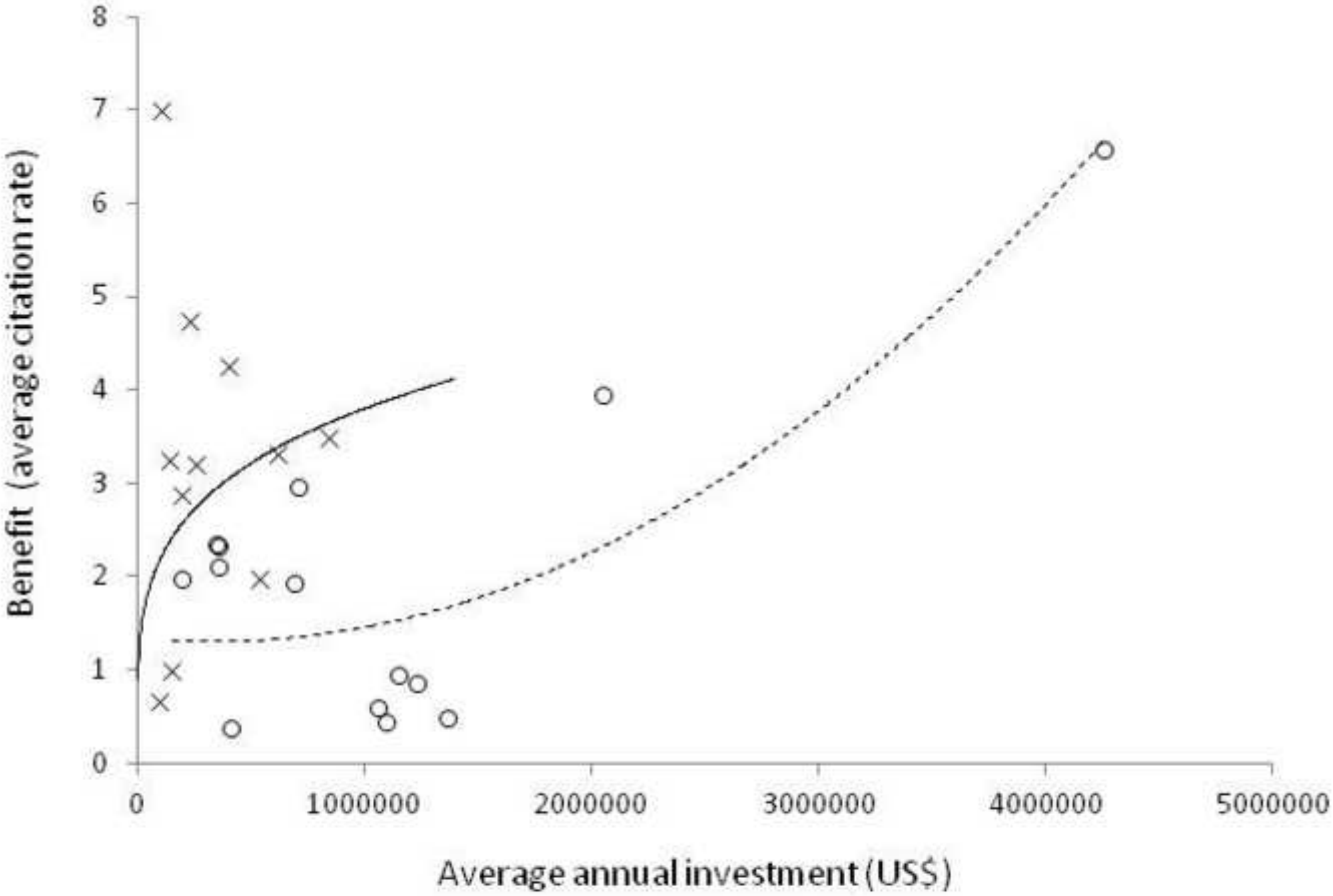

18
16
14
12
10
8
6
4
2
0
Benefit (number of papers)
0
5000000
10000000
15000000
20000000
25000000
Total investment in coordination (US$)

Figure 5


Benefit (average citation rate)
0
1
2
3
4
5
6
7
8
0
1000000
2000000
3000000
4000000
5000000
Average annual investment (US$)