Exploratory and confirmatory research in the open science era

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Abstract:

1. Applied ecological research is increasingly inspired by the Open Science movement. However, new challenges about how we define our science when biodiversity data is being shared and re-used are not solved. Among these challenges is the risk associated with blurring the distinction between research that mainly seeks to explore patterns with no *a-priori* articulated hypotheses (*exploratory research*), and research that explicitly tests *a-priori* formulated hypotheses (*confirmatory research*).
2. A rapid screening of a random selection of peer-reviewed articles suggests that neither experimental protocols nor hypothesis-testing *sensu stricto* are common in applied ecological research. In addition, most experiments are carried out on small spatial scales, which contrast with current global policy needs and research trends towards addressing large spatial and temporal scales. This latter trend make it unfeasible for policy to rely mainly on insights gained from experimental research.
3. To solve fundamental local, regional and global societal challenges, we need both exploratory and confirmatory research, and the fundamental (but different) role that hypothesis-testing and prediction play in applied ecological research should be revaluated.
4. A clearer distinction between exploratory and confirmatory research could be facilitated by allocating journal sections to different types of research; embracing new tools offered by the open science era, such as pre-registration of hypothesis; establishing new systems where *post-hoc* hypotheses emerging through exploration can also be registered for later testing; and more broad adoption of causal inference methods that foster more

structured testing of hypotheses about causal mechanisms from observational biodiversity data.

5. *Synthesis and applications*. To gain the full benefits from the open science era, researchers, funding bodies and journal editors should explicitly consider incentives that encourage openness about methods and approaches, as well as value the full plurality of scientific approaches needed to address questions in conservation science.

1. Rigorous science in applied ecology

As a response to the global biodiversity loss, conservation science and applied ecological research focus on describing patterns of biodiversity change, isolating the factors causing this change, and ultimately suggesting management solutions (Kareiva & Marvier 2012). Because biodiversity loss and ecosystem transformations are causing major challenges to present and future human societies (IPBES 2019), the rigor of the science that underpins policy and management decisions is decisive to the wellbeing of future generations of humans and the fate of our planet's biodiversity. Following some high-profile publications pointing towards a reproducibility crisis in fields such as psychology (Nosek & Collaboration 2015) and social sciences (Camerer *et al.* 2018), there is currently much focus in scholarly publications on the repeatability and reproducibility of scientific results (see e.g. the news feature in Nature by Baker 2016). Applied ecological research is not immune to these challenges, but so far the discussion has not been high on the agenda within this field. One key aspect of the discussion about scientific rigor (Nosek *et al.* 2018) is a revaluation of the distinction between research that mainly seeks to explore patterns in the data (hereafter *exploratory research*) and research that tests scientific hypotheses that are clearly stated before the study is conducted (hereafter *confirmatory research*).

In the philosophy of science, this distinction has been extensively discussed, and following the classical paper by Platt (1964) on strong inference the importance of confirmatory research has been long appreciated. Also within conservation science and applied ecology, several authors (including Caughley 1994; Betini, Avgar & Fryxell 2017; Sells *et al.* 2018) have called for more formal use of confirmatory research and application of the strong inference paradigm (sensu Platt 1964). However, a rapid screening of a sample from the applied ecological literature (**Box 1**) suggests that most researchers within the field do not follow the strong inference paradigm (Platt 1964; Sells *et al.* 2018), nor do they rely on clearly stated *a-priori* hypotheses that are tested with empirical data.

Here, we discuss how both exploratory and confirmatory research is needed in applied ecological research, and how both scientists, journal editors and funders should assist in the task of extracting the maximum value from different scientific approaches without blurring the distinction between exploration and confirmation.

1.1 A mature research community should value both exploration and confirmation

One consequence of the “Open Science” movement (Nosek *et al.* 2015) is the focus on open sharing of research data (Wilkinson *et al.* 2016). Increasing accessibility to data allows researchers to apply an ever-widening range of models to data for exploratory science. This contrast with the pleas for more widespread adoption of confirmatory research, where hypotheses are described *a-priori* and then carefully tested based on empirical data collected specifically for that purpose (Caughley 1994; Houlahan *et al.* 2017). We agree with the plea for more formal testing of scientific hypotheses in applied ecological research, but would also like to highlight the fundamental role that descriptive studies documenting the state of local or global biodiversity, or the natural history of species has for conservation science (Beissinger & Peery 2007; Pereira *et al.* 2013). Exploratory research could also generate new hypothesis that could formally be tested later. Moreover, a movement towards more planetary scale assessments, such as those carried out by the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES), makes it unfeasible for policy to rely mainly on insights gained from experimental research (Mazor *et al.* 2018; Box 1). Our rapid screening of the literature indeed suggests that large-scale studies often have a large impact, at least if measured through citation rates (**Box 1**).

Nevertheless, to avoid an ever-growing list of un-tested hypothesis emerging from exploratory research, we must also revaluate the fundamental (but different) role that hypothesis-testing and prediction play in applied ecological research (Houlahan *et al.* 2017). Only by testing *a-priori* articulated hypothesis can we robustly retain or reject the potential of a scientific hypothesis to describe natural phenomena. Unfortunately, researchers do not always follow this approach, and surveys have revealed a number of questionable research practices (Ioannidis *et al.* 2014; Fraser *et al.* 2018). Such practices include "*harking*" (Hypothesis After Results Are Known), where ad-hoc postdictions are presented as if they were already planned before the study was conducted, and "*p-hacking*" where researchers carelessly search for significant associations in the data (and often present them as if they were from *a-priori* hypotheses). Recent surveys suggest that they might be common also among ecologists and evolutionary biologists (Fraser *et al.* 2018). Without more frequent use of true hypothesis-testing, we risk that confirmation bias will result in overly self-confident 'storytelling' (Sells *et al.* 2018). Basing management actions on such research may lead to costly mis-management.

1.2 Novel ways to test ecological theories

Our brief survey of the literature (**Box 1**) (see also Betini, Avgar & Fryxell 2017; Sells *et al.* 2018) suggest that most research does not conform to strict hypothesis-testing. However, in the open science era, there are ample possibilities to increase the use and impact of confirmatory research, by more widely embracing new tools, methods, and increased data availability.

Strict experiments in applied ecology (**Box 1**) are generally conducted at small spatial scales (although there are some notable exceptions, e.g. Krebs, Boutin & Boonstra 1995; Wiik *et al.* 2019). This contrasts the fact that many ecological and policy processes operate at far larger scales (Estes *et al.* 2018). Better utilization of large-scale unreplicated natural experiments could improve understanding of causal relationships in ecological systems (Barley & Meeuwig 2017), especially the impacts of rare and extreme events (e.g. Gaillard *et al.* 2003). Such natural experiments provide researchers with the opportunity for a real-world test of a hypothesis, and can be seen as "conceptual" replications where different systems and approaches are used to test the same theory. A complementary approach is to integrate findings from small-scale manipulative experiments into analysis of large scale observational data (Kotta *et al.* 2019). Such integration will necessitate closer collaboration between ecologists working at different spatial scales, and between experimentalists and modellers (Heuschele *et al.* 2017). The increased availability of hierarchical statistical models that integrate data from disparate sources has high potential to facilitate such an integration (Isaac *et al.* 2019). In the new era of open science, large amounts of data from both field surveys and experiments are now becoming available, widening the range of opportunities for data integration.

Given our reliance on observational data, more insight into causal processes could be gained by more widely applying novel statistical methods that seek to strengthen a causality inference from observational data (Law *et al.* 2017). Causal inference approaches force researchers to think more deeply about the direct and indirect relationships of variables in their study systems (Ferraro, Sanchirico & Smith 2019). These approaches include controlling for confounding factors by matching (to control observable confounders) and use of panel data and synthetic controls to control for unobservable confounders, as well as instrumental variables to eliminate unobservable confounders (reviewed by Law *et al.* 2017). Time-series observational data are particularly useful because they are unidirectional - cause must precede effect (Dornelas *et al.* 2013) and approaches such as convergent cross mapping are designed to test for causal effects (Sugihara *et al.* 2012)

Insights into causality should not be seen as a “one-off” test, and an accumulation of knowledge through replication is fundamental for a robust knowledge base. Triangulation - whereby several approaches are formally applied to the same problem - is therefore useful for assessing the reliability of causal claims (Munafo & Smith 2018). In general, a wider adoption of systematic reviews and other structured evidence synthesis methods would allow more robust assessment of the evidence base (Pullin & Stewart 2006). In the open science era, evidence synthesis can increasingly be based on open data rather than on published effect sizes (Culina *et al.* 2018).

1.3 Journals, editors, and reviewers should assist in the change

Journal editors play an important role in facilitating scientific rigor of the studies that underpin real-life management decisions. This could further strengthened by creating new incentives for more honest and open reporting from the research process. We acknowledge that many of these processes are already starting to happen across the ecosystem of journals.

Pre-registration of research hypothesis has been advocated (Nosek *et al.* 2018), partly to distinguish between exploration and confirmation research. In the open science era, studies are increasingly based on pre-existing data, including data that have been previously analysed and with results published in scientific journals. This should not discourage *a priori* hypothesis development and pre-registration (Nosek *et al.* 2018). Journal editors should increasingly facilitate this shift by applying a model where authors declare their study design and identify at which stage in the process they developed their hypothesis (e.g. before or after data collection, before or after results were known). This could include a link to the pre-registered hypothesis (e.g. hosted on Open Science Framework (www.osf.io)), and potentially an associated "open science badge" (Kidwell *et al.* 2016) as a sign of an open research practice.

We also encourage journal editors to more actively encourage fair valuation of empirical case studies that mainly describe and document the state and trend of biodiversity. To accommodate this, more journals could explicitly allocate different sections to different types of studies (exploratory, methods, confirmatory/hypothesis testing etc). This will make the publication process more transparent and facilitate more honest reporting of how the study was performed, potentially reducing the incentives for *harking*.

Finally, we propose (as a counterpart to pre-registration of hypotheses) a model where hypotheses rising from exploratory research could also be registered so that they are readily available for testing in subsequent studies. Given the rise of global databases and repositories, such a model could make it feasible to track hypotheses to their source, and fair attribution of credit to those that originally proposed the hypothesis. It would also provide a clearer link between exploratory (hypothesis generating) and confirmatory (hypothesis testing) research.

2. Outlook

We should value the complimentary and important contributions of both exploratory and confirmatory studies, but be much clearer about the differences between them. In the open science era (Nosek *et al.* 2015), where more and more research is based on pre-existing (and often open) data, and where large-scale studies are needed to address key conservation policy challenges, a simple plea to follow the strong inference paradigm (Platt 1964) might not be sufficient. However, current incentives that promote the presentation of studies that are, by design and conduct, exploratory as if they were confirmatory is a disservice to scientific progress and a delay in solving real-world problems. The open science era has already radically improved the reproducibility of research; however, we argue that a cultural shift, involving researchers, journals, and funding bodies, is still needed towards full transparency and valuation of the plurality of research methods.

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Authors contributions: EBN conceived the idea for this work, after discussions with DB and JDCL. EBN and DB performed the literature survey for Box 1. EBN were responsible for writing the manuscript, with inputs from JDCL and DB. All authors edited and approved the final version of the manuscript.

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Box 1: Hypotheses and experiments in applied ecology

To gain a rapid insight into the current state of affairs in the scientific literature in applied ecology, we randomly sampled 159 papers published in eight journals covering conservation biology, applied ecology and wildlife management. We only included studies from terrestrial ecology, that were data-driven (i.e. not reviews or pure simulation studies), that presented the results from at least one statistical test, that presented original data or data from literature surveys, and focused on aspects of applied ecology relevant for biodiversity management and conservation. Based on these studies we assessed how often i) one or more clearly stated hypotheses were presented in the introduction, ii) multiple competing hypothesis were presented, and, iii) how often strict experimental designs were applied. In addition, we extracted the number of citations registered by Web of Science. A more comprehensive description of the inclusion criteria and data extraction procedures can be found in **Appendix S1**.

Based on our sample of research papers, it seems that clearly stating a research hypothesis in the introduction is surprisingly rare in the literature (**Fig 1a**). Overall, only about 19% of the studies presented clear hypotheses, whereas about 26% presented what we term "implied hypotheses" or "partly", where the hypothesis could be inferred from the text but was not presented clearly. After removing articles mainly focusing on methods development, the corresponding proportions were 23% (explicit hypotheses) and 28% (implicit hypotheses), respectively. Presenting multiple competing hypothesis, as described in the original presentation of the strong inference paradigm (Platt 1964) is even rarer, and only visible in 2 of the studies we reviewed.

Another hallmark of science is the use of well planned, randomized and replicated experimental manipulation to test for causal relationships (Platt 1964; Caughley 1994). Based on our review, however, the use of full experimental designs are rare, and only 12% of the studies we reviewed were based on randomized controlled experimental designs. In addition, 15% of the studies in our sample included Before-After-Control-Impact (BACI) or Quasi-experimental protocols. The majority of the randomized controlled experiments were performed on a local spatial scale (**Fig 1b**), although a few studies presented landscape scale experiments. In our sample, local scale studies in general received less attention in the literature compared to studies spanning larges spatial scales when measured in terms of citation rates (**Fig 1b**).

Figure Legends

Figure 1. *In **a)** the proportion of articles that reported clear hypotheses, implied or partly indicated hypotheses that were tested, and articles that did not present hypotheses. In **b)** the proportion of articles that used experimental, quasi-experimental/BACI or no experimental designs are matched with the corresponding spatial scales of the studies. The size of the circles indicates the number of studies. The colour key indicates citation rates (mean annual number of citations since the year of publication).*

Figures

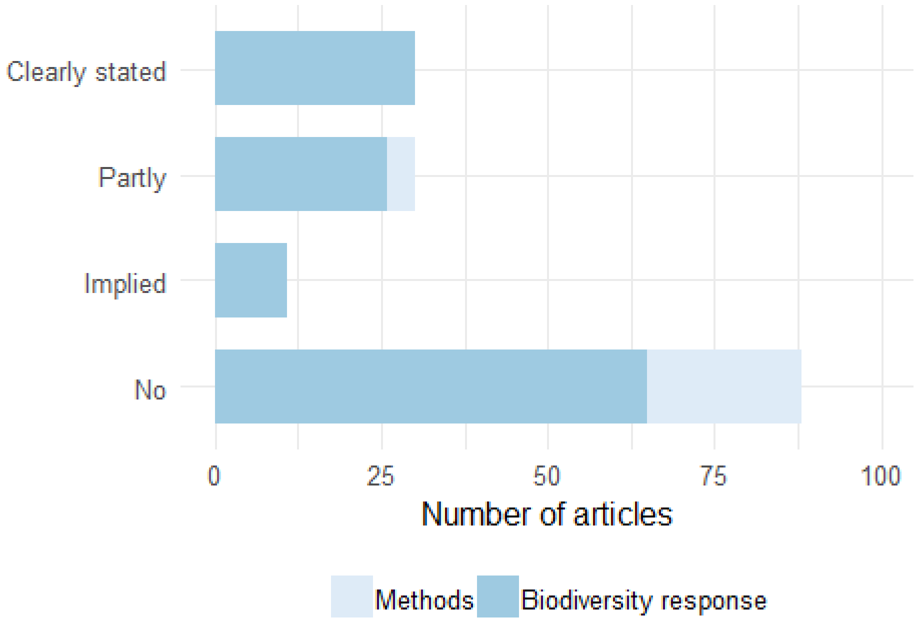

Fig 1a

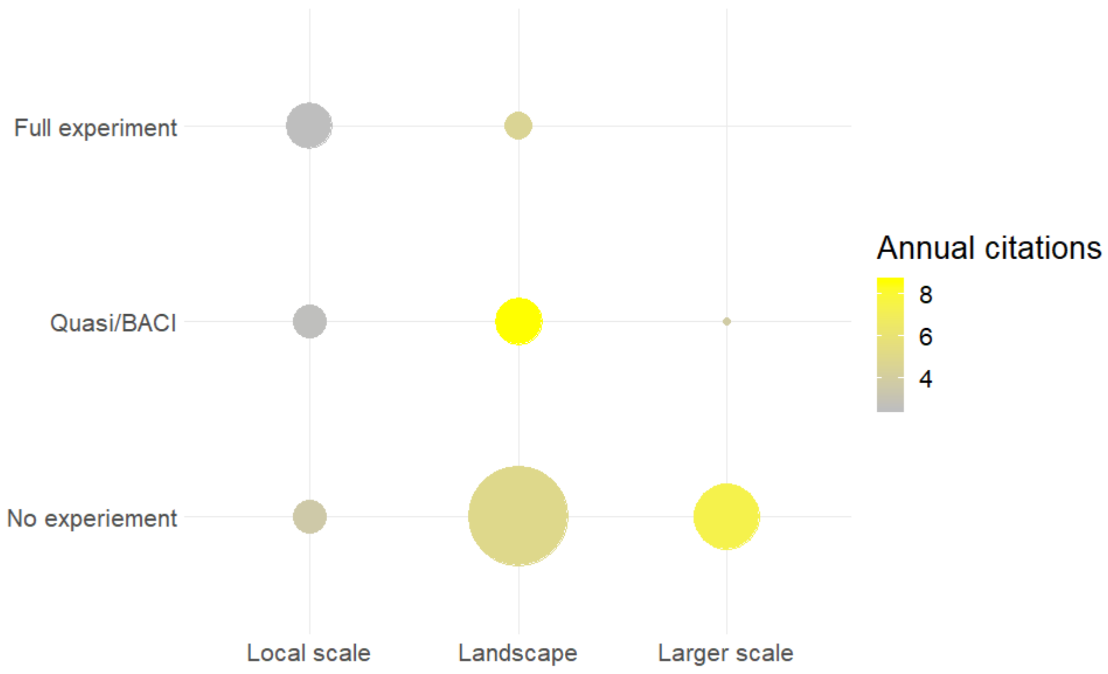
Full experiment
Quasi/BACI
No experiement
Local scale
Landscape
Larger scale
Annual citations
8
6
4

Fig 1b