Exploratory and confirmatory research in the open science era

Erlend B. Nilsen[1], Diana E. Bowler[1-4] & John D.C. Linnell[1]

1: Norwegian Institute for Nature Research, P.O. 5685 Torgarden, 7485 Trondheim, Norway

2: German Centre for Integrative Biodiversity Research (iDiv), Deutscher Pl. 5E, 04103 Leipzig, Germany

3. Institute of Biodiversity, Friedrich Schiller University Jena, Dornburger Straße 159, 07743 Jena, Germany

4. Helmholtz Center for Environmental Research - UFZ, Department of Ecosystem Services, Permoserstraße 15, 04318 Leipzig, Germany

Corresponding author: Erlend B. Nilsen (erlend.nilsen@nina.no)

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Abstract:

1. Applied ecological research is increasingly becoming a part of the Open Science movement. However, new challenges about how we define our science when biodiversity data is increasingly 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.
3. To solve fundamental local, regional and global societal challenges, we need both exploratory and confirmatory research; however, there is an urgent need to more clearly distinguish the two. This will require a revaluation of the important, but different, roles that each play in the scientific process.
4. A clearer distinction 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. 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.

Rigorous science in applied ecology

As a response to global biodiversity loss, conservation science and applied ecological research is increasingly focused on detecting patterns of biodiversity change, isolating the factors that are causing this loss, and ultimately suggesting mitigation measures or management solutions (Kareiva & Marvier 2012). Because biodiversity loss and ecosystem transformations are expected to cause 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 this 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 and journal editors should assist in the task of extracting the maximum value from different scientific approaches without blurring the distinction between exploration and confirmation.

A mature research community should value both exploration and confirmation

One consequence of a general movement towards "open science" (Nosek *et al.* 2015) is the focus on open sharing of research data (Wilkinson *et al.* 2016). Increasing accessibility of new data sources 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 that plea for more formal testing of scientific hypotheses in applied ecological research, but also underline the fundamental role that descriptive studies documenting the state or trends of local, regional or global biodiversity, or the natural history of species, has for conservation science (Beissinger & Peery 2007; Pereira *et al.* 2013). In addition, exploratory research plays a key role in generating new hypothesis that could formally be tested later. Moreover, the development of the United Nation's Sustainable Development Goals (SDGs) and 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 large impacts, 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 a scientific 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 and the personal beliefs of the scientists will result in overly self-confident 'storytelling' with weak scientific support (Hayward *et al.* 2019). Basing conservation planning and mitigation actions on such research may lead to costly mis-management.

Novel ways to test ecological theories

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

Strict experiments in applied ecology (**Box 1**) are generally conducted at small spatial scales (although there are som very notable exceptions, e.g. Krebs, Boutin & Boonstra 1995; Wiik *et al.* 2019). This contrasts with 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). A complementary approach, when experiments are not feasible, would be to apply methods that allow integration of findings from small-scale manipulative experiments into large-scale syntheses of drivers of biodiversity change. Such integration will necessitate closer collaboration between ecologists working at different spatial scales, and between experimentalists and modellers (Heuschele *et al.* 2017). The increased popularity of hierarchical statistical models, especially integrated population models, which integrate data from disparate data sources, could facilitate such an integration (Miller *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 establish causality 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), and time-series methods such as convergent cross mapping (Sugihara *et al.* 2012). Time-series data might be particularly useful because they are unidirectional - cause must precede effect (Dornelas *et al.* 2013). Triangulation, whereby several approaches are formally applied to the same problem, could serve as another model for increasing the reliability of causal claims (Munafo & Smith 2018).

Finally, to effectively synthesize evidence from causal claims across studies, 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 fact, in the open science era, evidence synthesis can be performed directly on open data rather than published effect sizes, increasing the range of questions that can be addressed (Culina *et al.* 2018).

Journals, editors, and reviewers should assist in the change

Science is not conducted in isolation in research labs, but rather represents a collective social endeavour involving many people with different roles to fill. Journals could play an important role in facilitating scientific rigor of the studies that underpin real-life conservation decisions. This could partly be achieved by creating new incentives for more honest and open reporting from the research process.

Pre-registration of research hypothesis has been advocated (Nosek *et al.* 2018), partly to distinguish exploration and confirmation research. In the open science era, studies are increasingly based on pre-existing data, and even data that have been previously analysed and with results published in a scientific journal. This should however not discourage *a priori* hypothesis development and pre-registration (Nosek *et al.* 2018). Journal editors could 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 initial data analysis etc). This could include a link to the pre-registered hypothesis that might be hosted on e.g. 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, especially reducing the incentives for *harking*, and reduce publication bias of significant studies.

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, which would allow for fair attribution of credit to those that originally proposed the hypothesis, and it would provide a clearer link between exploratory (hypothesis generating) and confirmatory (hypothesis testing) research.

Outlook

We should value the complimentary contributions of exploratory and confirmatory studies, but be much clearer about the fundamental 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. In applied fields like conservation biology, this will also delay progress in solving 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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Data accessibility: Data and R-scripts used to perform the randomization routines and produce figures for Box 1 is currently available here: https://osf.io/n8fum/

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: State of applied ecology as a science

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 conservation. From these studies, we assessed i) to which extent one or more clearly stated hypotheses were presented in the introduction, ii) whether there were multiple competing hypothesis and, iii) whether they applied an experimental study design. 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

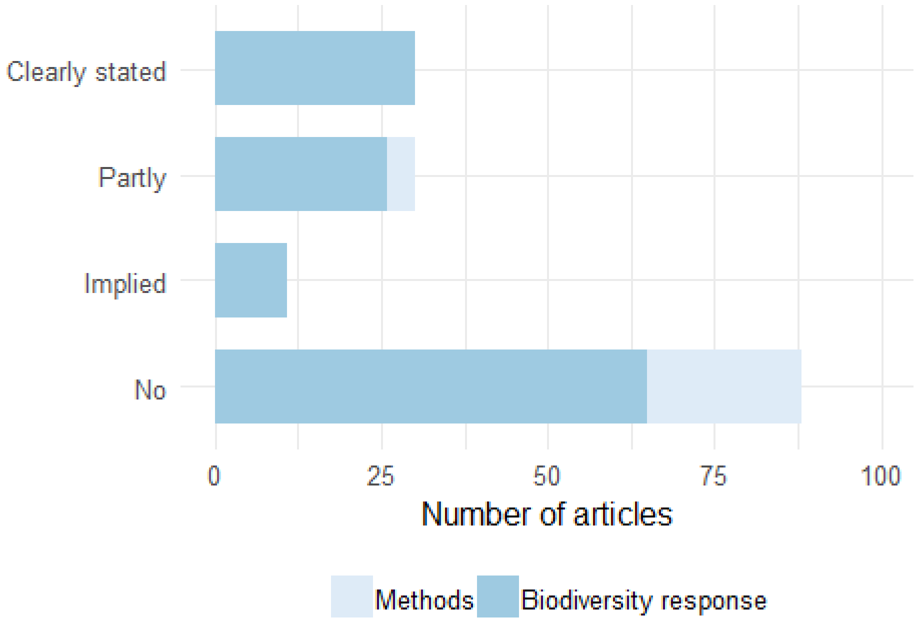

Fig 1a

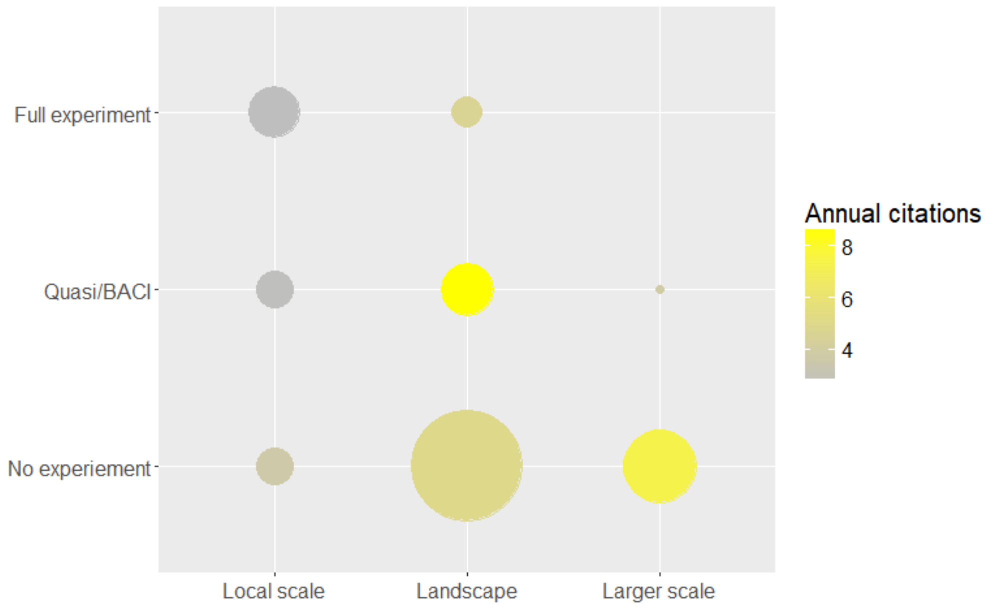
Full experiment
Quasi/BACI
No experiement
Local scale
Landscape
Larger scale
Annual citations
8
6
4

Fig 1b