

REPRODUCIBILITY AS A CATALYST FOR TRANSFORMATIVE INSIGHTS AND CULTURAL CHANGE IN FIELD BIOLOGY

PROJECT DESCRIPTION

The first paragraph of the project description should provide a concise, clear description of the proposed infrastructure innovation that will be developed under this award. It should describe, using a minimum of specialized language, what the infrastructure will consist of, how the proposed innovation will provide unique infrastructure or significantly improve upon existing infrastructure, and what science will be advanced through this infrastructure innovation. Specific attention should be paid to the anticipated impact on the community served by the proposed innovation.

CONCEPTUAL FRAMEWORK

A hallmark of science is replicability (Voelkl et al. 2020). Replication is collecting new data to test a claim from prior research (Nosek and Errington 2020a). Replication advances credibility of research by increasing confidence in the reliability of a finding, improving the precision of estimated effects, or identifying how our understanding of conditions needed to observe a finding might be limited. Corroborating findings with replication helps eliminate mistakes and questionable research practices and speeds scientific progress (Fraser et al. 2018, Redish et al. 2018), which is why it is fundamental to the scientific method (Popper 2005).

A surge of efforts to replicate the results of fundamental studies in fields ranging from chemistry (Bergman and Danheiser 2016) to the biomedical sciences (Errington et al. 2014, Amaral et al. 2019) reflects a general concern that this core principle of science may not be operating as well as expected in practice. For example, the Open Science Collaboration Collaboration (2015) replicated 100 psychology findings and observed successful replication of results for less than 40% of them. Observing differences between original studies and replications can be beneficial, however, by leading to the development of generative theory to account for the observed differences. For example, in exploring a failure to replicate one could identify previously unappreciated factors critical for observing the phenomenon of interest (Collaboration 2015). Of course, it is also possible that the original result was a false positive, in which case nothing would explain why the original study observed a finding but the replication did not. Over time replications either build confidence in and mature the theoretical understanding of a phenomenon, or they render the finding irrelevant because the conditions for demonstrating replicability cannot be identified (Nosek and Errington 2020a).

Field-based sciences such as Ecology, Behavior, and Evolution (EBE) could benefit from promoting replication (Kelly 2006, Huang 2014, Nakagawa and Parker 2015, Fidler et al. 2017), but the response of the EBE community to these calls has ranged from tepid to skeptical (Editors 2016, Schnitzer and Carson 2016). The reasons echo those put forward by scientists in other fields: a lack of incentives or professional rewards for carrying out replications, few journals willing to publish the results of replicated studies, and concerns about efficient use of scarce research funding (Nakagawa and Parker 2015, Schnitzer and Carson 2016, Fidler et al. 2017). In addition to these practical obstacles, however, many suggest a more fundamental conceptual one – that research in EBE is inherently impossible to replicate because it is carried out under unique biotic and abiotic conditions (Nakagawa and Parker 2015, Schnitzer and Carson 2016).

To be clear, there is no such thing as exact replication regardless of discipline and research context – there will always innumerable differences resulting from changes in season, laboratory conditions, historical circumstances, or the identity of participants. This is certainly true in an EBE context,

in which the biotic and abiotic conditions under which field studies are conducted will never be identical. But scientific claims are not historical ones, for which a finding is presumed to apply only in the original context. Scientific claims are statements about regularities one expects to observe across contexts when certain conditions are met. That is why replication is formally defined as attempting to reproduce a previously observed result with procedures that provide no a priori reason to expect a different outcome (Schmidt 2009, Collaboration 2015, Nosek and Errington 2017). This is why replications in EBE do not have to be conducted under biotic and abiotic conditions identical to those of the original study; given our present understanding of the phenomenon, the new environmental context should not reveal something different from the original one (Nosek and Errington 2020a). Of course, our ‘present understanding’ can be wrong, which is why a replication that does not produce the same finding as the original study can be so useful for testing and advancing theory – it forces one to assess whether the original study could have been a false positive, if the replication might have been a false negative, or to generate hypotheses for why the studies had different outcomes. This assessment may be especially important in the context of management or conservation, where one seeks confidence in the original conclusions, rather than broad theoretical generality.

The assertion that EBE research can’t be replicated may stem from confusion regarding precisely what constitutes a “replication”, especially with regards to geography and species identity (Nakagawa and Parker 2015, reviewed in Fraser et al. 2020). If the original claim is explicitly bounded by geography or species identity, then to qualify as a replication the methodology must respect those restrictions. If the original claim is more general, however, then the replication can in theory transcend geography and species identity within limits concordant with the extent of the original claim’s generality (Table 1). While replications are perhaps most straightforward to conceptualize when using species and methods identical to those in original study, they can be conducted with other systems if the replication design actively confronts the present understanding with a test that provides diagnostic information increasing or decreasing confidence in the original claim. Put another way, a replication is a theoretical commitment to specify a study design for which one expects the same outcome as the prior findings given our understanding of the phenomenon of interest (Nosek and Errington 2020a).

While expanding the domain of valid replications to include novel systems is conceptually exciting, this also requires exceptional rigor and a priori consensus regarding the study design and expected outcomes (Nosek and Errington 2020a). This challenge is further exacerbated if the theoretical expectations of the original study are underspecified, making it unclear if the claim should in fact recur in different locations or species. Ambiguous expectations lead to asymmetric inference – while observing consistent evidence builds confidence in the original finding, failing to do so doesn’t decrease confidence. Such asymmetric tests are therefore not replications. They are tests of generalizability (Nosek and Errington 2020a), which are useful for understanding the breadth and boundaries of a phenomenon but do not directly confront the original conclusion. In fields that have historically emphasized tests of generalizability, such as EBE, positive results can appear to establish the broad applicability of a phenomenon without ever actually testing its replicability – especially given the biases against publication of null results (reviewed in Fidler et al. 2017). Advancing theory in our discipline requires both testing predictions in new systems and assessing the validity of studies on which theory was built by attempting to replicate them (Cassey and Blackburn 2006, Fidler et al. 2017, Fraser et al. 2018).

Shifting the current research paradigm to one that values such replications requires three things: evidence of their potential to advance our scientific understanding (Fraser et al. 2020), a framework

for incentivizing, conducting, and publishing replication research (Nakagawa and Parker 2015, Fidler et al. 2017), and identifying potential barriers to their acceptance or implementation *even if shown to be intellectually valuable*. Academic societies are uniquely situated to promote the value of replications, provide opportunities for training and evaluation, and provide the incentives and outlets for sharing results. **We are proposing to coordinate the replication of fundamental field studies to evaluate the scientific and community impacts of this research method.** To do so, we will work in partnership with the Association for Tropical Biology and Conservation (ATBC). The ATBC is the ideal partner for this effort. In addition to providing opportunities for training and evaluation at its Annual Meeting regional chapter events, it has experience coordinating grant competitions with international applicants. It also publishes the the flagship journal in tropical biology (*Biotropica*), in which the results of replications will be published.

Our proposed Reproducibility Project — the first such effort in environmental biology – has five primary objectives:

1. To determine the extent of reproducibility in a sample of the fundamental literature in Tropical Biology
2. To identify obstacles to conducting effective replications, including such factors as failure to detail methodology in the original study, the extinction of species or loss of study site, changes in local, landscape, or global environmental conditions, advances in sampling technology, statistics and computational tools, analytical methods, etc.
3. To quantify predictors of replication success, such the location, ecosystem, and species with which the experiment was conducted and the extent to which the original study site and system has been modified by human activities
4. To identify aspects of the experiment that are/are not critical to a successful replication, such as study species or location, specific characteristics of the sample, or details of the materials and methods.
5. To advance the training of early-career scientists and collaboration among tropical biologists, especially the training of students in developing countries, North-South and South-South collaborations, and collaborations between Early-Career and Senior Scientists through conducting replications and training of researchers in open and reproducible research methods at societal meetings.

IMPACT ON THE RESEARCH COMMUNITY

This section of the project description should address the biological user community impacted by the proposed effort and provide evidence of the need for the proposed innovation as compared to existing capabilities. Proposals should also explicitly state how the proposed work will advance the capabilities of the biological research community as it specifically relates to the research as supported by the divisions within the NSF's Directorate for Biological Sciences.

Our project will have four major impacts on the science and scientific culture of tropical biology and other field-based disciplines. First, there is the *knowledge gained* by replicating the foundational studies of the discipline. Are the results of these studies similar when replicated decades later and in new locations? If not, are the new results qualitatively similar, equivocal, or contradictory? Do we have to revisit alternative hypotheses and conduct new research in light of the replication results? In answering these questions, the participants in our project will make major conceptual advances: they will both test and refine classical theories and accelerate the development of novel

ones.

Second, this initiative will drive an important *change in scientific culture*. The impediments to replicating prior work are the same in field biology as they are in other disciplines - limited financial resources for doing so, skepticism regarding the extent of a 'reproducibility crisis', and culture emphasizing novelty, often at the expense of rigor. We expect our results will demonstrate to this community of scholars why replication is essential, promote a vigorous discussion about the studies that are most urgent to replicate in light of the theoretical and applied impacts, and provide guidance for designing and describing studies that can be readily replicated. Our ambition is that tropical biology undergo a transformative change in scientific culture, with replication and reproducibility becoming integral components of rigorous research.

Third, our initiative will have a *global impact on the training of students and early career scientists*. Students conducting reproducibility trials as part of their senior theses, in field courses, or as part of their graduate research will immerse themselves in our field's fundamental studies and conduct rigorous research and analyses under the mentorship of senior colleagues. This enhanced training and the resulting publications - which in most cases would likely not be possible without the financial support and incentive from this project - will accelerate their development as scientists and strengthen their professional network through international collaboration and engagement with the ATBC. It is also a critical element of transforming the culture of tropical biology - while more senior scientists are often resistant to the emerging culture of Open Science, Early Career Scholars are more receptive to it, aware of its benefits, and eager to learn the requisite skills required to broadly share research protocols and results.

Finally, field-based sciences such as tropical biology face unique and inherent challenges to reproducibility from which many lab-based disciplines are buffered. This poses important philosophical questions about reproducibility, including fundamental ones such as what it means to 'reproduce' a study, if our goals should be replication or reproduction, and if replication is even possible. Our project is not the first to broach these questions, but it is the first in which they figure so prominently. The resulting dialogue between teams within and across reproducibility initiatives will *advance our understanding of science, its practice, and the consequences for science's relationship to society*.

PROJECT IMPLEMENTATION, MANAGEMENT, & EVALUATION

DEVELOPMENT PLAN: We envision a 5-year Reproducibility Project. In Year 1 we will solicit and select Principal Investigators (PIs) to guide the replication of five studies on our priority list. These PIs - with the assistance of the Center for Open Science, an ATBC Committee, and *Biotropica's* Editors - would develop and post the guidelines for replicating a study, including the protocols, data collection sheets, and scripts for statistical analyses to be used by participating researchers. The ATBC would then help PIs recruit a network of researchers in different locations to replicate the study. Implementing a local replication requires working with the PI's to pre-register the study (Chambers et al. 2014, Nosek and Lakens 2014) with *Biotropica's* Editorial Board, which peer reviews the design and provisionally accepts a Registered Report for publication prior to any data collection. This model, which has been adopted by a number of journals participating in Reproducibility Projects (see <https://cos.io/rr>), both enhances the credibility of projects and provides incentive for participation because it guarantees publication of results regardless of statistical significance or magnitude of the effects (Chambers et al. 2014, Nosek and Lakens 2014). Moreover, this model facilitates engagement of experts in the design of the methodology and leads to consensus on what constitutes a replication test of a study before the results are known (Nosek and Errington 2020b). This is valuable both for improving the quality of replication designs and to

address the potential for pre-existing beliefs to motivate accepting or dismissing a replication's outcome. Once the data have been collected, the PI's will work with the research teams to analyze and archive it and prepare the results-included Registered Report for submission to *Biotropica*.

When all of the replications have been completed, the PIs will conduct a meta-analysis of the entire network's results – also to be published in *Biotropica* – with all network members as co-authors. We anticipate these meta-analyses will be high-impact advances given the geographic scope, methodological consistency, and the conceptual importance to the field of the selected studies. That all participants would be authors or co-authors of two publications irrespective of their replication's outcome is a critical incentive we hope would encourage those who might otherwise be hesitant about repeating the work of others to participate.

PROJECT MANAGEMENT:

COMMUNICATION & DISSEMINATION

Describe how knowledge obtained through support of this work will be disseminated to its target audience and to the broader biological, interdisciplinary, and other audiences. When appropriate, describe how the products (instrumentation, software, research methods) of this work will be accessible to its target audience and to the broader biological, interdisciplinary, and other audiences. Provide a clear statement of relevant intellectual property considerations and any constraints these may place on access to the proposed resource.

OUTCOMES ASSESMENT:

Identify what metrics will be used to measure success toward the stated goals of the project (both Intellectual Merit and Broader Impacts) and by what process the projects will collect and evaluate them.

INTELLECTUAL MERIT

1-2 paragraphs

BROADER IMPACTS

Some of the most important advances in tropical biology have come from researchers forming networks to systematically collect observations of tree growth and diversity in permanent plots (Menke et al. 2012, Anderson-Teixeira et al. 2015, Poorter et al. 2016, Rovero & Ahumada 2017). The same is likely to be true as tropical biologists embrace “distributed experiments” (Fraser et al. 2013, Borer et al. 2014), in which the same experimental manipulation is implemented at geographically and ecologically disparate locations (e.g., Romero et al. 2020). The Reproducibility Project in Tropical Biology (RP:TB) we envision complements these efforts with a new means by which researchers throughout the tropics can collaborate to test and advance theory. Because many of the experiments proposed for replication are inexpensive to implement and monitor, and financial obstacles to individual participation will be eliminated when the RP:TB is finally funded, we expect this initiative will greatly expand the diversity of researchers participating in or leading networks. We especially hope the RP:TB will serve to stimulate much needed North-South and especially South-South collaboration (Stocks et al. 2008). The ATBC-organized workshops and symposia emerging from the project will also serve as an important tool for capacity building and the professional advancement of early career scientists, as will the integration of reproducibility projects and a culture of open science in field courses and other educational programs. Finally, the data from replications will be highly valuable for quantifying the generality, impact, magnitude, speed, and consequences of human-induced alteration of ecosystems. Nowhere is this need more critical than in tropical ecosystems, which are home to majority of the world's biodiversity and

human population, play a critical role in global climate, and are being transformed by humans at an unprecedented rate and scale.

It is essential to emphasize that this reproducibility project will have societal impacts that extend beyond the transformative effects on field-based disciplines. The research conducted by tropical biologists is critical for documenting threats to biodiversity, identifying priority areas for conservation, guiding the management of plants and animals harvested for human use, and informing policy at local, national, and international levels. These decisions rely in part on studies whose results may or may not be reproducible, however, which could have major - even catastrophic - consequences. For instance, one could overestimate the biodiversity in potential biological reserves based on snapshot surveys of bioindicator species (e.g., ants, understory plants, pollinators, frugivores/seed dispersers) whose results are anomalous.

Alternatively relying on studies that have not been replicated could lead to conservation action that is too narrow in scope to be effective or distracts from more important conservation priorities. For example, climate change is expected to lead to the extinction of biodiversity on mountains as warm-climate species move up in elevation, but to date only one survey of biodiversity along elevational gradients has been replicated. This study suggested the impacts were even more severe than predicted; replicating other such studies will help determine if resources devoted to conservation are appropriate, overly conservative, or should be redirected to other priorities.

In sum, there are few areas with greater policy implications in the 21st century than research on ecology, biodiversity conservation, deforestation, and climate change. Government policies addressing these issues have local, national, and international consequences, with economic, social, and cultural impacts. It is therefore essential that tropical biologists provide the policy-makers whose decisions will affect the health and well-being of the planet and its citizens with the most robust and reliable evidence available.

RESULTS FROM PRIOR NSF RESEARCH

When appropriate, this section must include evidence of deposition of samples, data and/or data products in recognized, accessible, community-accepted repositories by listing such repositories and, if practical, metadata. All publications, data, data products, programs and/or scripts that are specifically mentioned in the Results from Prior NSF Support section must be referenced in the References Cited section and must provide unique, resolvable and persistent identifiers (such as Digital Object Identifiers [DOIs]; Uniform Resource Locators (URLs), or similar).

Bruna: “SG: Synergistic effects of forest fragmentation and droughts on tropical plant demography” (DEB-1948607, \$214,390). **Intellectual Merit:** The project had two objectives (1) to test for lagged effects of precipitation extremes on the vital rates of the Amazonian understory herb *Heliconia acuminata*, and (2) to build integral projection models (IPMs) with lagged effects to simulate the dynamics of populations in forest fragments and continuous forest under IPCC scenarios for the Central Amazon. Effects of precipitation extremes on vital rates could be delayed up to 36 months, with more pronounced effects on plants in fragments than on those in continuous forest. IPMs suggest that populations in fragments will decline under all IPCC scenarios, while the positive lagged effects of drought on growth will lead populations in forest to increase. The project resulted in two published articles, with two more in preparation, along with a permanently archived demographic dataset (>66,000 plant × year records of >8500 plants) and code repositories with a real-time data summary and validation dashboard and code for users test for lagged effects with their data sets. **Broader Impacts:** The award supported 1 Postdoc and 2 REU students. The students gained skills programming, statistics, and using quantitative methods to test ecological

hypotheses. The postdoc's programming lessons and archives were fundamental to his being hired as a Scientific Programmer & Educator at the U. of Arizona. The PI developed educational materials on climate change and tropical forests for a general education course and data management for a graduate course.

Queenborough:

REFERENCES

- Fraser, H., A. Barnett, T. H. Parker, and F. Fidler. 2020. The role of replication studies in ecology. *Ecology and Evolution* 10:5197–5207.
- Nosek, B. A., and T. M. Errington. 2020a. What is replication? *Plos Biology* 18:e3000691.
- Nosek, B. A., and T. M. Errington. 2020b. Argue about what a replication means before you do it. *Nature* 583:518–520.
- Voelkl, B., N. S. Altman, A. Forsman, W. Forstmeier, J. Gurevitch, I. Jaric, N. A. Karp, M. J. Kas, H. Schielzeth, T. Van de Castele, and H. Würbel. 2020. Reproducibility of animal research in light of biological variation. *Nature Reviews Neuroscience* 21:384–393.
- Amaral, O. B., K. Neves, A. P. Wasilewska-Sampaio, and C. F. D. Carneiro. 2019. The brazilian reproducibility initiative. *eLife* 8:e41602.
- Fraser, H., T. Parker, S. Nakagawa, A. Barnett, and F. Fidler. 2018. Questionable research practices in ecology and evolution. *PLoS One* 13:e0200303.
- Redish, A. D., E. Kummerfeld, R. L. Morris, and A. C. Love. 2018. Reproducibility failures are essential to scientific inquiry. *Proceedings of the National Academy of Sciences* 115:5042–5046.
- Fidler, F., Y. E. Chee, B. C. Wintle, M. A. Burgman, M. A. McCarthy, and A. Gordon. 2017. Metaresearch for evaluating reproducibility in ecology and evolution. *Bioscience* 67:282–289.
- Nosek, B., and T. M. Errington. 2017. The challenges of replication. *eLife* 6:e23693.
- Bergman, R. G., and R. L. Danheiser. 2016. Reproducibility in chemical research. *Angewandte Chemie International Edition* 55:12548–12549.
- Editors, E. L. S. 2016. Ecology letters, and transparency and openness promotion (TOP) guidelines. *Ecology Letters* 19:725–725.
- Schnitzer, S. A., and W. P. Carson. 2016. Would ecology fail the repeatability test? *Bioscience* 66:98–99.
- Nakagawa, S., and T. H. Parker. 2015. Replicating research in ecology and evolution: Feasibility, incentives, and the cost-benefit conundrum. *BMC Biology* 13.
- Collaboration, O. S. 2015. Estimating the reproducibility of psychological science. *Science* 349.
- Errington, T. M., E. Iorns, W. Gunn, F. E. Tan, J. Lomax, and B. A. Nosek. 2014. An open investigation of the reproducibility of cancer biology research. *Elife* 3.
- Huang, X. L. 2014. Reproducibility in ecological research. *Science* 346:1307–1307.

Nosek, B. A., and D. Lakens. 2014. Registered reports: A method to increase the credibility of published results. *Social Psychology* 45:137–141.

Chambers, C. D., E. Feredoes, S. D. Muthukumaraswamy, and P. J. Etchells. 2014. Instead of “playing the game” it is time to change the rules: Registered Reports at AIMS Neuroscience and beyond. *AIMS Neuroscience* 1:4–17.

Schmidt, S. 2009. Shall we really do it again? The powerful concept of replication is neglected in the social sciences. *Review of General Psychology* 13:90–100.

Cassey, P., and T. M. Blackburn. 2006. Reproducibility and repeatability in ecology. *Bioscience* 56:958–959.

Kelly, C. D. 2006. Replicating empirical research in behavioral ecology: How and why it should be done but rarely ever is. *Quarterly Review of Biology* 81:221–236.

Popper, K. 2005. *The logic of scientific discovery*. Routledge.