Ten simple principles for engineering reproducible solutions to environmental management challenges from primary research.

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Abstract

An environmental management challenge is an opportunity to use fundamental science to inform evidence-based decisions for environmental stakeholders and conservationists. Contemporary science is embracing open science and increasingly conscious of reproduciblility. Synergistically, applying these two paradigms in concert advances our capacity to move beyond context dependency and singular, unidirectional linear thinking to reverse engineer solutions from published scientific evidence associated with one challenge to many. Solutions can scale, and we need to better reuse scientific literature. Herein, we provide a succinct list of principles that can guide those that seek solutions to address environmental management through primary scientific literature. This extends and supports science-policy-practice developments and the increasing attention to scientific co-production as a mechanism to better connect knowledge and sustainable societies.

Keywords

Conservation, decision making, environmental challenges, evidence, grand challenges, reproducible science, scientific co-production, scientific knowledge

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Introduction

Conservation decisions typically reside with legislators or with environmental managers. To focus on the latter, managers typically have scientific backgrounds and routinely navigate the technical literature. However, engagement with scientific literature is non-trivial for all practitioners because of time, restricted access, relevance of the science, and reporting standards. Environmental managers and conservationists need to be able to use primary evidence to inform decisions (Cash *et al.*, 2003; Koontz & Thomas, 2018) and provide clear roadmaps of change in coupled natural-human systems (Fischer & Riechers, 2019). Ideally, critical research is co-produced with stakeholders in key sustainability contexts (Maillet *et al.*, 2019; Regeer *et al.*, 2009). However, there are very high volumes of useful research produced globally and there can also be a gap in communication between basic science in these other contexts and management for at least three reasons. Firstly, the research is not a direct study of an ecosystem, and an immediate, real-world solution is needed by managers - preferably with a demonstrable outcome and reasonable cost estimate (Iacona *et al.*, 2018; Naidoo *et al.*, 2006). This is a very real limitation in the primary science literature restoration ecology for instance (Lortie *et al.*, 2018). Secondly, the link between the biology or ecology present in the literature is not articulately connected to the similar process for the system at hand. There are notable examples with journals just as the Journal of Applied Ecology, Basic and Applied Ecology, the Journal of Environmental Engineering, People and Nature, and others. Nonetheless, there remains an opportunity for solution development from publications in other journals that are not necessarily directly linked to stakeholders or co-produced. Context-specific findings in science are a legitimate and useful means to advance discovery, but at times, studies from one system can be re-purposed for insights into another (Fischer & Riechers, 2019). Finally, the capacity to see the forest for the trees for even large-scale or broad basic research study can be a challenge. Science can be very specialized (Baron, 2010), and mobilizing knowledge for solutions requires both detailed expertise, scientific synthesis tools (Lortie, 2014), or a focus on identifying the salient elements associated with a study (Hao, 2018; Lewinsohn *et al.*, 2015). Often, seeing the forest also requires sampling many trees. This leads to the general proposal here that experts that not currently engaged in collaboration and co-production with stakeholders can promote reproducible and mobile knowledge for many fundamental scientific endeavors by considering these principles. This is both a set of principles to enable reusable research by environmental managers and conservationists (Gerstner *et al.*, 2017) and inform solutions for the environmental crisis. We do not meant to imply that knowledge transfer is linear or exclusively the domain of experts (Calo, 2018; Fernández, 2016), but that the wealth of published environmental science can be made more accessible through these simple ideas.

An environmental management challenge is a problem presented in scientific literature or society that, when redefined and reviewed using these principles, can result in a solution to the original problem. Typically, a challenge is ethical, legal, social, or derived from implications associated with research and evidence of change or anthropogenic stress (Acocella, 2015; Bonebrake *et al.*, 2018). Grand challenges for the environment in particular are ones that necessitate connections between disciplines and require evidence from potential studies that examine different components of the environment such as

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climate, ecology, species biology, or research from any number of levels (Bonebrake *et al.*, 2018; Macpherson & Segarra, 2017). A (reverse-engineered) reproducible solution is a suggested solution to a challenge derived from identifying all the components of the challenge. In software engineering, this process includes analysis of the architecture of a system, examining the relationships between subsystems, and creating a mental model of how the system functions (Fiutem & Antoniol, 1996). The same process can be applied to basic science as a system for supporting environmental management decisions. It should be applicable to multiple local-extent challenges when adjusted to fit the circumstances (like a software application that can run under different operating systems). Finally, a tool or solution is the desired outcome from the primary research to support evidence-based/informed decision making in conservation (Maillet *et al.*, 2019). In this case, a tool is a methodology researchers can promote to either identify ways to measure/identify issues or to provide solutions for their specific challenge - not necessarily directly examined in a publication or produced through stakeholder collaboration a priori. Any tool is linked to its respective reproducible solution by the fundamental concepts of reproducibility (Baker, 2016). These can include conceptual replication, i.e. repeating the ideas, but there are many other solutions. Here, we propose that both direct replication (replicating the same approach in another context) and conceptual replication (repeated tests of the same concept but with different methods) (Kelly, 2006) will advance our capacity to explore reproducibility of basic science to different challenges associated with environmental management. The primary goal is to escape the ‘everything is context-specific’ assumption sometimes applied to many natural science sub-disciplines.

The heuristic developed here was inspired by the ‘ten simple rules’ paper format pioneered by Phillip Bourne in the field of computational biology (Bourne & Chalupa, 2006). We propose that by distilling the concepts that promote engagement with scientific literature outside of the research community, managers can rely on broader sources of scientific knowledge to make decisions in addition to those co-produced and collaboratively developed. Furthermore, researchers can reframe their scientific communication (when appropriate) to make it more relevant to managers without compromising their respective fundamental research programs. Here, we will outline and discuss simple “principles” scientists can use to make their research more applicable to managers and that managers can in turn use to identify basic science that fits their needs.

Principles

1. Reframe the problem as challenge. Doom-and-gloom is a pervasive theme in the media discussions of ecology and environmental sciences that reduces our productivity and capacity to solve problems. It can shut down even the most motivated of minds. Reframing a problem as a *challenge* can illuminate solutions. For example, human-wildlife conflict between carnivores and the people living near the Ruaha National Park boundary in Tanzania. The *problem* is that 98.5% of people perceive wildlife as a threat to their livestock resulting in increased likelihood for human-wildlife conflict (Dickman *et al.*, 2014). Re-framed, the *challenge* is to improve perception of wildlife in areas with high human-wildlife interactions. It is a small change in semantics but a potentially

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profound change in social context. The challenge can also include improving experiences for people with wildlife or reducing their losses to wildlife.

2. Describe the scope and extent of the challenge. Defining the scope of a challenge conceptually and the extent geographically will ensure that potential solutions fit the challenge. Moving across scales is a common issue in ecology (Sandel, 2015), and proposing a spatial scale, using common terms, and describing the breadth of the challenge will accelerate interdisciplinary solutions (i.e. the wildlife-human challenge above is ecological and societal). The challenge can be problematic on local, regional, or global scales, and solutions can be needed for each. Conceptually, the scope is broad in the human-wildlife conflict example whilst the extent is primarily local to the area surrounding the Southern border of the Ruaha National Park. Articulating scope and scale informs assessment of severity.

3. Explicitly link the basic science to management implications and policy. Perhaps the most facile principle, a simple description and definition of the basic scientific evidence in a study and how it can be reused is a fundamental step in linking science to evidence-based decision making for environmental challenges. In the wildlife-human challenge, depredation of livestock impacted 61.1% of households in some form, but livestock losses due to disease or theft were actually the most consistent negative drivers of total loss (Dickman *et al.*, 2014). Perception of loss and actual losses were not necessarily equivalent, and culture was shaping subsequent conflicts not direct evidence. Consequently, a clear and balanced statement of evidence can highlight limitations in the science relative to the social acceptability of a solution (Bonebrake *et al.*, 2018).

4. Propose implications of ignoring this challenge. A description of the impact a challenge on a system if left unchecked will help clarify the severity of the challenge. The trickle down effects and indirect implications of the challenge should also be examined. For instance, anti-carnivore sentiment will likely only grow as climate change and pressures to confine pastoral herders makes livestock more difficult to manage (Jones & Thornton, 2009; Lindsey *et al.*, 2009). Many large carnivores are already threatened and endangered, and further anthropogenic pressures on the populations will lead to severe declines in populations including potential extinction of keystone species (Bagchi & Mishra, 2006; Johnson *et al.*, 2006; Towns *et al.*, 2009); but it is often associated with underlying human-human conflict (Dickman, 2010). Hence, citizens are not only the recipients of scientific knowledge but relevant stakeholders in both the potential knowledge production processes and the consequences socially and ecologically (Fernández, 2016; Kates *et al.*, 2001). Implications should encompass both the ecology of a system and the people.

5. State the direct human needs associated with this challenge. State the direct needs of humans as part of the process of generating reproducible solutions for environmental challenges. The intrinsic value of the ecosystem is impossible to quantify (Davidson, 2013), but linking the challenge and its solutions to direct human needs makes it less likely to be dismissed. Identifying anthropogenic needs will help a problem solver create a solution that is appropriate for the challenge, and it can also prevent the emergence of new related challenges or pressures on the system in question. This statement can also include engagement with stakeholders as a mechanism to inform benefits and solutions

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(Colvin *et al.*, 2016; Reed, 2008). Benefits to stakeholders can include cultural ecosystem services and these will in turn further sustainable local planning and more directed science (Tew *et al.*, 2019). The science-practice connection is not that simple (Regeer *et al.*, 2009) but articulating human needs in any ecological system will go a long way to more acceptable science and collaboration.

6. List at least one limitation of the study and explain. There is no perfect experiment (Ruxton, 2018) or synthesis (Kotiaho & Tomkins, 2002). Critically reading the study associated with the challenge can mean the difference between success and failure of a derived management solution that otherwise follows all other principles presented here. A clear analysis of causation and correlation can help avoid a fatal misstep and ensures effective framing of expected outcomes with an environmental intervention for conservationists. This is not to say that interventions must always be cause-effect studies or that decisions cannot be made with compelling preliminary evidence or mensurative data. We are simply proposing that a statement of the relative strength of evidence and gaps in the research provides a future direction for additional research and for implementation.

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7. Explore the benefits of minimal intervention for stakeholders. Resources are limiting, and at times, the business-as-usual model can provide a guide to intervention for some environmental management challenges (Ferguson, 2015; Mosnier *et al.*, 2017). At the minimum, exploration of a hope-for-the-best strategy or minimal intervention is critical because of costs. Business-as-usual models can also provide an economic mechanism to value ecosystems services (Fu *et al.*, 2018; Karttunen *et al.*, 2018), and whilst this is not without debate, this can expand the breadth of stakeholders and potential investors in a solution for a particular challenge. A best and worst case scenario analysis is also likely a frequent need for many environmental challenges because of inertia in the socio-political structures that we use to manage people and resources.

8. List the tools applied to this challenge. In an environmental management challenge case study, there is typically at least one primary tool that the researchers used to explore a challenge, but there are many tools such as meta-analyses (Busch & Ferretti-Gallon, 2017), big data (Hampton *et al.*, 2013), mapping (Halpern *et al.*, 2008), modelling (Vogt *et al.*, 2017), citizen science (Burkle *et al.*, 2013), and team science (Nielsen *et al.*, 2017). The tools in basic biology and ecology relevant to environmental management can be reproducible if, at least conceptually, they can be replicated in another system or applied to similar challenge – i.e. citizen science as a means to collect environmental data (McKinley *et al.*, 2017) is relevant to many of the challenges we face including global warming, water quality, and declining biodiversity.

9. Link the primary reproducible tool to the outcome. A reproducible science tool can provide a means to collect data, detect patterns, directly solve an environmental challenge, or inform policy. If the paper was a direct test of basic ecology for an environmental challenge, this can be very straightforward. For instance, the paper entitled "Odonata (Insecta) as a tool for the bio-monitoring of environmental quality" (Miguel *et al.*, 2017) clearly provides a means to measure and detect. However, the other proposed roles can address challenges in a diversity of ways. The identification of or provision of research evidence is the most 'basic' role, and it is also likely the most typical role for much of ecology for example. Tools that can function in this capacity include surveys, citizen science data collection, mapping, open-access data, and modelling to predict changes. Tests in the second category that directly examine the efficacy of a management strategy or intervention can further include bio-monitoring (Miguel *et al.*, 2017), mitigation and remediation experiments (Zhu *et al.*, 2010), and population demography studies (Botero *et al.*, 2015). Studies that inform policy are typically more indirect and synthetic and can take the form of anthropocentric studies that consider ecological or environmental policy. Any of the above tools can serve this role, but some tools that fit most squarely include economic incentivization models (Tilman *et al.*, 2018), human health impact studies (Chiabai *et al.*, 2018), and human well-being monitoring associated with environmental interventions (McKinnon *et al.*, 2015).

10. Apply the tool to another challenge or explain how it is generalizable. This principle proposes that the primary tool is reproducible if it can be applied to another challenge or context. It ties together the concept that reverse-engineered reproducible solutions are relevant to more than the unpacked, single environmental management challenge case. This can promote increased in efficiency for tackling novel environmental challenges as they emerge, and it also supports the overarching philosophy here for basic science that we cannot continue to ignore reuse given the global environmental needs for better decision making.

Implications

These principles can distribute the burden of scientific communication between scientists and stakeholders and enable better two-way interactions with scientific knowledge. This is not a surrogate for scientific co-production with stakeholders, but it is a heuristic that can enable adaptive management for the environmental sciences from studies that are not necessarily coupled to issues or partnerships. A core tenet of adaptive management is that managing and learning should be connected and iterative in the natural resource sciences (Williams & Brown, 2016). Decision making adjusts as understanding improves both through doing and through learning. This is not a new approach to managing the environment but requires a well articulated framework to be an active process for stakeholders and to improve long-term conservation outcomes (McDonald-Madden *et al.*, 2010). Making the research literature more functional through these principles will accelerate the learning phase of adaptive management. We can make deliberation (i.e. planning) and iteration (i.e. testing) integrate with evidence by adopting these principles (Williams & Brown, 2016). Reuse is also not the sole criterion for useful science nor should it be, but professional advocacy and knowledge mobilization are increasingly important priorities for universities and science in general (Pace *et al.*, 2010). Evidence-informed decision making is a critical area for growth and knowledge in many disciplines (Aarons *et al.*, 2011; Roy-Byrne *et al.*, 2010; Tranfield *et al.*, 2003) – not just environmental management. Increased consumption and production of scientific evidence by managers and practitioners that is more accessible to a broader audience will result in increased functional use of scientific literature. Collaboration with stakeholders will facilitate this process at every step of the scientific endeavour, and open science will be pivotal to adaptive management opportunities. A recent discussion of rewilding

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ecosystems formally modeled societal context as a boundary that must always be considered in all dimensions of restoration efforts by managers and stakeholders (Perino *et al.*, 2019). Using at least some of these principles similarly advances connecting people to nature to primary research. This integrated thinking is critical. Better reporting of research and discussion of relevance and thus perception will increase the stickiness of our ideas and enable novel connections between evidence and outcome, challenge and solution, and people and nature.

Simple principles for the framing of environmental science that enable more connected science to people augment extensive discussion and developments in the field of science, technology, and society and the social studies of science. Knowledge transfer and scientific co-production are profoundly useful to the environmental sciences but at times can be decoupled from basic science (Lang *et al.*, 2012). Transdisciplinary science strongly contrasts with a linear knowledge-deficit model that assumes knowledge moves from experts to citizens and instead emphasizes that integrated thinking focusing on overlap between disciplines and between scientists and citizens eclipses simplistic models of scientific knowledge (Lang *et al.*, 2012). Joint production of knowledge is an ideal, but it is not without debate and challenges (Maillet *et al.*, 2019; Regeer *et al.*, 2009; Williams & Brown, 2016). It has been proposed that production of knowledge always includes social and cultural factors and that decision making is always political (Fernández, 2016). Knowledge-policy interactions in particular are likely non-linear and complex, require multiple knowledge domains with multiple perspectives, and are shaped by personal and professional filters. Moving from data to decisions must include consideration of biases, beliefs, values, and heuristics (such as the ones proposed herein) (Glynn *et al.*, 2017). Even with standardized and accessible data, it is a substantial challenge to develop mechanisms that incorporate these forms of evidence into policy development (Magnusson, 2019). Consequently, framing scientific publications in these fields to ensure that they provide the means for two-way interactions with evidence provides a means to translate principles into action. We implicitly adopted a 'science-policy-practice' perspective linking science to management (Dale *et al.*, 2019) in developing these principles to ensure that a wider subset of basic science can be used to inform decisions - primarily through a simple checklist that authors and readers can use to promote and structure reuse. Science is a movement, and the language we use is important (Wezel *et al.*, 2009). Knowledge is not a static concept held by experts but a series of actions that we engage with through principles, concepts, data, beliefs, and relationships (Maillet *et al.*, 2019). Here, we provide principles that we hope build a bridge and stepping-stones between publications that are not necessarily co-produced and immediately relevant to people that need to use, reuse, and interact with these ideas to inform sustainable societies.

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