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Review

Is Reintroduction Biology an Effective Applied Science?

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Reintroduction biology is a field of scientific research that aims to inform translocations of endangered species. We review two decades of published literature to evaluate whether reintroduction science is evolving in its decision-support role, as called for by advocates of evidence-based conservation. Reintroduction research increasingly addresses *a priori* hypotheses, but remains largely focused on short-term population establishment. Similarly, studies that directly assist decisions by explicitly comparing alternative management actions remain a minority. A small set of case studies demonstrate full integration of research in the reintroduction decision process. We encourage the use of tools that embed research in decision-making, particularly the explicit consideration of multiple management alternatives because this is the crux of any management decisions.

Trends

Reintroductions are an increasingly popular tool for the conservation of threatened species. The number of peer-reviewed reintroduction-related studies continues to grow almost exponentially.

Reintroduction biology is an applied science that supports all forms of conservation translocations. Its purpose is to provide knowledge that facilitates decisions about which management strategies to use.

As an applied science, reintroduction biology should be driven by, and respond to, management needs. This involves testing *a priori* hypotheses relevant to management at multiple ecological levels, and explicitly predicting and comparing the outcomes of management alternatives.

Recently, a small but increasing number of studies have sought this integration by combining predictive modelling, analysis of experimental and monitoring data, and decision-support methods.

From Reintroduction Biology to Reintroduction Practice

In the face of unprecedented biodiversity losses, effective strategies for the conservation of endangered species are urgently required [1–3]. Among conservationists there is almost universal agreement on the need for evidence-based management decisions and for science that supports conservation decision-making [4]. However, management decisions remain primarily based on the application of experience without careful evaluation of evidence [5–7]. For conservation management to be truly evidence-based, the science should be embedded within the management problem to facilitate the choice of a best management action. Conservation science generally seeks to undertake research aimed at providing information to help in choosing management actions; this role should provide better outcomes than would be achieved otherwise, and is our interpretation of applied science. However, most published conservation studies are not always explicit about how the information they present should be used by decision-makers, and thus might not achieve a complete connection between basic and applied science [8,9]. In general, science can support management by (i) predicting the consequences of management actions based on available evidence, (ii) reducing uncertainty around choices between alternative actions, and (iii) providing specialist tools to help select the best action for a given set of objectives. Successful examples in conservation range from experimentally testing non-lethal predator exclusion methods to protect shorebird colonies [10] to developing software for optimal design of nature reserves at the continental scale [11].

The science of reintroduction biology showcases well these general criticisms. Reintroduction is a globally important form of conservation management, but reintroduction programs are complex and require numerous decisions, all of which are subject to uncertainty. This uncertainty in turn makes it difficult to select the 'best' set of actions, frequently resulting in poor choices that have been blamed for the low success of past reintroduction efforts [12–14].

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Reintroduction biology, first formally recognised as a field of science at a conference in Australia in 1993, later published as a proceedings in 1995 [15], is increasingly called upon to facilitate those decisions [16]. Several authors have recommended that reintroduction studies should not only collect data from practice and seek patterns *a posteriori*, but should also focus on the uncertainties that make reintroduction decisions difficult, and rigorously evaluate project outcomes with the aim of improvement [1,17–22].

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Indeed, almost a decade ago, two of us published a paper in this journal that outlined the purpose of reintroduction biology as an applied science [17]. In that paper it was argued that 'reintroduction biology will progress faster if researchers focus on the questions that need to be answered to improve species recovery and ecosystem restoration. That is, reintroduction biologists should nominate the key research questions then use the best methods available to answer them, rather than addressing the questions that are most easily answered or that lend themselves to the most rigorous science.' Ten key questions for reintroduction biology were then identified across four levels: population establishment, population persistence, meta-populations, and ecosystems. Recognising that reintroduction biology to that date mostly focused on population establishment, the paper sought to encourage research across a broader spectrum of concerns. Moreover, concern was expressed that the focus on population establishment reflected the relative ease of research at that level, rather than its actual importance for improving reintroduction outcomes. Therefore, it was also recommended that reintroduction biology as an applied science should address *a priori* questions that capture uncertainty directly affecting management decisions. Whether those calls by Armstrong and Seddon [17] and similar advocates of evidence-based reintroduction [23,24], including the IUCN *Guidelines for Reintroductions and other Conservation Translocations* [25], are being heeded in the growing literature in this field remains to be ascertained.

We evaluate here whether the peer-reviewed published literature in reintroduction biology since its inception at a conference in 1993 and first publication in 1995 indicates increasing effectiveness in supporting reintroduction practice. Accordingly, we seek to understand whether reintroduction studies have (i) broadened their scope beyond population establishment to support problems relating to population persistence, meta-populations, and ecosystems, (ii) addressed defined *a priori* questions, and (iii) whether these questions clearly provide the scientific evidence required to select a best management action.

The Reintroduction Literature

We queried the reintroduction literature using the Web of Science citation search engine (23 November 2016 using the University College London institutional login), specifying the key words: reintroduc* OR re-introduc* OR translocat* in the title field, and monitoring OR population modelling OR experiment OR trial OR planning in the topic field, in the research areas of 'environmental sciences ecology', 'biodiversity conservation', and 'zoology' for the years 1995–2016 inclusive. We also queried the IUCN *Global Re-Introduction Perspectives* book series [26–30] and retrieved any additional peer-reviewed scientific articles cited within those case studies. We only included papers that studied vertebrates and excluded papers that were purely reviews. Our search identified 309 peer-reviewed scientific journal articles from Web of Science and an additional 52 peer-reviewed scientific journal articles from the IUCN publications. One author (G.T.) read each article fully and carefully evaluated the work against our criteria. To ensure reliability of categorisation, 10 papers were first simultaneously judged by three of the authors (G.T., S.C., and J.G.E.) and were consistently categorised. Within the introduction we searched for statements of key questions, hypothesis, and objectives, and within the methods and results we searched for whether or not the outcomes of more than one management action were tested. Although this is not a systematic review, we believe it provides a detailed picture of reintroduction biology, with its known bias toward vertebrates [31].

What Level of Questions Did the Papers Address?

We found that 61% (219/361) of papers addressed questions at the population establishment level, 32% (117/361) at the population persistence level, 4% (16/361) at the metapopulation level, and 3% (9/361) at the ecosystem level (Figure 1). These results mirror the findings of the 2008 paper of Armstrong and Seddon [17] who stated that the majority of reintroduction research to that point had focussed on population establishment. Analysis of the temporal trends in our dataset confirmed the lack of a clear change. Between 1995 and 2016, establishment and metapopulation studies decreased whereas persistence and ecosystem studies increased (in particular, studies addressing persistence in terms of genetic makeup). Multinomial logistic regression confirmed this trend, but suggested that the yearly rate of change was small and not statistically significant (proportional yearly rate of change, expressed by mean exponentiated regression coefficients: establishment, −1.8%; persistence, 2.2%; metapopulation, −4.9%; ecosystem, 8.3%; $P > 0.05$). Most importantly, the proportion of metapopulation- and ecosystem-level studies remained less than 5% by 2017 (Figure 1). Note that, although papers will often implicitly look at multiple questions, for the purpose of this review we assigned articles to only one question level, based on what we deemed to be the primary focus of each study.

Is Reintroduction Literature Question- and Management-Driven?

Armstrong and Seddon [17] argued that 'questions identified *a priori* will increase the amount of useful knowledge obtained from limited conservation funds'. If research does not address clearly defined *a priori* questions, it risks being purely descriptive; if it does not directly address uncertainties that are relevant to management, it risks being irrelevant for practical decision-making, regardless of its potential scientific interest. To determine the extent to which the reintroduction literature develops *a priori* management-driven questions, we carried out two analytical steps.

First, we categorised each publication as either clearly stating *a priori* questions or not (i.e., descriptive). Second, although developing questions *a priori* moves us closer to management-driven research, management decisions normally imply a choice between alternative actions [32,33]. Therefore, explicitly discriminating among those actions represents the best support that reintroduction science can provide to decision-makers. We categorised each of the 361 reintroduction papers into one of three categories: (i) studies that directly compared the

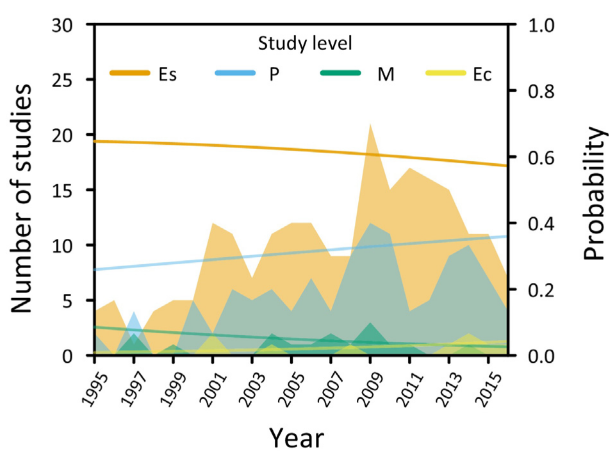

Figure 1. Temporal Trends in the Level of Question Addressed (Ec, ecosystem; Es, establishment; M, metapopulation; P, persistence). Shaded areas are the number of studies in each category each year. Lines are the mean probability of a study falling in each category in a given year, as predicted by multinomial logistic regression.

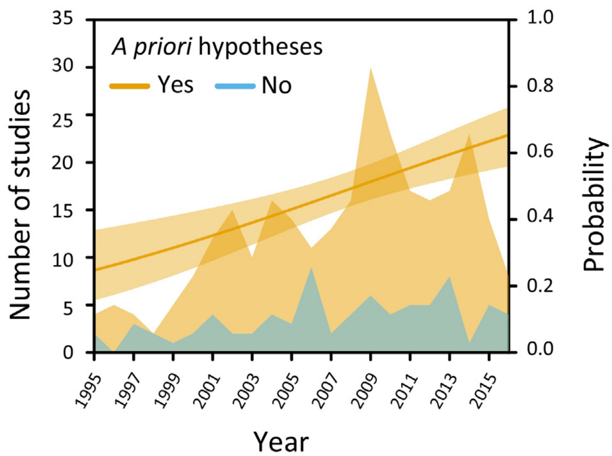

Figure 2. Temporal Trends in the Treatment of *A Priori* Hypotheses (Yes/No). Shaded areas are the number of studies in each category each year. The solid line indicates the mean probability of a study addressing *a priori* hypotheses in a given year, as predicted by logistic regression (the shaded area indicates the 95% CI).

consequences of alternative management actions, either by *a priori* predictive modelling or *a posteriori* analysis of field data (including deliberate manipulation by experiment or adaptive management), (ii) studies that analysed results under one management action and assessed them without reference to alternative actions, and (iii) studies that did not obviously identify or assess a management action, but published scientific information that was considered valuable for conservation.

We found an equal split between papers that clearly stated *a priori* questions, 49% (176/361), and those that did not, 51% (185/361) (Figure 2). Logistic regression suggested a marked increase over the study period: the mean probability that a published study addressed *a priori* questions increased from 24% in 1995 to over 64% in 2016 (Figure 2). Only one fifth of the reviewed articles (22%, 78/361) presented data comparing two or more management actions to directly support decision-making, in other words these were in category A (Figure 3). The majority of research articles (74%, 270/361) were in category B, in other words they analysed the results of one management action and then made *post hoc* recommendations about whether the action was suitable or not. The remaining few research articles (4%, 13/361) were in category C, making no explicit link between research and management. Multinomial logistic regression again confirmed these observed trends, with <1% relative yearly changes in all categories.

Is Reintroduction Biology Supporting Reintroduction Practice?

Throughout its two decade history the science of reintroduction biology has repeatedly been encouraged to better support reintroduction practice [17,18,34–37]. The publication frequency of reintroduction-related studies continues to increase, making more and more scientific evidence available to support reintroduction practice. However, this is not in itself an indication of better application: reintroduction science will not improve simply by producing more data [17]. Instead, it requires both scientific learning through experiments, prediction, and monitoring, as well as true integration into reintroduction practice, allowing managers to identify the actions that are most likely to achieve their objectives.

In this regard, our assessment shows that, despite frequent calls, reintroduction biology is not reaching its full potential in providing the evidence base to support management decisions. For

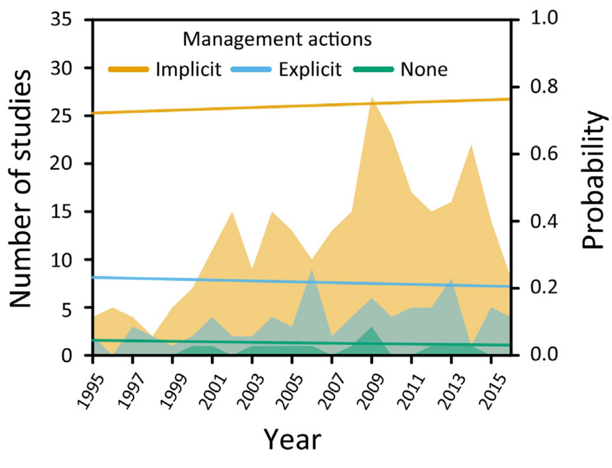

Figure 3. Temporal Trends in the Level of Comparison of Management Alternatives (Explicit/Implicit/None). Shaded areas are the number of studies in each category each year. Lines show the mean probability of a study falling in each category in a given year, as predicted by multinomial logistic regression.

example, resource-demanding and technically challenging metapopulation and ecosystem studies continue to represent only a small proportion of the reintroduction literature. This practical complexity reinforces the need for clear *a priori* thinking; in this regard it is encouraging to find that an increasing proportion of studies focus on answering *a priori* hypotheses. However, whether this latter trend represents a specific improvement of reintroduction biology or reflects the more general tendency to move away from descriptive studies, particularly in higher-profile peer-reviewed journals, cannot be discerned.

Perhaps the most important of our results is that over the past two decades there has been no appreciable increase in the proportion of studies that provide direct support for management decisions by explicitly comparing alternative actions. In many such cases, managers and decision-makers might be presented with evidence, but it is left to them to translate such information into a management decision. Only one fifth of the studies reviewed directly compared two or more possible actions (or treatment groups), either through predictive modelling before any practical implementation or from interpretation of data from field monitoring or deliberate manipulation as part of the reintroduction. This limitation is likely driven by practical constraints. Many reintroductions focus on highly endangered species where the potential for learning is limited by small sample sizes and difficulties in replication. However, these limitations reinforce, rather than diminish, the need for a strong theoretical basis for recovery plans, and make the alternative trial-and-error approach even more risky [38]. Where active comparison of management actions via experiments is still considered too risky, and learning is limited by other practical constraints such as small sample sizes, predictive modelling *a priori* and passive adaptive management [39] can still provide guidance. In general, explicit consideration of multiple actions, including 'doing nothing' options, can make even studies that directly assess only one action more relevant for management.

To summarise our findings, some encouraging trends are visible in the reintroduction literature: more studies are explicitly addressing *a priori* hypotheses. However, reintroduction biology still has great scope to better support reintroduction practice: broader-scale metapopulation and ecosystem-level studies are still rare, and, most importantly, few studies explicitly focus on assisting the choice among alternative management actions, which is the ultimate requirement of decision-making. The key to filling this gap is currently represented by a small set of more

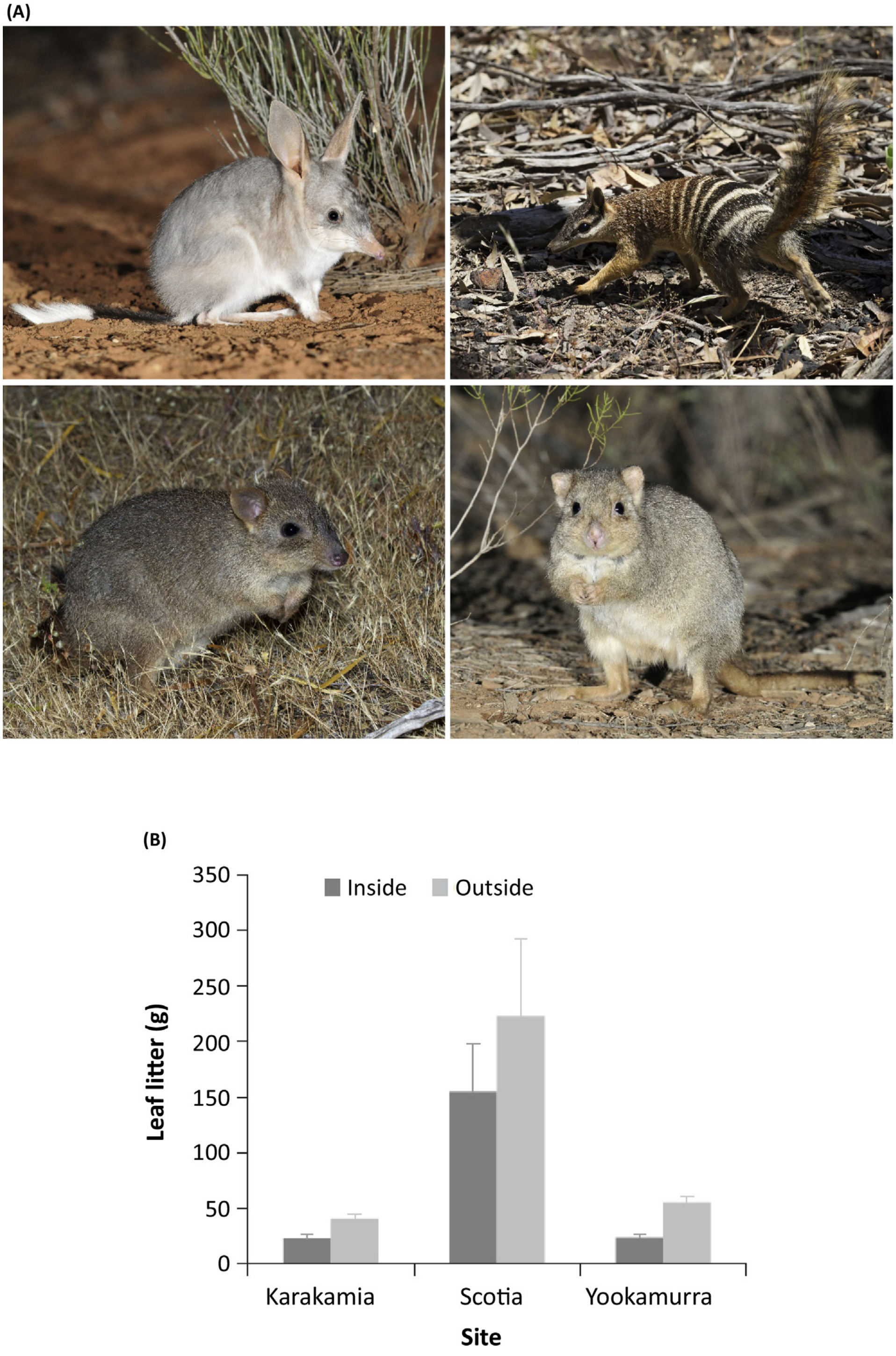

Figure 4. (A) Native Australian Mammalian Ecosystem Engineers. (Top left) The bilby (*Macrotis lagotis*), (top right) the numbat (*Myrmecobius fasciatus*), (bottom left) the woylie (*Bettongia ogilbyi*), and (bottom right) the boodie (*Bettongia lesueur*) are considered to be ecosystem engineers that have the potential to reduce fire intensity and spread by altering leaf litter accumulation and breakdown where these species (and others) are present (B). Photo credits: Bilby and Boodie, Wayne Lawler/Australian Wildlife Conservancy; Numbat and Woylie, Rohan Clarke.

Box 1. The Benefits of Reintroducing Ecosystem Engineers Back into the Australian Environment for the Management of Wildfire [44]

As in other parts of the world, wildfires are a natural occurrence in the Australian environment and have shaped the life-history traits of floral and faunal communities [45]. In Australia, burning has been used by indigenous peoples as a traditional ecological management tool for millennia; however, uncontrolled wildfires are becoming more frequent and intense, causing enormous economic, social, and environmental damage [44]. Australian terrestrial mammals such as the bilby (*Macrotis lagotis*), the numbat (*Myrmecobius fasciatus*), the woylie *(Bettongia ogilbyi*), and the boodie (*Bettongia lesueur*) (Figure 4A) are considered to be ecosystem engineers because they alter leaf litter accumulation and breakdown. Australia has seen a dramatic decline in small terrestrial mammals, and the loss of these species, particularly fossorial species, has been hypothesised to alter wildfire behaviour through increased leaf litter accumulation. Leaf litter is a hugely combustible material that, when in abundance, can facilitate the spread and intensity of fire [44,46]. The experimental study by Hayward *et al.* [44] aimed to determine whether this loss of ecosystem engineers did lead to an increase in leaf litter and therefore to an increase in fire intensity and rate of spread. The study was conducted at three Australian Wildlife Conservancy restoration sites where previously extinct fossorial species had been reintroduced into large, exotic-predator-free, fenced areas. At these sites, a pairwise fence-line comparison was replicated (where outside the fence-line represented locations with no reintroduced species). The paired sites inside and outside the fenced areas had otherwise similar vegetation and fire regimes, and data were collected on animal digging pits, leaf litter accumulation, and bare ground cover. The McArthur Mk5 Forest fire behaviour model which predicts the probability of a fire starting, rate of spread, and intensity based on environmental parameters was also applied to these sites. Results showed a significant decrease (24%, 95% CI 6–43) in leaf-litter mass inside the fenced areas (in the presence of reintroduced mammal ecosystem engineers) compared to outside (no reintroduced mammal ecosystem engineers) at all the three sites (Figure 4B). The fire behaviour model also predicted that flame height would be much higher outside (1.41 m) the fenced areas compared to inside (0.37 m), and that fire spread would be much faster outside fenced (0.18 km h^{-1}) areas compared to inside (0.12 km h^{-1}), equating to a 74% reduction in flame height and a 33% reduction in the rate of fire spread.

This is an example of an experimental study that explicitly tests the outcomes of more than one management alternative (reintroduction of native fossorial species or absence of these species), and answers an ecosystem-level question by highlighting the beneficial impact of these management actions on ecosystem function and restoration.

Outstanding Questions

Why has reintroduction science not adequately engaged with the decision-making process to date?

Is the failure to address key questions relating to metapopulation management, multispecies restorations, and ecosystem processes dictated simply by data availability and timelags between implementation and assessment?

Are there common patterns among fully applied reintroduction studies? For example, do geographical patterns reflect the general strength of ecological research, the structure of governance and recovery plans, the type of institution doing the research, or the level of funding available?

What structures for governance and engagement are necessary to ensure that reintroduction science is most relevant to management needs?

recent studies that illustrate clearly how to embed conservation science into practice by developing clear *a priori* questions that are immediately relevant to management, explicitly comparing two or more management actions [23,40–43]. An example is given in Box 1. We acknowledge that each article in our review was treated equally, regardless of its scale and the number of institutions involved, and that our inferences might have been different to some extent if these factors were taken into account.

Changes still need to occur in what reintroduction biology researches (expanding to a broader range of questioning spanning establishment to ecosystems) and in how it responds to management needs (by directly embedding within decision-making). By targeting uncertainties that are relevant for management, explicitly comparing the expected outcomes of alternative actions, and managing adaptively rather than by trial-and-error, reintroduction biology can best provide the scientific evidence needed to maximise the success of reintroduction practice.

Supplemental Information

Supplemental information associated with this article can be found online at http://dx.doi.org/10.1016/j.tree.2017.08.002.

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