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Reallocating budgets among ongoing and emerging conservation projects

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Article Impact Statement: Reallocating funding among conservation projects in response to shifting or emerging priorities may improve outcomes.

Abstract

Conserving biodiversity and combating ecological hazards require cost-effective allocation of limited resources among potential management projects. Project priorities, however, can be both stochastic and dynamic over time as underlying social-ecological systems progress, novel priorities emerge, and management capabilities evolve. Thus, reallocation of ongoing investments in response to shifting priorities could improve management outcomes and address urgent demands, especially where additional funding is not available immediately. Resource reallocation, however, could incur transaction costs, require additional monitoring and reassessment, and be constrained by ongoing project commitments. Such complexities may prevent managers from considering potentially beneficial reallocation strategies, reducing long-term effectiveness. We propose an iterative project prioritization approach based on marginal return-on-investment estimation and portfolio optimization which guides resource reallocation among ongoing and new projects. Using simulation experiments within two case studies, we explore how this approach can improve efficacy under varying reallocation constraints, frequencies, costs, and rates of project portfolio change. We found that periodic budget reallocation could enhance the management of stochastically emerging invasive weeds in Australia, reducing the overall risk by up to 50% compared to a static budget. Reallocation frequency and the rate of new weed incursion synergistically increase the conservation gains achieved by allowing unconstrained reallocation. Conversely, budget reallocation would not improve the IUCN conservation status of threatened Australian birds due to slow rates of transition among conservation states, and might increase extinction risk if portfolio reassessment is costly. While other project prioritisation studies may recommend periodic reassessment and reallocation, our findings reveal conditions when reallocation is valuable, and demonstrate a structured approach that helps conservation agencies schedule and implement iterative budget allocation decisions cost-effectively.

Introduction

Conservation projects are widely constrained by limited funding (McCarthy et al. 2012) and require prioritization and optimal budget allocation (Possingham et al. 2001; Gerber et al. 2018). Identifying an optimal project portfolio relies on estimating the cost-effectiveness and risks of candidate projects and then trading off the investment among projects (Wilson et al. 2006; Joseph et al. 2009). Various project prioritization tools for budget allocation have been developed (Joseph et al. 2009; McCarthy et al. 2010; Wilson et al. 2011) and several are being implemented (Joseph et al. 2009; Di Fonzo et al. 2017; Brazill-Boast et al. 2018). However, the cost-effectiveness and relative priority of conservation projects are not always static. Funded projects may underperform and new problems may occur and require timely investment. Public values toward biodiversity conservation and socio-political constraints on management options can change (van Eeden et al. 2017). Thus, the original resource allocation can become sub-optimal over time and even perform poorly if not adjusted.

Resource reallocation can bring significant potential benefits. For example, replacing the 1% least cost-effective of Australia's protected area with higher-performing sites would greatly improve vegetation conservation (Fuller et al. 2010). Similarly, reallocating the budget surplus from underperforming conservation programs in the US to underfunded species could erase funding deficits for many species (Gerber 2016). Timely response to events such as pest outbreaks or unexpected disturbances can also help prevent unnecessary losses due to delayed actions (Simberloff 2003). Several project prioritization tools are designed to be re-run periodically (e.g. Brazill-Boast et al. 2018), and some conservation agencies are adopting more adaptive frameworks such as the Open Standards for the Practice of Conservation (Conservation Measures Partnership 2013) to implement iterative reviews and adjust resource allocation (e.g. Bush Heritage Australia; Rebecca Spindler, personal communication).

However, budget reallocation can entail costs, risks and constraints, so managers must decide how and when to reallocate. Policy changes and the resulting budget and priority adjustment can incur transaction costs associated with changes in administration, capital, and legal contracts (Boettiger et al. 2016). Reallocating or ceasing projects poses a risk to assets such as longitudinal data, built capacity, and community support. Contracts with locked-in periods (e.g. payment for ecosystem services), and socio-political constraints (e.g. public pressure to support flagship species programs) can limit changes in investment level. Furthermore, portfolio reassessment can incur costs beyond that of within-project monitoring, such as synthesis of data across disparate operations and initial assessment of new projects. Additional expenses for portfolio reassessment can compete for funding with within-project monitoring and actions. The above reallocation concerns are often implicit or omitted in conservation project portfolio management. While it may be difficult to quantify all of these components, they can be introduced explicitly into a reallocation optimisation as costs and constraints to help support potentially challenging decisions.

Re-prioritizing conservation projects requires dynamic decision-making that responds to changes in project status and knowledge. As such, reprioritisation fits into the framework of adaptive management (Walters 1986). Guidelines and decision-support tools for adaptive management are well developed for action-level, dynamic decisions within a single project (Williams et al. 2009; Chadès et al. 2017), and have addressed the costs of monitoring and learning (Williams & Johnson 2015) and temporal constraints in action adjustment (Péron et al. 2017). However, such dynamic elements have rarely been investigated in project portfolio management at the organization level. Existing studies on conservation project prioritization have explored budget decisions among projects with multiple funding levels (Cattarino et al. 2016) and dynamic acceptance of new project opportunities (McDonald-Madden et al. 2008). Mean-variance portfolio optimization with correlated project risks has been developed to achieve best risk-return trade-offs (Ando & Mallory 2012). The value of budgeting flexibly across years has also been demonstrated (Lennox et al. 2017). But no study to date has investigated the value of iteratively adjusting a project portfolio under shifting threats and opportunities. It is unclear how characteristics of the management problems, such as reallocation frequency, rate of new project emergence, and reassessment costs, may influence the appropriate reallocation schemes and strategies.

Here we propose a workflow for planning and executing iterative budget reallocation among projects. It is based on marginal returns-on-investment (ROI) that characterize how funding to each project contributes to overall portfolio objectives over a time horizon, and allows for partial and full budget reallocation, reassessment costs, and reallocation constraints. The method distinguishes reassessment costs and within-project management costs, and finds a cost-effective reallocation schedule and investment levels for ongoing and new projects. Using simulation, we examine the conservation outcome under different reallocation strategies (e.g. no reallocation, only reallocate budget from completed projects, or unconstrained). We assess how reallocation frequency, the rate of portfolio change, and reassessment costs affect the benefits and risks of reallocation. We demonstrate our approach with two case studies with contrasting reassessment costs and portfolio dynamics (managing invasive weeds and threatened birds in Australia). A step-by-step guide with model details and descriptions of case study data usage are provided in Supporting Information.

Methods

Decision context

We consider managing a long-term resource budget to achieve conservation objective(s) with quantifiable utility measures over a specified time horizon. The total budget is to be allocated to multiple projects, each contributing to one or more of the objectives. The project pool itself can change as projects terminate or emerge. The total budget funds both within-project management actions via each project and the reassessment of project portfolio status, following a prescribed timing and frequency of reassessment and budget reallocation events. Note that we distinguish between monitoring costs within project management and costs for portfolio-level assessment and consider the former as part of within-project management costs.

Reassessment-reallocation schedules

Decision-makers prescribe a candidate project reassessment schedule specifying when information about the status and progress of each project is updated. Candidate schedules can be designed based on feasible budgetary (e.g., annual) or strategic (e.g., five year) cycles or the timing of existing monitoring schemes. Collected information helps refine estimates of project cost-effectiveness, thus informing reallocation needs. Whether frequent and comprehensive reassessment improves conservation outcomes would be assessed in advance using simulation (see below), so that decision-makers can select a schedule with good expected performance.

Module 1 'Assess': Estimate the marginal return-on-investment for each project

We estimate how a project is expected to perform under different levels of budget investment -- a marginal ROI function. Ecological management has used ROI in various formats for prioritization and resource allocation, with ROIs derived from expert elicitation, empirical or experimental data, or simulation of a dynamic process-based model (Hone et al. 2017). Here investment represents the resources, often money, allocated to a project from the current time point until the end of the management time horizon. Return is the expected benefits a project could produce over the remaining management time horizon given an investment plan from the current decision time step (e.g. probability of species being present 20 years later under annual budget of $100K). A marginal ROI curve therefore depicts how project performance changes with budget investment and can be re-estimated with reassessment information. Estimating ROIs over the remaining time horizon based on up-to-date project progress can capture project phase-dynamics, such as decreasing probability of conservation success over time if not managed early. Note that time-varying conservation costs are also tracked. For example, project upfront costs will not be counted in ROI at later time steps. Our approach uses the cumulative total cost as the 'investment' for ROI comparison among projects and can then impose an annual budget constraint in the 'prioritise' step to account for time-varying project expenses. For simplicity, in the case studies below we assume annual costs of a project to be static over the remaining time horizon. We also assume no project interactions, although we acknowledge that important project interactions (e.g. Auerbach et al. 2015) should be carefully addressed with extended modelling approaches such as mean-variance portfolio optimization.

Module 2 'Prioritise': Allocate resources to priority activities

Resource allocation among candidate projects can be prioritized by examining their ROIs, using a wide range of prioritization and optimization tools. Ranking-based project selection can be applied to sort projects with discrete ROI points (Joseph et al. 2009; Dodd et al. 2017). Mathematical optimization can be conducted on either continuous or discrete ROIs (McCarthy et al. 2010; Cattarino et al. 2016). Common objectives of project portfolio optimization, including maximizing the expected total utilities, minimizing losses or risks, or finding the Pareto frontier, are all implementable. Reallocation inflexibility can be incorporated as optimization or selection constraints (e.g. specifying selected ROI points or regions as infeasible), so that a selected portfolio is guaranteed to satisfy the constraints. For example, if the annual budget is capped and project cost structures are complicated and time-varying, additional constraints on maximum expenses in each time period can be included. Upon finding an (updated) portfolio, decision makers compare it against the ongoing portfolio and select the one with higher expected total benefits.

In the two case studies below, we demonstrate formulating portfolio optimization as separable programming problems (Stefanov 2013). Separable programming uses a finite number of auxiliary points to form a piece-wise linear approximation of a ROI function. Linear programming can then find the optimal investment portfolio (across projects) that maximize the expected total conservation benefits. This approach is myopic as it is based only on the project ROIs at the decision time step, yet allows us to find well-performing budget allocations without the need of a fully dynamic optimization (e.g. stochastic dynamic programming (SDP) (Marescot et al. 2013)), which is difficult to solve when there are many projects and potential project status. Separable programming problems can be solved efficiently using common linear programming solvers (e.g. Gurobi, CPLEX), and can further accommodate mixtures of discrete and continuous ROIs. For details, see Supporting Information.

Module 3 'Learn': collect data and reassess projects

Monitoring of ongoing and new conservation projects is conducted using pre-allocated reassessment budgets. Monitoring actions are project-specific and provide 1) adequate information about the system status that is used for between-project comparison (e.g. IUCN status), and/or 2) updated knowledge about management effectiveness and the future outlook. Data collected will help update project ROIs at the next reassessment-reallocation time step, where Module 1-3 will be repeated.

Case studies

Case study 1: Invasive weeds in Australia

The Australian Department of Agriculture, Water and the Environment maintains a list of exotic plant species with potential weed risk to Australia (Pheloung et al. 1999). Since the early 1990s, the State of Victoria, Australia, has operated a program that seeks to detect and ultimately eradicate high weed risk species before they become widespread (Dodd et al. 2015). Dodd et al. (2017) studied the optimal 20-year budget allocation to manage the hypothetical case where 50 weed species from the Australian list have established various sizes of infestation in Victoria. Labour costs of different management effort levels (monitoring/treatment rate: 1-3 times per year) were modelled with a stage-matrix model that tracks the size of infested area that needs treatment. A hazard rate model was then employed to estimate the probability of eradication as a function of species demographic traits and management efforts. The models considered infestation progress under delayed or no management, and the resulting decrease in probability of successful eradication. The most cost-efficient effort for each project was then identified and used to prioritize the allocation of resources, to minimize the overall weed risk (see Dodd et al., 2017 for model details).

Here we investigate how iterative budget reallocation may improve management over a 20-year horizon. We used model outputs in Dodd et al. (2017) as project ROIs for each of the 50 species, where returns are defined as the expected weed risk value at the terminal time (probability of eradication × species' risk value). We adjusted the probability of weed eradication from the hazard rate model to account for management history (Supporting Information). A range of reallocation frequencies and rates of new project emergence are investigated. We assume an initial project list of 30 out of the 50 hypothetical weed incursions in the original paper, with the stochastic incursion of the other 20 species modelled as a Poisson process with parameter λ = 0.25, 0.5, 1, 1.5, or 2 expected new projects per year). Project reassessment-reallocation events are scheduled at every 1-10 years, where all project ROIs are updated with observed project status (i.e. present/eradicated, extent of infested area). We assume zero additional cost in project reassessment as management actions already include monitoring. Following Dodd et al. (2017), the total budget was AU$29.14 M over 20 years, with a financial discount rate of 6% per annum. At each reallocation step, budget allocation is optimized using piece-wise linear separable programming with R 3.5.3 and Gurobi 9.0.0. Data and parameter details are provided (Table 1).

We simulated (1000 iterations) and compared the expected weed eradication outcomes of three management strategies: 1) S1: no reassessment or reallocation (i.e. omitted/new projects won't be funded); 2) S2: reassessment and constrained reallocation where the budget is only released from terminated projects (eradication success); 3) S3: reassessment and unconstrained reallocation where the budget of all projects can be increased or decreased. Note that in practice there can be logistical and stakeholder challenges in budget reallocation, so that real-world reallocation flexibility may be in between S2 and S3.

Case study 2: Threatened birds in Australia

In Australia, Garnett & Crowley (2000) identified 270 bird taxa as threatened or of conservation concern. McCarthy et al. (2008) assessed the statistical relationship between the monetary conservation investment to a species and the probability of the species changing IUCN status during years 1992-2000, based on national data collated in The Action Plan for Australian Birds (Garnett & Crowley 2000). They estimated the probability of each type of IUCN status change over an 8-year period (e.g. '+2', move up 2 IUCN categories; '0', stay the same). They then optimized resource allocation among the species, based on their IUCN status, over one or more time steps to minimize the expected number of extinct or threatened species (McCarthy et al. 2008).

Here we apply our reallocation protocol to bird conservation over a 16-year time horizon (two 8-yr time steps). The return is the expected penalty score at terminal time (to be minimized) (based on species' expected IUCN status weighted by penalty scores as in original study: Extinct = 1, Critically Endangered = 0.5, Endangered = 0.05, Vulnerable = 0.005, Near Threatened or Least Concern = 0). We use the statistical models from the original study to simulate species' IUCN status transition under different investment levels (AU\$0-1M per annum). The resource allocation portfolio is optimized using separable programming as above. We assume all 270 species projects are present from the beginning, with no new species projects arising. Note that it represents a conservative assumption about reallocation needs, as in practice additional projects can emerge over time. We tested a total budget of AU\$57.6M (the budget level during 1992-2000, see McCarthy et al. 2008) over 16 years. We assume that updating IUCN status for all species at the 8th year would cost AU\$6.85M (assuming a cost of AU\$25400 per species; Bland et al. 2015) in addition to monitoring efforts for within-project purposes. A financial discount rate is omitted in line with the original study. Data and parameter details are provided (Table 1).

We simulate (1000 iterations) and compare the same three reallocation strategies as in the weed invasion case study (S1-3). As the importance of reassessment costs may depend on the size of the total budget, we further explored a range of total budgets (AU$14.4M, 28.8M, and 115.2M). Since reassessment costs may be shared with within-project monitoring, we examined a contrasting scenario of zero reassessment costs. Since estimates of the transition probabilities between IUCN status are generally very low (<0.08 per eight-year), we further tested scenarios where all between-status transition probabilities are multiplied by a factor of 2, 3, 4, 5, and 6, under a total budget of AU$57.6M, to examine how reallocation benefits depend on rate of system change (Supporting Information).

Performance relative to stochastic dynamic programming

To examine how well our iterative myopic optimization performs, we constructed a set of reduced case study problems (5 projects each) and applied both our approach and SDP to compare their solution performance. We explored how reallocation frequency and rate of system change influence the performance gap between the two approaches (see Supporting Information).

Results

Invasive weeds in Australia

Iterative budget reallocation helped eradicate more weed species and eliminated more risk, compared to a static investment portfolio (Fig. 2). Mean conservation gains from both constrained and unconstrained reallocation (S2, S3) increased with the rate of new weed incursions (*ca.* 3.7% and 20.6% improvement over S1 when there is on average 0.25 and 2 new weed species per year, respectively, under a 10-yr reallocation frequency). However, as we reallocate more often, only unconstrained reallocation produced larger mean conservation gains (22.5% and 32.5% improvement over S1 when reallocating every 5 and 1 year, respectively, under an average of 1 new weed species per year) and had lower risks of performing worse than a static budget (proportion of 95% CI below zero decreased with increasing reallocation frequency). In contrast, as reallocation become more frequent, mean benefits of constrained reallocation were relatively constant or even diminishing. The performance discrepancy between constrained and unconstrained reallocation is largest if reallocation is frequent and new weed species emerge quickly. Figure 3 illustrates an example of the unconstrained reallocation scenario, showing how a management budget was re-distributed among existing and new projects over time, including pausing or stopping a weed eradication attempt to free up resources to focus on a higher priority weed eradication attempt.

Threatened birds in Australia

Under the data-informed IUCN status transition probabilities (as in McCarthy et al., 2008), conserving threatened bird taxa would not benefit from reassessment and reallocation. With a total budget of \$57.6M and reassessment costs of \$6.85M, simulated IUCN status changes under no reassessment nor reallocation (S1), constrained reallocation (S2) and unconstrained reallocation (S3) result in total penalty scores of 15.50 (1.13), 15.89 (1.20), and 15.80 (1.17) (mean (SD)) at the 16th year; the associated average number of species extinctions is 1.24, 1.48 and 1.45, respectively (*n* = 1000 iterations). Compared to the management outcome under S1, spending on reassessment (S2 or S3) actually increased the predicted number of species extinctions. When reassessment costs ($6.85M) occupy a large portion of some smaller total budgets (23.8% at $28.8M and 47.6% at $14.4M), strategies with reassessment may further increase extinction risks (Fig. 4, Supporting Table 1). Furthermore, we found no reallocation benefit even if reassessment has zero cost (average number of species extinction under S2 and S3 are 1.24 and 1.20, respectively). An example of the reallocation scenario under strategy S3 is illustrated in Fig. 5. Additional analyses with hypothetical, high transition probabilities between threat status categories show that reallocation benefits are greater as the transition rates increase, although such benefits can be outweighed if reassessment costs are high (Supporting Information).

Discussion

We present a structured workflow that complements existing project prioritization methods in helping managers identify cost-effective reallocation schedules and management strategies. While existing methods may recommend periodic reassessment and reallocation, we explicitly model the costs and outcomes of budget reallocation to identify what frequency of reassessment is expected to benefit management. Iterative budget reallocation has the potential to substantially improve conservation outcomes if conservation threats or needs shift rapidly, reassessment costs are low, and/or reallocation is frequent, as in our weed case study. It reflects how dynamic feedback controls can outperform open-loop management (e.g. Game et al. 2009; Rout et al. 2017). However, reallocation may be less beneficial and more likely to cause poorer outcomes when it is constrained, as in the weed study, or may become less valuable or even harmful for managing slow-changing systems with expensive reassessment costs, as in the bird case study. These results illustrate the complexity of making budget reallocation decisions, and how structured analyses can assist.

Our proposed iterative project prioritization can be implemented to varying extents in real-world decision-making, depending on availability of data and technical expertise. When projects status or emergence can be estimated by data-informed quantitative predictive models, we suggest that our iterative portfolio optimization can balance decision optimality and technical demands on managers. Compared to the theoretically optimal SDP method that requires detailed, per-time-step state transition probabilities of each project, our myopic optimization approach requires only estimating a single ROI over the management time horizon and can address many more projects (see Supporting Information). Our additional analyses also showed that, with a properly planned reallocation scheme, myopic optimization iterated with passively updated information represents an effective heuristic that approximates the optimal SDP solution well (Supporting Information), just as passive adaptive management often performs similarly to active adaptive management (e.g. Johnson et al. 2002; Rout et al. 2017). Also, our method can be flexibly extended to consider multi-objectives, time-varying costs and complicated constraints.

Adopting a structured way to plan for iterative portfolio update can still be valuable to conservation agencies even if detailed data or models are not available for a formal optimization. Managers can explicitly quantify their perceptions or assumptions about project ROIs and how likely new threats or opportunities may occur over time. Such information, even if uncertain, can help explore how reassessment and reallocation schedules may capture new management needs in the form of scenario analysis (e.g. "Will a 5-year reallocation cycle be responsive enough if large pest outbreaks occur frequently?"). Defining ROIs of both ongoing and potential projects over the same portfolio time horizon is also critical for ensuring effective project prioritization, whether through optimization or simple ranking heuristics (e.g. PPP), so that budget expenditure can be focused on the portfolio objectives.

Key determinants of reallocation benefits

Iterative budget reallocation may effectively improve management outcomes for rapidly changing ecological systems and project portfolio. For example, weed invasion, outbreak and eradication may occur within years or soon after disturbances such as floods or fire, quickly changing management priorities. By contrast, the slow transition dynamics of Australian birds in their IUCN categories and the absence of new species projects renders reallocation ineffective given its costs, and reduced reallocation benefits even in the absence of reassessment costs. To properly estimate reallocation needs, managers should therefore assess the likelihood and rate of significant system change or priority shift in their management context. For example, budget reallocation might be less beneficial for slowly developing threats (e.g. over-harvesting and climate change), than for rapidly emerging ones (e.g. habitat destruction, outbreaks of pests or diseases). Reallocation might also be less important for portfolios with static composition than for portfolios with high turnover rates. Furthermore, frequent and flexible reallocation can be an effective measure to respond to shifting socio-political environments and funding landscapes, such as during institutional reorganizations and political swings.

Frequency of budget reallocation can strongly influence the resulting conservation outcomes. If new threats or opportunities are likely to rapidly occur during a budget period and reassessment is not too costly, frequent budget reallocation within the period could help capture these events. Importantly, increasing the frequency of unconstrained reallocation can act synergistically with a higher rate of new project emergence and drastically improve conservation outcomes and reduce the risks of performing worse than a static budget (weed case study; Fig 2). Therefore, when project portfolio is dynamic and warrants budget reallocation, managers should aim at maximizing the frequency of unconstrained reallocation to achieve the best conservation gains. Note that, however, constrained reallocation may limit the outcome improvement from increasing frequencies (see discussion below).

Costs of portfolio reassessment can erode reallocation benefits and even result in poorer conservation outcomes than a static portfolio. Reallocation is worthwhile only if the expected performance gain outweighs the opportunity costs of reassessment expenditure, especially when funds are scarce. It is an important concern for conservation projects where additional monitoring efforts are needed for cross-project assessment beyond that for within-project use. For example, updating the conservation status of threated species may require national, standardized population viability information beyond smaller-scale population data used within a management project. Trading off reassessment costs and reallocation benefits requires evaluating how likely the additional information may lead to budget redistribution and improved management outcomes. Using a proportion of the budget to collect costly information would be sub-optimal unless that information contributes to effective reallocation, which requires a value-of-information analysis (Canessa et al. 2015) at the portfolio level. To fundamentally ameliorate such trade-off, managers should aim to strategically design within-project monitoring that simultaneously informs between-project comparison.

Implications for portfolio management strategies

Our results showed that committing to flexible, unconstrained budget reallocation is key to secure conservation gains. Missed opportunities due to reallocation constraints can be non-trivial, as revealed in our weed case study (mean outcome improvement is 40% lower in constrained reallocation compared to unconstrained reallocation, under annual reallocation and rapid new weed incursion) (Fig. 2). Furthermore, constraining reallocation to be only from completed projects can bring less benefit and incur higher risks of performing worse than a static budget (Fig. 2). The difference in performance occurs because constraints of reallocation limit the amount of newly released budget at each reassessment time point, so any new project would be implemented under a small and potentially sub-optimal budget. In comparison, if reallocation is fully unconstrained, frequent reallocation would allow new projects to be reallocated a budget at later time periods that is optimal for overall portfolio performance. In real world practice, the extent of reallocation constraints can be somewhere between the strategies considered here. It would be important for managers to assess and justify an appropriate level of reallocation flexibility. In this regard, our proposed method can be used to evaluate various forms of reallocation constraints and help policy design (e.g. how projects with fixed-term contracts or financial interdependency may affect potential reallocation benefits). When reallocation may not be useful, good initial allocation will be critical.

Unconventional and seemingly risky reallocation decisions can sometimes be rational and worthwhile. For example, ongoing management projects may be paused or terminated for reallocating resources toward other projects with higher priorities or immediate emergency and may later be resumed. That said, careful estimation of the expected loss and risks in pausing or terminating projects is required. Recent studies and discussion on conceptually similar management strategies, such as temporary and moveable protected area and strategic investment delays, have also stressed potential benefits that warrant consideration (Moilanen et al. 2014; Iacona et al. 2017). Unconventional resource reallocation strategies can potentially increase managers' capacity to tackle pressing and dynamic management needs.

Toward real world implementation

The uptake and implementation of structured resource allocation in real world conservation practice has been challenging. Evaluating the costs, benefits, and risks of a conservation organization's projects following a rigorous and standardized protocol is difficult (Armsworth 2014). Quality reassessment results may not always be available for all projects at synchronized timing due to potentially delayed, ineffective or omitted monitoring actions (Bottrill et al. 2011). If ROI estimation and usage is not yet widespread, fully dynamic budget allocation remains a long-term prospect. Carefully budgeted reassessment schemes and standardized cost-benefit reporting methods would support such transitions toward formal and accountable project evaluation and management. Wider adoption of structured decision analysis (Gregory et al. 2012) in conservation agencies would also facilitate the uptake of a resource allocation framework by practitioners, laying the foundations for adaptive portfolio reassessment and reallocation. Improved access to quantitative skills and optimization tools would also be critical to management agencies, and can be facilitated by wider research collaboration and the open access packages and tutorials.

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Tables

Table 1. Summary of data and parameters used in the two case studies

	Case study 1: Invasive weeds in Victoria, Australia	**Case study 2: Threatened birds in Australia**
Total budget (AU$)		
- Baseline	29.14M over 20 years	57.6M over 16 years
- Sensitivity analysis	-	14.4M, 28.8M, and 115.2M
Reallocation frequency (years between reallocation events)		
- Baseline	5	8
- Sensitivity analysis	1, 2, 3, 4, 6, 7, 8, 9, 10	-
Cost of reassessment (AU$)	0	0 or 25400 per species
Number of candidate projects		
- Initially present	30	270
- Emerging later	20	-
Average number of new project per year		
- Baseline	1	-
- Sensitivity analysis	0.25, 0.5, 1.5, 2	-
ROI features		
- Discrete/continuous	Discrete (monitoring rate of 0-3 times per year)	Continuous (AU$0-1M per year)
- Definition of utility	Expected weed risk impact score reduced at the terminal (probability of eradication × species' risk impact score)	Expected penalty score at terminal time to be minimized (based on species' expected IUCN status)
- Method of calculation	Stage-matrix model and hazard rate model, parameterized by data from past management and expert elicitation	Statistical regression analysis of past investment and IUCN status transitions in the focal species
- Individual project cost (AU$ over the time horizon)	Min: 0.16M Median: 1.37M	0-16M (hypothetically assumed)

	Mean: 2.87M Max: 11.83M Standard deviation: 3.36M	
- Expected project returns (utility) across possible investment levels	Min: 0 Median: 2170294 Mean: 11540934 Max: 108336176 Standard deviation: 21641908	Min: 0 Median: 0.005 Mean: 0.057 Max: 0.539 Standard deviation: 0.14
Data sources	Dodd et al. (2015) Dodd et al. (2017)	The Action Plan for Australian Birds (Garnett & Crowley 2000) McCarthy et al. (2008)

Figure Legends

Figure 1. The workflow of iterative budget reallocation among ongoing and new projects. Projects are assessed for estimating their ROIs (Module 1 "Assess"; blue bars), prioritised and (re)allocated budget to and from (Module 2 "Prioritise"; black bars), and monitored to update project status for reassessment (Module 3: "Learn", red bars). Ongoing projects may be paused or terminated (e.g. Project 2 after 1st reallocation). New project needs may occur in-between (re)allocation events but have waiting period (e.g. shaded area in Project 3) until being assessed and receiving budget allocation.

Figure 2. Iterative budget reallocation between different weed eradication projects can improve outcomes (mean with 95% confidence intervals (CI)). The expected improvement is generally higher if budget can be reallocated from on-going projects (strategy S3) rather than just completed projects (strategy S2) (red and black points, respectively), if reallocation is more frequent (x-axis, from right to left), and if there is a larger number of new weed invasion per year (panels, from top to bottom). Probability of poorer outcomes than that under static budget (i.e. proportion of 95% CI below zero; shaded area) is also generally lower in the above conditions. However, there are interactions between the effects (e.g. budget reallocation should be done less frequently if budget can only be reallocated from completed budgets).

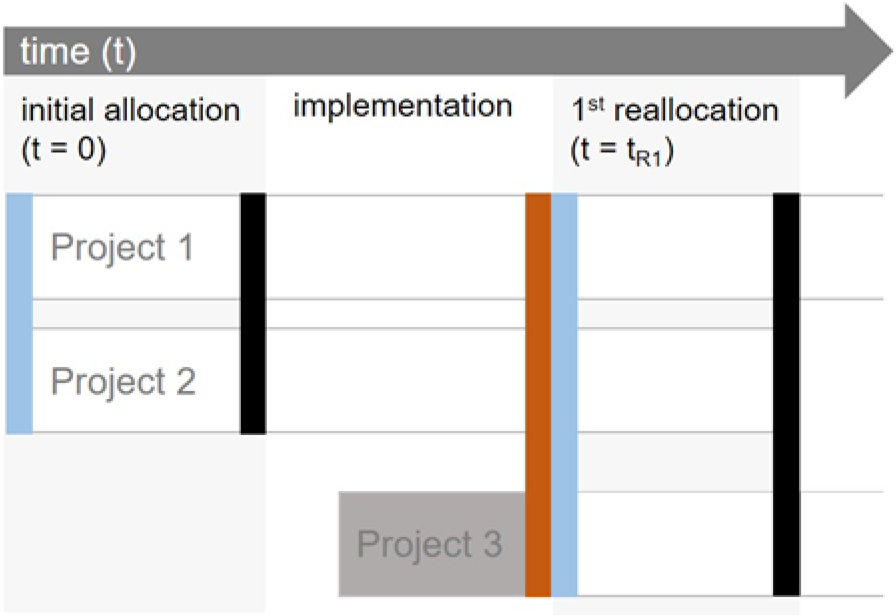
Figure 3. Example of a weed management scenario under unconstrained reallocation strategy (S3). The y-axis represents species projects 1-50, grouped into initially available projects (black) and projects that emerge during the 1st, 2nd, 3rd, and last 5-yr management periods (dark grey, light grey, white, and stripes, respectively). Length of bars represent effort levels invested in each species project (monitoring rate per year), with bar colour corresponding to species incursion groupings. Over time, weed projects may be closed if eradication is completed (labelled as 'E'), may be paused (labelled as 'P') and sometimes resumed later (labelled as 'R'). Note that the number of weed projects under active budget investment may vary over time.

Figure 4. Expected number of bird species extinctions by 16th year under static and unconstrained reallocation strategies (S1 and S3) across total budget levels, without or with reassessment costs (a, b). For b), the percentage of reassessment costs ($6.85M) in the total budget is also listed. Results are pooled across 1000 simulation iterations.

Figure 5. Example of bird conservation scenario under the unconstrained reallocation strategy (S3), with total budget $57.6M and reassessment costs of $6.85M. The y-axis represents species project 1-270, grouped and colour-coded according to initial IUCN status. Length of bars represent effort levels invested in each species project in the management period. The right-most colour bars indicate terminal IUCN status of each species at the 16th year.

Figures

Figure 1. The workflow of iterative budget reallocation among ongoing and new projects. Projects are assessed for estimating their ROIs (Module 1 “Assess”; blue bars), prioritised and (re)allocated budget to and from (Module 2 “Prioritise”; black bars), and monitored to update project status for reassessment (Module 3: “Learn”, red bars). Ongoing projects may be paused or terminated (e.g. Project 2 after 1st reallocation). New project needs may occur in-between (re)allocation events but have waiting period (e.g. shaded area in Project 3) until being assessed and receiving budget allocation.



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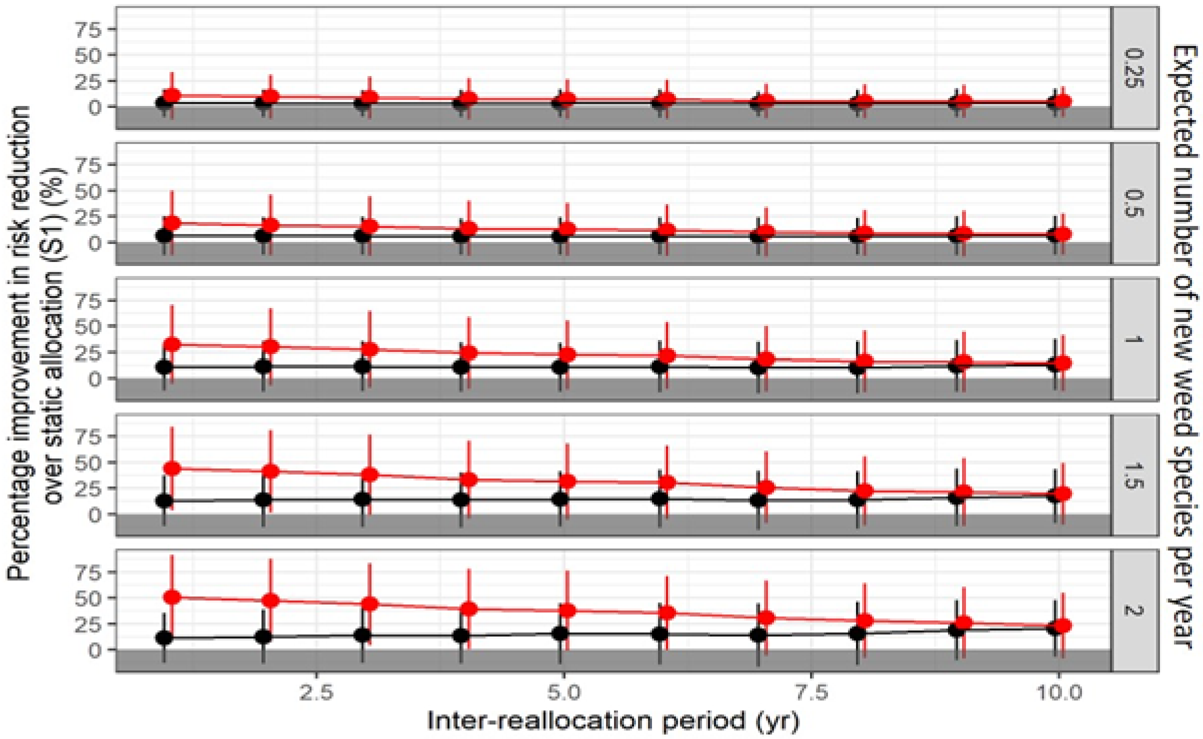

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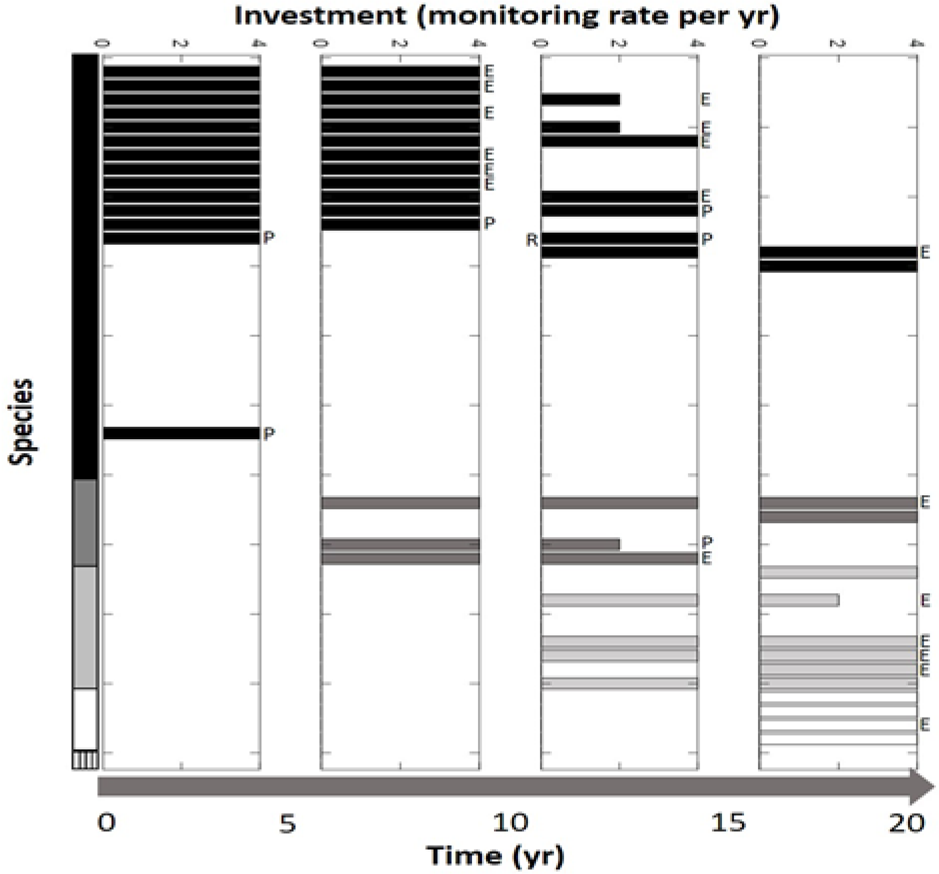

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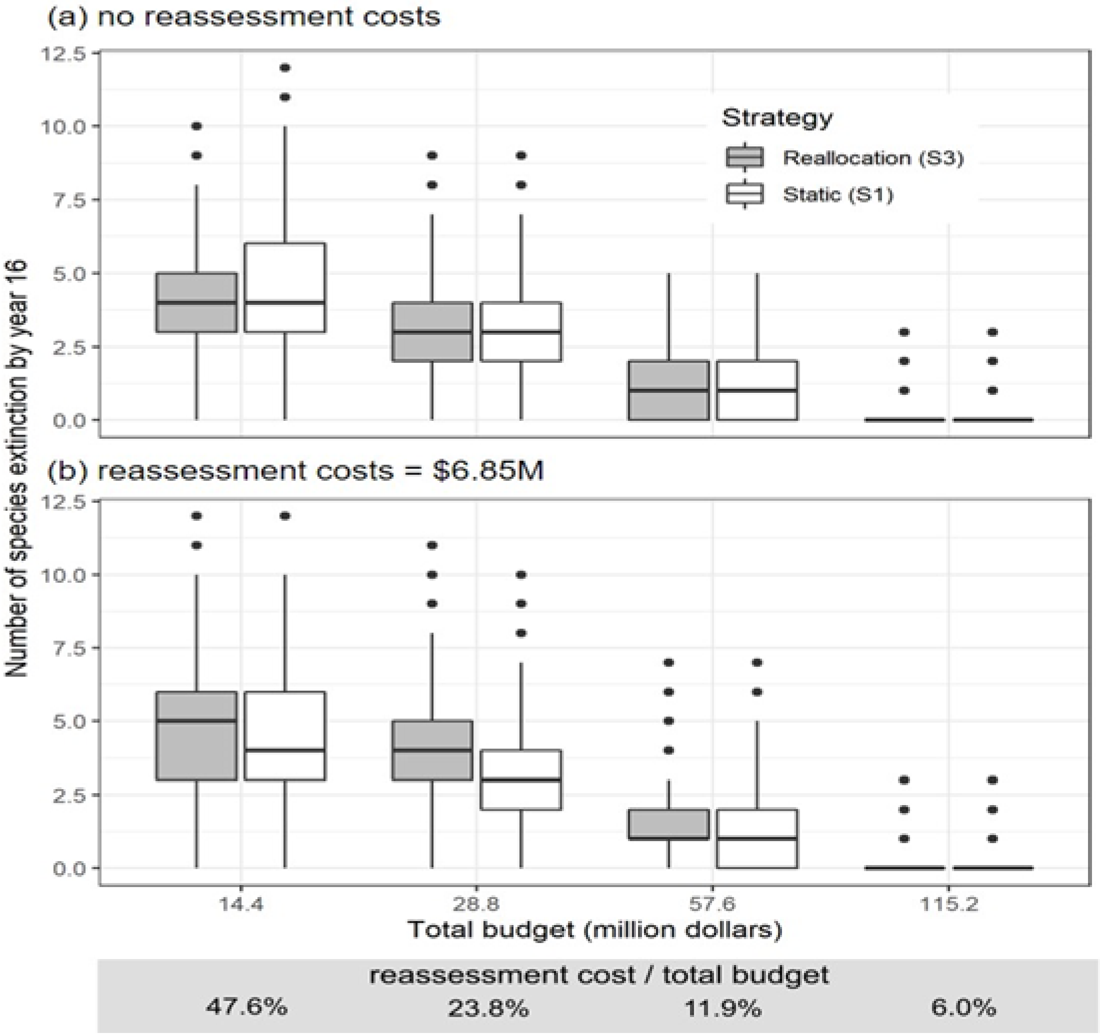

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