Biodiversity protection prioritisation: A 25 year review

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Abstract

There are insufficient resources available globally, nationally, and in many regions to conserve all species, habitats and ecosystems. Prioritisation of targets or actions is a rational response to resource scarcity. Prioritisation can be directed at areas for reservation, species, habitats or ecosystems for management, and threat management actions. The scale at which prioritisation is applied is a fundamental decision, and the range includes global, national, regional, and patch. Choice of scale influences availability of data and methods available for prioritisation. Since 1986 availability of data, computing power, and expertise available have all improved globally and in many countries. Approaches to prioritisation have evolved during the last 25 years as researchers from several disciplines including biology, ecology, decision sciences, mathematics, and economics have sought ways to achieve greater output from the resources available for biodiversity conservation. This review surveys the literature and groups prioritisation approaches into four categories: reserves and reserve selection; prescriptive costed biodiversity prioritisation**;** ranked costed biodiversity projects; and contracted costed conservation actions. A concluding section considers the limitations of current prioritisation approaches and points to areas for further development.

Additional Keywords: biodiversity protection, prioritisation, reserves, actions, costs, contracts

Introduction

For at least 25 years it has been clear that there are increasing threats to biodiversity and there are insufficient resources available to provide all the actions needed to support biodiversity. It has been, and is essential to make choices over where to apply conservation effort. Weitzman (1992, 364) observed ‘Yet the laws of economics apply to diversity also. We cannot preserve everything.’ In 2011 the Society for Conservation Biology held its twenty-fifth conference in Auckland and two symposia at that event focused upon prioritisation and evaluation of biodiversity projects. This paper draws upon the work of several presenters at that event and reviews developments in biodiversity prioritisation over the last 25 years. The topic is of course of practical importance, but the field has attracted attention from a range of both applied and theoretical researchers in Australasia, USA, and Europe. Conservation biology grew out of biology, and soon included ecologists, but the need for rigorous approaches to biodiversity protection prioritisation attracted researchers with decision science, mathematics, economics and other areas of expertise. The field also attracted specialists in linear programming, dataset collection and management who developed new programs to aid biodiversity protection prioritisation. For early researchers in ths field the rationale for prioritisation included maximising the amount of biodiversity protected and hence a focus on identifying where biodiversity was located. The need to prioritise due to limited resource availability in conservation is a classic microeconomic resource allocation problem and economists have increasingly focused on biodiversity protection questions and developed methods to tackle prioritisation challenges. Distinctive focuses of the work of [conservation] economists include the incentives faced by land managers and their behavioural responses to biodiversity conservation programs.

A large number of publications between 1986 and 2012 have addressed biodiversity prioritisation. There are earlier overviews of this literature and assessments of the state of the art (Margules and Pressey 2000; Sarkar 2002; Wilson *et al.* 2009). The current paper surveys the main prioritisation approaches developed during the past 25 years, points to key publications for each approach, considers their contributions, their scales of application, data requirements and limitations. Almost all of the prioritisation research completed seeks to support or promote biodiversity protection and much of it adopts the perspective of a social planner. A social planner's stance does not derive from biology or ecology, but from a (generally unstated) notion that biodiversity protection actions can be implemented – often by the state. Designation of reserve status for land is one seemingly simple, low cost way of providing biodiversity protection that a social planner can invoke. There are other ways besides reserve designation that biodiversity protection can be pursued, and a social planner might prescribe how best to do this. But even if those actions are delivered by the state they will require expenditures that must be budgeted for or costs to individuals and society that must be taken into acccount. There are other agencies besides the state that can provide biodiversity protection, particularly on private land, and incentives matter a lot to private sector actors when decisions are made about what, how and where to deliver biodiversity protection.

This review groups prioritisation approaches in four categories: 1) reserves and reserve selection; 2) prescriptive costed biodiversity prioritisation**;** 3) ranked costed biodiversity projects and 4) contracted costed conservation actions. It notes the impact that improved data availability, increased computing power, and growth in availability of prioritisation expertise has on methods available for use. A concluding section considers the limitations of current prioritisation approaches and points to areas where prioritisation research may head. Table 1 provides a summary of selected prioritisation approaches in each of the four categories.

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Reserves and reserve selection

An early approach to biodiversity prioritisation was provided by Myers (1988) who proposed the term ‘biodiversity hotspots’ and identified areas of such hotspots in tropical rainforest that were under threat. The idea of identifying areas where exceptional concentrations of endemic species were undergoing major loss of habitat seemed a useful way to identify areas that might be protected to preserve species. Myers *et al.* (2000, 853) calculated that ...’ as many as 44% of all species of vascular plants and 35 % of all species in four vertebrate groups are confined to 25 hoptspots comprising only 1.4% of the land surface of the Earth. This opens the way for a ‘silver bullet’ strategy on the part of conservation planners, focusing on these hotspots in proportion to their share of the world’s at risk species.’ The idea of biodiversity prioritisation achieved attention globally, but finding, funding, and firing the silver bullet has proved a large challenge.

The first publications on prioritisation focused on reserves and reserve selection. The term ‘reserves’ is shorthand for *in situ* protection of biodiversity. Many countries have a diverse set of parks and reserves that have been established over a century or more in some cases, and often without biodiversity protection as the principal selection criteria. In many cases, opportunism may have played a major role determining what areas were reserved (Pressey et al. 1983). The 1980s saw increased interest in going beyond opportunism and development of methods to systematically determine which areas would be reserved. Margules (1989, 2) commented that a key question tackled within this approach is ...’where should nature reserves be situated?’ The focus of this approach was … ‘that reserve networks should encompass maximum biological diversity’ and not just rare species or other goals (Margules 1989, 1). Margules commented that it was appropriate to focus on maintaining biological diversity because while much conservation effort targeted specific rare species, many species were unknown and hence could not be used in identification of sites to protect. Reserves were the unit of choice for *in situ* protection and a clear rationale was provided for this focus. Margules and Pressey (2000, 243) argued that reserves had long been used by societies to preserve natural areas and the underlying notion was to ...’separate elements of biodiversity from processes that threaten their existence in the wild.’ It was emphasised the geographic place, was the unit of analysis. Biodiversity is found at a place, places vary in the amount and importance of biodiversity they contain, and resources available are limited, so places must be ranked to identify the most important places to reserve (Sarkar *et al.* 2002). The success and usefulness of reserves in separating biodiversity from threatening processes it was argued, would be determined, first by how accurate they were in representing the range of biodiversity, and second whether reserve creation resulted in reduction in threatening processes so that the target biodiversity persisted (Margules and Pressey 2000). Accuracy of representation will be influenced by the way that reserves are compared, ranked, and selected. Persistence of biodiversity will be influenced by what threats there are and what occurs at each site.

In retrospect this approach seems to emphasise the supply of biodiversity, but to heavily downplay the cost of supply. However, some proponents did link reserve selection and management actions. Sarkar *et al.* (2002) proposed four stages for biodiversity planning and *management* (emphasis added). They recognise that comparing, ranking, selecting areas for in situ protection required data either from existing datasets, or from specifically created datasets. Data are scarce, costly to produce, and rarely as complete as might be desired by analysts and decision makers. If a data set is already available, and conservation goals have already been chosen, stage one required selection of surrogates to represent the biodiversity target. These surrogates for biodiversity might be species distributions (often vertebrates) and environmental variables such as rainfall, temperature or aspect. Stage two called for ordering of places (place prioritization) according to their biodiversity content as represented by the surrogates. Stage three provided a major challenge as it called for projection of futures for the biodiversity of interest – 'the viability problem'. Various methods may be used to complete a projection including population viability analyses, and threat assessments. Once these projections are completed, places can be reordered based upon ...'the biodiversity value of different places' (Sarkar *et al.* 2002; 340). The final stage is to devise management practices for each place, but particularly those places with the most valued biodiversity.

Considerable effort has been devoted to improving the availability of data and developing tools to project futures for biodiversity (Kremen *et al.* 2008). There are many aspects to biodiversity, and no one measure such as character or trait diversity can completely represent biodiversity, hence surrogates are required to both represent biodiversity and to measure biodiversity. Arguably this is not a serious impediment to reserve selection as what are needed are indicators of relative biodiversity, not absolute measures (Sarkar *et al.* 2002). Ultimately, the data on sites contains maps in some form of the chosen biodiversity surrogates.

Algorithms were developed to aid selection of sites by the application of explicit rules. The principle of complementarity first introduced by Vane-Wright *et al.* (1991) has received considerable attention and is argued to be central to systematic conservation planning (Segan et al. 2011; Leathwick et al. 2010). Sites are added to the list to be reserved if they add more biodiversity features beyond those already included in an existing set of reserves. Margules *et al.* (2002, 318) propose three sets of interrelated principles are applied when selecting sites: persistence and vulnerability, complementarity and efficiency, irreplaceability and flexibility. Other factors can be applied when decisions are made on reserves including acquisition costs and opportunity costs.

Many sites can provide multiple benefits including supporting biodiversity. Sites can vary greatly in the degree to which they support the persistence of biodiversity. Systematic conservation planning developed to enable planners to target areas that best represent biodiversity and provided opportunities for biodiversity to persist. Selecting the combination of sites which represent biodiversity in the least cost way is known as the minimum set problem. The maximal coverage problem aims to include as much biodiversity as possible given a pre-set budget (Segan *et al.* 2011). These are conceptually straightforward problems, but practically they are complex. Finding solutions to the problems requires use of large biological and socioeconomic datasets, and searching through the often huge solution space (Kremen et al. 2008). A range of decision support tools have been developed to handle these problems and they include Marxan (Possingham *et al.* 2000), Zonation (Moilanen 2007), C-Plan (Pressey *et al.* 2009) and ConsNet (Sarkar *et al.* 2009) (see Segan et al. 2011, 1435.) Marxan is the most widely used of these decision support systems, and has been used in over 100 countries. Core outputs from Marxan are zones for protected area sites. In its most recent version Marxan with Zones (Watts *et al.* 2009) enables planners to recognise sites may have multiple uses, and sites provide a range of levels of protection of biodiversity and to other objectives. These recent advances allow planners to identify much smaller areas for protection, at much lower cost than would occur under early versions which dichotomised levels of protection at sites. In essence Marxan with Zones identifies not just where to protect, but how to act at each site (Watts *et al.* 2009).

Does a focus on biodiversity richness and maximal coverage impact conservation action at a glocbal scale? Halpern *et al.* (2006) studied the expenditures by major conservation players, World Bank GEF, Conservation International, The Nature Conservancy, the World Conservation Union IUCN, Conservation International, World Wide Fund for Nature, and Birdlife International to determine if their expenditures were correlated with global priorities as indicated by biological values and threats. They conclude ... ‘biological factors are having little or no influence on spending patterns’. And … ‘global priority models are having little effect on how money is distributed among countries containing high-priority areas.' (Halpern *et al.* 2005, 62). A range of other factors play important roles driving conservation spending.

Prescriptive costed biodiversity activities

In the face of land use change, population growth, economic growth, and large numbers of invasive species, actions are essential to enable even representative proportions of biodiversity to persist. Biodiversity protection actions require expenditures, and often involve opportunity costs for areas reserved. During the 1990s a handful of publications appeared that recognised costs needed to be included in biodiversity prioritisation approaches. Not surprisingly, economists were among the first authors to explicitly recognise that costs needed to be included in prioritisation analyses (Weitzman 1998; Metrick and Weitzman 1998; Ando et al 1998). Costs in these first papers were linked directly to projects that would increase the probability of survival of a species. Weitzman (1998) introduced the Noah's Ark parable as a way to think about biodiversity preservation when society has a limited budget constraint. He argued that we can develop a cost effective ranking approach to determine which species (or other biodiversity unit) projects should have priority on the Ark. Ranking of each species project Ri could be determined using the following formula.

$$Ri = [Di + Ui] \times (\Delta Pi/Ci)$$

Di – distinctiveness

Ui - utility

ΔPi - Present value of change in conservation status

Ci - Present value of costs

Weitzman (1998) argued we should allocate the preservation budget (fill the Ark) with the highest ranked species projects – the maximal coverage problem. These are conceptual means to pursue biodiversity protection, but Weitzman (1998) and Metrick and Weitzman (1998) did not estimate empirical costs for real species projects.

Species ranking systems may provide a cost effective way of selecting species for the Ark, but an important question can be asked of outcomes from that prioritisation approach. How well will an Ark full of individually selected species contribute to ecological functioning? Perry (2010) adressed that question and drew upon functional ecology to construct a new measure of the ecological importance of species. In his prioritisation approach … 'Noah must create a thriving ecosystem rather than a zoo' (Perry 2010, 479). An objective function that differs from Metrick and Weitzman (1998) is proposed and the objective is to maximise the sum of the expected ecological importance of species. Perry argues Noah should seek species that will persist, but changing the probabilities of survival of species comes at a cost, and budgets are limited. Perry shows how a ranking equation can be used to prioritise species:

$$Rank_i = \frac{\Delta p_i(M_i)}{c_i}$$

Where Δp_i is the change in probability of survival of a species
M_i is a measure of the ecological importance of a species
c_i is cost of changing probability of survival of species i.

The implications of adopting the Perry approach are likely to be significant. He comments that some charismatic species favoured under a Metrick and Weitzman (1998) type ranking system, which have little current role in functioning ecosystems (spotted owl, grizzly bear, Californian Condor are examples), will not rank highly in an ecosytem importance ranking approach. Perry comments that the US Endangered Species Act could be revised to become the Endangered Ecological Interactions Act.

While Weitzman, Metrick and Weitzman and Perry focus attention on ranking species, Ando *et al.* (1998) directed their attention to selection of habitat to support species. Obtaining habitat will almost invariably be costly and Ando *et al.* (1998) was amongst the first papers to include empirical cost data in a habitat prioritisation analysis. In that study land prices by county were included when selecting habitat for 911 species, subspecies and populations protected or proposed under the US Endangered Species Act. Ando *et al.* (1998, 2127) caution that the results they generate are stylized and are not policy prescriptions, but ... 'the cost per site under the cost-minimizing solution is less than one-sixth of that under the site-minimizing solution.' Inclusion of economics in the analysis where costs are heterogeneous can lead to much more cost effective prioritisation.

After the first explicit recognition of the role of cost, a number of papers focused on the importance of costs for prioritisation at global or national scales. Balmford *et al.* (2000) use data on the likely costs of conserving each country's reserve network to determine if that impacts on global priority setting to achieve a range of conservation objectives. Because of the paucity of data on both species and costs, they caution their results should be seen as heuristics and not a blueprint for conservation investments. Nevertheless, Balmford *et al.* (2000) conclude that ... 'integrating cost data with biological information substantially increases the cost–efficiency of resulting priority sets.' Once sensitised to the contribution that costs might make to prioritisation results, subsequent research focused on improving cost data quality, and Balmford et al. (2003) pointed to a startling result. Globally, annual costs of protection of conservation sites range from less than US$0.10 per km^2 to more than US$1 million per km^2. This seven order of magnitude spread is considerably greater than the range of biodiversity benefits as measured by endemism per km^2 or number of threatened species per km^2. Balmford *et al.* (2000) note that costs are lowest in less developed regions, biodiversity richness is highest in low income regions, and current biodiversity protection investments are greatest in high income regions. Reprioritisation of biodiversity investments on cost effectiveness grounds may well be warranted. This is a crucial point of difference from earlier work on reserve selection approaches which focused on biodiversity richness and encompassing maximum biological diversity.

Most, if not all, prioritisation approaches developed before 2004 treated biodiversity and human systems as static (Meier *et al.* 2004, 615). But in a world of rapid economic growth, climate change, growing threats to many species, and limited annual budgets, dynamic aspects of prioritisation need to be considered. Meier *et al.* (2004) examine the impact of confronting several assumptions inherent in conservation planning models up until that date, including inability to reserve complete networks instantaneously, uncertainty about when and where opportunities for investment may arise, varying budget constraints, and degradation through time of unprotected sites. Their goal was to understand how dynamics of ecological and human systems may affect performance of strategies for creating reserve networks (Meier *et al.* 2004, 616). Conservation approaches need to focus on benefits, costs and threats. Stochastic dynamic programming (SDP) is needed to handle these situations but SDP is computationally intensive and impossible where there are more than about 20 conservation sites. Meier *et al.* (2004) demonstrate that analysis of conservation planning problems can be completed where degradation rates and uncertainty are high, by adopting some simplifying rules for selecting sites then comparing results to ad hoc and comprehensive conservation plans. Their results suggest that (Meier *et al.* 2004, 615) ... 'simple decision rules such as protecting the available site with highest irreplaceability or with the highest species richness, may be more effective' ... than comprehensive reserve designs which cannot be implemented immediately.

A focus on expected benefits from protection is a distinguishing feature of much conservation planning research. In contrast, Naidoo et al. (2005) focus on the gamut of costs that need to be considered in biodiversity project prioritisation. They show (Naidoo *et al.* 2005, 681) that biological-focused conservation planning ... 'implicitly assumes that all areas are equally costly, which is incorrect.' Naidoo *et al.* (2005) indentify five types of conservation costs: acquisition costs, management costs, transaction costs, damage costs, opportunity costs. They expand on an important point made earlier by Balmford *et al.* (2000), the importance of including costs depends not just on the correlation between biological benefits and costs, but ... 'more importantly, [on] the relative variability of costs compared with the variability of biological targets' Naidoo *et al.* (2005, 683). For real world conservation prioritisation, dynamics and uncertainty over budgets, threats and opportunities, points to the importance of prioritizing the sequence of conservation investments.

Naidoo *et al.* (2005, 685) point as well to a further limitation to conservation planning ... 'the lack of implementation of most conservation plans suggests conservation planners have historically not been overly concerned with practical factors that will influence implementation, such as costs of plans.' Real world prioritisation as opposed to prescriptive conservation planning requires focus on genuine conservation projects if it is to be effective.

Wilson *et al.* (2007) advanced prescriptive conservation planning by combining geographic priorities with a fund allocation formula that recognised the costs of alternate conservation actions that address specific biodiversity threats. Many conservation actions however, do not require (expensive) land purchases. A six step process is developed named the Conservation Investment Framework (CIF) to identify a feasible set of actions given a fixed annual budget. The six steps (Wilson *et al.* 2007, Figure 2) require:

1. defining the conservation objective,
2. specifying a budget,
3. identifying key threats to achieving the objective,
4, identifying actions to abate threats (including area receiving each action, cost per unit area of each action, and biodiversity benefits of each action),
5. scheduling investments in order to maximise the objective by allocating funds to actions that maximise biodiversity benefits per dollar invested,
6. update species – investment relationships given changes in area receiving and requiring investment in each conservation action until the end of the project term.

Wilson et al. (2007) applied this Conservation Investment Framework to 17 terrestrial Mediterranean ecoregions. Data availability, information on incremental biodiversity benefits from specific actions, and on incremental costs of actions are major challenges for this approach and heuristics such as species – investment curves, and rules such as 'maximise short term gain', are adopted to enable completion of investment prioritisation. The study found (Wilson *et al.* 2007, 1855) the interplay of three main factors drives investment schedules: 1) the relationship between the additional areas invested in each ecoaction and the biodiversity benefit, 2) the cost of this investment, and 3) the existing level of investment. The empirical results of applying the CIF indicate that considerably more biodiversity can be protected than would occur if land were purchased for protection, and priorities shift through time as investments are made. An important point to note is the study, similar to many other conservation plans ...' assumed that each eco-action will be totally effective in abating the relevant threat' (Wilson *et al.* 2007). Complete effectiveness is of course far from assured for real world biodiversity protection actions.

Polasky *et al.* (2008) develop spatially explicit biological and economic models to determine 'where to put things' while considering both biodiversity and economic returns. Their biological model incorporates habitat preferences, area requirements, and dispersal ability between habitat patches for terrestrial vertebrate species. Their economic model incorporates site characteristics and location to predict economic returns for various land uses. 'Use of the spatially explicit models enables search for efficient land use patterns that maximize biodiversity conservation objectives for a given level of economic returns and vice versa' (Polasky *et al.* 2008, 1524). Their model is applied to the Willamette Basin, USA and the empirical results show that it is possible to maintain a high level of biodiversity in the region and to generate large economic returns through careful spatial land management. A key factor supporting this result is the generalist nature of much of the vertebrate biodiversity in the region. Polasky *et al.* (2008, 1520) comment that the results are suggestive rather than prescriptive. The most important set of issues not included relate to land use change and dynamics (Polasky *et al.* 2008, 1522).

These costed biodiversity prioritisation studies can be described as prescriptive conservation planning. A wise social planner is present striving to find cost effective ways to protect biodiversity, often on privately owned or managed land, but limited attention is provided to on the ground delivery of biodiversity protection actions, the incentives for those actions, their effectiveness, monitoring of actions and the level of biodiversity protection outputs (McDonald-Madden *et al.* 2011).

Ranked biodiversity projects

The decade since 2002 has seen the development of several prioritisation approaches which focus on identifiable conservation projects. These studies put into practice the approach first proposed and advocated by Weitzman (1998), namely calculation of (weighted) benefit cost ratios for a range of projects, followed by prioritisation based upon each project's rank relative to other biodiversity protection projects. Possingham *et al.* (2002) provide a bold early example of this approach and study

18 management options for Australia's terrestrial and freshwater biodiversity. For each of the 18 projects, nine steps were followed to enable estimation of some key metrics (Possingham *et al.* 2002):

1. outline the nature of the current risk to biodiversity of each threatening process
2. state the objective(s) in addressing each risk
3. list some management options to reduce or remove each risk stating these as specific and quantifiable as possible
4. quantify the risk in terms of the number of native species at risk due to that particular threatening process
5. extrapolate from that number of species using a choice of multipliers to calculate biodiversity benefits depending on the assumed effectiveness of the action
6. estimate the financial cost of the management option
7. calculate the cost per species secured
8. describe the nature of the collateral benefits (beyond that to biodiversity, such as carbon storage) and
9. estimate the value of the most important items.

Completion of those nine steps enables calculation and comparison of each project's key metrics: number of species saved, area of project site, cost per hectare, total costs, number of species saved per million dollars, value of collateral benefits, and value of collateral benefits : cost ratio. Possingham *et al.* (2002, 21) aid comparison of projects by ranking projects on two criteria, collateral benefit : cost ratio and species secured per $1m. Projects are grouped into high, medium and low scores on the two main criteria. High-High ranked projects are attractive and Low-Low ranked projects are unattractive. This approach to prioritisation requires input from experts as well as use of existing databases. Significant assumptions are made when estimating numbers of collateral species, valuing collateral benefits using value transfer appproaches, and when estimating the effectiveness of management options. The results calculated for each of the 18 projects are illuminating with numbers of species secured per $1m ranging from 95 to 1. Collateral benefit : cost ratios range from 40 to 0.3.

While Possingham *et al.* (2002) compare regional or national scale projects, the approach of ranking projects by benefit : cost ratios can be applied at various scales. It was implemented for New Zealand single species projects by Joseph *et al.* (2008, 2009), and for patch scale projects in the Kimberly region of West Australia Carwardine *et al.* (2011). Joseph *et al.* (2009) adapt the Noah's Ark framework by including a measure for likelihood of success of projects and focus on Project Efficiency E of each project.

$$W_i \times B_i \times S_i$$

$E_i =$ ___________

C_i

Where W_i is the species weight,

B_i is the biodiversity benefits,

S_i is the probability of success, and

C_i is the cost of project i.

Joseph *et al.* (2009) follow a nine step process to identify highest ranked projects: 1) define objectives; 2) list the biodiversity assets (threatened species); 3) weight the assets; 4) list the potential species management projects; 5) calculate the cost of each project; 5) predict the benefits to species of each project; 6) estimate the likelihood of success of each project; 7) state the constraints to protection action; 8) combine all of the information on costs, values, benefits, likelihood of success and rank projects on benefits/$ and 9) choose projects based upon the weighted probabilistic benefit : cost ratios.

Joseph *et al.* (2009) considered only species distinctiveness and assumed the utility of all species was equal. Wi, taxonomic distinctiveness, is assumed inversely related to number of related species – the inverse of the product of the number of branches at genus, family and order nodes. Benefits were defined as the difference between probability of the species being secure in 50 years 'with management' and 'without management'. Present value of costs over 50 years were calculated using a one percent discount rate. Expert judgment was used to estimate likelihood of securing each species in 50 years. This expert judgement method with input from 105 persons during a 1.5 year research period, calculated project efficiency scores for over 2000 biodiversity protection projects. It generated a rank-ordered list of projects for senior managers to use when making resource allocation decisions.

Joseph *et al.* (2009) observe that the method provides a systematic, transparent, and repeatable method for prioritizing actions to minimize the number of extinctions. Empirical output from the process indicates that by incorporating management costs, benefits, and likelihood of success the return on conservation investment is substantially improved. The ... 'number of species managed and expected overall benefit to threatened species is increased remarkably.' (Joseph *et al.* 2009, 337).

Carwardine *et al.* (2011) adapted the approach used in Possingham *et al.* (2002) but applied it at regional scale. Given alarming declines in biodiversity in the Kimberly region, expert knowledge was garnered in two workshops to: identify key threats, propose threat management actions, estimate costs of actions over a 20 year period, estimate feasibility of implementation over various land tenures, and estimate probabilities of persistence over 20 years (Carwardine *et al.* 2011). Outputs from this approach include the likely outcomes per dollar spent on each action in each bioregion, and these can be ranked in terms of their cost-effectiveness, and priority threat management actions identified. Merit ordering threat management actions allows summary charts to be produced showing incremental gains of wildlife species able to persist as the annual budget is increased.

Ranking of biodiversity protection projects is a considerable advance over ad hoc choice of projects or approaches which summed various idiosyncratic measures to calculate a total score for each project. Transparent, systematic, multiplicative means to quantify expected project output, and subsequuent comparison to project costs, provide a logical, defensible basis on which to rank projects and enable better-informed choices by decision makers. A limitation to their effectiveness is the gap between availability of project ranking systems and their implementation by decision makers.

Contracted costed conservation actions

This section reviews some of the key issues relevant to biodiversity prioritisation on private land. Biodiversity prioritisation began by focusing on which places to reserve. Those places could be state owned, private property or other tenures. Effective biodiversity protection requires implementation of on ground actions. The effectiveness of actions can be influenced by take up rates of biodiversity protection policies by landowners or managers, reactions by landowners to incentives provided to reduce threats to or conserve biodiversity, and accuracy of metrics used to select biodiversity provision. Some recent prioritisation studies include focus on these aspects of prioritisation (White and Sadler 2012; Polyakov *et al.* 2012). New approaches have been used in some countries to recruit landowners to deliver biodiversity protection, and new methods developed to select areas for protection. Where these new approaches involve payments to landowners, accuracy of monitoring and penalties for non-compliance by landowners can become important issues (Crowe *et al.* 2010). Several prioritisation approaches have included consideration of the expected effectiveness of actions (Joseph *et al.* 2009; Carwardine *et al.* 2011) but it has recently been identified as a component of prioritisation that warrants closer attention (Pannell *et al.* 2012).

Hajkowicz *et al.* (2007) note that competitive tendering for conservation contracts are increasingly used in Australia, USA and the EU. They explore alternative techniques for the selection of conservation contracts under competitive tender systems, and focus on selection of natural resource management projects. Purchase of biodiversity protection contracts can be viewed as a knapsack problem where each contract has a cost (takes up space in the knapsack), and delivers a benefit (biodiversity gains). The budget available determines the size of the knapsack. Purchasing bodies (NGO, state or national conservation organisations) can select projects that maximise total biodiversity benefits, subject to the budget constraint. If there is a binary decision variable the problem can be formulated as an integer linear programming problem. Hajkowicz *et al.* (2007, Table 1) survey purchasing strategies employed in agricultural land management and environmental programs in USA, Australia, EU and judge that the knapsack formulation represents independent environmental projects quite well. They explore the relative performance of five purchasing strategies and determine that improved optimisation algorithms such as a commercial software package GAMS OSL 3 based upon linear relaxation achieved significant increases in environmental benefit within the budget compared to other purchasing strategies. They note (Hajkowicz et al. 2007, 53) that concerns over biodiversity project complementarity continue to pose a challenge for users of integer programming approaches to prioritisation.

White and Sadler (2012, 1) observe that conservation investment decisions require … 'allocation of limited public funds between assets that change stochastically through time in response to management action and the environment.' They argue that while mathematical decision theory can solve integer programming problems and software such as Marxan finds an approximate least cost conservation plan, little attention is paid to the role of incentives in many conservation planning approaches. If conservation action is to occur on private land, there is likely to be information asymmetry between funding agencies and landowners. As well, conservation plans often underestimate the costs of effective action to protect biodiversity. White and Sadler (2012) target is to develop a more realistic model of conservation planning and they pursue this by auctions for supply of biodiversity protection by landowners. Their model sees a regulator recruiting bush fragments to a conservation scheme, within a fixed budget. An empirical case study in North East Wheatbelt Regional Organisation of Councils (NEWROC), Western Australia, uses Landsat data on land condition for 465 bush fragments from 1988-2007. Markov transition matrices are used to model change in land condition, and existing species-area relationships are applied to the study region. White and Sadler (2012) compare two planning schemes for selecting bush fragments: a first best scheme that assumes perfect information on effort and fencing by landowners with payment based on actual effort, and a second-best fixed payment scheme based on observed fencing but unobservable effort. Extension of the models occurs by way of various sensitivity analyses including level of conservation effort and adverse selection. The authors judge the research results indicate that society should consider innovative approaches to biodiversity protection such as use of output-based (or mixed input and output-based contracts) as they avoid the moral hazard problem, provide a strong incentive for landowners to understand biodiversity condition and learn how to reduce risk of failure to achieve outcomes.

The use of contracts for biodiversity protection requires purchasers to select from the bids of competing suppliers, and so to prioritise. There is a derived demand for on ground actions by landowners as the ultimate goal sought is enhanced biodiversity. Contracting, monitoring and enforcement are not costless, and there are challenges in measurement of output. But contracted supply of biodiversity protection offers new opportunities to prioritise using rigorous, transparent procedures. It demands at least some measurement of output, and bypasses implementation gaps. Audits should report if there are stark cases of 'money for nothing'.

Evolution in approaches to prioritisation

A retrospective review of research and empirical application of biodiversity prioritisation methods reveals multiple approaches to prioritisation have been developed during the last 25 years. There are a range of scales at which prioritisation can be applied. Prioritisation can be directed at places, species, actions, and purchases. Significant changes in thinking about many of these topics have occurred since 1986. The earliest prioritisation research focused heavily on place and on reserve selection. Deciding which places to prioritise requires information, which is always scarce for planners. The prescriptive stance adopted in many of the 'reserve selection' studies is that of a wise social planner. Improvements in availability of data and in decision support software have increased the sophistication of the work of the wise planners. But the chasm between reserve selection and implementation of selections provides a large reality check whether at global, national or regional scale. As Margules and Pressey (2000, 250) observed 'There is a world of difference between the selection process ... and making things happen on the ground.' 'Some only exist on paper, never having been implemented.'

Choices almost always involve cost, such as the opportunity cost of habitat reserved or protected, and very often operational costs of managing sites, and species, or delivering actions. Ranking approaches that include economic costs of protection as denominators, lead decision makers towards prioritisation based upon cost-effectiveness. A range of studies that include economic considerations alongside biological and ecological considerations, consistently point to superior outcomes, whether in a maximal coverage or a minimum set formulation.

Application of ranking approaches in real project decision-making has recently occurred in a few countries. Researchers and conservation agencies report that application of economic considerations, together with models from biology and ecology does bring large gains from this mode of prioritisation.

Biodiversity protection can occur on both public and private land. A new set of challenges must be met when attempting to prioritise actions on private land, including incentive provision, behavioural responses, monitoring and contract enforcement. This newest area of prioritisation research contains a number of areas of ongoing study including choice of output metrics, accuracy of effectiveness estimates, and adequacy of monitoring levels.

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Table 1. Features of selected approaches to biodiversity prioritisation

Authors	**O**bjective	**S**cale	**M**ethods	**C**omments
Reserve selection				
Myers, 1988	Maximise retention of biodiversity	Global	Use criteria and data to find global hotspots	Potential supply only, no explicit costs. Expert input.
Margules, 1989	Maximise retention of biodiversity	Patch, region	Heuristic for minimum set of reserves	Potential supply only, no explicit costs. Databases needed
Mittermeier et al, 1999	Reserve selection	Gobal	Rank sites for their endemism /km2	Potential supply only, no explicit costs. Databases needed
Possingham et al, 2000	Maximise retention of biodiversity	Patch, region	Rank sites using SDP, Marxan	Potential supply only, no explicit costs. Databases needed.
Moilanen et al, 2007	Maximise retention of biodiversity	Patch, region	Rank sites using Zonation	Potential supply, no explicit costs. Databases needed
Prescriptive costed prioritisation				
Weitzman, 1992	Efficient protection of diversity	National	Diversity theory	Prescriptive only
Metrick and Weitzman 1998	Most valuable species on Noahs Ark	National	Rank species by Benefit : Cost ratios	Benefits and Costs considered but not real projects
Wilson et al, 2007	Cost effective protection	17 ecoregions	Conservation Investment Framework	Benefits and costs recognised for planning, but not real actions
Polasky et al, 2008	Optimal choice of habitat	Patch	Benefits and Costs for each habitat patch	Benefits and costs recognised for planning
Perry, 2009	Maintain ecosystem functioning	National	Rank Ecosystems by their contribution	Ecosystem benefits and costs considered, but not real projects
Ranked costed projects				
Possingham et al, 2002	Select high output projects	Patch, national	Rank by Benefit : Cost ratios	Potential projects, proxies for benefits and costs. Expert input needed
Faith et al, 2003	Maximise gain in biodiversity persistence	Regional	Biodiversity Viability Analysis	Potential projects, species distribution annd other databases needed
Joseph et al, 2009	Cost effective actions for species	Patch, national	Project Prioritisation Protocol	Real projects, considers B:C ratios. Expert input and databases
Carwardine et al, 2011	Cost effective effort selection	Patch, state	Rank actions by Benefit : Cost ratios	Real projects, considers B:C ratios. Needs expert input and databases
Contracted costed actions				
Hajkowicz, 2007	Optimisation of conservation actions	Patch, region	Linear programming	Real projects, recognises costs, uses proxies for benefits
White and Sadler, 2012	Optimal conservation investments	Patch, region	Conservation planning model	Real projects, models supply behaviour, and changes in condition