Clear consideration of costs, condition and conservation benefits yield better planning outcomes

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Abstract

The conservation benefit of a management action depends on what would have happened in absence of an intervention, and whether the conservation objective is to maintain existing biodiversity values, or to restore those that have been lost. How this benefit is calculated and considered in spatial prioritisation analyses could influence the expected cost-effectiveness of management, although this has not previously been explored. Here, we use a comprehensive decision theoretic approach to identify management priorities in a region of ecological, cultural and economic significance, the Great Western Woodlands (GWW) of south-western Australia. To demonstrate how cost, condition and conservation benefits affect prioritisation outcomes, we consider two different conservation objectives: the maintenance of native vegetation communities, and the restoration of natural fire regimes. We compare the results from (1) our comprehensive approach, to priorities identified using two alternative approaches: (2) consider generic management costs (travel, labour) and assume that landscape condition is homogenous, or; (3) use landscape condition as a surrogate for the cost of management, i.e. areas in poor condition are assumed to have high costs. We demonstrate that prioritisation outcomes differ substantially depending on how the benefits and costs of a management action are calculated. Using landscape condition as a surrogate for management costs resulted in priority areas that were least cost-effective. To avoid misspent conservation funding, we argue that care must be taken to incorporate the most appropriate cost and condition metrics into spatial prioritisation analyses, and that conservation benefits must be derived from a clearly specified objective.

Key words

Conservation planning, condition, costs, conservation benefit, decision theory, fire management, Weibull distribution, mortality function, Marxan

Introduction

Decisions about where to implement conservation management across a landscape need to take into account both the likely benefits of a implementing an action and its associated costs. Conservation planning tools can solve a range of spatial prioritisation problems by identifying priority areas where biodiversity could most efficiently and effectively be protected or managed to ensure its persistence (Moilanen et al., 2009). These tools focus on the principles of cost-effectiveness and representativeness of conservation features, as it is well understood that explicitly considering both the costs and benefits of conservation is essential when making decisions about where to prioritise investments, in order to identify the most cost-effective options for conserving biodiversity. Despite this knowledge best practice approaches are rarely followed (Armsworth, 2014; Joseph et al., 2009; Maron et al., 2013; Naidoo et al., 2006).

The benefit derived from a particular management action depends on what would have happened in the absence of an intervention (Ferraro and Hanauer, 2014; Maron et al., 2013; Possingham et al., 2015). Often, the expected benefit of an intervention is simply calculated as the present-day conservation value of a site – for example, the current presence or distribution of species or ecosystems. The assumption behind this approach is that in absence of the intervention, all of the conservation value of a site would be lost in the future. This would only be reasonable in the case where existing values are likely to diminish without the security provided by a particular intervention, such as a protected area. This was a key assumption in many early conservation planning analyses which focussed on representation in protected area networks (Possingham et al., 2000; Pressey et al., 1994) and the legacy of this simplifying assumption persists (Maron et al, 2013).

In recognition that land and seascapes are rarely in a pristine state, several studies have sought to include measures of landscape condition into spatial prioritisation exercises (Fraschetti et al., 2009; Game et al., 2008; Harris et al., 2014; Heiner et al., 2011; Kiesecker et al., 2009; Klein et al., 2009; 2013; Linke et al., 2012; Tallis et al., 2008). Often, the objective of such exercises has been to identify areas where biodiversity should be protected – that is, to maintain existing values into the future. In order to achieve this objective, it has been common to identify sites for protection that have a low degree of anthropogenic impact, i.e. sites in 'good condition'. This has been achieved in several studies by considering landscape condition as a proxy for the cost of management (Ban and Klein, 2009). For example, Heiner et al. (2011) identified priority areas that met representation targets for threatened and endemic fish species by minimising the total 'cost'; where cost was an index of cumulative anthropogenic impacts representing landscape condition.

However, considering condition as a proxy for the cost of management could generate misleading results (Armsworth, 2014). The condition of a site does not reveal the type of management action that should be implemented, or who should bear the costs (Adams et al., 2010). The condition of a site is unlikely to adequately capture variation across a full range of cost types, such as transaction, implementation, maintenance and opportunity costs (Armsworth, 2014; Naidoo et al., 2006). Furthermore, combining multiple types of costs (such as condition as a cost proxy and monetary costs) into an analysis is only feasible where each cost has the same unit of measurement (Ban and Klein, 2009). There is currently limited scope to comprehensively incorporate estimates of both condition and cost in a spatial prioritisation exercise (but see Moilanen et al., 2011). Game et al. (2008) and Klein et al. (2013) are two studies that simultaneously consider estimates of condition alongside monetary costs, but they focus only on minimising selection of sites in poor condition, which may not always be the desired conservation objective.

The focus of conservation planning is shifting from solely prioritising for protected areas, and towards new objectives of identifying areas for targeted management to ameliorate negative impacts and to improve ecosystem health (Budiharta et al., 2014; Moilanen et al., 2011; Wilson et al., 2010). This includes targeting control of invasive species (Auerbach et al., 2014; Evans et al., 2011), reduction of poaching (Plumptre et al., 2014), or management of fire (Richards et al., 1999; Wilson et al., 2007). In many cases, the objective may be not only to protect existing values, but also to restore lost values through improving the condition of the system (Law et al., 2015; Possingham et al., 2015). In such cases, conservation management actions may be more efficient and effective if directed toward areas that are currently in poor condition, assuming that the degrading processes can be addressed and condition improved as a consequence. This requires a clear understanding of the conservation objective, and how costs should be considered alongside estimates of condition.

Incorporating condition estimates into spatial prioritisation analyses without explicit consideration of the conservation objective, and the management action(s) that will deliver that objective, could have profound implications for the estimated expected benefits from management. For example, the analysis conducted by Kiesecker et al. (2009) identified priorities for conservation in areas with high 'landscape integrity', by minimising the selection of sites in poor condition. Landscape integrity was estimated by combining eight factors, including roads, mines, oil and gas pipelines, oil and gas wells, residential development, agricultural lands, as well as invasive species, and fire condition class (Copeland et al., 2007; Kiesecker et al., 2009). While it makes sense to identify sites for protection that are currently not affected by existing developments, invasive species and inappropriate fire regimes are two pressures that can be reduced through active management; hence a larger conservation benefit (Maron et al. 2013) may have been achieved by prioritising areas affected by these for active management. In the absence of a clearly articulated conservation objective and knowledge of the relevant management actions to meet that objective, there is a risk that condition may be incorrectly accounted for in spatial prioritisation analyses, and the resulting conservation priorities may not deliver the benefits to conservation as expected.

Given this history of confusion, we need an approach to clearly and consistently account for both condition and cost simultaneously in spatial prioritisation – in order to identify where the greatest conservation benefit can be achieved with respect to a particular objective, and at the least cost. Decision science can assist in framing and solving complex problems such as this by: defining clear objectives and constraints related to the problem, evaluating the consequences of management actions with respective to the objectives, and selecting the best option (Gregory et al., 2012; Polasky et al., 2011; Tulloch et al., 2015). A comprehensive decision-theoretic approach would allow the conservation benefit of a given management intervention to be correctly formulated and considered within a spatial prioritization exercise, along with data on the monetary costs of such an intervention.

In this study, we explore three approaches for incorporating costs, condition and conservation benefits into spatial prioritisation analyses, and discuss their implications for the resulting conservation priorities using a case study of the Great Western Woodlands in south-west Western Australia. We define two different conservation objectives: maintaining native vegetation in its current condition, and restoring natural fire regimes through improving landscape condition. We develop and apply a comprehensive decision-theoretic approach for incorporating condition by using information on the condition of sites to calculate the conservation benefit of particular management actions (Maron et al. 2013). We then compare the results from our (1) comprehensive approach, to spatial priorities identified using two alternative approaches commonly applied in conservation planning: (2) consider generic management costs (travel, labour) and assume that landscape condition is homogenous, and; (3) landscape condition is used as a surrogate for the cost of management, i.e. areas in poor condition are assumed to have high costs.

Methods

Study region

Our study region is the Great Western Woodlands (GWW) of south-western Australia, which stretches east from the agricultural wheatbelt of Western Australia towards the western edge of the semi-arid Nullarbor Plain (Figure 1). Covering an area of almost 16 million hectares, the GWW is the world’s largest remaining Mediterranean woodland. The eucalypt-dominated woodland is contained within a mosaic of shrubland and mallee which supports a globally significant diversity of flora and fauna (Figure 2, Judd et al., 2008; Watson et al., 2008). The Mediterranean-style climate of low and variable rainfall coupled with infertile soils has historically prevented the incursion of intensive agriculture and livestock grazing, leaving the

GWW in a largely intact state. Although the region escaped the historical large-scale clearing for intensive wheat and sheep farming, approximately a third of it is under pastoral lease for cattle or sheep. In addition, historical logging to support the expansion of mining operations from the late 1800s till the mid-1900s has influenced vegetation structure and terrestrial carbon stocks (Berry et al., 2010). Present threats to biodiversity in the region include changes in fire regimes, ongoing mining operations and exploration activity, as well as introduced herbivores, carnivores and weeds (Figure 3, Watson et al., 2008). Climate change is expected to result in a general warming trend with drying from the north to south, with further impacts on rainfall and fire frequency (Prober et al., 2012). We divided the study region into 1 km^2 square planning units (162,163 in total) which we employed as sites available for management.

Conservation features

We employed 39 broad floristic formations as a surrogate for biodiversity across the GWW (Table 1), represented in a state-wide pre-European vegetation map (Department of Agriculture Western Australia, 2005). Areas where native vegetation had been removed (agricultural areas, towns and built up areas, infrastructure) were excluded from the analysis. Available data on threatened fauna and flora localities compiled from State Government agencies (Judd et al., 2008) are of coarse resolution, inconsistent in spatial extent, and biased towards roads and major towns due to limited ecological surveys of the region (Duncan et al., 2006; Watson et al., 2008), hence they were not included in the spatial prioritisation analysis. We also included key biophysical features in the landscape identified as important determinants of the distribution of biodiversity: salt lakes, granite outcrop formations, 16 priority ecological communities and the distribution of old growth woodland (see Supplementary Material S1). In total, 60 conservation features were considered.

Conservation objectives

We considered two conservation objectives relevant to our study region. The first objective was to maintain the existing (i.e. present-day) condition of native vegetation through ground-based management activities. The second objective was to restore condition, in terms of the natural fire regime, of currently degraded areas. We aimed to either maintain or restore 30% of each conservation feature for each case.

'Maintain' objective: A key defining feature of the study region is the overall integrity of the landscape (Prober et al., 2012; Watson et al., 2008), with over 79% of its geographical area classified as containing 'intact' vegetation (Thackway and Lesslie, 2006). Maintaining ecological intactness has been identified as a key focus of conservation efforts in the region (Prober et al.; 2012). Under this conservation objective, we assumed that ground-based management would maintain current landscape condition and that without such management the condition will gradually degrade over time. For the sake of this example, we consider any on-ground management activity as contributing to this conservation objective. Such activities may include weed control, invasive animal management, and managing impacts from mining and exploration (remediating exploration lines and drill pads, filling in exploration pits, removing discarded exploration refuse, and plugging open drill holes). The costs of such activities would vary considerably, and in a real situation the differences in cost would need to be factored into the prioritisation exercise. However, in order to facilitate a clear comparison between this 'maintain' scenario and the 'restore' conservation scenario, we calculate only indicative costs based on the cost of travel to the management site; with travel to site likely to be a) a key component of activity costs and b) the main component that is likely to vary depending on site location.

'Restore' objective: Changed fire regimes are also considered to be a key threatening process in our study region, with substantial increases in woodland areas burnt in recent decades, likely attributable to a combination of increased human ignitions from mining and tourism, as well as increased lightning frequency and days of extreme fire danger (Prober et al., 2012; Watson et al., 2008). Active fire control, commonly carried out aerially, is required to control fires and reduce the departure of the fire regime from what is considered to be 'natural' for the area. Under this objective, we assumed that aerial-based management activities would restore landscape condition and that without such activities the condition will remain in its existing degraded state. As is the case with the 'maintain' conservation objective, we considered only fairly generic travel costs (see next section for details) for the purposes of this example. However, it would be straightforward to expand our work to capture more specific actions and their associated costs, and indeed this would be necessary to do in real-life prioritisation exercise.

We present the 'maintain' and 'restore' conservation objectives here as separate and independent analyses, whereas in practice it may be desirable to pursue multiple objectives simultaneously

(Cattarino et al., 2015). Indeed, departure from the natural fire regime would affect the intactness of vegetation, hence trade-offs and synergies between these objectives are likely. Although we recognise the possibility of interactions between the threats and actions considered in our conservation objectives, for simplicity we do not consider them in the present study since our key purpose is to demonstrate the derivation and application of our comprehensive approach.

Management costs

For the maintain objective, we assumed ground-based management via car travel (Law, 2010). Costs were calculated spatially using a 100m raster grid. Return travel cost was calculated as:

$$TrRoad_i = 2\sum Dist_{ij}(Lab_j + Vehicle_j)\,, \qquad (1)$$

where $Dist_{ij}$ is the distance in kilometres from each 100m pixel (i) to the nearest road type (j), and then along roads to the nearest main town. Lab_j is the cost of labour for travel on each road type j per kilometre. $Vehicle_j$ is the cost of vehicle use and fuel for travel on each road type j per kilometre. Travel costs were based on the use of a mid-size diesel 4WD, and we assumed that on-ground management was conducted twice-per year (Supplementary Material S2). The final costs varied from \$0/km^2/year (in the centre of the largest regional town Kalgoorlie) up to \$3,544/km^2/year, with an average of \$979/km^2/year ± 557.

For the restore objective, we assumed that aerial fire management would be undertaken. To determine a spatial representation of aerial management, we assumed a fixed-wing aeroplane would be hired from Perth and fly to Kalgoorlie, which is the key base for aerial management operations in the study region (Supplementary Material S2, Ryan Butler, pers. comm.) The final costs varied from \$3,347 (management of fire in the location of Kalgoorlie) up to \$327,176/km^2/year, with an average of \$127,272/km^2 /year ± 53,102.

Condition

We considered two alternative spatial metrics as surrogates for the condition of vegetation at each site. For the maintain objective, we represented the relative intactness of vegetation using the Vegetation Assets, States and Transitions (VAST) framework (Lesslie et al., 2008; Thackway and Lesslie, 2006). VAST describes the state of vegetation across Australia according to the degree of human modification, by incorporating spatial information describing land use, remoteness and native vegetation cover. Vegetation is classified into one of a seven states (0-VI), where the benchmark is based on an estimate of pre-European conditions (Lesslie et al., 2008). We combined classes 0 ('naturally bare') and I ('residual') into a single category to represent intact areas, and classes IV ('replaced - adventive') and V ('replaced - managed') into one category ('replaced') to represent where native vegetation had been cleared for non-native pasture or crops. We converted our five VAST classes into a continuous condition variable ranging from 0 (poor condition) to 1 (good condition; Figure 4a).

For the restore objective, we developed a spatial metric to represent the condition of a site with respect to its natural fire regime. Previous studies have demonstrated a methodology that quantifies the dissimilarity between an ecological system's current condition and its natural range of variability, with respect to a pre-European benchmark (Hann and Bunnell, 2001; Provencher et al., 2008; Rollins, 2009). However, this approach measures 'departure' from natural ecological conditions for an ecological system in its entirety, and is unable to spatially differentiate between parts of an ecological system that are in good or poor condition. To derive a spatial analogue of this metric, we developed a method that estimates the difference between the observed and expected fire-affected proportions of each vegetation type in each planning unit. We assumed fire intervals modelled by O'Donnell et al. (2011) for the Lake Johnston region, a relatively undisturbed landscape in the south-west of the study region, to represent the 'natural' regime (frequency) for key vegetation types, and subsequently calculated the 'departure' from this natural regime across the landscape. We used a spatial database of fire history information (Department of Environment and Conservation Western Australia, 2012), which details the spatial extent and date of fires for the study region between 1941 and 2012.

The Weibull probability distribution is commonly used to represent the probability of fire in a landscape as a function of time since last fire (Johnson and Gutsell, 1994; McCarthy et al., 2001; Moritz, 2003). The cumulative probability of a fire occurring (also known as the mortality function) can be written as:

$$F(t) = \Pr(T \le t) = 1 - e^{(-t/b)^c}, \qquad (2)$$

where T is a random variable denoting the time or interval at which a fire occurs, t is time, c is the Weibull shape parameter, and b is the Weibull scale parameter.

We determined the year since last burn (YLB) for each 100 m pixel in the study region. We then calculated the proportion of 100 m pixels contained in each vegetation structural type *s* (shrubland, mallee, thicket and woodland) that were burnt in the most recent fire, and plotted this observed distribution against the theoretical distribution as informed by O'Donnell et al. (2011). Departure (D) for each pixel q was then calculated as:

$$D_{qs} = abs[P(t)_s - F(t)_s], \tag{3}$$

where $P(t)_s$ is the observed proportion of vegetation structural type *s* burnt in year *t*, and $F(t)_s$ is the expected proportion of vegetation structural type *s* burnt in year *t* under a natural fire regime. The absolute value was taken to ensure D is always a positive number, and to also represent that departure from landscape condition is two-sided: an area could be burnt too frequently, or too infrequently. To generate the final condition layer, we calculated average departure for each planning unit *i* (1 km^2), and subtracted from 1; resulting in a continuous variable from 0 (poor condition) to 1 (good condition) (Figure 4b). A site where there is complete departure from natural fire regime therefore has a departure value of 1 (see Supplementary Material S2 for further information).

Spatial prioritisation approaches

We used the conservation planning tool Marxan (Ball et al., 2009) to identify priorities for management. Marxan seeks to minimize the total cost of sites in a reserve network, whilst meeting a set of targets for conservation features. The basic problem that Marxan solves is:

$$\text{minimize } \sum_{i}^{N} x_i c_i \tag{4}$$

$$\text{subject to } \sum_{i}^{S} x_i r_{ij} \geq T_j \text{ for all } j, \tag{5}$$

where x_i is a control variable indicating if a planning unit (i = 1, …, N) is selected (x_i = 1) or not

(x_i = 0) and c_i is the cost of the planning unit. Equation (1) is minimized subject to the target T_j being met for all conservation features (j = 1, …, S), where r_{ij} is the conservation benefit for feature j in planning unit i.

We used Marxan to evaluate three alternative approaches to spatial prioritisation (Table 2): (1) a comprehensive approach that calculates the conservation benefit of implementing management at each site using estimates of landscape condition, alongside monetary costs of management most relevant to the chosen conservation objective (Figure 5); (2) ignoring condition, with the cost of management calculated according to estimated monetary costs of management based on accessibility via road or aerial travel; and (3) condition as a cost surrogate, in which the cost of implementing management is inversely related to landscape condition, and we seek to minimise selection of sites in poor condition. Details of each of these approaches are below.

1. Comprehensive approach

The comprehensive approach incorporates the conservation benefit as defined by Maron et al. (2013) into spatial prioritisation analyses: that is, the difference in value between what would occur with management action, and what would occur without management. Here, γ_i is a continuous variable bounded between 0 (poor condition) and 1 (good condition). We scaled the conservation benefit r_{ij} in each site for each feature with respect to the condition of the site such that:

$$r_{ij} = a_{ij}(\gamma_{M,i} - \gamma_{0,i}), \qquad (6)$$

where a_{ij} is the area within planning unit i which contains feature j, $\gamma_{M,i}$ is the condition of site i that would occur with management action, and $\gamma_{0,i}$ is the condition of site i that would occur without management action. This allows us to include both information on condition and management costs (as c_i) in the problem formulation.

For the maintain objective, we assume that conservation values contained within sites selected for management action $\gamma_{M,i}$ will neither improve nor degrade from its current condition, but will be maintained in its current state, γ_i. Sites not selected for management are assumed to degrade over time such that condition in absence of management action $\gamma_{0,i}$ is equal to 0 (Figure 6a).

Where the objective is to restore landscape condition, we set $\gamma_{M,i}$ as equal to 1, indicating that management would successfully restore the site back to good or 'pristine' condition. Restoration is rarely 100% effective, hence there might be cases where $\gamma_{M,i}$ is less than 1. Sites not selected for restoration would remain in their existing condition state γ_i (Figure 6b).

The assumed trajectories for landscape condition with management and in absence of management under our two conservation objectives (Figure 6) are by necessity simplified for the purposes of this study. However, in a situation where better information exists on the effectiveness of particular management actions and on the expected ecological response to management, this detail could easily be incorporated into the analysis framework we present here.

2. Ignore condition

In contrast to the comprehensive approach, a simpler formulation of the benefit of implementing management is:

$$r_{ij} = a_{ij}, \tag{7}$$

This formulation considers only whether a conservation feature is represented in a particular site, and does not account for how a feature may respond given the presence or absence or a management activity.

The second approach considers the benefit of managing a site *i* as in equation 7, and identifies priorities by minimising the total monetary cost of management according to equations 4 and 5 for both the maintain and restore conservation objectives (Table 1).

3. Condition as cost

The third approach ignores management costs, and considers the current condition γ_i of a planning unit *i* to inform the value of c_i, the cost of the planning unit. In the case where the conservation objective was to maintain existing condition, the selection of sites currently in poor condition is minimised. Here, c_i is therefore inversely related to landscape condition, and scaled from 1 (good condition) to 5 (poor condition):

$$c_i = 5 - 4\gamma_i \tag{8}$$

In the case where the conservation objective is to restore lost condition, the selection of sites currently in good condition is minimised. In this case, c_i is positively related to landscape condition, and scaled from 5 (good condition) to 1 (poor condition):

$$c_i = 4\gamma_i + 1 \tag{9}$$

Mis-specified objective

If a conservation objective is not clearly specified prior to undergoing a spatial prioritisation analysis, there is a risk that cost may be considered in a way which is incompatible with the intended planning goal. For example, if the intended goal is to identify spatial priorities for restoration, but site cost is calculated according to equation 8, the Marxan algorithm will actively minimise the selection of sites in poor condition, and so will not prioritise sites where the greatest conservation benefit could be delivered through restoration. We explored the consequences of a mis-specified conservation objective in a hypothetical scenario where the 'condition as cost' approach was used to meet the 'restore' objective, but considered the incorrect formulation of cost (equation 8).

Marxan analyses were calibrated, and all scenarios were run with 100 repetitions and 10 million iterations. The boundary length modifier (BLM) is used in Marxan analyses when there is a desire to influence the degree of connectivity between planning units selected as conservation priorities. The higher the BLM, the more connected the priority sites will be (Game and Grantham, 2008). Given that our interest in this study was to understand how spatial priorities were influenced by different derivations of conservation costs and benefits, we set the BLM equal to 0 such that it did not influence the results.

Comparing results

Each of the three approaches we use to identify conservation priorities incorporate condition in different ways, and consider alternative calculations of cost and benefit (Table 2). Our comprehensive approach considers the value of the site in terms of the conservation benefit being delivered (equation 6), whereas the remaining two approaches use a simple formulation of benefit (equation 7). To enable comparison of results from our three approaches, we consider the sites identified as priorities using the monetary cost only and condition as cost approaches, and then report on the total conservation benefit (equation 6) that would be delivered as summed across all sites in the study area. Similarly, the condition as cost scenario does not consider monetary costs to identify priorities, but we draw upon our cost layers to determine the total cost of targeting these priority sites for management.

For each set of Marxan analyses (two conservation objectives, three spatial prioritisation approaches = 6 analyses), 100 near optimal solutions were identified, with the 'best' solution being the solution which meets all conservation targets for the lowest score (equations 4 and 5). The selection frequency is measure of how frequently a planning unit is selected out of the 100 near optimal solutions for each analysis. We examined the congruence between solutions derived using each of our three approaches by calculating the Pearson correlation coefficient (ρ) using the 'stats' base package in the R statistical software (R Development Core Team, 2014). Where there is a high correlation between the selection frequencies of solutions, this indicates that the spatial priorities identified by the two approaches considered are broadly similar. We do not consider significance values, and report only on the correlation coefficients, as these are unaffected by spatial autocorrelation (Nhancale and Smith, 2011). The level of spatial agreement between the best solutions found using each approach was determined by calculating the Cohen's kappa coefficient of agreement (κ) between pairs of scenarios, using the 'psych' package (R Development Core Team, 2014). If pairs of solutions are in complete agreement then κ value equals one. If κ value is less than 1, it means less than perfect agreement between pairs of solutions. If κ is negative, it indicates that the pair of solutions agrees less than would be expected by chance (Cohen, 1960).

Results

'Maintain' conservation objective

Using our comprehensive approach, in order to meet the 30% target for the maintenance of conservation features in our study region, we found that 27% of the planning units were selected for management, at a cost of approximately $32 million per year (Table 3). The comprehensive approach accounted not only for the monetary cost of ground-based management, but also the conservation benefit gained from implementing management accounting for the condition of each planning unit.

Using the 'ignore condition' approach, we found that the estimated cost required to implement management actions in the planning units selected was similar to the comprehensive approach (4% less, Table 3), and the total conservation benefit was also very similar (3% less). There was a strong positive correlation between the selection frequency of planning units identified using the 'ignore condition' compared to the comprehensive approach ($\rho = 0.90$), but poor to moderate spatial agreement in their respective best solutions ($\kappa = 0.28$).

When monetary costs were ignored and landscape condition was incorporated as a cost layer ('condition as cost'), we found that the total monetary cost of meeting conservation targets was 56% greater relative to when the comprehensive approach was taken. That is, by considering landscape condition as a surrogate for management cost, the true monetary cost of achieving the 'maintain' objective would be far greater than anticipated. In comparison, the total conservation benefit achieved would be only slightly greater (8%, Table 3). There was no correlation and no spatial agreement between the solutions found by the comprehensive and 'condition as cost' approaches ($\rho = 0.04$, $\kappa = 0.01$).

'Restore' conservation objective

In order to meet the 30% target for restoring natural fire regimes, the best solution identified using the comprehensive approach selected 28% of all planning units for management (Table 3). The total cost incurred to meet the 'restore' objective would be far greater than when seeking to achieve the 'maintain' objective, as the cost of implementing aerial management exceeds that of on-ground management by several orders of magnitude.

Similar to as found with the 'maintain' objective, when the 'ignore condition' approach was used, the total cost and conservation benefit delivered were similar to that achieved using the comprehensive approach (Table 3). Again, there was a strong positive correlation between the selection frequency of solutions identified using the comprehensive and monetary cost only approach ($\rho = 0.90$), but poor to moderate spatial agreement in their respective best solutions ($\kappa = 0.25$).

When landscape condition as informed by departure from the natural fire regime was used as a surrogate for cost ('condition as cost'), the total cost of meeting conservation targets was 36% higher relative to the comprehensive approach, yet the additional conservation benefit delivered was negligible (Table 3). There was a low positive correlation and no spatial agreement between the solutions found by the comprehensive and condition as cost approaches ($\rho = 0.14$, $\kappa = 0.03$).

There was a moderate positive correlation between the priority locations identified using the comprehensive approach for ground-based management under the maintain objective, and priorities for aerial-based management to meet the restore objective ($\rho = 0.30$, Supplementary Material S3). However, there was no spatial agreement between the two best solutions ($\kappa = 0.03$).

Mis-specified objective

Lastly, to evaluate the importance of correctly specifying the conservation objective, we considered a situation where the conservation objective may be mis-specified (Table 3). Here, we found that as a result of the incorrect formulation of cost (equation 8), there was severe underachievement in meeting the conservation target: a 63% target shortfall occurred as a result of mis-specifying the conservation objective (168% difference in conservation benefit, Table 3).

Discussion

In order to identify the most cost-effective options for conserving biodiversity, we need to be able to estimate the expected benefits of a management action relative to what would happen in absence of management (Ferraro, 2009; Maron et al., 2013). The most appropriate management action(s) to implement in a particular situation will vary depending on whether the conservation objective is to maintain existing values or to restore lost values, and where the greatest conservation benefit can be achieved for the least cost (Polasky et al., 2011; Possingham et al., 2015; Wilson et al., 2009). Although this is intuitive, only a small number of studies have explicitly accounted for the conservation benefit of a management intervention when identifying spatial priorities (Game et al., 2008; Klein et al., 2013; Maron et al., 2013). This is because most studies have assumed that biodiversity is in a pristine state. Few, if any, land or seascapes are devoid of anthropogenic impacts (Halpern et al., 2008; Sanderson et al., 2002), and so it is necessary to account for the location, magnitude, and implications of these disturbances when identifying priorities for management (Tulloch et al., 2015). A comprehensive approach is needed to provide clarity over how the conservation benefit should be calculated with respect to a specific conservation objective at hand, alongside information on management costs and landscape condition.

Aided by the principles of decision theory, we demonstrated the application of a comprehensive approach to identifying cost-effective priorities for conservation in degraded landscapes. By clearly articulating the conservation objective, the expected conservation benefit of implementing management, and the specific actions to deliver those benefits, it is possible to devise a conservation plan that will provide a more robust and cost-effective guide for management. When we considered two alternative approaches commonly used to identify conservation priorities, namely, considering the monetary costs of conservation and ignoring landscape condition (Carwardine et al., 2010; Januchowski-Hartley et al., 2011), and using landscape condition as a proxy for the cost of management (Heiner et al., 2011; Kiesecker et al., 2009; Klein et al., 2009), we found that priority locations for management and/or the total expected costs of implementing management differed substantially to what was found using our comprehensive approach.

When we assumed that landscape condition was homogenous and considered only the monetary costs of management, a similar total conservation benefit was collectively delivered by the identified priority sites relative to those identified by our comprehensive approach, but there was low spatial overlap in the locations of priority sites identified by each approach. We found that this was true in our case study region for both the ‘maintain’ and ‘restore’ conservation objectives (Table 3). Under a circumstance where the locations of priority areas selected for conservation are not important, then our results suggest that considering monetary costs alone could deliver a similar total conservation benefit compared to using a comprehensive approach that considers both costs and condition. In this case, further criteria may be needed to differentiate between alternative solutions. Although we have not considered spatial connectivity in the present analysis, this is factor which would further differentiate the solutions derived from alternative approaches. The spatial configuration of priority areas can be a key concern for planners (Beger et al., 2010; Linke et al., 2012; Magris et al., 2014), as there may be a preference for larger and more connected conservation areas for ecological reasons (to facilitate dispersal, reduce edge effects), as well as to gain economies of scale from management (Game et al., 2011).

When we ignored monetary costs and prioritised sites for management using condition as a cost proxy, the total costs of meeting targets under the maintain and restore conservation objectives were found to be 56% and 36% more expensive, respectively, compared to priorities identified using our comprehensive approach. These findings indicate that substituting condition for cost in spatial prioritisation analyses can have adverse consequences for the cost-effectiveness of land management. The most common justification for the use of condition as a cost metric in conservation planning is to minimise the selection of sites in poor condition, in order to ensure areas of higher ecological integrity are protected within a reserve network (Heiner et al., 2011; Kiesecker et al., 2009; Klein et al., 2009). However, this approach overlooks two key issues. First, sites currently in good condition will not necessarily require the least financial resources to manage. For example, areas of high vegetation intactness (and therefore good condition) in our study region were further away from roads and major cities, making it more costly to travel to for management ($\rho = 0.25$). There was a weak positive correlation between aerial travel cost and sites requiring restoration of fire regimes ($\rho = 0.10$, Supplementary Materials S3). Second, areas in good condition may not be located where the greatest conservation benefit could be achieved through a management intervention, as this requires consideration of the conservation objective (maintain or restore) and of the counterfactual scenario – what would have happened in absence of management (Ferraro et al., 2009; Maron et al, 2013; Figure 6).

We recognise that a target-based planning approach may not be appropriate in all situations (Di Minin and Moilanen, 2012; Laitila and Moilanen, 2012). Our comprehensive approach could easily be incorporated into a non-target based planning framework such as Zonation. Our 30% target is arbitrary, but we chose to keep this component of the analysis constant to ensure that the effects of different calculations of costs and benefits could easily be seen in the results. We tested the sensitivity of our findings to target selection by considering a 10% target, and found the results were broadly consistent with those of the 30% target analysis (Supplementary Materials S4). The only difference we found under the 10% target was that the total monetary cost of meeting conservation targets using the ‘condition as cost’ approach relative to the comprehensive approach was even higher than found under the 30% target (100% greater cost for ‘Maintain’, and 68% greater for ‘Restore’). Hence, our finding regarding the inefficiency of using condition as a surrogate for cost was amplified when a lower conservation target was considered.

Our findings also expose the consequences of incorporating condition into conservation planning analyses without first clearly defining the planning objective (Game et al., 2013) – whether it is to maintain existing values, or restore lost values. We found that when we naïvely incorporated fire departure as a surrogate for cost using our ‘condition as cost’ approach, sites already in ‘good’ condition were prioritised for restoration. As a result, there was a significant target shortfall (63%) compared to when we applied our comprehensive approach to meet our ‘restore’ conservation objective. This discrepancy in the benefits achieved using the ‘condition as cost’ approach is a result of a mismatch between the conservation objective (in this case, restoration), and how condition is incorporated into the analysis. Imposing a cost on areas where active management is required to deliver outcomes for conservation simply directs action away from areas where the conservation benefits would be highest. Our comprehensive approach provides a clear framework which, if followed, could better inform decisions for incorporating cost and/or condition into conservation planning in a way that is consistent with the conservation objective (Copeland et al., 2007; Kiesecker et al., 2009).

Previous studies have incorporated estimates of condition into spatial prioritisation analyses as a probability of a site being lost in the absence of a management intervention (Game et al., 2008; Klein et al., 2013), and have considered what we have termed the simple formulation of benefit (eq 7). Whereas in this study, condition has been incorporated into the calculation of conservation benefit (eq 6), and we have implicitly assumed that the probability of achieving this conservation benefit with a management intervention, and the total loss of conservation benefit in absence of the intervention, is 100%. The advantage of our approach is that we have been able to account for the conservation benefit with respect to different conservation objectives (maintain or restore), and two alternative management actions (ground based vs aerial based management), rather than simply the probability of the loss of a site as a result of a lack of protection (Game et al., 2008; Klein et al., 2013). Our results also clearly showed that the locations of priority sites differed depending on which conservation objective and management action was considered (Supplementary Material S3).

In this study, we considered the dilemma of how to robustly integrate both monetary costs and landscape condition into spatial prioritisation analyses. Our main focus was on proof of concept, and to demonstrate the derivation and application of our comprehensive approach rather than to capture the full range of complexities associated with prioritising conservation management actions. Although we have made considerable effort to develop spatially explicit representations of landscape condition and the monetary costs of management, there are some limitations. First, we considered only travel and labour costs as an indicator of the cost of implementing conservation management, whereas the true cost is likely to be higher once the cost of equipment and other materials are considered. The cost layers used in our analyses for the 'maintain' and 'restore' conservation objectives were sufficiently distinct (in terms of spatial variation, and difference in magnitude of costs) to demonstrate that the most appropriate management action(s) and their associated costs will vary depending on the conservation objective at hand, and thus will affect prioritisation outcomes. Further refinements could be made to more accurately reflect the true costs of specific management activities, and these could easily be incorporated into the approach we have presented here.

Second, we have assumed that our spatial estimates of condition are an accurate reflection of reality, and that condition will improve with management, or decline if no intervention occurs according to an assumed trajectory (Figure 6), consistently across the landscape. Our portrayal of particular management actions being associated with our 'maintain' (weed and feral animal control) and 'restore' (fire management) conservation objectives is also quite specific to the GWW. However, these conservation objectives are generalizable, with differences in condition baselines, management trajectories, and the most appropriate management actions needed to meet conservation objectives likely to vary from place to place. Our comprehensive approach is sufficiently general such that it could easily be applied in other environments and planning conditions.

Additionally, we considered only two generic management approaches in a study region threatened by multiple degrading processes, including invasive species, mineral exploration and extraction, agricultural expansion and climate change (Prober et al., 2012; Watson et al., 2008). The management approaches considered, and the presence of other threatening processes, will all influence the ways in which landscape condition is incorporated into planning, but we have not considered how to mitigate more than one threat simultaneously here. Future studies could account for both multiple objectives and multiple conservation actions with tools such as Marxan with Zones (Hermoso et al., 2015; Law et al., 2015; Tulloch et al., 2014)

Conclusions

Our findings show that failing to appropriately incorporate the monetary costs of management alongside landscape condition, or incorrectly calculating conservation benefits can lead to sub-optimal conservation plans with compromised efficiency and effectiveness. Our study demonstrates the importance of clearly defining conservation objectives, and ensuring that data most relevant to the specific conservation objective being considered are used to explore the consequences of alternative management actions. There are logical ways to integrate condition and cost into the spatial prioritisation of conservation actions – we hope that this paper provides clarity over how this can be done - by calculating the benefit of an actions as the improvement in condition above and beyond what would have otherwise occurred, and considering the cost of a site as the cost of actions that could be taken at that site.

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