Conservation Biology

Contributed Paper

Conservation Planning when Costs Are Uncertain

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Abstract: *Spatially explicit information on the financial costs of conservation actions can improve the ability of conservation planning to achieve ecological and economic objectives, but the magnitude of this improvement may depend on the accuracy of the cost estimates. Data on costs of conservation actions are inherently uncertain. For example, the cost of purchasing a property for addition to a protected-area network depends on the individual landholder's preferences, values, and aspirations, all of which vary in space and time, and the effect of this uncertainty on the conservation priority of a site is relatively untested. We investigated the sensitivity of the conservation priority of sites to uncertainty in cost estimates. We explored scenarios for expanding (four-fold) the protected-area network in Queensland, Australia to represent a range of vegetation types, species, and abiotic environments, while minimizing the cost of purchasing new properties. We estimated property costs for 17, 790 10 × 10 km sites with data on unimproved land values. We systematically changed property costs and noted how these changes affected conservation priority of a site. The sensitivity of the priority of a site to changes in cost data was largely dependent on a site's importance for meeting conservation targets. Sites that were essential or unimportant for meeting targets maintained high or low priorities, respectively, regardless of cost estimates. Sites of intermediate conservation priority were sensitive to property costs and represented the best option for efficiency gains, especially if they could be purchased at a lower price than anticipated. Thus, uncertainty in cost estimates did not impede the use of cost data in conservation planning, and information on the sensitivity of the conservation priority of a site to estimates of the price of land can be used to inform strategic conservation planning before the actual price of the land is known.*

Keywords: cost uncertainty, conservation decisions, land acquisition, protected areas, reserve selection, sensitivity analysis

Planificación de la Conservación Cuando los Costos son Inciertos

Resumen: *La información espacialmente explícita sobre los costos financieros de las acciones de conservación pueden mejorar la habilidad para la planificación de la conservación para alcanzar metas ecológicas y económicas, pero la magnitud de esta mejoría puede depender de la precisión de las estimaciones de costos. Los datos sobre costos de acciones de conservación son inherentemente inciertos. Por ejemplo, el costo de la adquisición de una propiedad para agregarla a una red de áreas protegidas depende de las preferencias, valores y aspiraciones de los propietarios individuales, que son variables en tiempo y espacio, y el efecto de esta incertidumbre sobre la prioridad para la conservación de un sitio ha sido relativamente poco probada. Investigamos la sensibilidad de la prioridad para la conservación de sitios a la incertidumbre de las estimaciones de costos. Exploramos escenarios para la expansión (4 veces) de la red de áreas protegías en Queensland, Australia para representar un rango de tipos de vegetación, especies y ambientes abióticos, minimizando al mismo tiempo los costos de la adquisición de propiedades nuevas. Estimamos los costos de propiedad para 17790 sitios de 10 × 10 km con datos sobre valores no mejorados. Sistemáticamente cambiamos los costos de*

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Paper submitted September 30, 2009; revised manuscript accepted February 8, 2010.

Conservation Biology, Volume 24, No. 6, 1529–1537
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DOI: 10.1111/j.1523-1739.2010.01535.x

propiedad y notamos como estos cambios afectaron la prioridad de conservación de un sitio. La sensibilidad de la prioridad de un sitio a cambios en datos de costos fue muy dependiente de la importancia del sitio para alcanzar metas de conservación. Los sitios que fueron esenciales o no importantes para alcanzar metas mantuvieron prioridades altas o bajas respectivamente, independientemente de las estimaciones de costos. Los sitios con prioridad de conservación intermedia fueron sensibles a los costos de propiedad y representaron la mejor opción para ganancias de eficiencia, especialmente si podían ser adquiridos a un precio menor al anticipado. Por lo tanto, la incertidumbre en las estimaciones de costos no impidió el uso de datos de costo en la planificación de la conservación, y la información sobre la sensibilidad de la prioridad de conservación de un sitio a estimaciones del precio del terreno puede ser utilizada en la planificación estratégica de la conservación antes de que se conozca el precio actual del terreno.

Palabras Clave: adquisición de tierras, análisis de sensibilidad, áreas protegidas, decisiones de conservación, incertidumbre de costos, selección de reservas

Introduction

Patterns of biological diversity vary spatially, as do the financial costs of conservation actions such as land purchase and management (Wilson et al. 2009). Historically, approaches to conservation prioritization have not accounted explicitly for the costs of actions (Kirkpatrick 1983; Possingham et al. 2006; Carwardine et al. 2007; Linke et al. 2007), but the number of published examples of systematic conservation planning assessments that are informed by economic data is increasing (Naidoo et al. 2006). Approaches to priority setting that account for the relative costs of conserving alternative sites (e.g., Ando et al. 1998; Carwardine et al. 2008*a*, *b*; Smith et al. 2008; Wikberg et al. 2009) or undertaking alternative actions, such as funding recovery plans for different species (e.g., Bottrill et al. 2008; Joseph et al. 2009), make efficient use of conservation funds.

Conservation costs are typically uncertain during the planning phase. For many conservation actions, costs are predicted on the basis of proxies of the real cost (Naidoo et al. 2006). In marine reserve design, the costs of conservation are usually estimated on the basis of the fisheries net income that would be forgone if an area was protected (e.g., Stewart & Possingham 2005; Klein et al. 2008; Smith et al. 2009). The cost of land acquisition for expanding protected-area networks in terrestrial systems has been predicted using recent property sales (McDonald-Madden et al. 2008), unimproved land values (Ando et al. 1998; Carwardine et al. 2008*a*), and data on agricultural profitability (Naidoo & Iwamura 2007; Carwardine et al. 2008*b*). The real cost of purchasing a property will differ from the predicted cost as a function of the quality and resolution of the predicted data and on factors that influence the real price a landholder is willing to accept (Goodwin et al. 2003; Knight et al. 2006). This price will depend on factors such as the history of land ownership, amenability of the owner to conservation, and the owners perceived future benefits from the current land use (Hajkowicz et al. 2007).

The lack of reliable data on the costs of conservation actions is one reason cost data are omitted during the prioritization process (Kremen et al. 2008). Planning with inaccurate cost data may not deliver the gains in conservation-planning efficiency that studies predict (Ferraro 2003; Perhans et al. 2008), although Pannell (2009) suggests that use of uncertain cost data results in more efficient priorities than ignoring cost altogether. The concern that cost data might result in expensive but biologically important areas being overlooked or areas of low biological value being prioritized because they are cheap (Naidoo et al. 2006; Pannell 2009) is exacerbated when cost estimates are highly inaccurate. To the best of our knowledge, differences between predicted and real costs or changes in the current prices of land for conservation, and their effect on conservation planning, have not been examined.

Typically, conservation plans are developed from data that represent the best available knowledge. When properties become available for purchase, the organization responsible for expanding the protected-areas network decides whether acquisition is warranted. If the price being offered is substantially different from the cost used for the original prioritization, does the conservation plan still provide valid guidance? Should the organization buy a property at an especially cheap price even if the property was not a high priority in the original plan? Alternatively, should a property be purchased that was identified as irreplaceable for meeting conservation goals, even if its price is much more than expected?

We provide a practical approach for undertaking conservation planning assessments when information on costs is uncertain. We examined the sensitivity of the relative priority of sites to a range of cost values; determined the cost range over which each site is a high priority; and devised a practical approach for determining whether to invest in a site if it becomes available at a different cost than predicted. Our case study was the expansion of the protected-area network in Queensland, Australia, which is a current priority of the state government (Queensland Government 2008). The expansions aimed to increase the protection of a range of vegetation types, species, and abiotic environments, up to 15% of their historical range (considered the maximum politically viable target at this time), while minimizing the cost of purchasing new properties.

Rather than ignoring uncertainty, or avoiding uncertain data, conservation scientists have found ways to explicitly address uncertainty in biological information (Regan et al. 2002; Wilson et al. 2005). For example, species occurrences can be treated as probabilistic, and priority actions or sites can be identified that are robust to information uncertainty (e.g., Halpern et al. 2006; Moilanen et al. 2006; Nicholson & Possingham 2007). These approaches are used in planning situations in which data that are relatively certain are not expected to become available. Accurate data on the cost of land acquisition, however, eventually become available when land purchases are offered. Therefore, it would be useful to know the cost range over which a property is likely to be a good investment.

Methods

Case Study Data Set

The area of Queensland is 185 million ha, about 7.6 million ha (4.6%) of which is designated as protected (e.g., national parks). The state holds information on the delineation of 1.97 million properties at an average property size of 600 ha (minimum 0.0002 ha, maximum 7 million ha) with an average unimproved land value of approximately $AU630/ha. The unimproved value is estimated by the state valuer general and represents each property's sale price less the value of built structures.

Planning on a property-based scale is computationally challenging and socially unacceptable. Hence, we used a 10 × 10 km grid to generate 17,790 evenly sized planning units (hereafter sites) that covered Queensland (offshore islands excluded).

We assigned each 10 × 10 km site an average cost per hectare on the basis of the unimproved land values derived from the property-based shapefile. Sites that overlapped with no information on land value (5%) were assigned the average values of their corresponding local government area. We multiplied the average cost per unit area by the area of native vegetation in the site (we did not consider conservation actions in areas of non-native vegetation) and added a transaction cost of US$10,000 to each site to represent administrative fees incurred when purchasing properties in Australia (Carwardine et al. 2008*a*). Thus, we estimated the cost of purchasing all native vegetation in each site. If over 50% of the area of a site overlapped an existing protected area or Aboriginal land, we classified it as belonging to those tenures. Existing protected areas (International Union for Conservation of Nature categories I–IV) were given a cost of zero and were selected in all scenarios. We assumed Aboriginal land was unavailable for acquisition; hence, we did not consider those lands in our analysis. We recognize, however, that valuable conservation outcomes can occur on Aboriginal land through other actions.

We used the Queensland subset of the biological data set described in Carwardine et al. (2008*a*). This data set includes four types of conservation features, which we assumed are reasonable surrogates for overall biological diversity in Queensland: 384 vegetation types, created by giving each broad vegetation group in the National Vegetation Information System (2001) a unique type in each bioregion (Australian Government 2005); 128 environment types (environmental domains derived from climate, terrain, and soil attributes; Mackey et al. 2008); distribution of 387 species of national environmental significance (Australian Government 1999); and distribution of 487 nonmigratory bird species (Birds Australia 2005) (total of 1386 features). As in Carwardine et al. (2008*a*), we removed the extent of each conservation feature that occurred in areas cleared of native vegetation because we did not consider the costs of restoring native vegetation. We determined the extent of each feature in all areas of native vegetation in each site. We set targets for all features at 15% of their historical (pre-1750) extent.

Planning Scenarios

We used the conservation planning software Marxan (version 1.9.5; Ball et al. 2009) to investigate the conservation priority of sites and the sensitivity of each site to the cost parameter. Marxan uses a simulated annealing algorithm to generate multiple alternative solutions, all of which are close to optimal and have similar costs. We used Marxan and the estimates of acquisition costs for each site to determine 100 alternative combinations of sites that would meet our 15% conservation targets and minimize the predicted cost of land acquisition. We did not use a spatial aggregation objective because our planning units were larger than most protected areas in the region and we did not want to confound changes in spatial aggregation with changes in cost. Each site's predicted priority was the proportion of the 100 solutions in which the site was included, all of which met the conservation feature targets while minimizing the predicted estimates of cost. High-priority sites were therefore those with features contained in few other sites, or few other cost-effective sites, either because the features were naturally rare or the site had lost native vegetation since European settlement.

In a real-world planning situation, properties within each 10 × 10 km site would likely become available for acquisition at a different price than predicted originally. We tested the effect of differences in cost estimates on the relative priority of each site. Ideally the sensitivity of each site's conservation priority to the cost data would be tested independently of other sites or with all combinations of cost changes. Due to the trade-off between comprehensiveness and computational constraints, however, we tested the sensitivity of sites in 10 separate groups (each group contained a random, exclusive 10% of the total number of sites). We then systematically changed the cost of sites in each group and reran Marxan to find 100 alternative solutions that achieved the same conservation objective for 170 different cost scenarios. In each scenario, we changed the costs of one random group of sites by one of the following proportional decreases × 0.9, 0.8, 0.7, 0.5, 0.3, 0.1, or 0.01 or one of the following increases ×1.1, 1.2, 1.3, 1.5, 1.7, 1.9, 2.2, 2.5, 3, or 4. A scenario was a combination of 1 of the 10 groups and its price change. The range of cost change was from 0.01 to four times the predicted cost to ensure capture of the full range of potential real costs of each site. We tested finer increments around the predicted values to allow accurate detection of sensitivity close to these predicted values. Because our study area and data set were large, it is unlikely that dependencies between sites in each 10% group would substantially affect our results.

Analyses

We measured the change in relative priority of each site over the full range of cost alterations. We estimated the sensitivity of each site to cost on the basis of proportional change in cost required to alter the predicted priority of a site by 20%. As we increased costs above the predicted, we measured the proportional change required to reduce the predicted priority of a site by 20% (i.e., from a conservation priority of 100–80%). A robust site was one that did not decrease in priority by 20% over the range of cost change (up to four times the predicted cost). When costs were reduced below the predicted cost, we measured the proportional change required to increase the predicted priority of a site by 20% (e.g., 50–70%). A robust site was one that did not increase in priority by 20% over the range of cost change (down to 0.01 times the predicted cost).

Within each scenario, we classified a site selected in >80% of solutions as high priority and a site selected in <20% of solutions as a low priority. An intermediate-priority site was selected in 20–80% of solutions. We determined the critical cost at which a low- or intermediate-priority site became a high-priority site and the cost at which a high- or intermediate-priority site became a low priority. We mapped these critical costs for each site. We investigated eight specific sites (a–h) that covered a range of initial priority values and degrees of sensitivity in more detail to gain deeper insight into how a change in cost drives a change in site priority. Finally, at each increment of conservation priority (0–100%), we calculated the average proportional change in predicted cost for a site to change priority status.

Results

Predicted Priority Areas

Approximately 29.9 million ha (17.2% of the planning region), including existing protected areas, was required to meet the 15% representation targets for all conservation features. Of these sites, 6% (3.5% of sites when existing protected areas were excluded) were selected in 100% of solutions, which indicated they were key sites for representing targets cost-effectively (Fig. 1a). High-priority sites contained features that occurred in few sites or in few sites that were cost-effective. These included the areas west of Diamantina National Park in central Queensland, areas south of Camooweal Caves National Park on the northern border of Queensland and Northern Territory, and many areas scattered throughout the Brigalow Belt and the Queensland coastal zone. Another 9% of sites were required to meet targets for the remainder of features, but spatial flexibility existed within the landscape for achieving these targets. A number of intermediate-priority sites occurred near high-priority sites. A large proportion of sites (72.3%) were low priority.

Site Sensitivity to Cost Uncertainty

Overall, sites were sensitive to the cost parameter. The majority of sites decreased in priority by 20% when their cost was increased to 1.7–1.9 times the predicted cost (Fig. 1b) or increased in priority by 20% when their cost was reduced to 0.7–0.5 times the predicted cost (Fig. 1c).

Sites varied in their sensitivity to uncertainty in cost in direct proportion to their predicted priority values (Fig. 2). Sites with predicted priority of 100% were most robust, with more than 80% of these sites maintaining their high-priority status regardless of cost changes. Sites with predicted priorities of 0% were also relatively robust, with 40% of sites maintaining low-priority status regardless of cost changes. Almost one-third of high- (>80% predicted priority) and low-priority (<20% predicted priority) sites were robust to decreases and increases in cost. Sensitivity was greatest for intermediate-priority sites (predicted priority of 20–80%); many changed priority by 20% with changes of only 0.1 in the cost parameter (Fig. 2). Sites with predicted priorities of 70–79% were less likely to increase in priority by 20% compared with other intermediate sites because this would involve displacing sites in the robust priority category of 90–100%. Similarly, sites with predicted priorities of 20–29% were less likely to decrease in priority by 20% compared with other intermediate-priority sites because many robust sites were in the site-conservation priority category of 0–10%.

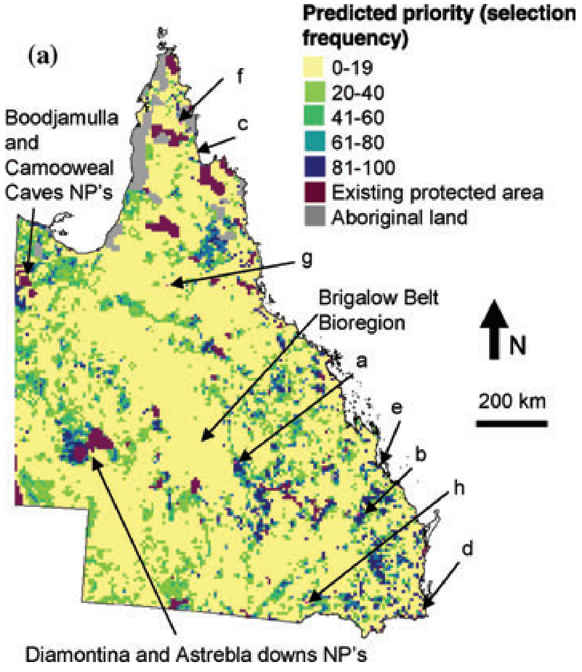
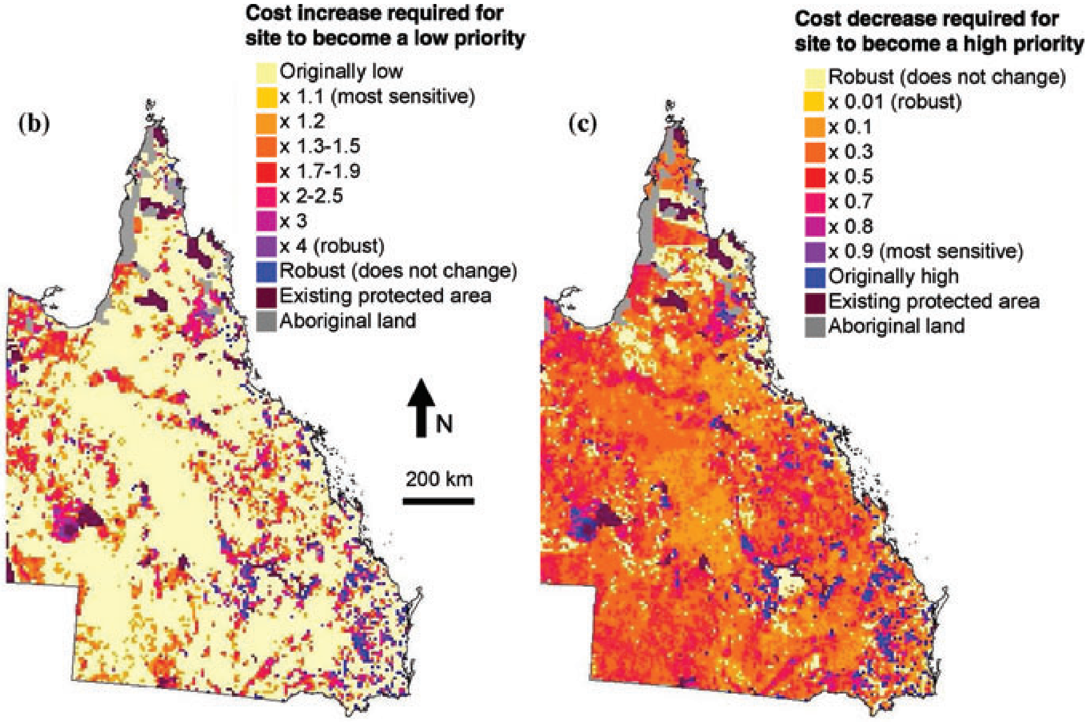


Figure 1. (a) Relative conservation priority of sites on the basis of predicted estimates of cost (a–h, locations of case-study sites). (b) Proportional increase in cost required for each intermediate- and high-priority site to become a low-priority site. (c) Proportional decrease in cost required for each low- and intermediate-priority site to become a high-priority site.



Effects of Cost Changes on Site Priority

Sites a–h (Fig. 1a) had a range of sensitivities to changes in cost (Fig. 3). Sites with 100% conservation priority contained features that did not occur in any other sites, or in any other affordable sites, and were generally robust to cost changes. Site a contained the only remaining Acacia sparse shrubland within the Brigalow Belt South bioregion. Hence, this site was selected in 100% of solutions regardless of its cost. Site b remained a high priority even with a 400% increase in cost, despite the existence of its rarest feature (environmental domain 75) in 284 other sites, because the cost of the site was relatively low. In contrast, site c, was of high priority because it protected Angophora mixed woodland in Cape York Peninsula (occurred in 74 other sites), but when the cost

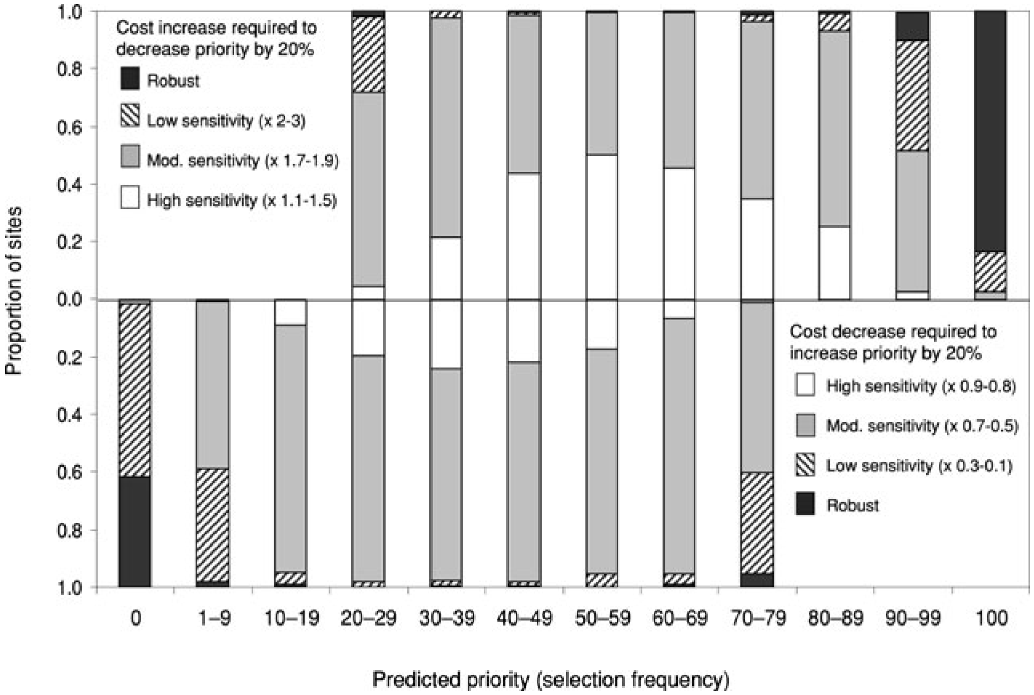


Figure 2. Sensitivity of the conservation priority of sites to changes in cost of the site (bars, cost change required to change the priority of a site by 20%, for example, from a site conservation priority of 100% to a priority of 80%). The y-axis shows the proportion of sites, grouped by their predicted priority, that were robust to cost changes and those that were of high, moderate, and low sensitivity to changes in cost. The top panel shows scenarios for which costs were higher than predicted, and the bottom panel shows scenarios for which the cost was lower than predicted.

of the site increased by 30–50%, it lost high-priority status because other sites become more cost-effective for protecting the feature.

Site d was typical of an intermediate and sensitive priority site. This site was relatively expensive and was selected in only about 50% of solutions, despite containing 298 features, including one of only seven occurrences of magnolia (*Zieria collina*). Sites with a similar assemblage were available at approximately 130 and 60% of this site's predicted cost; hence, an increase or a decrease in the cost of site d made it a high or a low priority, respectively, at approximately these same percentage bands (130 and 60%). A small number of sites remained at intermediate-priority status both when their cost was increased and when it was decreased. For example, site e contained 207 features, the rarest of which (environmental domain 131) occurred in 49 sites. Site e was relatively cheap, and the next-cheapest site that represented this feature was more than 100 times the price; hence, changes in the cost of site e did not substantially affect its conservation priority.

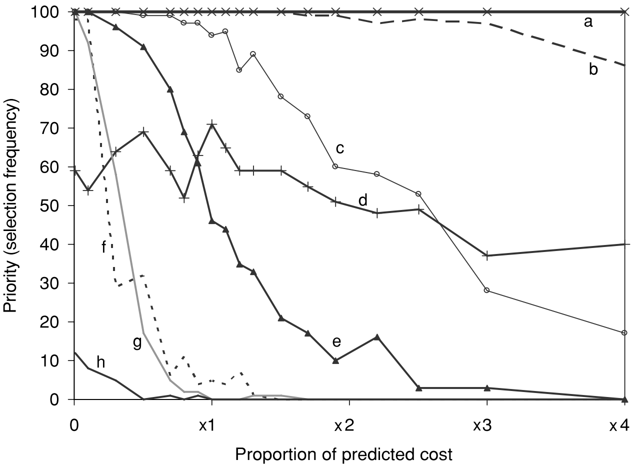


Figure 3. Changes in conservation priority of eight sites with changes in predicted cost of the site for randomly selected case-study sites a–h (site locations shown in Fig. 1a).

Most sites with a conservation priority between 1% and 20% were sensitive to changes in cost and became of higher priority when available at a cheaper price. For example, site f contained 199 features, none of which were particularly rare. A decrease in site f's cost to 20% of the predicted cost made this site cheaper than another site that also represented site f's rarest feature, the Collared Kingfisher (*Todiramphus chloris*); hence, site f became a high-priority site. Some sites with predicted priorities of zero were also sensitive to changes in cost. For example, site g became a high priority at 10% (i.e., a reduction of 90%) of the predicted cost because it became more important for representing the relatively common Red-backed Fairy Wren (*Malurus melanocephalus*) than the next cheapest site. Most sites with a predicted priority of zero remained of low priority regardless of cost decreases. For example, site h remained of low priority because its rarest feature was the Black-eared Cuckoo (*Chrysococcyx osculans*), which has a relatively wide range and occurred in 675 sites.

Discussion

The conservation priority of sites that were essential or unhelpful for meeting conservation targets was typically robust to a considerable range of changes in cost estimates. The fact that sites with very high and very low-conservation values maintained their priority status regardless of the cost of the site means that the status of sites of high-conservation value will not be affected when economic data are uncertain and that sites with low value will not be identified as of high priority simply because they are cheap. This finding suggests that the paucity of accurate cost data need not impede use of cost data in conservation planning (Pannell 2009). The relative priority of most of our intermediate-priority sites was sensitive to the predicted cost data. This suggests that the consideration of cost data and its uncertainty for intermediate-priority sites represents the greatest potential for efficiency gains.

The sensitivity of conservation priority to cost data will vary among planning data sets and objectives. Previous work shows it is particularly important to include costs in conservation prioritization when cost varies more than biological value (Ferraro 2003); if cost and biological value are positively correlated (Ferraro 2003), which is the case in most conservation-planning data sets, including our own (Naidoo et al. 2006); and in the absence of a complementarity or target-based objective (Bode et al. 2008; Perhans et al. 2008). We built on this body of research by finding that the effect of cost data on conservation priority varied substantially among sites on the basis of the sites' importance for meeting conservation targets, which was reflected in their predicted priority. The overall sensitivity of sites to cost may vary depending on data availability and may be lower where cost correlates negatively with biological value. Our key conclusion—that high- and low-priority sites are most robust to cost error—is likely to hold whenever a complementarity or target-based objective is used to ensure efforts are directed to a range of conservation features. Like Pannell (2009), we believe that when both biological and cost data are available, both types of data should be incorporated in an approach that accounts for cost uncertainty.

Increasing the quantity and quality of data on the costs of conservation actions is an important priority for future research; however, many costs of conservation actions cannot be predicted perfectly. Most terrestrial conservation plans do not include only properties for sale; rather, they assess all sites within a landscape that might be priorities if they become available in the future. Adaptive approaches that inform land-purchase decisions have been developed (e.g., Meir et al. 2004; Turner & Wilcove 2006; McDonald-Madden et al. 2008), but these approaches are limited to planning problems with few sites. We ignored the fact that as one site is purchased, the priority of another changes. This allowed us to investigate the sensitivity of site priorities to cost and to map site sensitivity to cost over a large area. Thus, our outputs should be useful accompaniments to traditional maps of conservation priority.

The results of our exploration of scenarios of protected-area network expansion in Queensland suggest that almost 30 million ha is required to represent 15% of the historical extent of all vegetation types, environmental domains, birds, and species of national environmental significance. This is approximately four times the current protected-area network in Queensland, and considerably larger than the state government's goal to increase the total area of land under conservation to 20 million ha by 2020. Prioritization of areas important for conservation will therefore be required over the next 10 years. Our best estimate of the relative conservation priority of each site in Queensland is shown in Fig. 1a, which is the typical product of a systematic conservation assessment: a map representing a snapshot assessment of relative priority derived from predictions of the cost of land (although in many cases this cost is ignored during the planning phase).

A site will often become available at a much higher or lower cost than predicted, and the investor may not have the time, resources, or expertise to redo the entire analysis. We suggest that, along with a map of predicted priorities the initial planning process include a sensitivity analysis to generate maps of the cost thresholds at which a site becomes or ceases to become a priority (Figs. 1b & c). Such an analysis would help inform decisions about whether to invest in a property that becomes available at a cheaper or more expensive price than predicted. Sites shown in blue in our Fig. 1b are likely to be important for conservation regardless of their cost and are high priorities for further investigation into property availability and price.

In our analysis we did not consider all the information needed for a real-world planning task (Knight et al. 2006 or the interaction between the desirability of one site as a conservation investment and the likelihood that other sites will become available (McDonald-Madden et al. 2008). For a more comprehensive assessment, one would need information on social values and preferences

(Ban et al. 2009); landholder willingness to participate in conservation; threats to species persistence; spatial connectivity (which may be important for species persistence [Virolainen et al. 1999]); site availability (Knight & Cowling 2007); and a complete biological data set. Altering sites' costs in 10% groups resulted in only a rough estimate of the sensitivity of predicted priority to cost—an automated approach could be developed to test individual site sensitivity to cost. We assumed that the average cost was correct, which is unlikely to be valid in many situations. This assumption did not affect our results on the relative sensitivity of each site to cost error, but it may affect estimates of the critical cost range over which a site is a high or low priority. These kinds of data and solutions could be incorporated into our approach, although in many cases their addition would come at the expense of its current simplicity and ease of application.

Our results suggest that target-based conservation planning can proceed with uncertain cost estimates with a low probability of compromising conservation targets or spending funds on sites of poor conservation quality. It is nonetheless important to consider cost data because efficiency can be gained through careful evaluation of intermediate-priority sites. Our approach may help improve the cost-effectiveness of conservation planning in situations where costs are unknown. By using information on a single estimate of priority and on the cost range over which a site is likely to be a priority, conservation professionals will be better equipped for making real-world conservation decisions.

Acknowledgments

We thank B. Mackey, the Australian Department of Environment, Water, Heritage and the Arts, the Queensland Valuer General, and Birds Australia for data; and R. Fuller, C. Hempel, S. Howell for useful discussions; and M. Bode for helpful comments on a draft manuscript.

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