LETTER

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# Systematic planning can rapidly close the protection gap in Australian mammal havens

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**Abstract**

In the last 30 years, islands and fenced exclosures free of introduced predators (collectively, havens) have become an increasingly used option for protecting Australian mammals imperiled by predation by introduced cats (*Felis catus*) and foxes (*Vulpes vulpes*). However, Australia's network of havens is not expanding in a manner that maximizes representation of all predator-susceptible taxa, because of continued emphasis on already-represented taxa. Future additions to the haven network will improve representation of mammals most efficiently if they fill gaps in underrepresented predator-susceptible taxa, particularly rodents. A systematic approach to expansion could protect at least one population of every Australian predator-susceptible threatened mammal taxon by the addition of 12 new havens to the current network. Were the current haven network to be doubled in number in a systematic manner, it could protect three populations of every Australian predator-susceptible threatened mammal taxon.

**K E Y W O R D S**

conservation fencing, introduced species, islands, pest control, predation, systematic conservation planning, threatened species, translocation, wildlife management

# 1 | INTRODUCTION

Australian mammals face severe challenges from introduced predators (Johnson, 2006; Woinarski, Burbidge, & Harrison, 2014). Introduced cats (*Felis catus*) and foxes (*Vulpes vulpes*) have been identified as the principal cause of most of the >30 extinctions of Australian mammals over the last 200 years, and have caused rapid and severe declines of many other species (Legge et al., 2017; McKenzie et al., 2007; Woinarski, Burbidge, & Harrison, 2015). Many Australian mammal taxa now persist only in a small number of refugial populations where introduced predators are either naturally absent or occur at low density (Letnic, Koch, Gordon, Crowther, & Dickman, 2009), or in areas where predators have been controlled through ongoing management. These species are at high risk of extinction from demographic population failure (Beissinger & Westphal, 1998), catastrophic events (Courtenay & Friend, 2004; Hebblewhite, White, & Musiani, 2010), and the continuing threat of introduced predators (Legge et al., 2017).

The susceptibility of many Australian mammal species to introduced predators has led to the promotion and adoption of conservation areas where introduced predators are naturally absent or have been removed (Burbidge, Legge, & Woinarski, 2018; Hayward, Moseby, & Read, 2014; Legge et al., 2018). Here, we follow Legge et al. (2018) in denoting such predator-excluded areas as "havens," noting that comparable concepts are labeled differently in other places (e.g., "sanctuaries" in New Zealand; Innes, Burns, Sanders, & Hayward, 2015). Currently, Australia's network of havens

consists of 101 predator-free islands and 17 fenced areas that contain predator-susceptible mammal taxa. Of these existing havens, 39 (17 fences, 22 islands) are due to human intervention (i.e., fenced exclosures; islands to which threatened mammals have been translocated, sometimes following eradication of introduced predators: hereafter "created havens"). The remainder are islands that have never had foxes and cats and which have historical populations of threatened mammal taxa ("natural havens"). A further 14 havens are currently being developed (i.e., areas being fenced or islands from which predators are being eradicated; Legge et al., 2018). Although these havens encompass a tiny proportion of these species' historical ranges, they provide taxa with insurance against extinction. Current havens contain 188 populations of 38 nationally threatened nonvolant mammal taxa (representing 32 species) that are susceptible to predation by introduced predators (Legge et al., 2018). Havens, particularly fenced exclosures, are expensive to establish, require ongoing maintenance, and (due to their restricted area) limit the size of translocated or in situ populations (Hayward & Kerley, 2009), while sometimes creating dispersal and connectivity barriers, particularly to large mammals. However, because many native species are so sensitive to invasive predators (Marlow et al., 2015), haven creation has become a major component of conservation in Australia, as well as New Zealand and Hawaii (Burbidge et al., 2018; Dickman, 2012; Hayward et al., 2014; Legge et al., 2018; Young et al., 2012).

The Australian haven network emerged through an ad hoc process, with multiple government agencies and

nongovernment groups creating havens based on individual priorities and opportunities (Ringma, Wintle, Fuller, Fisher, & Bode, 2017). Despite this lack of coordination, the network has made a substantial contribution to mammal conservation at a national scale, and has undoubtedly prevented (to date) the extinction of many taxa. However, the current network exhibits substantial gaps in species representation (Ringma et al., 2018b). The principles of systematic conservation planning (Margules & Pressey, 2000) demonstrate that large and irreversible opportunity costs can accrue through unsystematic expansion and direction, and that coordinated planning and action can deliver enormous improvements in representativeness.

In previous publications, we have: (1) summarized the susceptibility of Australian terrestrial nonvolant mammal species to introduced predators, thus identifying the species that need representation within havens (Radford et al., 2018); (2) analyzed the extent to which the current haven network protects predator-susceptible threatened mammals (Legge et al., 2018); (3) identified areas of inefficiency in the current haven network at a national scale (Ringma et al., 2018b); and (4) developed methods for the systematic allocation of new havens (Ringma et al., 2017). Here, we integrate the findings of these studies into principles for a strategic national network of havens, as a guide for its future expansion. The approach and principles are also relevant to networks of conservation havens elsewhere in the world.

## 2 | METHODS

### 2.1 | Conservation objective

The primary purpose of most havens is to reduce probability of global extinction for target taxa, however, we note that the creation of havens and reintroductions also serve other objectives, such as the restoration of ecosystem function (Manning, Eldridge, & Jones, 2015). In the analyses that follow, our conservation objective is to provide comprehensive and adequate protection to all Australian mammals that are threatened primarily by cats and foxes. We maximize this objective by efficiently choosing locations for new havens.

We define comprehensive to be the inclusion within the haven network of populations of all 67 mammal taxa that have "high" or "extreme" predator susceptibility, as defined by Radford et al. (2018). We acknowledge that this focus does not consider other Australian taxa (particularly birds and reptiles) that are susceptible to introduced predators (Woinarski et al., 2017, 2018), and may benefit from fences. We define "adequate" protection by considering a species to be secure when it is distributed across six or more havens. This value is based, in part, on the threshold used by the IUCN to demarcate Endangered and Vulnerable assessments (Criterion B,

Geographic Distribution; IUCN, 2017). We also acknowledge that havens must be large enough to allow for populations of threatened taxa to be genetically and demographically viable. In Ringma et al. (2017), we identify a methodology to empirically estimate population viability and note that while viability is often considered in relation to a threshold value of population size, in fact the population size-viability relationship is continuous; hence, categorizations are subject to individual managers' interpretation of viability thresholds. For reference, a breakdown of havens considered to contain viable populations, and their size, is outlined in Legge et al. (2018).

### 2.2 | Data compilation

Sixty-seven extant Australian mammal taxa are extremely or highly susceptible to introduced predators (Legge et al., 2018; Radford et al., 2018). For each taxon, we produced historic distribution maps, based on occurrence records from the Mammal Action Plan (Woinarski et al., 2014) superimposed onto Interim Biogeographic Regionalization for Australia (IBRA, Commonwealth of Australia, 2017) subregions (these divide the Australian mainland into 419 biogeographical units). Tasmanian subregions were not considered for new havens as the island currently acts as a refuge for many predator-susceptible taxa. The historic distribution maps were validated by Australian mammal experts, focusing on identifying undocumented historic occurrences that would expand the number of suitable subregions for each taxon. Population estimates for each taxon were extracted from the Mammal Action Plan (Woinarski et al., 2014), supplemented where possible by more recent (and sometimes unpublished) data from populations in existing havens.

We purposefully chose to map species distributions, and to prioritize management actions, at a coarse bioregional scale. Conservation planning, including strategic fencing, can operate at very fine spatial resolutions (e.g., 5 km grids; Ringma et al., 2017), supported by species distribution modeling. For the creation of new havens for threatened Australian mammals, however, high-resolution models would create a false sense of precision. The best location for a haven depends on a suite of environmental, economic, logistic, and societal factors that must be assessed case-by-case, and which cannot be effectively considered at a national and continental scales. These factors include the challenging decision about whether a haven should be an island or a fence when IBRA subregions are located in proximity to neighboring island habitat. It also includes factoring future climates into decision making—for example, by locating havens in climate refugia, or within future climate envelopes (but see Morán-Ordóñez, Lahoz-Monfort, Elith, & Wintle, 2016, where climate forecasts for broadly distributed species such as Australian mammals are unreliable). Additionally, as identified in Ringma, Hanson, Barnes, Fisher, and Fuller (2018a), historic

records for the majority of Australian threatened mammals are subject to extensive sampling bias, resulting in considerable uncertainty in statistical habitat suitability models. For these reasons, we use generalizable priorities for haven placement at a coarse spatial scale, allowing for local decision makers and context to determine the precise locations for new havens within those subregions.

## 2.3 | Prioritization method

The prioritization identified which of the 419 subregions should be targeted for future haven projects based on the taxa they are known to have historically contained. Part of the efficiency of the process is to maximize species' inclusion within each new haven; hence, all new projects should contain as many compatible species as possible within the same haven. Of course, habitat variation within subregions may mean that not all taxa can be accommodated at the same site, in which case either multiple havens would need to be created (Bode, Brennan, Morris, Burrows, & Hague, 2012), or the species in most need of protection should be prioritized.

For the purposes of this optimization, the state of the haven portfolio is described by a $(1 \times 419)$ protection matrix, which indicates the number of havens currently found in each of Australia's 419 IBRA subregions

$$\mathbf{H} = [1, 0, 0, 2, \dots, 0].$$

Each of the 67 predator-susceptible mammal taxa can persist in a subset of the IBRA subregions, categorized based on current or historic occurrence records within each subregion. Suitability is captured in a $(419 \times 67)$ binary matrix

$$\mathbf{S} = \begin{bmatrix} 1 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}.$$

The amount of protection offered to each taxon by a network of havens is calculated as $\mathbf{P} = \mathbf{H} \times \mathbf{S}$, whose 67 elements indicate the number of havens in which each taxon is found. The strategic objective of this national network is to protect each taxon in at least six havens. This is equivalent to choosing a protection matrix $\mathbf{H}$ where the following penalty function, $B$, is less than or equal to zero:

$$B = \sum_{i=1}^{67} \max \left\{ 0, \left(6 + \mathbf{G}_i - \mathbf{H}_i\right)^z \right\}.$$

The exponent $z > 1$ ensures a penalty for currently well-represented species so that the function will first ensure that each taxon enjoys the same level of protection. At high values where $z > 1$, new populations of well-represented taxa are disproportionately penalized. We set the value of $z = 4.5$ so that the first representation of a taxon is valued equally to the

second representation of two taxa. This ensures the sequence in which new havens are allocated maximizes gap filling for under-represented species.

The $(1 \times 67)$ matrix $\mathbf{G}_i$ corrects the benefit function for those taxa that are currently not found in existing havens that could potentially support them. For example, if there are three havens in the current network that could potentially support bilbies (*Macrotis lagotis*), but only two have bilbies, then $G_{bilby} = 1$.

We formulate the haven prioritization as a combinatorial minimal set-coverage problem, common in conservation planning

$$\min_{\mathbf{P}} C = \sum_i \mathbf{H}_i, \quad s.t. \ B \leq 0,$$

and we identify solutions by applying a greedy stochastic search over values of $\mathbf{P}$. We start with a randomly valued protection matrix, whose values are random integers less than 7. Search steps (random additions or subtractions to $\mathbf{P}$) are accepted by the algorithm if they decrease $B$ but do not increase $C$, or decrease $C$ but do not increase $B$. Search steps that increase either metric are accepted with a probability that decays exponentially with time. Searches are terminated if $10^4$ search steps have been taken without any improvement. Only solutions where $B \leq 0$ are accepted.

## 2.4 | Analyses

We used the methods described above to undertake a series of analyses for the potential future Australian haven network. First, we searched through each of the 419 IBRA subregions, in turn, calculating how much the penalty function would decrease if a single new haven was added to that subregion. Second, we calculated an optimal greedy myopic solution to the set coverage problem, by iteratively creating new havens in IBRA subregions, based on the maximum immediate benefit to the penalty function. The value of $\mathbf{P}$ was iteratively updated after each new haven was added. The network grows until $B \leq 0$. We then contrasted the performance of this "greedy heuristic" method against two alternative scenarios. A "random" strategy, where new haven locations were chosen by selecting IBRA subregions at random, and a "business-as-usual" strategy, where we extrapolated change in species' representation using an exponential linear regression fitted to data from new havens created since 1990. This represents a likely trajectory where new havens continue to be created in an ad hoc nature.

## 3 | RESULTS

In the current haven network, nine taxa (16%) already meet our adequacy criteria, occurring in six or more havens, while 29 (43%) of predator-susceptible taxa are not protected in any
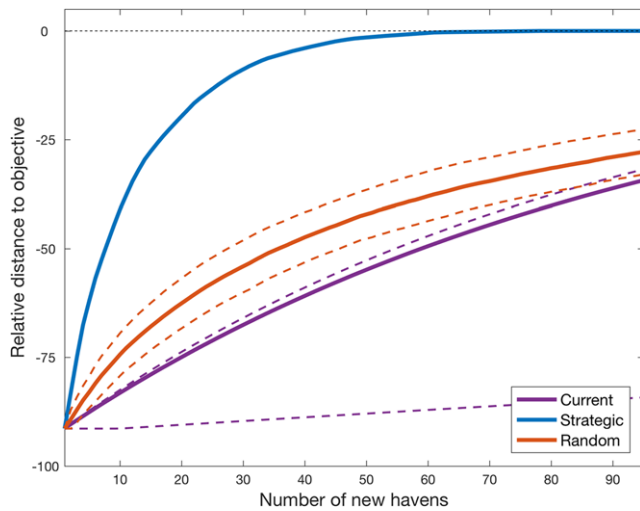
**FIGURE 1** Accumulation curves demonstrating progress toward our final target (all taxa represented within at least six havens) with each new haven. Current or "business-as-usual" trajectory (purple line) is based on fitted diminishing regression of taxa represented in new havens created since 1990. Our best solution (blue line) uses a greedy heuristic to choose location and constituent taxa in new havens based on the amount they contribute to closing our target gap. For comparison, the red line depicts the expected return on new haven projects selected at random. Dashed lines depict 95% confidence bounds for random and "business-as-usual" scenarios



**FIGURE 2** The proportion of predator-susceptible taxa represented in one to six havens, respectively, with the successive addition of new havens using systematic methods

haven (Table S1). More populations of extremely susceptible taxa are represented in created havens than highly susceptible taxa (2.1 ± 0.6 SE *cf.* 0.7 ± 0.5 SE populations per taxon ($F_{2,67} = 2.62$, $P = 0.016$). There is a strong taxonomic bias, with twice as many populations in created havens for marsupial species than rodent species ($F_{2,67} = 1.94$, $P = 0.097$).

Using a greedy systematic approach, our overall conservation objective of having each taxon in at least six havens, requires 94 new havens to be created (Figure 1). However, some predator-susceptible taxa still occur, although not necessarily securely, in refugial wild populations (outside of havens); when counting these populations as contributing to the conservation objective of six populations per taxon, 47 new havens are required. The trajectory of current efforts performs considerably worse than strategic methods, and worse even than random expansion (Figure 1).

Providing adequate representation for all taxa in six havens requires the created haven network to more than triple (i.e., 94 new havens; compared to the current 39). However, if we only seek to protect every taxon in at least one haven, only 12 more are required (Figures 2 and 3; Table S2). By doubling our current investment in a systematic manner (from 39 to 78 created havens), nearly all taxa could be represented in three havens, while increasing the proportion of taxa represented in four to six havens (Figure 2).

High-priority locations shift as new havens are created (Figure 4 and Table S1), resulting in a constantly updating
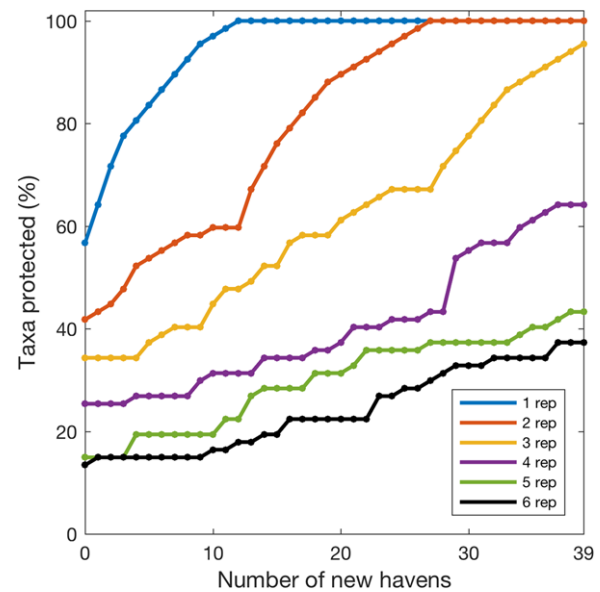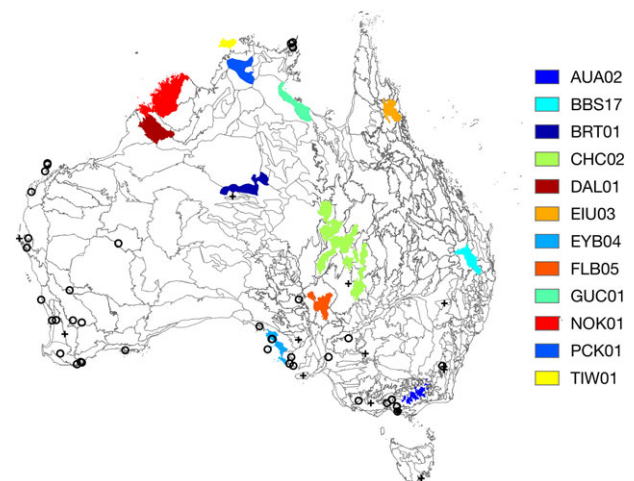


**FIGURE 3** Locations of the 12 biogeographic regions where havens could be established to provide representation for all currently unrepresented taxa. These IBRA subregions are: AUA02, Victorian Alps; BBS17, Eastern Darling Downs; BRT01, Yuendumu; CHC02, Sturt Stony Desert; DAL01, Fitzroy Trough; EIU03, Hodgkinson Basin; EYB03, Eyre Hills; FLB05, Northern Flinders; GUC01, Limmen; NOK01, Mitchell; PCK01, and Pine Creek; TIW01, Tiwi. The location of current, created havens are marked with "o" and havens which are planned in the future or under development are marked with "+"

priority ranking (Ringma et al., 2017). In total, our solution space selects from 35 IBRA subregions (Table S2) which in combination contain the minimum set of locations required to protect focal taxa.
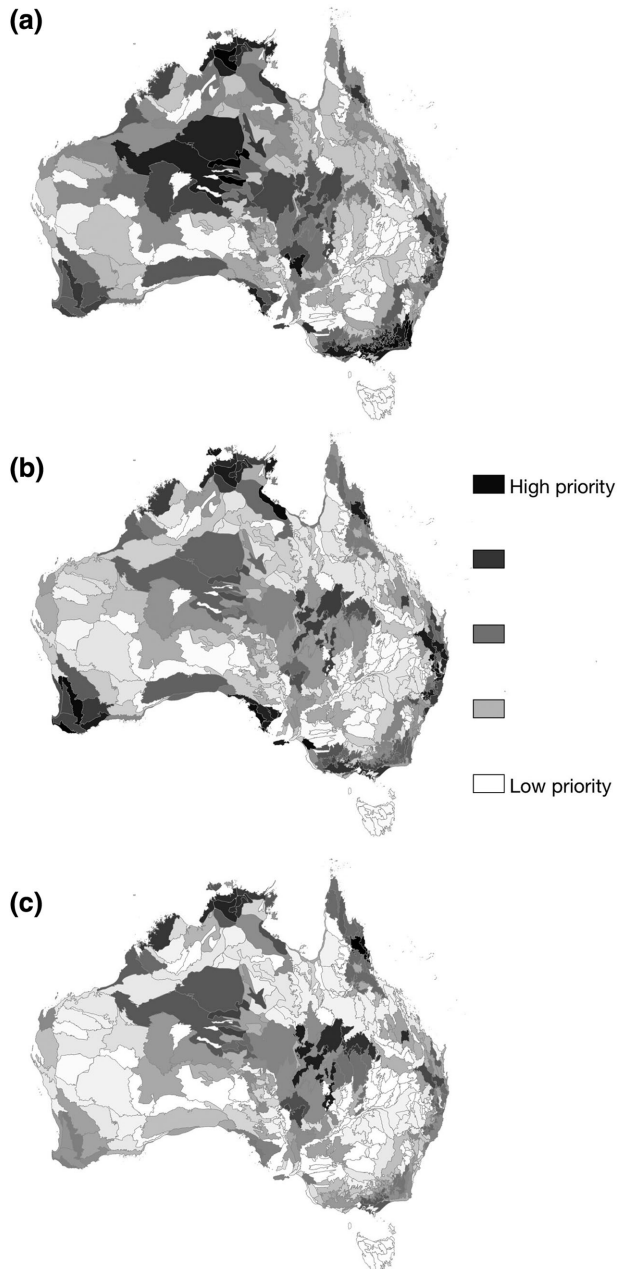
**(a)**



**(b)**



High priority

Low priority

**(c)**



**FIGURE 4** The change in priority locations for new havens (A) at present, (B) after five new havens, and (C) after 10 new havens, are established to prioritize currently unrepresented taxa. See Tables S1 and S2 for bioregional priorities for individual taxa

## 4 | DISCUSSION

A systematic conservation planning approach to haven creation requires fewer overall havens to provide comprehensive and adequate protection for all predator-susceptible threatened nonvolant mammals, compared with business as usual. Retrospective evaluation suggests that if equitable representation had been recognized as an objective from the inception of the created haven network, then all currently unrepresented taxa would be protected by at least one haven. However, the current network has resulted in some taxa being worse off than if havens had been situated at random. For example, the 11 most recently created havens have failed to add any new taxa to the network (Ringma et al., 2018b, but note that projects now in development aim to add new species). This suggests that the unsystematic nature of haven network expansion in Australia risks the same inefficiencies as seen in the historic expansion of many conservation reserve networks (Pressey, Humphries, Margules, Vane-Wright, & Williams, 1993; Stewart, Noyce, & Possingham, 2003; Stewart, Ball, & Possingham, 2007) and such inefficiency is likely to also characterize decentralized fencing and conservation networks outside of Australia.

Using a systematic method, new taxa can be incorporated to the haven network more efficiently than under the current, business-as-usual trajectory. If the current network of created havens was doubled in number, then the current approach would add 10 of the 29 currently unrepresented taxa, whereas, using systematic methods, this same number of new havens could provide roughly three populations of all 67 target taxa, and six representations of 40% of taxa (Figure 2).

Each haven is expensive to establish and maintain, so efficiency in expansion of the haven network is critical, as is working toward a long-term target defined by comprehensiveness and adequacy. While the rate at which new havens are being created is increasing, each new project requires years of planning, construction, eradication of introduced species, and then translocations. Translocations themselves may be limited by the small sizes of source populations (Morris et al., 2015), further constraining growth of the haven network. At the current rate of expansion (16 new havens in the last 10 years), the most efficient combinations of new havens required to secure all predator-susceptible Australian mammals would not be completed for over 50 years. However, species' extinction risks are most reduced by their first haven (Ringma et al., 2017). As all taxa could be represented with only 12 new haven projects (Figure 3 and Table S2), this crucial milestone is achievable within a decade.

Various factors, including the limited coordination among organizations involved in the collective network of havens, have resulted in gaps in representation for some taxa, and over-representation for others (Legge et al., 2018). But this imbalance also occurs for good reasons, as evidenced by the historical prioritization of extremely susceptible taxa (e.g., boodie, *Bettongia lesueur*), over highly susceptible taxa (e.g., heath mouse, *Pseudomys shortridgei*). Moreover, some highly predator-susceptible taxa that are not represented in havens (e.g., some *Petrogale* spp.) because local populations are afforded some protection using alternative methods, such as intensive, sustained, and effective poison-baiting of predators (Kinnear et al., 2010). Finally, some taxa are difficult to protect in havens, particularly fenced havens, due to being smaller than the fence mesh currently used to exclude cats and foxes

and high material costs of finer mesh, having irruptive life histories (e.g., some *Pseudomys* spp.) or large home ranges (e.g., chuditch, *Dasyurus geoffroii*), being good climbers or burrowers (e.g., *Phascogale* spp.), or living in challenging terrain (e.g., mountain pygmy possum, *Burramys parvus*).

Each new haven project has made a substantial contribution toward securing individual taxa and achieving local conservation objectives, but when viewed as a collective, haven expansion is performing well below its potential for securing all threatened predator-susceptible mammal taxa from extinction. A coordinated approach could minimize the number of new havens required to reduce extinction risk for the greatest number of predator-susceptible taxa, while reducing overall cost. Moreover, our approach ensures that representation gaps are dealt with fairly across taxa, ensuring maximum reduction in inequality if haven construction stopped at any point. The level of coordination required to perform optimally is difficult to implement given the diverse group of conservation organizations involved, each with their own priorities, especially as taxa and spatial priorities will change with time as the haven network grows. However, it is important that implementing organizations are aware of the taxa that are already relatively well-protected, and those taxa that are poorly represented, so that future havens can provide the most collective benefit. Organizations involved in haven projects often collaborate, usually for specific projects, for example by coinvestment, or sourcing animals for translocations. Mechanisms to support and enhance these collaborations would be valuable, for example by financially supporting multispecies recovery teams, and by brokering cofunded investments across jurisdictions and organizations to achieve placement of havens in areas that have been neglected to date.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.