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Priority threat management of non-native plants to maintain ecosystem integrity across heterogeneous landscapes

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Summary:

1. Invasive non-native plants have negatively impacted on biodiversity and ecosystem functions worldwide. Because of the large number of species, their wide distributions and varying degrees of impact, we need a more effective method for prioritizing control strategies for cost-effective investment across heterogeneous landscapes.

2. Here we develop a prioritization framework that synthesizes scientific data, elicits knowledge from experts and stakeholders to identify control strategies, and appraises the cost-effectiveness of strategies. Our objective was to identify the most cost-effective strategies for reducing the total area dominated by high impact non-native plants in the Lake Eyre Basin (LEB).

3. We use a case study of the ~120 million ha LEB that comprises some of the most distinctive Australian landscapes, including Uluru-Kata Tjuta National Park. More than 240
non-native plant species are recorded in the LEB, with many predicted to spread, but there are insufficient resources to control all species.

4. LEB experts identified 12 strategies to control, contain or eradicate non-native species over the next 50 years. The total cost of the proposed LEB strategies was estimated at AU$1.7 billion, an average of AU$34 million annually. Implementation of these strategies is estimated to reduce non-native plant dominance by 17 million ha – there would be a 32% reduction in the likely area dominated by non-native plants within 50 years if these strategies were implemented.

5. The three most cost-effective strategies were controlling Parkinsonia aculeata, Ziziphus mauritiana and Prosopis spp. These three strategies combined were estimated to cost only 0.01% of total cost of all the strategies, but would provide 20% of the total benefits. Over 50 years, cost-effective spending of AU$2.3 million could eradicate all non-native plant species from the only threatened ecological community within the LEB, the Great Artesian Basin discharge springs.

6. Synthesis and applications. Our framework, based on a case study of the ~120 million ha Lake Eyre Basin in Australia, provides a rationale for financially efficient investment in non-native plant management and reveals combinations of strategies that are optimal for different budgets. It also highlights knowledge gaps and incidental findings that could improve effective management of non-native plants; for example, addressing the reliability of species distribution data and prevalence of information sharing across states and regions.
The regular movement of people and commerce have breached biogeographic barriers, initiating an unprecedented period of global species migration and homogenization (Elton, 1958; Crosby, 1986; Ceballos et al., 2010). Investment in non-native species management is occurring worldwide in an effort to stem the negative impacts on biodiversity, ecosystem function and agricultural production (Levine & D’Antonio, 2003; Sinden et al., 2004; Pimental et al., 2005). The estimated annual expenditure on non-native plant control in Australia is AU $1.5 billion (Sinden et al., 2004), and US $9.6 billion in the United States (Pimental et al., 2005). It is often unclear which management strategies represent the best investments because of the challenge of measuring the impact of non-native species and prioritizing strategies accordingly (Vila et al., 2011). There is also uncertainty around the amount of funding required to manage priority non-native species and how best to spend these funds to minimize spread and establishment.

Despite the prolific spread and dominance of many non-native plant species, there is mixed evidence that non-native plants have caused direct extinctions of native species (Davis et al., 2011). However, there is substantial evidence that non-native plants can transform ecosystem processes, such as water and nutrient cycling, fire frequency, and sediment transport (D’Antonio & Hobbie, 2005; MacDougall & Turkington, 2005; Simberloff, 2006). Combined with other disturbances such as tree clearing, grazing, irrigation, high fire frequency, soil disturbance or fertilization, non-native plant species are often better able to profit than native species and become dominant (Firn et al., 2008; Davies et al., 2009). Under these multiple stressors, native plant biodiversity often declines (MacDougall et al., 2013) and as a result, key ecosystem functions are altered (Vila et al., 2010; Vila et al., 2011).
Once established, non-native species can change the structure of ecosystems, such as the conversion of grassland to woodland (Figure 1).

In many regions, prompt management action is hampered by a lack of empirical data on the impacts of threats and the responses of species and ecosystems to management strategies to address threats. A growing body of research investigates methods for undertaking conservation management appraisal and prioritization using the knowledge of experts and stakeholders to complement formal scientific data (Burgman et al., 2011; Martin et al., 2012b). Expert information has been used to evaluate the cost-effectiveness of a range of strategies to assist decision making for saving threatened species (Possingham et al., 2002; Carwardine et al., 2012; Pannell et al., 2012; Chades et al., 2014; Firn et al., In press). Given the urgency of many conservation issues and the difficulty of managing threats including the invasion of non-native plants, evidence suggests that in many cases it is better to make decisions using expert knowledge, rather than to take no action due to insufficient data (Martin et al., 2012b).

These priority threat management approaches evaluate the alternative cost-effectiveness of management strategies, where the expected benefits of each strategy (not measured in dollar terms) are divided by the expected costs (Cullen et al., 2005). The potential benefits of strategies can be measured as the improvement in species habitat protected (Carwardine et al., 2008) or improvement in species persistence (Joseph et al., 2009; Carwardine et al., 2012). The costs are usually financial management costs and/or opportunity costs (Naidoo et al., 2006). The expected benefits of the management strategies are the product of the potential benefits multiplied by the feasibility of the management strategies, or the
likelihood that the benefit will be achieved. Technical, social and political factors can all
influence the feasibility of a management strategy.

To date, such priority threat management approaches have not been used to assess the
management of threats posed by non-native plants on the integrity of native ecosystems.
This is particularly challenging because of the vast distributions of non-native plants and
aforementioned knowledge gaps making assessments difficult. Given the negative impacts
of non-native plants across large expanses of habitat there is much to be gained by ensuring
time and money are spent most efficiently and effectively.

Here we provide a rational and transparent framework for cost-effective investment in non-
native plant species management across a heterogeneous landscape. Our objective is to
identify which control strategies are likely to be most cost-effective for reducing the total
area dominated by high impact non-native plants in each bioregion of the Lake Eyre Basin
(hereafter LEB), central Australia; where there are many non-native species (~240 species),
with varying impacts across the region, and limited resources make it impossible to invest in
managing them all. Our approach appraises cost-effectiveness of a set of possible
management strategies by drawing on empirical data and expert information to estimate
the expected benefits and costs of each strategy (Joseph et al., 2009; Carwardine et al.,
2012; Pannell et al., 2012). While the strategies evaluated for controlling, containing and
eradicating non-native species are not new, we develop a unique approach for evaluating
their cost-effectiveness, and relative priority for reducing the impact of non-native plants in
the LEB over 50 years.

We specifically aim to: (i) develop a defensible non-native plant management prioritization
framework; (ii) apply our framework to assess a costed suite of management strategies
using a simple but novel approach to estimate biodiversity benefits; (iii) quantify the likely
area of plant invasion within geographical subunits of the LEB and the area that can be
feasibly managed for non-native species and (iv) appraise the most cost-effective
management strategies depending on budgets.

Materials and methods

Case study

The Lake Eyre Basin (LEB) covers approximately 120 million ha of arid and semi-arid central
Australia, spanning one sixth of the Australian continent (Figure 2) and multiple states:
Queensland, South Australia, New South Wales and the Northern Territory. The LEB is the
fifth largest internally draining system in the world and one of the least degraded systems in
Australia. LEB habitats include internationally recognized wetlands such as the Ramsar listed
Coongie Lakes, grasslands such as the Astrebla Downs National Park and deserts such as the
Simpson Desert National Park. The LEB Great Artesian Basin (GAB) discharge springs
wetlands (Figure S1 in Supporting Information) are listed as endangered under the
Australian Commonwealth Environmental Protection and Biodiversity Conservation Act
1999. These permanent springs in an otherwise semi-arid to arid landscape with highly
variable rainfall support at least 13 endemic plant species and 65 endemic fauna species
(Fensham et al., 2007).

More than 240 non-native plants are recorded in the LEB, including 20 Weeds of National
Significance (WONS; the federal government classification for the most significant weeds in
The current distributions of seven of these WONS are predominantly within the LEB
including: *Prosopis* spp. (mesquite complex: *Prosopis pallida* (single-stemmed), and *Prosopis glandulosa*, *Prosopis juliflora*, *Prosopis velutina* (multi-stemmed)), *Parkinsonia aculeata* parkinsonia, *Tamarix aphylla* athel pine, *Opuntia* spp. and *Cylindropuntia* spp. (cacti grouping, more than 14 spp.), *Cryptostegia grandiflora* rubber vine, *Jatropha gossypifolia* bellyache bush, and *Vachellia nilotica* prickly acacia (Figure 1).

In addition, a number of high impact non-native plants have limited distributions within the LEB but have the potential to spread in the higher rainfall (semi-arid) regions, e.g. *Ziziphus mauritiana* chinee apple, and *Bryophyllum* spp. (mother of millions grouping: *Bryophyllum delagoense*, *Bryophyllum houghtonii* and *Bryophyllum pinnatum*).

Buffel grass *Cenchrus ciliaris* L. has been introduced across the LEB for pasture production and is the most widely distributed non-native plant species across the LEB (Marshall et al., 2011). Buffel grass has a “dual impact” in the LEB, being of economic value to many graziers and one of the most serious threats to rangeland biodiversity (Martin et al., 2006; Friedel et al., 2009; Pavey & Nano, 2009; Grice et al., 2012).

**Data collection**

We collated existing information on the distribution of 243 non-native plants that are recorded within the LEB from the scientific literature and the Atlas of Living Australia (Atlas of Living Australia website). Further information required for the analysis was gathered from stakeholders and experts (hereafter ‘participants’) at a three-day workshop and follow-up consultations using a structured elicitation approach. Participants during and in follow-up consultations after the workshop included resource managers from local natural resource management boards, non-government organizations, Aboriginal Land Council Members,
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land managers, indigenous rangers, park managers, graziers, scientists, state and territory
governments, and the Federal Department of Sustainability, Environment, Water,
Population and Communities, including several involved with the Lake Eyre Basin Scientific
Panel and Community Advisory Committee. Of the 33 experts contacted, 19 contributed in
some form, and 11 attended the workshop. Information on the three-day structured
elicitation process, biodiversity of concern and invasive plants recorded in the LEB were sent
to participants prior to the workshop and an independent facilitator ran the workshop.

The first step in the structured elicitation process was to identify a set of management
strategies for individual or groups of non-native species that have a significant impact in the
Basin. Twelve strategies were identified at the start of the workshop (Table S1). Participants
then estimated the potential benefit and cost of implementing each strategy.

i. Estimating benefits and costs of strategies

Participants provided the information required for the benefit metric by estimating the
expected proportion of invadable habitat in each bioregion that each non-native species (or
group) is likely to dominate (>30% coverage at a site) in 50 years:

- without implementation of any strategy; and
- with implementation of the strategy targeted to manage that non-native plant
  species (or group).

For each of these scenarios participants gave their best guess, upper (most optimistic) and
lower (most pessimistic) bounds, and a level of confidence that the ‘true’ estimate lays
within this range (Martin et al., 2012b; McBride et al., 2012). Participants quantitatively
defined dominance and invadable habitat. Dominance was defined as a level of cover
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exceeding 30%. If a non-native plant was dominant at a site, participants agreed that the
site would be considered dramatically altered. The invadable habitat was assumed to be the
proportion of suitable habitat for the non-native species in each bioregion, which also
considers the likelihood of the success.

Participants agreed that the target for managing the threatened ecosystem GAB discharge
springs would be to remove all non-native plant species and prevent new introductions. The
benefits of the GAB discharge springs strategy was estimated for the entire LEB rather than
each bioregion.

Participants during the workshop and in follow-up consultations costed each non-native
plant control program action within each bioregion over 50 years, and estimated the annual
costs/ha of managing (eradicating, containing or controlling) each non-native plant at high
and low densities and provided realistic time frames for management over 50 years (e.g.
treatment every 2, 10, 20 or 25 years). In all cases the costs of undertaking each strategy $i$
by its component actions in each bioregion $j$ were estimated by considering the costs of
previous and current management activities and spatial variants such as land tenure and
remoteness. The economic cost $C_{ij}$ was the cost in present day Australian dollars of activities
associated with strategy $i$ in bioregion $j$ over 50 years.

We used the best available data on the distributions of non-native plant species although
only occurrence data with coarse resolutions were available. The potential distributions of
most non-native plant species were obtained from the Weeds of National Significance
(WONS) program (Thorp & Lynch, 2000). Potential distribution maps for mother of millions
and chinee apple were assessed by overlaying 50-km$^2$ squares (a similar approach was used
in the WONS mapping) over occurrence maps downloaded from the Atlas of Living Australia
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(Atlas of Living Australia website), as it was assumed that the area surrounding an existing
population of a non-native plant species will have the highest likelihood of becoming
invaded. For buffel grass distribution, we used habitat suitability maps created for this
species using key indicative variables e.g. soil moisture, soil type, temperature, rainfall,
grazing intensity and fire frequency (Martin et al., 2012a).

Individual estimates by experts of strategy benefits in a bioregion were aggregated by
averaging. The total expected benefit, $B_{ij}$ of strategy $i$ in bioregion $j$ was defined by:

$$B_{ij} = \frac{A_{ij}\sum_{k=1}^{N}(b_{jko} - b_{ijk})}{N}, \quad \text{eqn 1}$$

where:

- $A_{ij}$ is the total area of invadable habitat (ha) in bioregion $j$ for the non-native species
  managed under strategy $i$
- $b_{jko}$ is the proportion of invadable area dominated by the non-native species if no
  action is taken in bioregion $j$ estimated by expert $k$ over the time period (50 years)
- $b_{ijk}$ is the proportion of invadable area dominated by the weed under strategy $i$ in
  bioregion $j$ estimated by expert $k$ over the time period (50 years)
- $N$ is the number of experts who made an estimate for strategy $i$ in bioregion $j$.

To analyse the sensitivity of our results to participant uncertainty, this process was repeated
using the upper and lower bound estimates for the proportion of invadable habitat
dominated by the non-native plant species with and without strategies being implemented.

**Cost-effectiveness ranking approach**
Cost-effectiveness analysis provides a ranking of strategies based on an expected cost to benefit ratio, where the benefit is not measured in terms of dollars (Levin & McEwan 2001). To determine the total expected cost for a strategy over a bioregion, we summed the cost of all actions required to implement each strategy in a bioregion. For strategies with actions that were costed on a per hectare basis, we used maps of the current distribution of each non-native species and information on the treatment area for each strategy to convert the cost information into an average cost per year over 50 years for each bioregion. In all cases one-off costs, such as building a fence, were counted once, while on-going annual costs, such as maintaining the fence, were summed over 50 years using a rate of 2% per year to calculate net present value, a low discount rate that is considered to be appropriate for inter-generational public goods (Weitzman, 1998; Gollier & Weitzmann, 2010).

The cost-effectiveness, $CE_{ij}$, in ecological terms, of each strategy $i$ in each bioregion $j$ was calculated by:

$$CE_{ij} = \frac{B_{ij}}{C_{ij}}$$  \hspace{1cm} \text{eqn 2}

where $C_{ij}$ is the total cost of strategy $i$ in bioregion $j$. The strategies were then ranked by their cost-effectiveness across all bioregions and within each bioregion.

**Best spatial sets of strategies for a range of budgets**

The cost-effectiveness approach ranks the most cost-effective strategies, but may not identify the optimal set of strategies to implement for a given budget. Providing the optimal combinations of strategies for a given budget can be useful information to aid managers to negotiate budgets on the basis of expected outcomes. For example, we may discover that a small increase in budget could lead to a sharp decrease of invaded area, an additional cost that decision makers may find worthwhile to invest in. Alternatively, the optimal set of
solutions may reveal that investing half of the budget leads to almost the same benefits as
investing the entire budget. Identifying these thresholds of high or negligible return on
investment provides critical information to decision makers when allocating appropriate
budgets.

Finding the optimal combinations of strategies that minimizes the total area invaded at any
given budget across all bioregions requires solving a spatial combinatorial optimization
problem (0–1 knapsack problem (Bellman, 1957):

$$\max \sum_{i,j \in S,N} B_{ij} x_{ij} \text{ subject to } \sum_i C_{ij} x_{ij} \leq \text{Budget}$$  \hspace{1cm} \text{eqn 3}

Where $x_{ij}$ is a binary decision variable that denotes whether ($x_{ij}=1$) or not ($x_{ij}=0$) a strategy
$i$ in bioregion $j$ is included in the optimal set of strategies. A vector $x \in \{x_{1,1}, x_{1,2}, \ldots, x_{|S||N|}\}$
represents a combination of selected strategies. $S$ represents the set of strategies listed in
Table S1 and $N$ the number of bioregions. $B_{ij}$ identifies the benefits of implemented
strategy $i$ in bioregion $j$. We used dynamic programming to find the optimal set of decisions
for budgets ranging from $0 to $2.160 million (Bellman 1957). Algorithm details are
presented in Text S1.

Results

Workshop participants defined 12 management strategies (Table S1) focussing on 10 non-
native plant species considered to significantly impact biodiversity in the LEB now or in the
future (Table 1). With the exception of buffel grass, mother of millions and chinee apple, all
species are classified as WONS (Thorpe & Lynch 2000). Each strategy consisted of one or
more supporting actions, many of which were spatially linked to IBRA (Interim
Biogeographical Regionalisation of Australia) bioregions.
The first strategy was an overarching recommendation for improved mapping, information sharing, education and extension efforts in order to facilitate the more specific non-native plant management strategies. This LEB prevention and monitoring strategy was estimated to cost $17.5 million in total over 50 years. Strategy 12 involved the investment of $2.3 million over the next 50 years to eradicate all non-native plant species from the GAB discharge springs, which was estimated at the Basin level. We were not able to compare quantitatively strategies 1 and 12 with strategies 2–11 (Table S1). However when predicting the expected benefits for reducing the dominance of the non-native plants over 50 years, experts assumed that strategy 1 would be implemented.

The total cost of implementing all 12 non-native plant management strategies over the next 50 years was estimated at $34 million per year (Total = $1.7 billion; Table S1). Implementation of these strategies was estimated to result in a reduction of non-native plant dominance by 17 million ha (a potential 32% reduction), roughly 14% of the LEB (Table 1). To put this in perspective, on average, implementing all strategies would cost approximately $100 per hectare for the 50-year period, or $2 per hectare per year. If only targeting WONS, the total cost was estimated to be $2.3 million per year for 50 years (Total = $113 million). The strategy for controlling, eradicating and containing buffel grass was the most expensive representing over 90% of the estimated costs, requiring >$30 million annually for 50 years (Total = $1.5 billion, Figure 3). This strategy would account for 0.06% of the total benefits with an estimated reduction in invaded extent of 1 million ha.

Amongst the 10 species-specific management strategies, the top five most cost-effective for the entire LEB were the management of: 1) parkinsonia, 2) chinee apple, 3) mesquite, 4) rubber vine and 5) bellyache bush. These strategies combined would cost approximately
$254,000 per year and are estimated to achieve 30% of the total benefits (Table 1, Figure 3). An additional budget of 1 million per year could see avoidance of 16 million ha (94% of the estimated benefits) of land dominated by prickly acacia, mother of millions and Athel pine (Figure 3). Benefit estimates by the experts varied depending on the strategy with standard deviations being more than half the average best guess estimate for three strategies: chinee apple, athel pine and cacti (Table 1).

The cost-effectiveness rankings remained the same for all 10 of the basin-wide strategies when calculated with the best guess and upper estimates for expected benefits (Table 1), but did vary with the lower estimates. Using the lower estimates for benefits, parkinsonia was the most cost-effective strategy, mesquite the second most effective, followed by chinee apple, rubervine and bellyache bush. Mother of millions changed ranks with prickly acacia so that the two species became the sixth and seventh most cost-effective strategies respectively.

The top five most cost-effective strategies within separate bioregions (Figure 2) were the management of (Table 2 & S2): 1) parkinsonia in the Channel Country, 2) parkinsonia in the Desert Uplands, 3) mesquite in the Mitchell Grass Downs, 4) parkinsonia in the Mitchell Grass Downs, and 5) mother of millions in the Desert Uplands.

When considering implementing strategies at the bioregional level, we found the best combinations of strategies for all budgets by solving the knapsack problem (see Materials and methods). Because we are seeking to maximize the impact of management and minimize our spending at the same time, the solution is a Pareto frontier where every point of the curve represents an optimal solution. In our case, the Pareto frontier exhibits four distinct thresholds (A, B, C and D, Figure 4). When the budget was below $513,000 per year
the total invaded area could reach more than 10 million ha across the LEB (Figure 4A). The benefit of managing non-native plants could be doubled if the yearly budget was increased by about $300 000 per year allowing the implementation of strategy 'S11. prickly acacia' in the Mitchell Grass Downs bioregion (Figures 4 & 5B). Invasion of most of the potential area could be avoided for a yearly budget of about $1.35 million (Figures 4 & 5C).

**Discussion**

In the LEB, like many regions of the world, there are more non-native plant species than resources to manage them, and a significant amount of knowledge concerning the location and best control strategies for managing non-native plants is held in the experience and knowledge of natural resource managers (Bart, 2006). Previous attempts at non-native plant species prioritization such as the Australian Weeds of National Significance (Australian Weeds Committee, 2012) were based on the potential ecological and agricultural impacts. The results of our approach, which appraises the benefits and costs of management of these high impact species using a structured elicitation process, provide a prospectus for guiding further investment in non-native species management and in improving information availability and sharing across governmental boundaries.

Our analyses suggest that management of several WONS such as parkinsonia and mesquite are likely to be more cost-effective investments than others in large parts of the LEB. Management of parkinsonia was estimated as both relatively cheap and to have high benefits, so control of parkinsonia was consistently ranked as the most cost-effective strategy across the LEB. Other non-native plants will be more costly to manage, but may still be cost-effective to control. Implementation of all non-native plant species was estimated to come at a modest cost ($2 per ha per year on average), but not all strategies are equally
useful, particularly when the budget is limited. We show that there are thresholds in the
effectiveness of investment, so that it is important to ensure that the budget allocated to
the LEB is realistic to achieve the desired level of impact. While there are cost-effective
strategies that can be implemented for less than $513 000 per year, investing less than this
amount means that at least 10 million ha of the LEB remains vulnerable to invasion. Our
results suggest $900 000 per year could make a substantial improvement on the total area
potentially invaded by non-native plants in the LEB by implementing the most effective
strategies (control of prickly acacia, Figures 4 &5). Costs per year may appear low given the
large spatial extent of the LEB, but strategies were not recommended to be applied to all
areas of the LEB, and only where non-native plant control was considered feasible,
reasonable or a high priority.

Buffel grass management was orders of magnitude more expensive than the management
of all other species considered, because of its wide distribution and its high value for
rangelands within the LEB. The high costs and low cost-effectiveness ranking for buffel grass
control may motivate research into more effective management strategies for buffel grass
and also strongly suggest that key sites should be prioritized for protection from buffel grass
dominance (e.g. sites of high cultural value such as Uluru National Park (Grechi et al., 2014)).

The framework we develop here could be applied to find the most ecologically cost-
effective solutions for non-native plant control in any management area where multiple
stakeholders and landowners reside. A key characteristic of the framework is flexibility, as it
can be tailored to a region’s geographical, biological and social characteristics, and the
strategies assessed can be updated to suit different perspectives or to account for updates
and changes in situations and information. The cost-effectiveness analyses are completed in
a spreadsheet that is provided to the managers of a region following completion of the study and can be updated when necessary. There are many uncertainties in future conditions for undertaking non-native plant species control and eradication in the LEB and many other landscapes, such as the consequences of climate change and future developments not considered in the analysis, which may compound existing threats. A precautionary approach suggests that we should increase investment early, then monitor and review the effectiveness of actions and be aware of emerging threats. A flexible approach, like the one presented here, also means that identified priorities can be integrated with existing and future priority setting approaches.

We also make some assumptions with our priority threat management approach. The expert-elicited strategies were designed to have an equal chance of being implemented, provided resources were available. Participants chose strategies that were considered feasible if resources are available, with a few exceptions: for example an organic farmer may be reluctant to spray a non-native plant and lose their certification. In these cases, cost-effectiveness was likely overestimated. Estimates of the costs and benefits for the strategies may prove to be higher or lower than predicted because they were based on expert and local knowledge. Changes to these estimates could affect priority rankings. This is why the flexibility of our approach is important – policymakers and land managers can update spreadsheets when more information becomes available or situations change.

We also assumed that dominance of habitat by one non-native plant has an equal impact to dominance by another non-native plant and that a cover of greater than 30% was a threshold indicating a species has a biodiversity impact. In reality a variable range of impacts would occur prior to and beyond this binary threshold, depending upon non-native plant
type, ecosystem type, existing dominant and threatened species, and other threats. Our approach could be extended to incorporate differential weights to quantify estimates of higher impacts for some non-native plants over others, which could vary depending on characteristics of each bioregion.

Our analysis does not include how potential interactions between strategies will change the expected benefits and costs of strategies, although non-native plant management could be carried out for more than one non-native plant at a time. In these cases the cost-effectiveness of carrying out management strategies could be underestimated.

Although we used the best data available on the current and potential distributions of non-native plants in each of the LEB bioregions, it was recognized by all participants that knowledge of the distributions of non-native plant species is patchy and unreliable, evidenced by the recommendation of strategy 1 that included the centralization of mapping, monitoring and surveillance and information sharing for non-native species incursions and extents.

Conclusion

A major challenge facing managers when controlling non-native plants is that there are numerous species, each with varying levels of impact. Additionally, the values placed on impacts depend on the objectives of management and the resources available to control or eradicate them. Therefore it is critical to evaluate systematically which non-native species, management actions, and locations should be invested in to provide the greatest benefits for ecosystem integrity per unit cost.

Our approach is applicable to non-native species management across large landscapes worldwide because it is, systematic, knowledge-based, and can be easily updated as
improved information on the costs and expected benefits for invasive plant management become available.

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Data Accessibility

Data is archived with CSIRO public data access portal. Please follow this link:


References


Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1: Estimates of the cost of actions that make up the specific non-native plant species strategies.

Table S2: Appraisal of key non-native plant management strategy in each of the LEB bioregions.
Figure S1: Map of known locations of the GAB discharge springs within each of the LEB bioregions.

Text S1. Dynamic programming algorithm to find the optimal spatial sets of strategies at various budgets.

Table S3. Dynamic programming algorithm used to calculate the set of optimal solutions for all budgets.
Table 1: Appraisal of key non-native plant management strategies across the Lake Eyre Basin – average of estimated expected benefits (reduction in total area potentially invaded by the non-native plant species in ha over 50 years, n = 1–6 participants per estimate, based on best guess, upper benefit estimates and lower benefit estimates), standard deviation of ‘best guess’ benefit estimates, net present value of costs (50 years) and cost-effectiveness (CE). Some actions as indicated in Table S1 were not costed over 50 years, but the values are shown this way for comparison purposes. All costs presented are in Australian dollars; m = millions and t= thousands.

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<th>Rank (CE)</th>
<th>Best guess</th>
<th>Rank (CE) Upper</th>
<th>Rank (CE) Lower</th>
<th>Strategy (S)</th>
<th>Average benefits (dominated area avoided, ha) best guess (Δ upper and Δ lower)</th>
<th>Average benefits best guess standard deviation</th>
<th>Average annual costs (50 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (40.8)</td>
<td>1 (42.3)</td>
<td>1 (28.8)</td>
<td>S3. parkinsonia</td>
<td>1.7 m (+60 t, - 487 t)</td>
<td></td>
<td>758 t</td>
<td>$40 678</td>
</tr>
<tr>
<td>2 (19.1)</td>
<td>2 (22.7)</td>
<td>3 (13.3)</td>
<td>S9. chinee apple</td>
<td>34 t(+17 t, -10 t)</td>
<td></td>
<td>26 t</td>
<td>$1797</td>
</tr>
<tr>
<td>3 (18.8)</td>
<td>3 (21.04)</td>
<td>2 (14.0)</td>
<td>S2. mesquite</td>
<td>2.1 m (+252 t, -546 t)</td>
<td></td>
<td>995 t</td>
<td>$112 681</td>
</tr>
<tr>
<td>4 (13.5)</td>
<td>4 (14.1)</td>
<td>4 (10.5)</td>
<td>S4. rubber vine</td>
<td>1.2 m (+50 t, -277 t)</td>
<td></td>
<td>92 t</td>
<td>$92 301</td>
</tr>
<tr>
<td>5 (11.1)</td>
<td>5 (12.7)</td>
<td>5 (7.8)</td>
<td>S6. bellyache bush</td>
<td>71 t (+10 t, -21 t)</td>
<td></td>
<td>6 t</td>
<td>$6391</td>
</tr>
<tr>
<td>6 (10.6)</td>
<td>6 (12.7)</td>
<td>7 (6.0)</td>
<td>S11. prickly acacia</td>
<td>10.1 m (+1.9 m, 4.4 m)</td>
<td></td>
<td>956 t</td>
<td>$955 678</td>
</tr>
<tr>
<td>7 (10.1)</td>
<td>7 (11.5)</td>
<td>6 (7.2)</td>
<td>S8. mother of millions</td>
<td>53 t (+7 t, -14 t)</td>
<td></td>
<td>5 t</td>
<td>$5340</td>
</tr>
<tr>
<td>8 (6.6)</td>
<td>8 (7.1)</td>
<td>8 (3.30)</td>
<td>S10. athel pine</td>
<td>331 t (+18 t, -168 t)</td>
<td></td>
<td>155 t</td>
<td>$50 071</td>
</tr>
<tr>
<td>9 (0.7)</td>
<td>9 (0.9)</td>
<td>9 (0.5)</td>
<td>S7. cacti (e.g. coral, harissia, devils rope)</td>
<td>713 t (+127 t, -200 t)</td>
<td></td>
<td>455 t</td>
<td>$1 004 986</td>
</tr>
<tr>
<td>10 (0.03)</td>
<td>10 (0.04)</td>
<td>10 (0.03)</td>
<td>S5. buffel grass</td>
<td>1.1 m (+32 t, -174 t)</td>
<td></td>
<td>477 t</td>
<td>$30 898 881</td>
</tr>
</tbody>
</table>
Table 2: Summary of the average annual expenditure on each of the non-native plant species strategies and the proportion spent, where the strategies are ordered into decreasing cost-effectiveness. The buffel grass strategy was not included in the bioregion level analyses.

<table>
<thead>
<tr>
<th>Strategy (S)</th>
<th>Proportional allocation to each bioregion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MGD</td>
</tr>
<tr>
<td>S3. parkinsonia</td>
<td>67%</td>
</tr>
<tr>
<td>S9. chinee apple</td>
<td>100%</td>
</tr>
<tr>
<td>S2. mesquite</td>
<td>38%</td>
</tr>
<tr>
<td>S4. rubber vine</td>
<td>21%</td>
</tr>
<tr>
<td>S6. bellyache bush</td>
<td>–</td>
</tr>
<tr>
<td>S11. prickly acacia</td>
<td>87%</td>
</tr>
<tr>
<td>S8. mother of millions</td>
<td>74%</td>
</tr>
<tr>
<td>S10. athel pine</td>
<td>3%</td>
</tr>
<tr>
<td>S7. cacti (e.g. coral, harissia, devil’s rope)</td>
<td>81%</td>
</tr>
</tbody>
</table>

MGD = Mitchell Grass Downs, DEU = Desert Uplands, CHC = Channel Country, BHC = Broken Hill Complex, STP = Stony Plains, FLB = Flinders Lofty Block, MCR = MacDonnell Ranges, SSD = Simpson Strzelecki Dunefields, FIN = Finke, BTP = Burt Plains, Tanami = Tan, MII = Mount Isa Inlier
Figure 1: a) Photo of the endemic Mitchell Grass Downs site (54 million ha across eastern and northern Australia on clay and silt rich soils with a mean annual rainfall of 200–550 mm falling mostly in summer) b) Photo of Mitchell Grass Downs site being invaded by prickly acacia *Acacia nilotica*, which is converting these natural grasslands to open shrubland (photo credit Jennifer Firn).
Figure 2: Map of the Lake Eyre Basin (LEB) showing Interim Biogeographic Regionalisation for Australia (IBRA), spanning one-sixth of the Australian continent.
Figure 3: Total dominated area avoided (>30% cover) by the implementing of the ten key non-native plant species management strategies at increasing levels of annual investment into non-native plant species control when assuming each strategy, when selected, was implemented across the Lake Eyre Basin.
Figure 4: Optimal sets of strategies at the bioregion level for reducing the total area invaded with budgets ranging from AUD$0 to $2.2 million per year represented as a Pareto frontier (see Figure 5 for detailed sets). Additional budget between A and B or C and D will be insufficient to invest in additional strategies to decrease the expected invaded area. The set of strategies in area D only brings small additional benefits. A budget = $513 000, B budget = $829 000, C budget = $1.34 million and D budget = $2.04 million.
Figure 5: Optimal set of strategies for a given budget. Additional budget between A and B or C and D will not lead to the selection of additional strategies and decrease of the expected invaded area. Grey areas represent strategies that are selected and white areas represent strategies that are not selected in the optimal set for the given budget. A budget = $513 000, B budget = $829 000, C budget = $1.34 million and D budget = $2.04 million. MGD = Mitchell Grass Downs, DEU = Desert Uplands, CHC = Channel Country, BHC = Broken Hill Complex, STP = Stony Plains, FLB = Flinders Lofty Block, MCR = MacDonnell Ranges, SSD = Simpson Strzelecki Dunefields, FIN = Finke, BTP = Burt Plains.
Table S1: Estimates of the cost of actions that make up each of the specific non-native plant species strategies, including costs (discounted) for the actions over 50 years, and average annual costs over the 50 years (some actions as indicated below were not costed over 50 years, but the values are shown this way for comparison purposes). All costs presented are in Australian dollars.

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Description of actions</th>
<th>Net present value (50 years, discounted)</th>
<th>Average annual costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Prevention and monitoring program for all weeds</td>
<td>Develop weed management task/plan basin-wide</td>
<td><strong>$160,729</strong></td>
<td><strong>$3,215</strong></td>
</tr>
<tr>
<td></td>
<td>Mapping, monitoring and surveillance (ground and aerial, build on weed spotters network)</td>
<td><strong>$217,651</strong></td>
<td><strong>$4,353</strong></td>
</tr>
<tr>
<td></td>
<td>Centralised information sharing for weed incursion/extents</td>
<td><strong>$20,000</strong></td>
<td><strong>$400</strong></td>
</tr>
<tr>
<td></td>
<td>Secure positions: two FTEs, one FTE for mapping and centralised information sharing and one FTE for on-ground activities</td>
<td><strong>$8,333,540</strong></td>
<td><strong>$166,671</strong></td>
</tr>
<tr>
<td></td>
<td>mesquite awareness campaign</td>
<td><strong>$76,651</strong></td>
<td><strong>$1,533</strong></td>
</tr>
<tr>
<td></td>
<td>bellyache bush awareness campaign</td>
<td><strong>$76,651</strong></td>
<td><strong>$1,533</strong></td>
</tr>
<tr>
<td></td>
<td>chinee apple awareness campaign</td>
<td><strong>$76,651</strong></td>
<td><strong>$1,533</strong></td>
</tr>
<tr>
<td></td>
<td>buffel grass awareness campaign</td>
<td><strong>$217,651</strong></td>
<td><strong>$4,353</strong></td>
</tr>
<tr>
<td>S2. mesquite (<em>Prosopis glandulosa</em>)</td>
<td>Eradicate from the following bioregions: Mitchell Grass Downs (MGD), Desert Uplands (DEU), Broken Hill Complex (BHC) and the Channel Country (CHC); $800,000 investment in the first year and then $300,000 per year for next four years.</td>
<td><strong>$3,028,191</strong></td>
<td><strong>$60,564</strong></td>
</tr>
<tr>
<td></td>
<td>Periodic suppression of new infestations over time; investment of $200,000 per year for the first three years and repeated every 10 years</td>
<td><strong>$2,605,187.3</strong></td>
<td><strong>$52,118</strong></td>
</tr>
<tr>
<td>S3. parkinsonia</td>
<td>Prevent spread into Diamantina National Park by eradicating from Springcreek and Diamantina river north of the National Park up to the western river convergence</td>
<td><strong>$471,346</strong></td>
<td><strong>$9,427</strong></td>
</tr>
<tr>
<td></td>
<td>Eradicate from the following bioregions: Stony Plains, Broken Hill (STP) Complex (BHC), Flinders Lofty Block</td>
<td><strong>$343,193.00</strong></td>
<td><strong>$6,864</strong></td>
</tr>
<tr>
<td>(FLB) (SA)</td>
<td>Control downstream outliers and establish large-scale buffer zones in the Georgina and Thomson Rivers (downstream of Boulia and Jundah/Windorah respectively). Requires initial control program (three years) then periodic suppression every 10 years.</td>
<td>$716,065</td>
<td>$14,321</td>
</tr>
<tr>
<td>Impact reduction through introduction and proliferation of dieback biological control agents in established infestation areas of the MGD, DEU and CHC</td>
<td>$503,278</td>
<td>$10,066</td>
<td></td>
</tr>
<tr>
<td>S4. rubber vine</td>
<td>Contain and control in DEU</td>
<td>$2,264,776</td>
<td>$53,896</td>
</tr>
<tr>
<td></td>
<td>Eradicate from MGD, CHC</td>
<td>$1,920,286</td>
<td>$38,406</td>
</tr>
<tr>
<td>S5. buffel grass</td>
<td>Contain in STP, Finke (FIN) and control in all other SA bioregions</td>
<td>$421,611</td>
<td>$8,432</td>
</tr>
<tr>
<td></td>
<td>Control in MacDonnell ranges (MDR) to reduce hot burns – especially along creeks</td>
<td>$228,386,768</td>
<td>$4,567,735</td>
</tr>
<tr>
<td></td>
<td>Control and locally eradicate (including rehabilitation) and prevent incursions into clean areas in gazetted conservation areas in Queensland</td>
<td>$1,316,135,691</td>
<td>$26,322,714</td>
</tr>
<tr>
<td>S6. bellyache bush</td>
<td>Eradicate from DEU</td>
<td>$319,543</td>
<td>$6,391</td>
</tr>
<tr>
<td>S7. cacti (e.g. coral, harissia, devil’s rope)</td>
<td>Contain all cacti spp. in southern part of SA, eradicate to north</td>
<td>$3,613,715</td>
<td>$72,274</td>
</tr>
<tr>
<td></td>
<td>Control and contain all cacti elsewhere</td>
<td>$46,635,538</td>
<td>$932,711</td>
</tr>
</tbody>
</table>
| S8. mother of millions | Eradicate from urban areas in all areas of the Basin | $26,948 | $539  
| | Control and contain in DEU, MGD and any other occurrences | $240,033 | $4,801  
| S9. chinee apple | Eradicate from MGD | $89,826 | $1,797  
| S10. athel pine | Eradicate weedy and high risk Athel pine from Queensland (e.g. MGD and CHC), and Northern Territory, except from the lower FIN | $1,358,496 | $27,170  
| | Control in South Australia | $1,145,048 | $22,900  
| S11. prickly acacia | Eradicate from South Australian part of CHC | $10,000 | $200  
| | Eradicate from Northern Territory part of MGD | $20,000 | $400  
| | Prevent further spread southwards down the three big rivers (from Stonehenge on cooper system, converging Diamantina and Western and Wokingham creek, Boulia on the Georgina) | $32,052,078 | $641,042  
| | Containment and progressive reduction of already infested areas - DEU, MGD, CHC | $12,579,442 | $251,589  
| S12. GAB discharge springs | Eradicate all non-native plants from the discharge springs | $2,253,453 | $43,069  
| | | $1,689,549,071 | $33,333,017 |
Table S2: Appraisal of key non-native plant management strategy in each of the bioregions of the LEB – estimated average expected benefits (reduction in total area potentially invaded by the non-native plant species), average costs (discounted) and cost-effectiveness (CE). Not all strategies were costed within all bioregions, as not all non-native plant species can become established within each of the LEB bioregions, because of low and unpredictable rainfall and low nutrient edaphic conditions. Strategies were ranked based on their cost-effectiveness within each of the bioregions and also across all bioregions. The buffel grass strategy was not included in the bioregion level analyses. All costs presented are in Australian dollars (m = millions and t = thousands).

<table>
<thead>
<tr>
<th>Bioregions</th>
<th>Strategies</th>
<th>Rank CE within bioregion</th>
<th>Rank CE across LEB</th>
<th>Average benefits between experts over 50 years (ha)</th>
<th>Average Annual costs</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitchell Grass Downs</td>
<td>S2. mesquite</td>
<td>1</td>
<td>3</td>
<td>1.5m</td>
<td>$43,226</td>
<td>35.6</td>
</tr>
<tr>
<td></td>
<td>S3. parkinsonia</td>
<td>2</td>
<td>4</td>
<td>931t</td>
<td>$27,103</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td>S10. athel pine</td>
<td>3</td>
<td>6</td>
<td>32t</td>
<td>$1,712</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>S9. chinee apple</td>
<td>4</td>
<td>8</td>
<td>23t</td>
<td>$1,797</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>S11. prickly acacia</td>
<td>7</td>
<td>9</td>
<td>9.6m</td>
<td>$829,783</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td>S4. rubber vine</td>
<td>5</td>
<td>11</td>
<td>187t</td>
<td>$19,203</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>S8. mother of millions</td>
<td>6</td>
<td>22</td>
<td>1t</td>
<td>$3,968</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>S7. cacti</td>
<td>8</td>
<td>33</td>
<td>175t</td>
<td>$811,090</td>
<td>0.2</td>
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<tr>
<td>Desert Uplands</td>
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<td>2</td>
<td>162t</td>
<td>$3,355</td>
<td>48.3</td>
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<tr>
<td></td>
<td>S8. mother of millions</td>
<td>2</td>
<td>5</td>
<td>28t</td>
<td>$1,372</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td>S6. bellyache Bush</td>
<td>3</td>
<td>12</td>
<td>61t</td>
<td>$6,800</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td>S4. rubber vine</td>
<td>4</td>
<td>13</td>
<td>400t</td>
<td>$53,896</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>S2. mesquite</td>
<td>5</td>
<td>14</td>
<td>79t</td>
<td>$13,114</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>S7. cacti</td>
<td>6</td>
<td>26</td>
<td>41t</td>
<td>$14,189</td>
<td>2.9</td>
</tr>
<tr>
<td>Channel Country</td>
<td>S3. parkinsonia</td>
<td>1</td>
<td>1</td>
<td>450t</td>
<td>$3,355</td>
<td>134.1</td>
</tr>
<tr>
<td></td>
<td>S10. athel pine</td>
<td>2</td>
<td>7</td>
<td>104t</td>
<td>$6,292</td>
<td>16.70</td>
</tr>
<tr>
<td></td>
<td>S4. rubber vine</td>
<td>3</td>
<td>10</td>
<td>196t</td>
<td>$19,203</td>
<td>10.20</td>
</tr>
<tr>
<td></td>
<td>S2. mesquite</td>
<td>4</td>
<td>18</td>
<td>197t</td>
<td>$43,226</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>S11. prickly acacia</td>
<td>5</td>
<td>25</td>
<td>373t</td>
<td>$125,894</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>S7. cacti</td>
<td>6</td>
<td>34</td>
<td>14t</td>
<td>$107,43</td>
<td>0.10</td>
</tr>
<tr>
<td>Broken Hill Complex</td>
<td>S3. parkinsonia</td>
<td>1</td>
<td>21</td>
<td>8t</td>
<td>$2,288</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>S10. athel pine</td>
<td>2</td>
<td>27</td>
<td>13t</td>
<td>$4,580</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>S7. cacti</td>
<td>3</td>
<td>30</td>
<td>50t</td>
<td>$31,424</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>S2. mesquite</td>
<td>4</td>
<td>32</td>
<td>20t</td>
<td>$13,114</td>
<td>1.53</td>
</tr>
<tr>
<td>Stony Plains</td>
<td>S10. athel pine</td>
<td>1</td>
<td>17</td>
<td>21t</td>
<td>$4,580</td>
<td>4.6</td>
</tr>
<tr>
<td>Location</td>
<td>Species (N)</td>
<td>Area (ha)</td>
<td>Year</td>
<td>Costs ($)</td>
<td>Benefit ($)</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>--------------</td>
<td>-----------</td>
<td>------</td>
<td>-----------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>Flinders Lofty Block</td>
<td>S3. Parkinson</td>
<td>2</td>
<td>20</td>
<td>$2,288</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S7. Cacti</td>
<td>3</td>
<td>23</td>
<td>$9,427</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Simpson Strzelecki Dunefields</td>
<td>S10. Athel Pine</td>
<td>1</td>
<td>15</td>
<td>$2,288</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S10. Athel Pine</td>
<td>2</td>
<td>24</td>
<td>$4,580</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S7. Cacti</td>
<td>3</td>
<td>31</td>
<td>$31,423</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Finke</td>
<td>S10. Athel Pine</td>
<td>1</td>
<td>19</td>
<td>$7,915</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>MacDonnell Ranges</td>
<td>S10. Athel Pine</td>
<td>1</td>
<td>16</td>
<td>$7,915</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Burt Plains</td>
<td>S10. Athel Pine</td>
<td>1</td>
<td>29</td>
<td>$7,915</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Tanami Mt Isa Inlier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1 prevention and control programs for all non-native plants</td>
<td></td>
</tr>
</tbody>
</table>
Figure S1: Map of known locations of the GAB discharge springs within each of the LEB bioregions. Data sourced from the IBRA and Department of Sustainability, Environment, Water, Population and Communities, Australia Commonwealth Government.
Text S1. Dynamic programming algorithm to find the optimal spatial sets of strategies at various budgets.

Intuitively, let us assume we computed an optimal solution \( x \) for a given budget \( b \). If we remove a strategy \( j \) with benefit \( B_j \) from the optimal solution, the remaining solution \( x-\{ x_j \} \) will remain optimal if the budget available is \( b-C_j \), where \( C_j \) is cost. This optimal substructure property allows us to solve knapsack problems using dynamic programming. Dynamic programming solves a small sub-problem of the knapsack and then extends this solution iteratively until the complete problem is solved.

\[
\max \sum_{j \in S} B_j x_j \text{ subject to } \sum_{j} C_j x_j \leq \text{Budget}
\]

Where \( x_j \) is a binary decision variable that denotes whether \( (x_j=1) \) or not \( (x_j=0) \) a strategy \( j \) is included in the optimal set of strategies. A vector \( x \in \{x_1, x_2, \ldots, x_{|S||N|}\} \) represents a combination of selected strategies. \( S \) represents the set of strategies listed in Table S1 and \( N \) the number of bioregion. \( B_j \) identifies the benefits of implemented strategy \( j \). Below we provide the details of the dynamic programming algorithm we used to solve our knapsack problem. The algorithm is in two parts. The first part computes the dynamic programming equations for all budgets (Table S3, Lines 1-18, Figure 4) by applying Bellman recursions. A strategy is either too expensive to be selected (Line 7) or if it isn’t we evaluate the added benefits of selecting this strategy (Line 10). If the strategy \( j \) improves upon previous strategies, it is selected. The strategy contributes \( B(j) \) at a cost of \( C(j) \) (Lines 11-14). The second part of the algorithm retrieves the optimal decisions by exploring the temporary variable \( A \) (Table S3, Lines 19-36, Figure 5). Interested readers can refer to (Kellerer et al., 2004) for additional details and alternative approach to solving knapsack problems.
Table S3. Dynamic programming algorithm used to calculate the set of optimal solutions for all budgets adapted from Hans et al. (2004).

**Dynamic programming for all budgets**

**Input variable:**
- \( n \): total number of strategies
- \( B \): vector of benefits of length \( n \)
- \( C \): vector of costs of length \( n \)
- \( C_{\text{max}} \): maximum budget we are willing to invest.

**Output variable:**
- \( z_n(0..C_{\text{max}}) \): optimal allocation of funds for all budgets
- \( X(1..n,0..C_{\text{max}}) \): optimal decisions for all budgets

```
1  A = zeros(0..n,0..C_{\text{max}}); \% we need A to retrieve X
2  For budget b=0 to C_{\text{max}}
3      z_0(b)=0; \% initialise the first value
4  endFor
5  For Strategy j=1 to n
6     For budget b=0 to C(j)-1
7          z_j(b) = z_{j-1}(b) \% strategy j is too expensive
8     endFor
9     For budget b=C(j) to C_{\text{max}}
10        if z_{j-1}(b-C(j))+ B(j) > z_{j-1}(b) then
11           \% select strategy j by adding benefits to z_j(b)
12           z_j(b) = z_{j-1}(b-C(j)) + B(j)
13           \% update A
14           A(j,b) = 1
15        else z_j(b)=z_{j-1}(b)
16        endif
17     endfor
18  endFor
```
% We have calculated all the $z_j(b)$ including the optimal solution $z_n(b)$ for all budget $b$. We now need to retrieve the optimal decision $X$ from $A$

For budget $b=C_{max}$ to $0$ % for all budgets
strategy={};
j=n;
c=b;

While $j>=1$ and $b>0$
  While $j>=1$ and $A(j,c)==0$
    $j=j-1$; % strategy $j$ has not been selected
  endwhile
  If $j>=1$ and $A(j,c)==1$
    strategy=strategy + {j}; % strategy $j$ was selected
    c = c - C(j); % update cost, look for the next strategy selected
    $j=j-1$; % update strategy number
  endif
endwhile

X(strategy,b)=1;
endfor

% We have retrieved all the optimal decisions.

References