


Conserving biodiversity and Indigenous bush tucker: Practical application of the strategic foresight framework to invasive alien species management planning

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Abstract

Invasive alien species are a major driver of global biodiversity loss. Constrained conservation budgets demand that threat abatement strategies take into account the heterogeneity of areas in need of protection, such as significant ecological and cultural sites, as well as the competing values, preferences, and objectives of stakeholders. We used strategic foresight to assess the threat that invasive alien grasses pose to environmental and Indigenous cultural values on the floodplains of a co-managed, World Heritage-inscribed national park. We found strategic foresight to be a useful framework to set management priorities that simultaneously conserve biological and cultural diversity. However, it required the development and application of novel ecological and participatory tools and significant time, financial, and human resources. This was the first study to apply strategic foresight to weed management planning in a realistic, culturally complex setting and our work provides an exemplar for the application of the strategic foresight framework and our tools to other contexts.

KEYWORDS

cultural values, dynamic planning, invasive species, Kakadu National Park, management strategy, protected areas, scenario planning

1 | INTRODUCTION

Invasive alien species (IAS) are a significant threat to the ecological integrity of ecosystems globally and a primary driver of biodiversity loss (Butchart et al., 2010). This has led to global targets to mitigate their impacts under the Convention on Biological Diversity (CBD) Aichi Targets (2010). In December 2016, the Conference of the Parties (COP) to the

CBD agreed to make use of scenarios and models of biodiversity and ecosystem services and to “compile information on the potential consequences of invasive alien species on social, economic and cultural values, including the values and priorities of Indigenous peoples and local communities” (CBD, 2016). The COP also invited governments to “adopt a participatory process by identifying and engaging Indigenous people, local people and relevant stakeholders from an early stage,

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and to develop and use participatory decision-support tools to increase transparency in decision-making" (CBD, 2016).

Meeting the CBD's identified need for IAS management requires not only understanding IAS ecology, including modes, patterns, and impacts of invasion, but also their impacts on social systems and cultural values, particularly those of Indigenous peoples, a topic which has received little attention to date (Ferrier et al., 2016; Langton, 2003; Pfeiffer & Voeks, 2008). This is particularly important given the growing recognition of Indigenous rights and livelihood interests within protected areas (Dudley, 2008). Indigenous territories comprise approximately one-fifth of the world's land (Popkin, 2016) and the extent of Indigenous owned lands being managed for both cultural and conservation values is expanding (e.g., Australia's Indigenous Protected Areas; Altman & Jackson, 2014; Watson, Dudley, Segan, & Hockings, 2014). IAS management must also consider the spatial heterogeneity of the cultural, ecological, and other values that it aims to protect, which may not be spatially congruent. For instance, areas important for cultural practices, such as rock art painting or the collection of traditional materials, may not overlap with areas that are rich in species or support rare or endemic species.

A range of decision frameworks (Schwartz et al., 2017) support IAS management and are suitable for multiobjective planning: (1) strategic foresight (SF), (2) systematic conservation planning, (3) structured decision-making, (4) open standards for the practice of conservation, and (5) evidence-based practice. For example, recent IAS planning approaches have used existing decision support tools from systematic conservation planning (Adams & Setterfield, 2015; Januchowski-Hartley, Visconti, & Pressey, 2011) and structured decision-making (Firn et al., 2015) to design optimal management plans for invasive plants. Of the five common decision support frameworks, SF is particularly well suited to IAS management because of the emphasis it places on the conditions of uncertainty and urgency (Cook, Inayatullah, Burgman, Sutherland, & Wintle, 2014). IAS management is often characterized by a lack of knowledge, or knowledge accompanied by large uncertainties, and a need to act quickly to avoid infestation and its costly impacts.

The aim of this article is to provide an example of how to meet the CBD's recommended actions for IAS management to protect both ecological and Indigenous cultural values. To this end, we applied the tools within an SF framework (Hines, 2006) because it supports informed decision-making across temporal and spatial scales, where a range of possible, probable, or desirable futures must be accounted for across a diverse set of stakeholders (Cook et al., 2014; Figure 1). In particular, we used scenario planning to explore how different management strategies perform given specific weed threats and the potential for competing and conflicting stakeholder values. To support the scenario planning process, we devel-

oped dynamic weed management software; the generalized software is applicable to any weed management context. We present here the application of this process and tools to address management of two invasive alien grass species on the floodplains of Kakadu National Park, an Australian Indigenous comanaged park inscribed on the World Heritage list for its outstanding natural and cultural values.

2 | METHODS

We used Kakadu National Park (Figure 2) as a case study because it is one of the few World Heritage areas listed for both natural and cultural significance (Wellings, 2007). Recognition of cultural significance is based on its cave paintings, rock art, and archaeological sites, and for being directly associated with living traditions of outstanding universal significance. A population of approximately 500 Indigenous people live within Kakadu (Palmer, 2007). Kakadu comprises approximately 20 Indigenous clan estates and its ~120 traditional owners are recognized under Australian statute (*Aboriginal Land Rights [Northern Territory] Act 1976*) as owners of approximately half the park (Director of National Parks, 2016; Palmer, 2007). Most of the remaining area is under claim by Indigenous groups (Director of National Parks, 2016). The park is managed by a Board of Management which has a majority of members (including the Chair) who are nominated by traditional owners. Kakadu is acclaimed for its joint management arrangements which establish a partnership between Indigenous land-owners and the Director of Australia's National Parks agency (Wellings, 2007).

Kakadu's floodplains (Figure 2) are inundated annually during the wet season (Ward et al., 2014) and support a diversity of species including fish, turtles, and waterbirds (Finlayson et al., 2006). Kakadu's Ramsar-listed floodplains provide Indigenous people with foods (plant and animal species native to Australia that are known locally as "bush tucker"), such as magpie goose, fish, and turtles and other materials used for weapons, utensils, weaving, and medicines (Ligtermoet, 2016; McGregor et al., 2010). In a manner common to the human ecology of many north Australian wetlands (Jackson, Finn, & Featherston, 2012), utilization of floodplains enables Kakadu's land-owners to maintain important communal aspects of social and economic life based on cultural continuities.

Kakadu's floodplains, and associated values, are at immediate risk from two invasive alien grasses, para grass (*Urochloa mutica* [Forsk.] T.Q. Nguyen) and olive hymenachne (*Hymenachne amplexicaulis* [Rudge] Nees; McGregor et al., 2010; Setterfield et al., 2013). Both species form monocultures, displacing the diverse mosaic of native vegetation. The social complexity of the floodplains (Jackson, Storrs, & Morrison, 2005) requires that managers are conscious of the small-scale

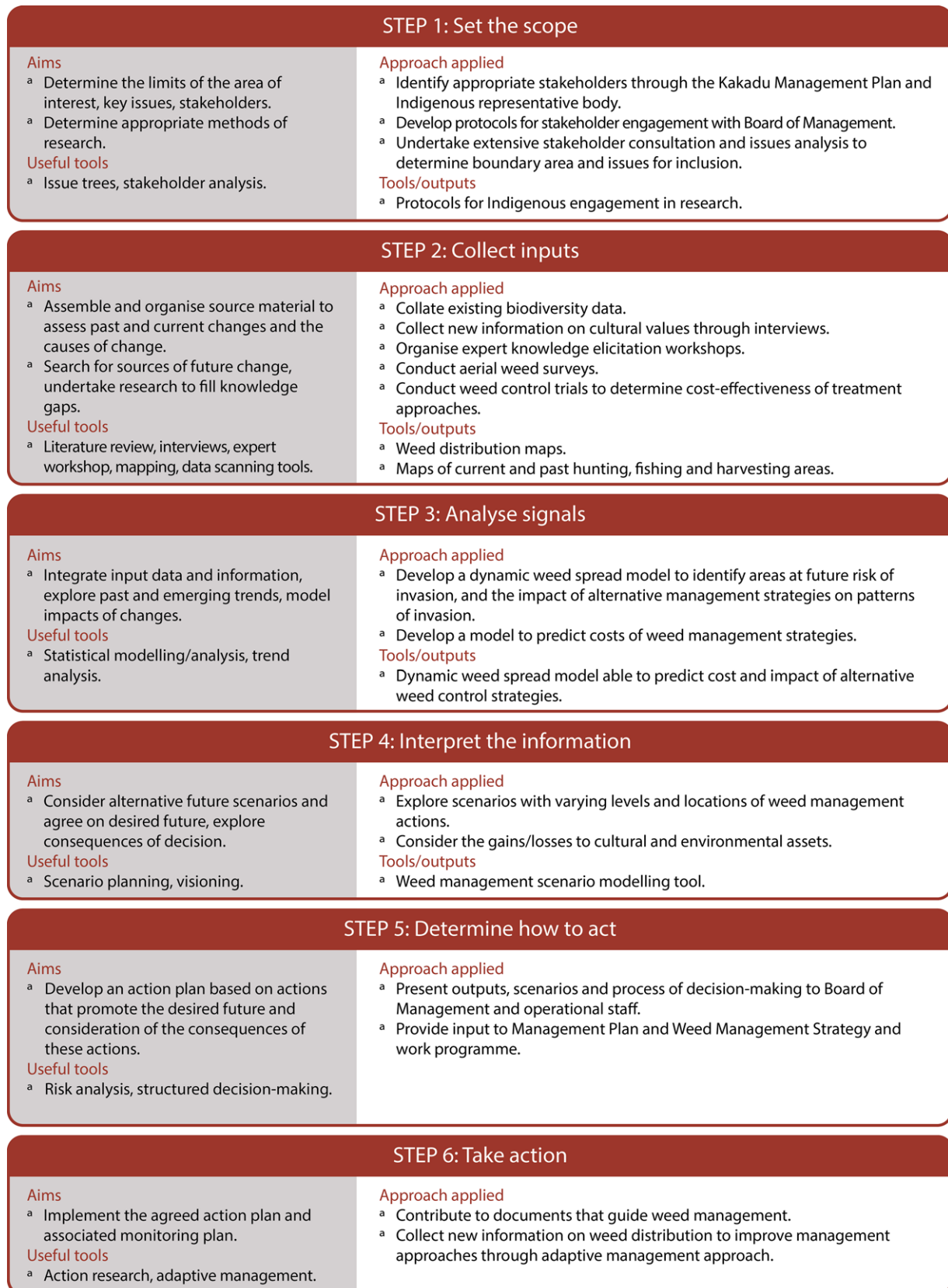


FIGURE 1 Six stages of the strategic foresight process showing the aims and useful tools (from Cook et al., 2014; shaded) and the approach that we used at each stage and the tools/outputs we produced



FIGURE 2 (a) Location of Kakadu National Park (KNP) in Australia; (b) Uninvaded floodplain systems have a diversity of native plant species; (c) Invaded wetlands are dominated by a monoculture of IAS para grasses; (d) The magpie goose (*Anseranus semipalmata*) was once widespread across eastern Australia but is now restricted to northern Australia. Uninvaded floodplains in KNP provide important breeding and feeding sites for this species. The meat and eggs are a favorite food for Indigenous people and the large aggregations of geese on the floodplains are an attraction for tourism; (e) Interviews with Indigenous land-owners were conducted to identify important sites for harvesting and to confirm weed distributions mapped from aerial surveys which were then used to model future weed distribution under different management scenarios (Pictured: Jessie Alderson and Samantha Setterfield); (f) Interviews with the KNP weed management team were conducted to help develop a cost of control model and to determine realistic weed management scenarios (Pictured: Kelly Scheepers, Fred Hunter and Sue Jackson). The outcomes of these scenarios were discussed with Park managers (Indigenous and non-Indigenous staff) and with Indigenous land-owners. (Photos Michael Douglas)

nature of Indigenous political organization, patterns of tenure and custodianship, and the potential for weed management strategies to generate conflict by creating winners and losers.

3 | STRATEGIC FORESIGHT

We used an SF approach (Hines, 2006) and followed the six steps presented by Cook et al. (2014) to guide environmental decision-making using SF planning (Figure 1). In particular,

we used scenario planning to forecast the future state of the floodplains given different management scenarios. We developed software to assist in the design and evaluation of management scenarios.

4 | MAPPING CULTURAL AND ECOLOGICAL ASSETS

We sought to involve all Indigenous land-owners affiliated with Kakadu's floodplains. A formal process, coordinated by

the Aboriginal representative organization, the Northern Land Council, identified people with customary rights and interests in the study area. Interviews were undertaken with 37 people in one-on-one or small-group settings to describe and map important areas for resource use, such as hunting and fishing, and list the species harvested from these sites. These sites were mapped into three types of activities: magpie goose hunting, long-necked turtle hunting, and other bush tucker. The interviews also identified areas that were previously but no longer used, and explored the drivers of change in resource use.

We chose to concentrate on bush tucker sites as a measure of the direct use and value of floodplain to the Indigenous economy for two reasons. Firstly, hunting, fishing and gathering are vitally important cultural practices with economic and social benefits (Jackson, Finn, & Scheepers, 2014). Traditional owners consistently seek to prioritize this use in Park management (Director of National Parks, 2016). Secondly, it is relatively easy to make this variable spatially explicit and therefore more readily comparable with existing ecological criteria for conservation, in contrast to culturally sensitive sites of religious or spiritual significance. The history of mapping of sacred sites in north Australia shows the process to be fraught with difficulties (Jacobs, 1993). Furthermore, the provisions of the lease between Aboriginal Land Trusts and the Director of National Parks refers to a number of measures to ensure the confidentiality and sensitive treatment of sacred sites under joint management. For these reasons, we did not seek information on sacred sites or other intangible cultural heritage. Traditional owners of the study area consented to the scope of the project and Parks Australia granted permission under a protocol that complied with national standards of research ethics.

To investigate the benefits of weed management for broader ecological values, we compiled existing predicted species presence for key fish (black bream and barramundi) and turtle species (long neck and pig-nosed) and wet and dry season magpie geese presence (compiled from 2000 and 2003 surveys; Kennard, 2011).

5 | MODELING

We developed a generalized, spatially explicit cellular automata approach to link an existing dynamic spread model (Adams et al., 2015) to weed growth and management models (Table 1 and Supplementary Materials). The model has a user-friendly interface, is easily parameterized for any invasive plant species, and can accommodate an unlimited number of species for management. This enables users to apply our modeling approach to any system. This software is freely available (Kool, 2018).

Our dynamic management model incorporates two management actions defined through consultation with Park managers and based on global best practice (e.g., Moore, Runge, Webber, & Wilson, 2011; Panetta, 2007): containment and control. Containment involves delineating a zone and preventing spread to areas outside the zone (Grice, Clarkson, Friedel, Ferdinands, & Setterfield, 2010). No action is taken within the containment zone, so the area and density of weeds will increase within that zone. Containment is *in perpetuity* whereas control continues for a finite time period, based on infestation density. Control involves the on-ground chemical control of infestations until local eradication is achieved. We have used existing knowledge of control efficacy and costs from limited trials of para grass (McMaster, Adams, Setterfield, McIntyre, & Douglas, 2014) and olive hymenachne (Clarkson, Grice, & Still, 2012; DEH, 2003) to parameterize our management model and quantify the significant costs of control and containment. However, the required duration of control to achieve the desired outcome (local eradication) and the feasibility of this requires further research to reduce the uncertainty associated with our current model.

At the start of a simulation, the placement of management actions is initialized based on a user-specified management map. This allows for the design of management scenarios by stakeholders, such as park managers, and evaluation of the performance of these scenarios using the software. Each management action sets rules for whether a cell can spread or grow (Table S1). For each future time step, new infestations are dynamically detected and placed under containment or control based on species-specific attributes. For generalized steps and case study assumptions, see Table 1 (and see Adams & Setterfield, 2016 for a similar approach).

6 | MANAGEMENT SCENARIOS

We ran a range of management scenarios, three of which are presented here:

Baseline – No management. This is the status quo, involving no additional management action. It is used as a baseline against which to measure the benefits of additional management.

Scenario 1 – Strategic management approach (Figure 3c). Due to the extent of para grass invasion on the Wildman and Magela floodplains, containment boundaries reflecting natural barriers were selected. Olive hymenachne and para grass infestations outside the containment zone were placed in on-ground control.

Scenario 2 – Strategic management + Indigenous priorities for resource access (Figure 3d). This scenario included all management actions from Scenario 1 and additional

TABLE 1 Simulation steps, eligibility, and specification attributes. The simulation steps for infested cells are presented in the order in which they occur for each annual time step. For each step, we indicate eligibility requirements for each step and also specifications for each step. For example, only cells that are infested and in no control or containment core management zones can spread. Spread is influenced by both the species (sets distance and rate) as well as age (species-specific age eligibility for spread). Last, we list specific assumptions made for our Kakadu case study (see Supplementary materials for further details)

| Simulation step | Step definition | Zone eligibility | Specification attributes | Kakadu case study assumptions |
|---------------------------------|--|---|--|---|
| Monitor | Monitoring occurs on a periodic basis (every 2 years). Every cell is monitored and the probability of detecting an infestation is conditioned on density. | All | Density | Probability of detection is based on previous aerial surveys |
| Set management zones and manage | If an infested cell is detected during monitoring, then it is placed into a management zone (ground control, containment) based on species-specific rules. | All detected infested cells | Size, species | We defined species-specific eligibility criteria for management zones (Table S1) based on species ecology and expert advice. |
| Cost accounting | If a cell is in a management zone, then the cost and labor hours for management of individual cells are summed across the floodplain to calculate total annual cost and management effort (labor hours). | Control, containment | Management zone, year of management | The cost of each management action was based on published cost estimates of ground control of para grass for varying density classes (McMaster et al., 2014) and expert advice (Table S2) |
| Growth | If a cell is infested, then the density growth of each cell is deterministic model based on time since first infested. | Infested cells in no control and containment core zones | Age, species | We developed growth estimates for each species based on expert advice and published growth rates (see Supplementary Materials). |
| Spread | Spread occurs based on a spatially explicit stochastic model (Adams et al., 2015). | Infested cells in no control and containment core zones | Age, species | We used published calibrated spread values and spread model approach (Adams et al., 2015). |
| Update cell status | Update density (decreased density for controlled sites, increased density for uncontrolled sites, newly infested sites assigned low density). | All | Species, management zone, year of management | |

on-ground control at impacted bush tucker sites where there was a desire from Indigenous land-owners to regain access. This scenario addresses the Kakadu Management Plan goal of maintaining customary resources use on the floodplains and the associated metric of “the abundance of significant species is increased or maintained” (Director of National Parks, 2016, p. 58).

We ran each management scenario from the current known weed distributions from 2010 (Figure 3) to 2030 (20 years) for 100 runs.

7 | SCENARIO EVALUATION

We interpret the qualitative aims of Kakadu's Management Plan as a set of quantitative objectives: minimize the total extent of weeds, minimize the impact on assets, maximize cost-efficiency, and ensure the management is feasible and effective. To evaluate the performance of each scenario in achieving these objectives, we defined five related evaluation criteria in collaboration with stakeholders (Figure 1a setting the scope and see Table 2 for details of criteria).

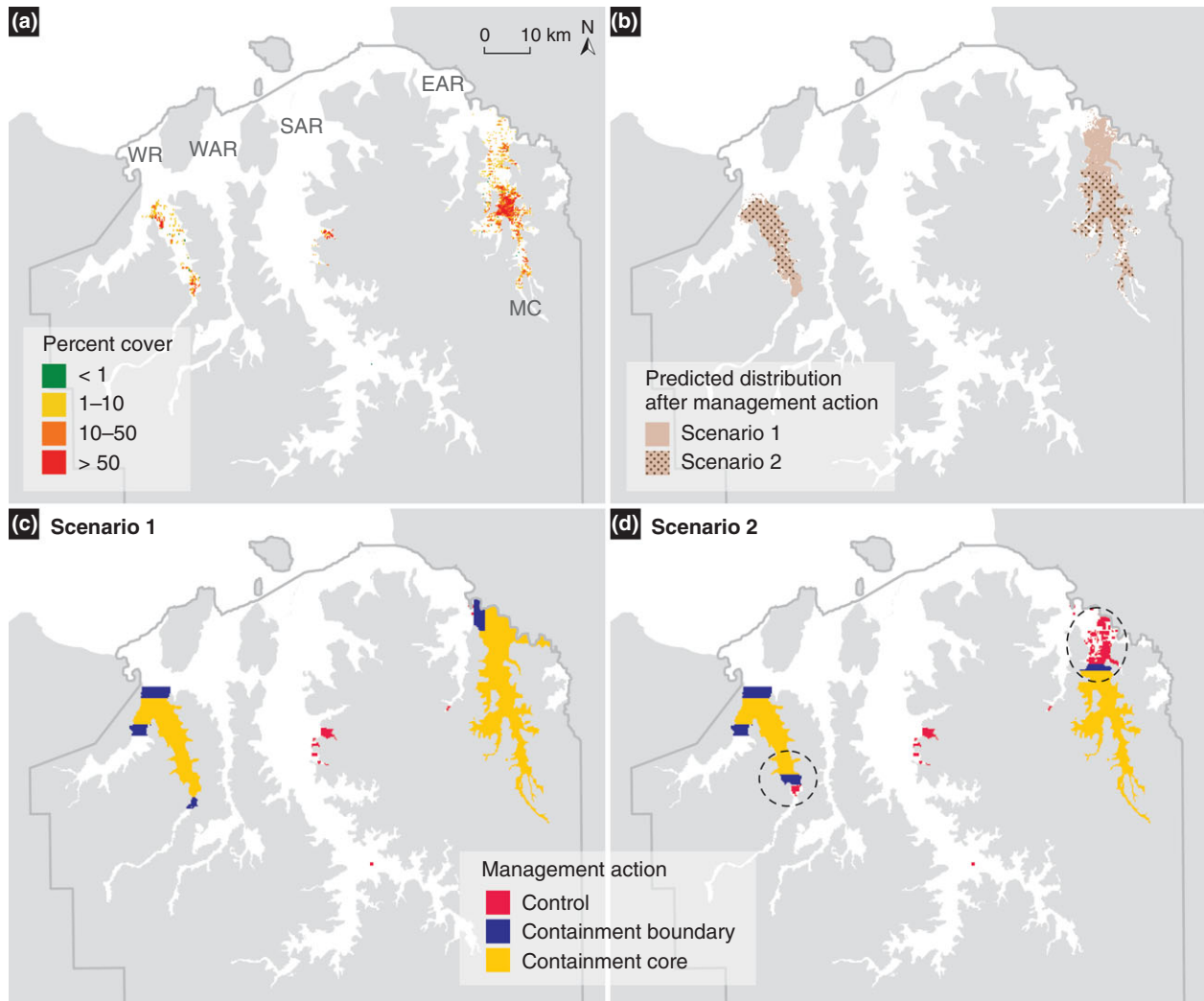


FIGURE 3 (a) Aerial survey of para grass cover (Setterfield et al., 2013); extensive infestations occur on the Magela and Wildman floodplains, while the South Alligator is still relatively free of this weed. (b) Predicted para grass cover at the end of management period for Scenario 1 and 2. (c) Management zone for Scenario 1. (d) Management zone for Scenario 2. Circled areas highlight the locations where control was focused to improve bush tucker harvesting under this Scenario

8 | RESULTS

The literature review and discussions with Indigenous land-owners and park managers for SF Stage 1 identified the high risk of alien grass invasion, particularly: displacement of native plants, loss of magpie goose nesting and feeding sites, reduced access for subsistence activities, and increased fire intensity and the consequent loss of turtles aestivating in floodplain soil (McGregor et al., 2010; Setterfield et al., 2013). We developed a shared understanding of the SF process and agreed that scenarios should consider benefits and costs across all floodplains (Figure 1), rather than using individual floodplains as management units.

For SF Stage 2, we produced the first Kakadu-wide distribution map of the two weeds (Figure 3a; Setterfield et al., 2013); with 3,200 and 800 ha of the floodplains invaded by

para grass and olive hymanachne, respectively. This highlighted the heterogeneous nature of weed invasion; parts of the Magela Creek and West Alligator floodplains were heavily invaded whereas most of the South Alligator floodplain was weed-free. In addition, we conducted weed control trials to investigate herbicide and fire application costs and effectiveness (McMaster et al., 2014). The results of the trial informed the control model we used.

In addition to producing weed distribution maps, we also produced the first comprehensive map of bush tucker sites (Figure 4 and for a full list of species recorded see Table S3), which revealed that bush tucker is harvested from ~25% of the total floodplain area. The remaining floodplain area (~75%; Figure 4) is not used for bush tucker because either the sites are inaccessible, the target species are not present, or they yield relatively low catches per unit of effort expended. For

TABLE 2 Quantitative objectives set relating to plan aims and associated evaluation measures

| Objective | Evaluation measure |
|---|---|
| Minimize the total extent of weeds | Total infested area of floodplain (hectare) |
| Minimize the impact of weeds on assets (biodiversity and bush tucker sites) | Avoided percentage (%) of each asset infested (species distributions (biological assets), bush tucker sites mapped (cultural assets)). Avoided percentage is defined as avoided infestations within an asset (final infested area in a scenario [1 or 2] minus the baseline infested area [hectare] in the absence of management) divided by total area of asset. We assume that all assets have a binary negative response to being infested such that a site must not be infested in order to accrue a benefit. While this is a simplistic response function, it reflects the fact that we have limited knowledge of how different assets interact with infestation. |
| Cost-efficient | Cost per hectare avoided infestation defined as the present value of total run cost (based on a 3% discount rate) divided by avoided infestations (hectare). |
| Feasible | We consider feasibility in terms of total cost, as a measure of overall resourcing needed, and team weeks per year as a measure of staffing needed to complete the planned management. We convert predicted labor hours per year into team weeks based on existing Kakadu resourcing (personnel work 38 hours a week and teams consist of four personnel). |
| Effective | We measure the effectiveness of the containment zone to achieve its intended purpose by calculating the proportion of runs per scenario in which a new infestation is established outside of the containment boundaries. |

example, the Wildman River system poses access challenges because of its distance from town and rough terrain. The highest density of bush tucker sites was on the South Alligator floodplain, due to its accessibility and the variety and abundance of bush tucker.

Importantly, the interviews revealed changes in floodplain use over time. Most currently used sites were also used in the past (Figure 4b). However, some previously important sites are no longer used and other sites have only recently come into use (Figure 4). Of those areas used in the past but no longer used (Figure 4), Indigenous land-owners attributed reduced visitation and use to weed infestation and saltwater inundation. For example, one noted that “para grass is everywhere around the floodplain” when discussing areas on the Magela floodplain that are no longer used. Para grass was well recognized as a threat to future cultural use. One Indigenous land-owner described how para grass had changed a highly valued part of the Wildman River system (Figure 4):

“I go to Four Mile Hole – beautiful turtle place, nearly every year and to Boggy Plains. Para grass changes it. It's like a spring, a mat. Turtle sits underneath, harder to get them out. Donkeys, pigs spread it,” she said. “One day it's going to be over-run. There were never any weeds here until they started to bring feed in for the cattle.”

Another noted that para grass restricts access, making harvesting difficult, and that the burning of para grass can result in the death of estivating turtles. Such changes have additional social impacts, including transferring hunting pressure from one clan estate to another when “outsiders” with weak or no

customary rights to harvest resources move in to sites managed by others:

“At Cannon Hill, there's too much para grass so they all come here. It puts pressure on other clan's resources. There used to be biggest mob turtle there. When you burn it (para grass), you cook up the turtle.”

For SF Stage 3, we used historical records and weed mapping to develop a model of the future distribution of the two weeds (Figure 3 and Adams et al., 2015). This revealed areas highly suitable for invasion downstream of current infestations, and on floodplains currently free of large infestations (e.g., South Alligator).

For SF Stage 4 (Figure 1), scenarios were developed using our dynamic weed management model, enabling us to forecast the future distribution of weeds under varying levels of management expenditure (Figure 3). The baseline scenario predicted that without increased management effort, 14% (~32,000 ha) of floodplain area will be invaded by para grass by 2030 (Table S4). This scenario highlighted that sites valued by Indigenous land-owners are among the areas most likely to be invaded. This is potentially due to the fact that para grass is highly suited to areas that retain water well into the dry season; these areas are also the most productive habitats for bush tucker species such as magpie geese and turtles.

Scenario 1 would protect ~10,000 ha of floodplain over a 20-year period (Figure 3). This represents only 4% of Kakadu's total floodplain area, but delivers substantial benefits to all cultural assets with avoided percentage infested ranging from 0.6% for pig-nosed turtle habitat to 28% for

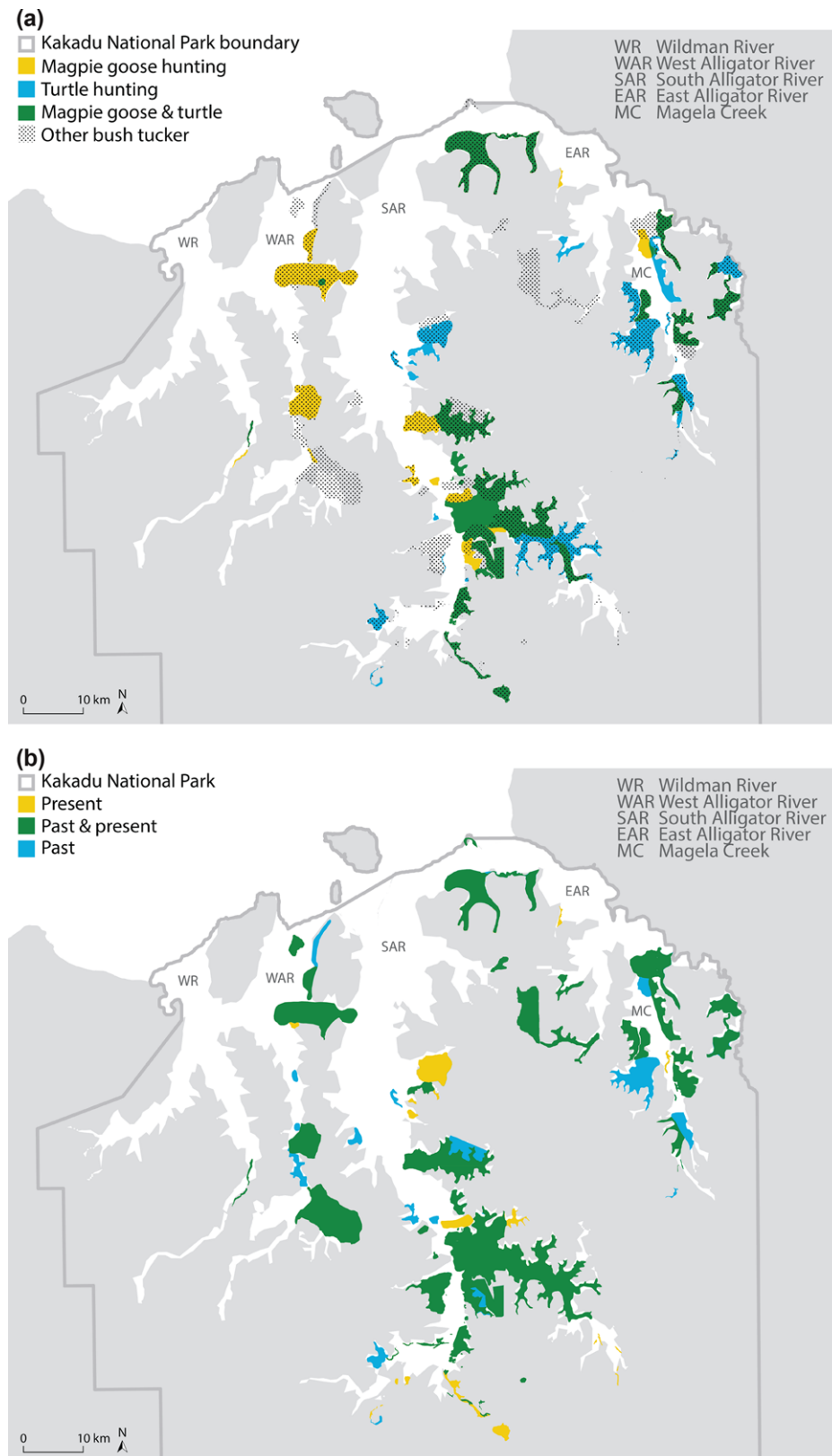


FIGURE 4 (a) Bush tucker sites including sites for turtle and magpie goose hunting and other bush tucker in Kakadu National Park. (b) Bush tucker sites over time showing sites that are currently used and have been used in the past (past-present), areas used in the past but no longer used (past), and areas that have only recently been a focus for harvesting (present)

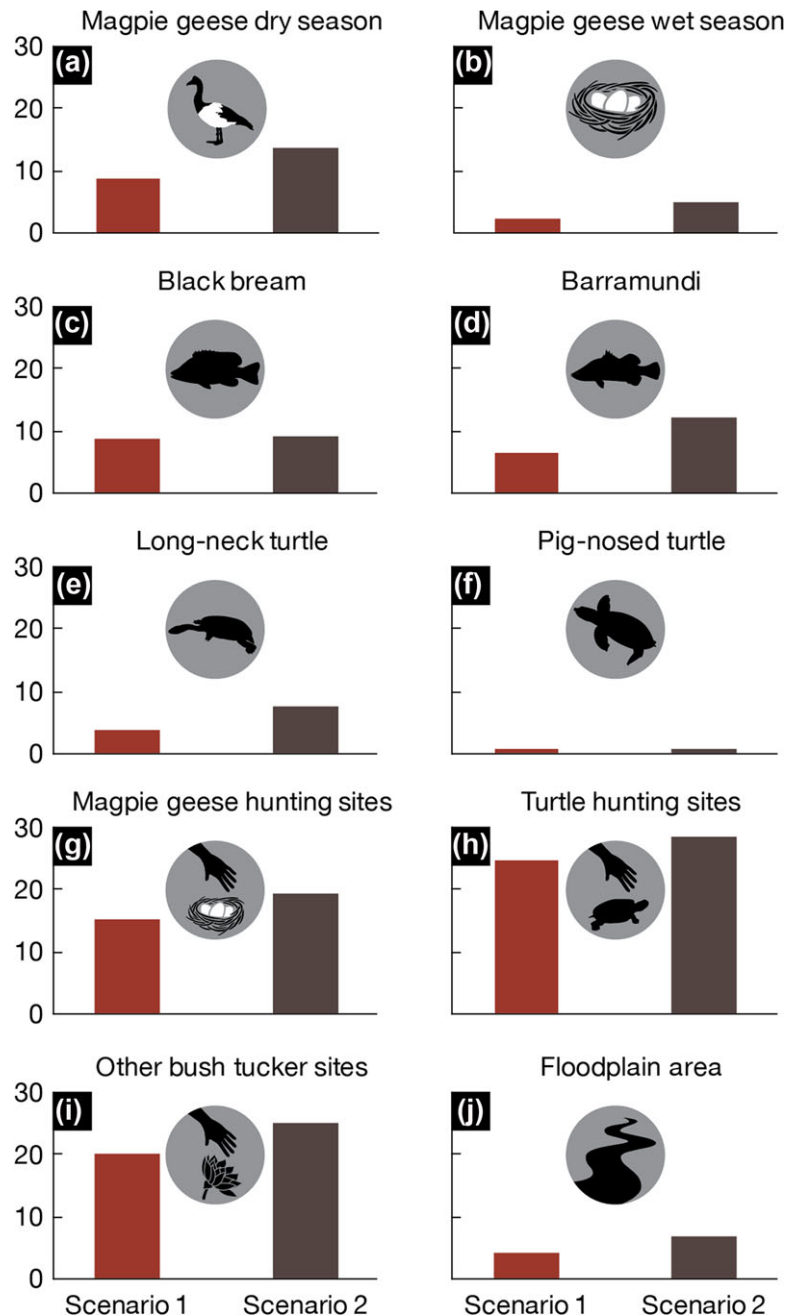


FIGURE 5 Average avoided percentage of area infested for each ecological value, cultural value, and overall floodplains infested for each scenario. (a) magpie geese wet season (b) magpie geese dry season (c) black bream (d) barramundi (e) long neck turtle (f) pig-nosed turtle (g) magpie geese hunting sites (h) turtle hunting sites (i) other bush tucker sites (j) floodplains

turtle hunting sites (Figure 5). Scenario 2 doubles the area of avoided infestation across all bush tucker sites compared to Scenario 1. The cost of implementing both scenarios is greatest in the first 7 years when ground control programs are required to eradicate local infestations, with the cost of the initial management period approximately double for Scenario 2 compared to 1 (Figure S1). Thereafter, maintaining containment boundaries required a similarly small annual investment for both scenarios (~\$A50,000 per annum; Figure S1).

The gains and costs of alternative scenarios were very important considerations for the participatory planning step, which included an evaluation of social impacts, particularly the geographical variation in weed distribution under each scenario and the consequences for different land-owner groups. Scenarios 1 and 2 protect significant harvesting grounds on the South Alligator where the number and size of small outlier populations of para grass is low, but increasing (Figure 3). However, the benefits of Scenario 1 are distributed very unevenly among Kakadu's clan estates.

Traditional custodians of the harvesting areas on the Wildman River floodplain will eventually have their important sites heavily invaded, and there are further losses for the customary users of the remaining areas on the Magela floodplain. In contrast, Scenario 2 delivers further reductions in infestations across all assets as well as additional benefits to both these clans by restoring access to favored bush tucker sites on both floodplains (Figure 5). Across both scenarios, the greatest gains were achieved for the three bush tucker categories, particularly magpie goose hunting sites (Figure 5g-i). However, a critical consideration is the distribution of benefit across clan groups. For example, under Scenario 2, there is a 19% increase in magpie goose hunting area across the Park, but this represents a 100% increase for traditional custodians of the Wildman floodplain and a 40% increase for traditional custodians of Magela floodplain.

Although the larger and more equitable distribution of the gains under Scenario 2 comes at a greater initial cost, it is slightly more cost-efficient than Scenario 1 (average cost per avoided infested hectare of \$A252 vs. \$A287; Table S4). Scenario 1 is, however, more effective in maintaining containment boundaries than Scenario 2; 55 of 100 runs in Scenario 1 experienced a breached containment boundary, compared to 99 of 100 runs in Scenario 2. Scenario 1 could be achieved with one additional team of managers (four people), whereas Scenario 2 would require two additional teams (Figure S1).

For the final two SF stages, we presented the maps, tools, and results from scenarios to the Park's management team and the Kakadu Board of Management, the statutory authority with responsibility for park management. The results were well received by the Board of Management and Park management staff. The Traditional Owner Board members appreciated that the prioritization approach explicitly considered Indigenous values as well as conservation values. The Director of National Parks described it as the perfect example of research that was focused on improving management of the Park. The Cultural Heritage and Biodiversity Manager particularly valued an approach that was based around engagement with Traditional Owners and considered this approach to be a model that could be applied to other natural resource management plans (e.g., feral animals) and in other habitats in Kakadu.

These final steps were designed to inform the development of the Kakadu Management Plan (2016) and the associated Weed Management Strategy. These two documents guide the on-ground weed management activities in the Park and were both under development when we conducted the research.

9 | DISCUSSION

We find the SF approach, comprising significant stakeholder engagement at all stages, scenario planning, and development

of software to support scenario analyses, provided an excellent foundation for participatory analysis of possible management futures for Kakadu's floodplains, a culturally and ecologically complex decision-making context. To our knowledge, this is the first example of implementation of an SF approach to IAS management planning that seeks to protect both ecological and Indigenous cultural values while identifying the social impacts of potential trade-offs.

The application of SF to weed management planning in Kakadu allowed us to explore a range of possible futures and facilitate the negotiation process among stakeholders to identify preferred management futures. We measured the effectiveness of specific actions in terms considered important to a statutory authority with responsibility for managing a very large World Heritage site and to a cultural minority with customary rights of ownership and environmental management obligations that operate at a smaller scale.

The ability to test multiple strategies is highly relevant to IAS where the feasibility of different management strategies is not known *a priori*. Our approach provides comparative outputs from scenarios that help interpret the signals and evaluate the performance of alternate futures. In particular, we estimated financial and human resources required for management scenarios, and the spatial distribution of actions and their likely effectiveness. For example, the estimated human resources indicate that in order to implement Scenario 1, an additional weed management team (four personnel) is required; Scenario 2 requires two additional weed management teams (eight personnel). The scenarios explicitly demonstrate where costs will be incurred, such as for the intensive management of a containment zone and eradication of new infestations resulting from breaches of the containment zone.

Implementing the SF approach was time-intensive (~3 years) and required the development of specialty software and a multidisciplinary research team (ecologists, social scientists, software developers) and the commitment of time from managers and stakeholders. This time investment is not necessarily unique to the SF framework. Our experience implementing a systematic conservation planning approach for IAS (Adams & Setterfield, 2015) was that similar levels of resourcing and team skills are required. The model outputs include maps of valued features, such as sites important for biodiversity conservation and for bush tucker, and the modeled distribution of weeds which enable managers and stakeholders to interpret and negotiate which scenarios best reflect their varied management objectives. The benefit that SF provides over alternative frameworks is that SF supports the testing of multiple possible recommendations and a more dynamic and iterative revision of preferred strategies.

Our experience supports the growing evidence of the potential for SF to support ecological decision-making (Cook et al., 2014; Coreau, Pinay, Thompson, Cheptou, & Mermet,

2009), but it also highlights the need for appropriate time and resourcing. We provide a set of steps and practical tools which may reduce the time and capital investment required by others. Our experiences can assist others attempting to protect biodiversity and sociocultural values that rely on the health of ecosystem processes and to ensure the legitimacy of local environmental management institutions and, for these reasons, it could be readily adapted for other threat abatement contexts such as climate change.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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