Optimal dynamic control of invasions: applying a systematic conservation approach

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Abstract. The social, economic, and environmental impacts of invasive plants are well recognized. However, these variable impacts are rarely accounted for in the spatial prioritization of funding for weed management. We examine how current spatially explicit prioritization methods can be extended to identify optimal budget allocations to both eradication and control measures of invasive species to minimize the costs and likelihood of invasion. Our framework extends recent approaches to systematic prioritization of weed management to account for multiple values that are threatened by weed invasions with a multi-year dynamic prioritization approach. We apply our method to the northern portion of the Daly catchment in the Northern Territory, which has significant conservation values that are threatened by gamba grass (*Andropogon gayanus*), a highly invasive species recognized by the Australian government as a Weed of National Significance (WONS). We interface Marxan, a widely applied conservation planning tool, with a dynamic biophysical model of gamba grass to optimally allocate funds to eradication and control programs under two budget scenarios comparing maximizing gain (MaxGain) and minimizing loss (MinLoss) optimization approaches. The prioritizations support previous findings that a MinLoss approach is a better strategy when threats are more spatially variable than conservation values. Over a 10-year simulation period, we find that a MinLoss approach reduces future infestations by ~8% compared to MaxGain in the constrained budget scenarios and ~12% in the unlimited budget scenarios. We find that due to the extensive current invasion and rapid rate of spread, allocating the annual budget to control efforts is more efficient than funding eradication efforts when there is a constrained budget. Under a constrained budget, applying the most efficient optimization scenario (control, minloss) reduces spread by ~27% compared to no control. Conversely, if the budget is unlimited it is more efficient to fund eradication efforts and reduces spread by ~65% compared to no control.

Key words: Andropogon gayanus; connectivity; invasive species management; Marxan; scheduling; systematic conservation planning; vulnerability.

Introduction

The impact of invasive species on natural values can be significant including alteration of ecosystem processes and species composition (Ehrenfeld 2010). Invasive species are often listed as a threat to biodiversity and have been linked to species extinctions (Kingsford et al. 2009, Butchart et al. 2010). While the risks of invasive species to biodiversity are recognized, effective control or eradication programs may require long periods of funding with large associated costs and there are limited budgets to support such actions (Panetta 2007, Simberloff 2009, Panetta et al. 2011).

Given that environmental damages caused by invasive species can be significant (Pimentel et al. 2005), it is critical to allocate limited financial resources carefully. Yet, despite the widespread acceptance of systematic conservation approaches around the world, and the demonstrated cost effectiveness and accountability of these methods, application to regional weed management has only just begun (Januchowski-Hartley et al. 2011). Januchowski-Hartley et al. (2011) demonstrated the financial benefits of using a spatially explicit planning framework and accounting for the variable costs of different actions. However, this study was limited to a single time step, with the authors highlighting the need to extend this approach to a multi-year scheduling approach.

Limited resources require managers to schedule management actions across space and time (Possingham et al. 2009), but systematic approaches to scheduling optimal location of control efforts are limited (Epanchin-Niell and Wilen 2012). Two iterative heuristics commonly applied to scheduling problems include minimizing loss (MinLoss), which prioritizes sites that are both important for meeting objectives and likely to be lost without intervention, and maximizing gain (MaxGain), which prioritizes sites only based on values

contributing to objectives and not whether the site is under threat or not. Studies have found that MinLoss outperforms MaxGain for retaining conservation features when habitat loss is considered (Wilson et al. 2006). It has been demonstrated that high habitat-loss rates can amplify the differences between good and poor approaches to scheduling management actions (Pressey et al. 2004, Visconti et al. 2010a, b). Given invasive species can have high rates of spread, previous research findings suggest that a MinLoss approach may outperform a MaxGain approach to scheduling invasive management when spread is considered.

Scheduling management of invasive species requires an understanding of the spatial distribution of infestations through time as well as the variable costs and benefits of management (Epanchin-Niell and Hastings 2010, Epanchin-Niell and Wilen 2012). We build upon the framework presented by Januchowski-Hartley et al. (2011) by extending the decision making process from a single time step to a multi-year scheduling problem and explore the performance of these two heuristics. We address the following two research questions: (1) Is minimizing loss better than maximizing gain when the spatial spread of the invasive species is considered? (2) Does eradication or control perform best under constrained and unconstrained budgets?

Based on our results, we provide recommendations for optimal scheduling of management actions and demonstrate the utility of a multi-year dynamic approach.

METHODS

Study species

Invasive grasses, such as the African grass *Andropogon gayanus* Kunth. (gamba grass), pose a major threat to savannas (Brooks et al. 2004, Setterfield et al. 2010). Gamba grass is a perennial C_4 grass that forms large tussocks in excess of 3 m high and displaces the much shorter native vegetation (Brooks et al. 2010). Gamba grass is one of five species of tropical invasive grasses that have been listed as a national Key Threatening Process (KTP) for Australia and has recently been listed as an Australian Weed of National Significance (WONS). Significant ecological impacts result from gamba grass invasions including increases in fire severity leading to a reduction in tree canopy and severe impacts on the understory (Rossiter et al. 2003, Brooks et al. 2010, Setterfield et al. 2010). Rapid spread of gamba grass has been observed from initial source paddocks in northern Australia and suggests explosive rates of spread analogous to highly invasive plants elsewhere. Modelling predicts that most of Australia's mesic savanna is suitable for invasion, including ~380 000 km^2 of the Australia's Northern Territory (Northern Territory Government 2009), as well as large savanna areas in Queensland and Western Australia (Hutley and Setterfield 2008). The current known area of gamba grass infestations in the Northern Territory extends south approximately 350 km from Darwin to Katherine in the Daly River Catchment. It is estimated that gamba grass covers 1–1.5 million ha of the Northern Territory (DLRM 2014) and is abundant in the Darwin rural region including a core infestation in Litchfield National Park (~100 km south of Darwin).

Study region

We select our study region to include key environmental assets with significant gamba grass infestations, such as Litchfield National Park. The study region covers ~1.2 million ha and includes the northernmost portion of the Daly catchment, which encompasses Litchfield National Park as well as the Daly River (Fig. 1). The Daly catchment is a priority for both development and conservation, with notable features such as the Daly River, one of northern Australia's largest rivers with unusually consistent year-round flow, extensive gallery (rainforest) vegetation, and five recognized sites of conservation significance (NRETAS 2009). We consider seven conservation features that are high priority for gamba grass management including the protected areas region in Litchfield, which is recognized for high biodiversity (biodiversity zone), a region in Litchfield recognized for its tourism sites (tourist zone), rainforest vegetation, and three sites of conservation significance (Anson Bay and associated coastal floodplains, Finnis River coastal floodplain, and Daly River middle reaches). Within the study region, there are seven significant stakeholders who control 99% of the land area including managers of national parks, aboriginal land trusts, pastoral properties and crown lease land. The remaining 1% of land area is held predominantly by small landholders with an average parcel size of 150 ha. Aerial surveys for the region provide a distribution map of infestations; however, we updated the existing aerial survey data to include other survey data provided by local property managers to provide a more comprehensive distribution map.

Planning units

The current distribution of gamba grass infestations for the Northern Territory was developed based on a 250-m grid for the region (Petty et al. 2012). We therefore create a uniform 250-m grid across our study region ($n = 313 544$) to be consistent with existing maps and models available for gamba grass. We use the 6.25-ha cells as our planning units and calculate the costs and benefits of managing the infestation in each grid cell separately.

Simulation approach

We extended the recent approaches to systematic prioritization of weed management (Januchowski-Hartley et al. 2011) to a multi-year scheduling problem. We set explicit objectives for management of gamba grass taking into account spatially heterogeneous environmental values. We followed the framework detailed by
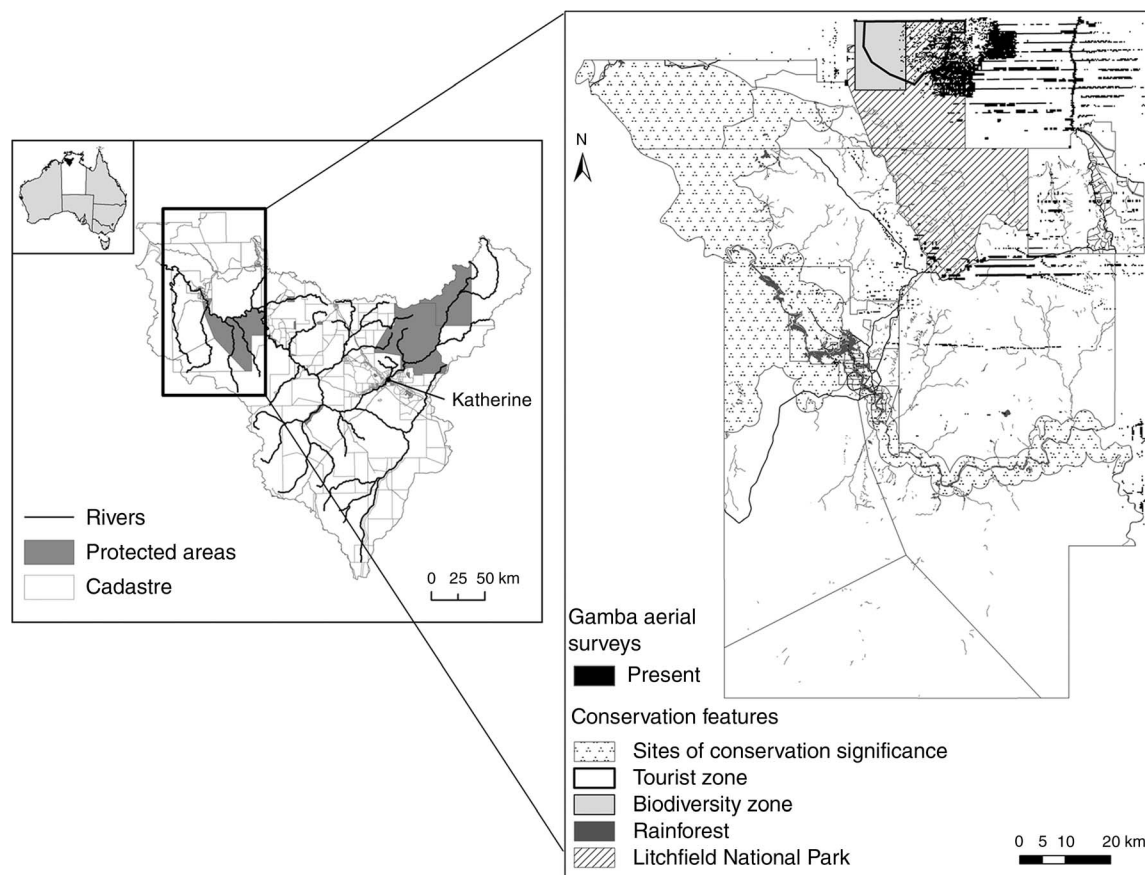
Fig. 1. Study area in the northwest portion of the Daly Catchment, Australia. On the left, the Daly Catchment cadastre, national parks, and rivers are shown to provide regional context. The inset shows the Australian states in gray, Northern Territory in white, and the Daly catchment in black. On the right, the study region is shown enlarged with conservation features: sites of conservation significance, rainforest galleries, protected areas, high biodiversity value region in Litchfield, and high tourism value region in Litchfield. Mapped gamba grass infestations identified from aerial surveys are shown in black.

Adams and Setterfield (2012) for designing multi-year weed management programs as described here. For each year we simulate growth and spread of gamba grass and management of gamba grass in the study region. The simulation annual cycle followed these steps: (1) Select planning units for management. We consider two budget scenarios. For each budget scenario we select planning units until the budget is exhausted. (2) Simulate gamba grass spread. (3) Simulate gamba grass density growth. (4) Update maps for selection strategy. At the end of each annual time step we update the map of gamba grass available for management, calculate the costs of eradication and control (which are a function of size and density of infestation and year of treatment), and update the vulnerability matrix (used for the MinLoss strategy).

We interfaced Marxan (for selection of planning units in step 1) to our dynamic biophysical model (steps 2–4) using Matlab (R2012b, Version 8.0; MathWorks, Natick Massachusetts, USA).

Each simulation is run for 10 years to reflect a 10-year management plan for gamba grass. We also run the simulation in the absence of any management for 10 years and consider this the baseline. The performance of each simulation is measured with several criteria. First, we calculate the total spread prevented across the full study region regardless of conservation status as the final area infested in the baseline of no management minus the final area infested in the management scenario. We also record the present value of expenditures using a 5% discount rate for each scenario and calculate the cost of avoided infestations as the present value divided by total spread prevented. Last, for each conservation feature in the final time step of each scenario, we record the total area that is infested and not being managed, the total area under active management (control of eradication) and the total area that was eradicated during the 10-year management period and is clean in the final time step. Lastly, we consider two static scenarios in which a one-off investment is provided for complete management of all infestations regardless of conservation status and calculate the present value of management costs for control and eradication as well as the avoided infestations and cost of avoided infestations.

Scenario design

When selecting planning units for management (step 1) we consider two potential management actions: local control and local eradication of gamba grass infestations. Local control is defined as the management of gamba grass to prevent spread and prevent further increases in size and density and includes actions such as chemical treatment of the boundaries of infestations. Control efforts must occur in perpetuity in order to effectively stop increases in size of gamba grass infestations. Local eradication of gamba grass is defined as the total elimination (including accumulated seed bank) of gamba grass within a planning unit through intense chemical treatment of the infestation over a timeframe of 6–8 years depending on the size and density (for details, see Adams and Setterfield 2013). We consider two scheduling approaches: MaxGain and MinLoss. In the context of invasive species management, MaxGain is similar to asset recovery in that infested planning units that are important to meeting objectives will be prioritized, while MinLoss will prioritize both asset recovery and prevention by selecting infested planning units of high priority and planning units that threaten important assets.

Combining the two scheduling approaches with the two management actions results in four scheduling scenarios: scenario 1, MinLoss and local control; scenario 2, MaxGain and local control; scenario 3, MinLoss and local eradication; scenario 4, MaxGain and local eradication.

Biophysical model of gamba grass growth, spread, and control

We model the growth of gamba grass as a deterministic increase in the density class of each infested planning unit. The deterministic growth model as a function of time since first infested is

$$d(t) = \begin{cases} 1, & t \leq 7 \\ 2, & 7 < t \leq 11 \\ 3, & t > 11 \end{cases}$$

where density class 1 is scattered infestation (<10% cover), 2 is medium infestation (10–50% cover) and 3 is dense infestation (>50% cover). The deterministic growth model is based on discussions with experts (scientists and land managers highly familiar with gamba grass) and examination of a time series of aerial photographs.

We adapted the spread model approach presented by Williams et al. (2008), which combines dispersal direction based on cardinal direction from wind data, dispersal distance using a negative exponential distribution and habitat suitability to constrain establishment; we simulated spread events stochastically using this parameterization as opposed to estimating probability of infestation at a site (for a similar application see Steel et al. 2014). Thus, for each time step the number of spread events from a planning unit was estimated using a Poisson distribution (the Poisson distribution is a commonly applied count distribution for estimating fecundity, e.g., see Buckley et al. [2005]), distance of each spread event was estimated using a negative exponential distribution, direction of each spread event was estimated using a cardinal direction distribution and establishment in a new planning unit was constrained by habitat suitability. We estimated spread rate based on historic distribution (mean number of spread events estimated to be 50 based on historic and current distribution of gamba grass taking into account average suitability in the region). We used a published mean spread distance of 500 m (Petty et al. 2012). We estimated the cardinal direction distribution based on the approach presented by Steel et al. (2014) where the proportion of wind blowing in each direction during time of seeding (June–July) was recorded based on data from the Bureau of Meteorology (prevailing south easterly winds). We constrained establishment in planning units using modelled habitat suitability (see Appendix). To reflect the known biology of gamba grass, infested cells had to reach an age of 7 years in order to spread (based on known reproduction time of a minimum of 2 years of age and investigation of aerial photos in which new infestations were only detected after neighboring infestations were approximately 7 years old).

We assume that once a planning unit is selected for control or eradication that it does not grow or spread. We also assume that once a planning unit is selected for management, it must remain under management for the duration of the simulation (for control) or until the management time period is completed (for eradication, 5–7 years depending on initial density) (for more details, see Adams and Setterfield 2013). For eradication we assume that density is decreasing over the time period such that at the end of the treatment period the planning unit is uninfested (costs are therefore time dependent, see *Cost of control and eradication*).

Cost of control and eradication

We model the costs of gamba grass management using control and eradication cost models developed by Adams and Setterfield (2013). The cost models are a function of infestation size, density, and year of treatment. We define infestations as each planning unit that is infested. This neglects that neighboring planning units may be managed as a single infestation. Therefore our estimated costs do not take advantage of economies of scale of managing larger infestations, but we consider this approach to be conservative given different land managers may define infestations and approach management in different ways. All costs are therefore calculated for each planning unit based on the density class in the relevant time step and a size of 6.25 ha (250-m grid planning units).

Management action selection strategies

We test our four different strategies for allocating management actions under two budget scenarios. The first budget scenario applies a constrained annual budget of AUD$600 000 (AUD, Australian dollars) and the second budget scenario allows an unlimited annual budget. The annual budget of AUD$600 000 was selected to reflect budgets received by other parks for strategic weed management programs of high threat species (e.g., Kakadu Mimosa team annual cost of AUD$500 000; DEH 2004) and to reflect the likely costs of fire management associated with regional gamba grass infestations if there is no immediate investment in a management program (AUD$550 000 in fire management costs estimated for 2013 in Batchelor region; Setterfield et al. 2014). Each of the four strategies has a unique objective function. The objective function for all four scenarios aims to jointly minimize the cost of management of infestations, minimize the probability of re-infestation of managed infestations, and meet the targets set for management of conservation values. Therefore each objective function contains three mathematical components: (1) the cost of managing the planning units selected (c_i); (2) probability of infestation; (3) target penalty, which is equal to the cost of raising a feature up to its target representation level.

The first two components of the equation are the same for both the MaxGain and MinLoss strategies. We vary the calculation of the targets and target penalty (the third component of the equation) to produce a MaxGain and MinLoss strategy: the MaxGain strategy accounts for those conservation features currently infested while the MinLoss strategy also accounts for those conservation features that are vulnerable to infestation. For the MaxGain strategies, we set a target t of 100% for all conservation features j that are currently infested C_j. This means that we want to manage 100% of infestations within all identified conservation features (i.e., the protected areas region in Litchfield, Litchfield tourism zone, Litchfield biodiversity zone, rainforest galleries, and sites of conservation significance). Any infestations that are not within conservation features are not targeted for on ground management under the MaxGain objective function. For the MinLoss strategies, in addition to the targets for currently infested features, we also set a target t of 100% of the expected features at risk (CR_j) expressed as

$$CR_j = \sum_{i=1}^{N_s} \sum_{h=1}^{N_s} v_{ih} a_{jh}$$

where N_s is the number of planning units, v_{ih} is the vulnerability of planning unit h due to spread from planning unit i (calculated as the probability of spread from i to h from the spread model) and a_{jh} is the amount of feature j in planning unit h. Any infestations that are not within conservation features are not targeted for

management under the MinLoss objective function unless they are within spread distance to a conservation feature.

We minimize each objective function with the Marxan software (Ball et al. 2009). Marxan uses a simulated annealing algorithm to find good solutions to the generalized objective function

$$\text{minimize} \sum_{i=1}^{N_s} x_i c_i + b \sum_i^{N_s} \sum_h^{N_s} x_i (1 - x_h) cv_{ih} + \sum_j^{N_f} \text{FPF}_j \text{FR}_j H(g_j) \left(\frac{g_j}{t_j} \right)$$

where x_i is a control variable with value 1 for selected planning units and 0 for units not selected, c_i is the cost of planning unit i, N_s is the number of planning units, N_f is the number of features, and t_j is the target level for feature j (Ball et al. 2009). The first part of the equation minimizes the penalties associated with the cost of the network and was used in our scenarios to reflect the variable costs of eradication and control (component 1). The second part of the equation minimizes the penalties associated with the configuration or shape of the network. In our case this part of the equation reflects our objective to minimize re-infestation of managed planning units (component 2). The parameter cv_{ih} reflects the cost of the connection, in this case the probability of spread from planning unit i to h calculated based upon the spread model. The parameter b, is the boundary length modifier (BLM), a user-defined variable that controls the importance of minimizing the total boundary length of the selected areas. For each scenario, we selected the BLM with the method described by Stewart and Possingham (2005), intended to achieve a level of connectivity between selected areas that does not unduly increase the overall cost of the solution. The third part of the equation minimizes the penalties associated with shortfalls in the targets for each feature (component 3). FPF_j is the feature penalty factor that determines the relative importance of meeting the representation target for feature j. We apply a FPF of 10 for all features. FR_j is the cost of meeting the target for feature j starting from no representation in the reserve network (details in Ball et al. 2009). The shortfall or gap in management g_j for MaxGain is the unmet representation target calculated as

$$g_j = C_j - \sum_{i=1}^{N_s} x_i \times C_j.$$

For MinLoss, the shortfall is

$$g_j = CR_j - \sum_{i=1}^{N_s} x_i \times CR_{ij}$$

where CR_{ij} is the conservation value j at risk from

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TABLE 1. Summary statistics of runs.

Conditions	Total area infested (ha)	Total 10 year expenditure (AUD$)	Total avoided infestations (ha)	Total eradicated area (ha)	Cost of avoided infestations (AUD$/ha)
Static estimates for complete management					
All initial infestations controlled	0	13 815 000	94 000	0	147
All initial infestations eradicated	0	19 541 000	94 000	11 000	208
Annual budget $600 000					
Scenario 1, MinLoss and local control	69 000	4 635 000	25 000	0	185
Scenario 2, MaxGain and local control	77 000	4 637 000	17 000	0	273
Scenario 3, MinLoss and local eradication	74 000	4 637 000	20 000	1 300	232
Scenario 4, MaxGain and local eradication	81 000	4 635 000	13 000	1 100	357
Unlimited annual budget					
Scenario 1, MinLoss and local control	33 000	12 584 000	61 000	0	206
Scenario 2, MaxGain and local control	44 000	10 994 000	50 000	0	220
Scenario 3, MinLoss and local eradication	33 000	11 700 000	61 000	8 400	192
Scenario 4, MaxGain and local eradication	44 000	10 154 000	50 000	8 400	203

Notes: The costs and benefits of complete control and eradication are given as static scenarios in addition to summary statistics for scenario runs under a constrained annual budget of AUD$600 000 (AUD, Australian dollars) and unlimited annual budget. For each run, the total area infested at time step 10 is given, the present value (PV) of expenditures over the 10-year period assuming a 5% discount rate, the total avoided infestations in runs where there was management (the baseline no-management final infestation value of 94 000 ha is used for calculations), the total infested area that was eradicated in year 10 where there was local eradication and the cost of avoided infestations (calculated as PV/total avoided infestations). Budget management scenarios are minimizing loss (MinLoss) and maximizing gain (MaxGain).

planning unit i calculated as

$$CR_{ij} = \sum_{h=1}^{N_s} v_{ih} \times a_{jh}$$

This represents the difference in expected conservation values at risk from gamba grass invasion and the number of infestations in conservation features avoided through management. The Heaviside function, $H(g)$, is a step function taking the value of zero when $g = 0$ and 1 otherwise.

RESULTS

In the initial time step ($t = 0$), there is 11 000 ha of infestations in the study region. In the absence of any control, over the 10-year period, there is an eightfold increase in infestations to 94 000 ha ($t = 10$). In order to control all initial infestations, an initial annual budget of AUD$2.4 million is needed, which declines to a recurring annual budget of AUD$1.6 million by year 6 (present value of control of all initial infestations is AUD$13.8 million, Table 1). In order to eradicate all infestations, an initial annual budget of AUD$6.7 million is needed, which declines to AUD$0.5 million by year 6 (present value of eradicating all initial infestations is AUD$19.5 million, Table 1).

Regardless of on-ground strategy (control or eradication) or budget, the MinLoss approach outperformed the MaxGain approach. For example, under the limited budget scenarios, MinLoss resulted in a ~50% increase in prevented spread compared to MaxGain (Table 1).

Given a limited budget, it is more effective to fund control efforts in terms of avoided infestations and cost-effectiveness (best-performing scenario, MinLoss and local control; Table 1). If the budget is not limited, eradication outperforms control and is more effective in terms of avoided infestations and cost effectiveness (best performing scenario, MinLoss and local eradication; Table 1).

In the constrained budget scenarios, the allocation of budget across conservation features was similar and reflects the original percentage of features infested (Table 2). However, the level of management in terms of total hectares managed was much lower in the local eradication scenarios (scenarios 3–4) compared to the local control scenarios (scenarios 1–2) due to the relative cost of action per ha of eradication. The spatial allocation of management effort within conservation features differed between MinLoss and MaxGain scenarios (Fig. 2), with MinLoss scenarios allocating more effort to the boundaries of features. These patterns are visually apparent in the Litchfield infestation: there are fewer infestations managed under the eradication scenarios (Fig. 2c, d) compared to control scenarios (Fig. 2a, b) and MinLoss scenarios (Fig. 2a, c) allocate more effort to the northwest border of the infestation to prevent further spread into the biodiversity and tourism zones.

The unlimited budget allocated effort to all infested features, resulting in the same patterns of investment across features for all scenarios. The important difference between local control and local eradication

TABLE 2. Area (ha) of conservation features infested.

	Initial, infested	No control, infested	MinLoss			MaxGain		
Feature			Infested	Managed	Eradicated	Infested	Managed	Eradicated
a) Annual Budget AUD$600 000								
Control								
SOCS	1 830	15 790	8 510	1 160	0	12 210	1 090	0
Tourist	3 690	9 310	4 680	2 050	0	5 370	1 890	0
Biodiversity	290	2 060	630	280	0	840	250	0
Rainforest	560	7 130	5 280	500	0	5 300	470	0
Protected area	5 690	31 830	13 680	3 120	0	24 760	2 700	0
Total features	7 510	46 810	25 050	4 200	0	35 830	3 800	0
Other infested	3 530	47 030	44 210	390	0	40 990	790	0
Total Infested	11 040	93 840	69 260	4 590	0	76 820	4 590	0
Eradication								
SOCS	1 830	15 790	11 210	510	510	12 680	1 050	160
Tourist	3 690	9 310	7 130	460	520	6 480	990	660
Biodiversity	290	2 060	1 090	80	150	1 140	340	90
Rainforest	560	7 130	5 440	300	80	5 510	540	90
Protected area	5 690	31 830	20 400	900	830	26 430	1 890	800
Total features	7 510	46 810	31 920	1 560	1 280	38 920	2 680	930
Other infested	3 530	47 030	42 460	1 580	60	41 930	860	160
Total infested	11 040	93 840	74 380	3 140	1 340	80 850	3 540	1 090
b) Unlimited annual budget								
Control								
SOCS	1 830	15 790	80	2 130	0	230	2 230	0
Tourist	3 690	9 310	0	3 690	0	0	3 690	0
Biodiversity	290	2 060	0	290	0	0	290	0
Rainforest	560	7 130	340	1 920	0	910	3 070	0
Protected area	5 690	31 830	40	5 820	0	170	6 110	0
Total features	7 510	46 810	460	9 270	0	1 300	10 810	0
Other infested	3 530	47 030	32 360	5 010	0	43 130	0	0
Total infested	11 040	93 840	32 820	14 280	0	44 430	10 810	0
Eradication								
SOCS	1 830	15 790	90	260	1 890	230	360	1 950
Tourist	3 690	9 310	0	0	3 690	0	10	3 710
Biodiversity	290	2 060	0	10	290	0	0	290
Rainforest	560	7 130	420	1 110	860	1 070	1 590	1 250
Protected Area	5 690	31 830	30	80	5 740	130	440	5 780
Total features	7 510	46 810	540	1 430	7 920	1 430	2 350	8 390
Other infested	3 530	47 030	32 940	3 970	430	42 340	0	0
Total infested	11 040	93 840	33 480	5 400	8 350	43 770	2 350	8 390

Notes: Where no conservation feature is present we use the term "other infested." (a) Annual budget of AUD$600 000 scenarios. (b) Unlimited annual budget scenarios. The initial extend of infestations ($t = 0$) as well as the final infestation ($t = 10$) under no control is provided and for each management scenario the final extent ($t = 10$) as well as the areas under management and eradicated are given in hectares. The term managed means either under active control or eradication in the final time step ($t = 10$) depending on the action applied in the scenario. SOCS, sites of conservation significance.

scenarios is that, in year 10, all of the initial infested assets are fully recovered under the eradication scenarios (~8400 ha) while in the control scenarios these assets will require funding in perpetuity (Table 2, Fig. 3). The difference in spatial allocation of effort between the MinLoss and MaxGain scenarios is visually apparent in the southeast corner of Litchfield Park (Fig. 3). In the MinLoss scenarios, effort is allocated to infestations as they approach the boundary, thus preventing invasion within the park (Fig. 3a, c). Similarly, along the riparian rainforest galleries outside the park, effort is allocated along the edges, preventing invasion (Fig. 3a, c). In contrast, the MaxGain scenarios allocate effort within conservation features once they are infested (Fig. 3b, d).

Rainforests appear to be particularly difficult to defend and recover from invasion due to their typically linear geometry and hence high perimeter to area ratio. This is apparent in the large increase in infested rainforest patches across all scenarios regardless of budget (Table 2). Along the southwest border of Litchfield Park, it is visually apparent that it requires a large amount of on-ground effort to defend the long stretches of riparian rainforest (Fig. 3) compared to protecting the border of the park.

DISCUSSION

Our finding that MinLoss outperforms MaxGain confirms previous studies findings in which MinLoss performs best particularly when there are high rates of habitat loss (Wilson et al. 2006, Visconti et al. 2010b). This finding is consistent with the expectation that an optimal invasive control strategy must be forward
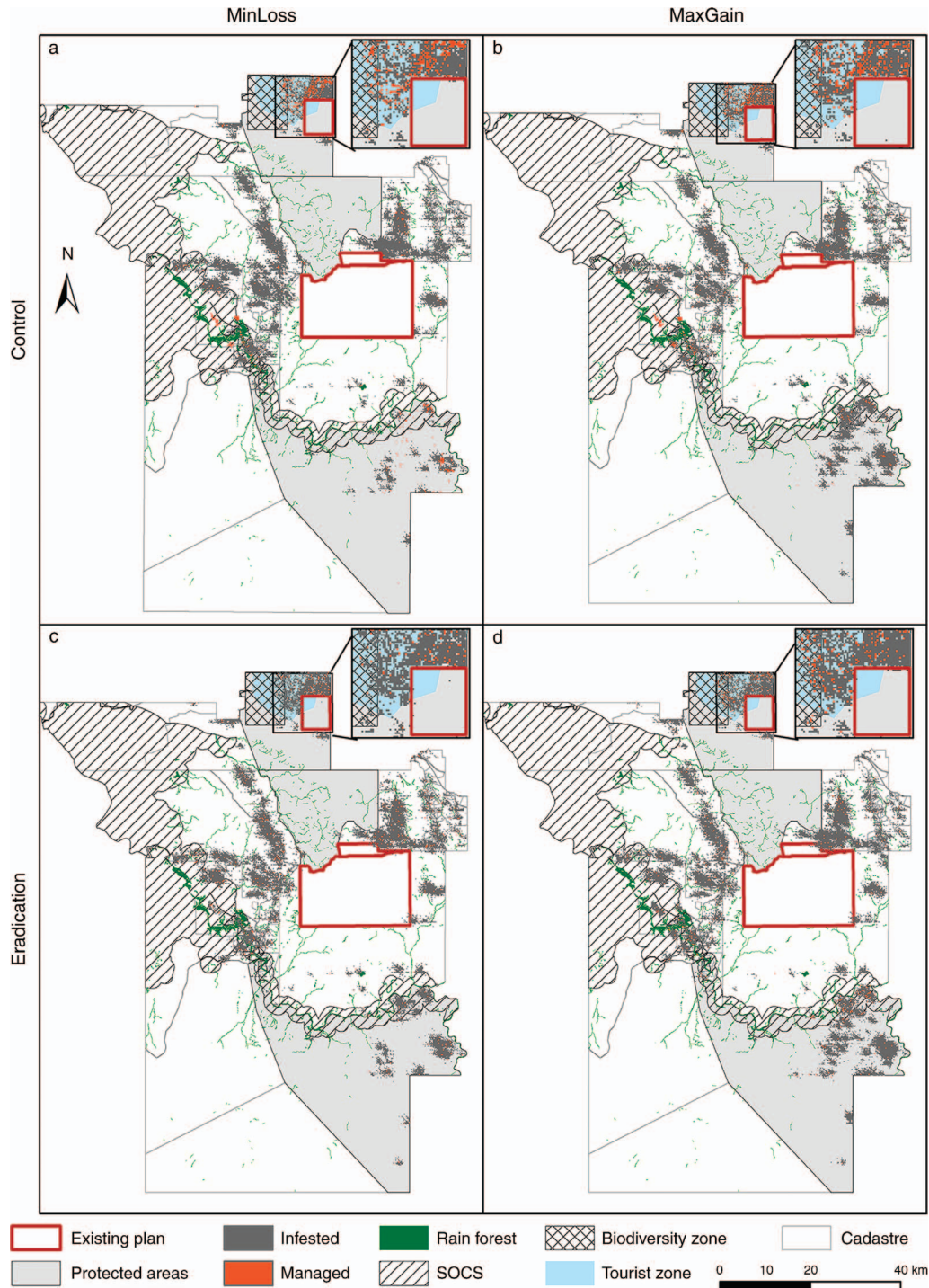
Fig. 2. Final distribution of gamba grass infestations (dark gray) and managed infestations (orange) at time step $t = 10$ for the four scenarios under a constrained budget of AUD\$600 000 a year. The infested region in Litchfield is zoomed into for each scenario to highlight spatial differences in selected areas for management. Conservation features include sites of conservation significance (SOCS), rainforest galleries, protected areas, the high biodiversity zone identified in Litchfield (biodiversity zone) and the tourism zone identified in Litchfield (tourist zone). Areas that are infested but under other management plans or arrangements are shown in red outline. (a) Scenario 1, MinLoss and local control; (b) scenario 2, MaxGain and local control; (c) scenario 3, MinLoss and local eradication; (d) scenario 4, MaxGain and local eradication. Budget management scenarios are minimizing loss (MinLoss) and maximizing gain (MaxGain).
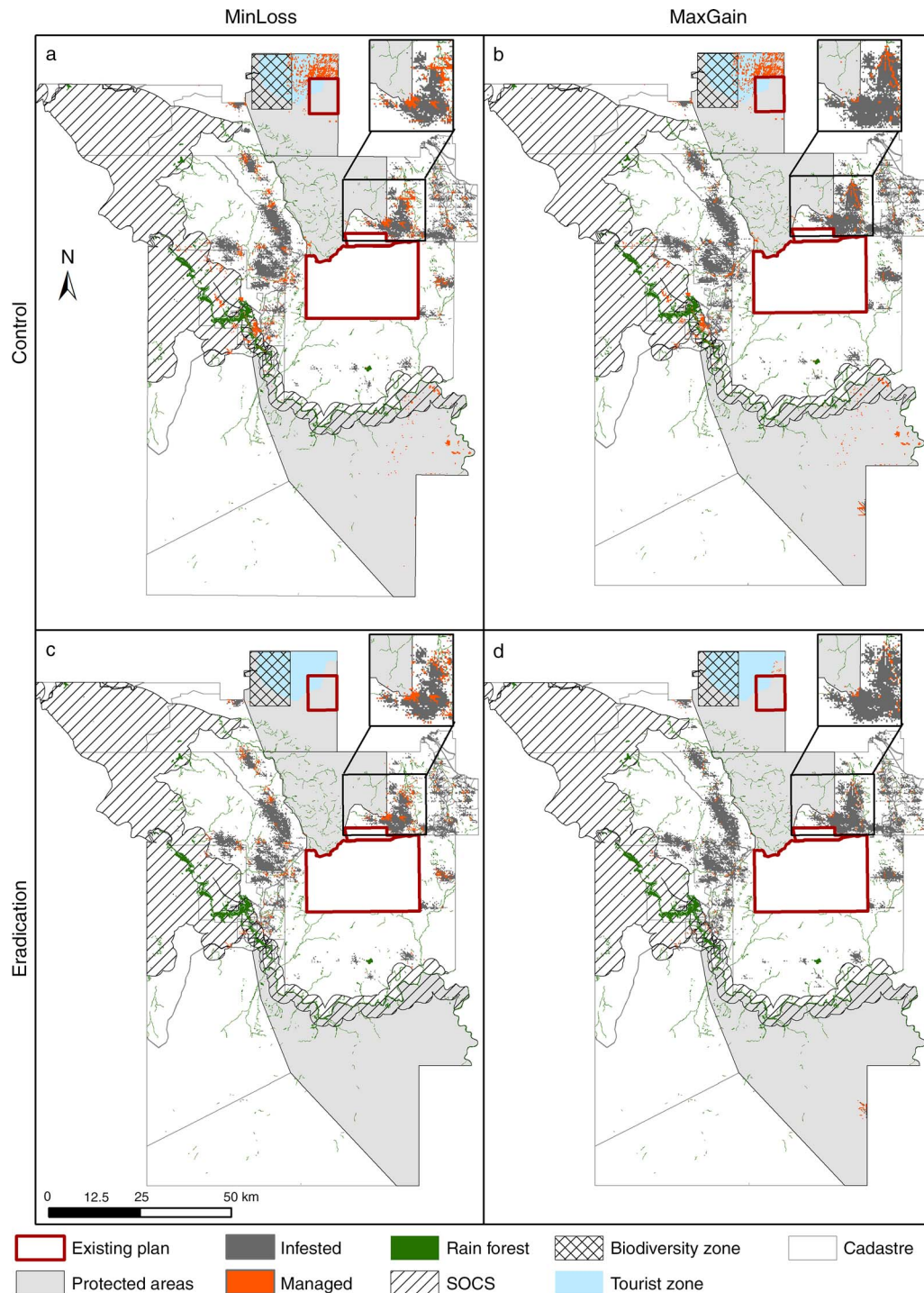
FIG. 3. Final distribution of gamba grass infestations (dark gray) and managed infestations (orange) at time step $t = 10$ for the four scenarios under an unlimited annual budget. The southeast border of Litchfield is zoomed into for each scenario to highlight spatial differences in selected areas for management. Conservation features include sites of conservation significance (SOCS), rainforest galleries, protected areas, the high biodiversity zone identified in Litchfield (biodiversity zone), and the tourism zone identified in Litchfield (tourist zone). Areas that are infested but under other management plans or arrangements are shown in red outline. (a) Scenario 1, MinLoss and local control; (b) scenario 2, MaxGain and local control; (c) scenario 3, MinLoss and local eradication; (d) scenario 4, MaxGain and local eradication.

looking to prevent the spread of the invasive species into high value sites (Epanchin-Niell and Wilen 2012). The relative performance of the MinLoss and MaxGain strategies in our case study is consistent with previous studies but is likely to reflect the rapid spread associated with gamba grass and may not hold for other invasive species with slower rates of spread. As such an important next step will be to explore the generalizability of our findings to a range of reasonable spread rates.

Given the rapid rate of spread in our study region, under a limited budget it is best to control invasions rather than invest in local eradication, which is consistent with invasion management recommendations (Panetta 2009). However, in our study region many of the infested planning units are still at low density levels. Therefore, it is more cost-effective to invest in eradication rather than control if there is an unlimited budget, which is consistent with the nonspatial findings of Adams and Setterfield (2013), which demonstrate that for smaller infestations eradication is more cost effective. Given the rate of invasion, the size and density of these infestations will rapidly increase such that if action is delayed, eradication will no longer be a cost-effective option and the costs of control will have dramatically increased (over 10 year time frame there is an eightfold increase in invasion given no management action). This demonstrates the immediate need for strategic management of gamba grass in the region in order to control the infestations while management is still operationally feasible and is consistent with recommendations to act early in the invasion (Puth and Post 2005, Epanchin-Niell and Wilen 2012).

Our study is the first study to our knowledge that extends a static systematic conservation planning approach (Januchowski-Hartley et al. 2011) to a multi-year dynamic scheduling approach for strategic allocation of invasion management. By applying a systematic conservation planning approach, we targeted planning units that contributed to multiple targets (complementarity) thus delivering greater benefits than simply targeting features based on cost effectiveness or simplified metrics of site value (e.g., Epanchin-Niell and Wilen 2012). In addition, by applying an existing and widely used systematic conservation planning tool, Marxan, we believe that our approach can be easily adapted to other regions and species and may be more accessible to managers. Furthermore, applying a multi-year approach allowed us to estimate both the benefits of action in terms of recovered and managed assets but also prevented losses of assets from spread. It also provides a more detailed understanding of how management efforts will vary spatially and temporally by providing annual allocations of efforts across planning units. For example, if a static planning approach were taken, the need to protect the southeast boundary of Litchfield would not be identified as this only becomes a priority as spread occurs from neighboring properties. In addition, a multi-year scheduling approach allows for the

consideration of dynamic levels of management effort and the associated costs. For example, the costs of control are relatively stable through time while eradication costs are much larger in the first years of the program and then dramatically decline through time. By allocating effort through time, the variable levels of funding through a control or eradication program can be estimated and planned for to ensure that adequate resources are available for the duration of treatment.

An important aspect of dynamic planning is the effect of uncertainty on decision making and outcomes. Visconti et al. (2010a) found that depending on uncertainty levels, using a MaxGain approach can deliver better results. Given our limited understanding of rates and patterns of spread of gamba grass, our estimated spread rate and distance for use in our simulations have high levels of associated uncertainty. A necessary next step would be to quantify the levels of uncertainty associated with the spread model and incorporate this into the decision framework to assess the robustness of strategies to this uncertainty.

Our results are consistent with the generalized spatial-dynamic problems explored by Epanchin-Niell and Wilen (2012), in particular that the optimal strategy (control or eradicate) depends both on the available resources and the level and location of invasion relative to the overall landscape. However, our approach also provides insights into the utility of applying systematic conservation planning principles. For example, we prioritized infestations with multiple conservation features, such as the boundary of the invasion in Litchfield where the biodiversity and tourism zones overlap, demonstrating a central tenet of systematic conservation planning: complementarity (i.e., conservation areas should be selected to maximize the differences in their biotic content [Sarkar et al. 2006]). Our approach provides insights into both the utility of spatial-dynamic planning and systematic conservation planning in prioritizing management of invasive species.

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SUPPLEMENTAL MATERIAL

Ecological Archives

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