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Cost and feasibility of a barrier to halt the spread of invasive cane toads in arid Australia: incorporating expert knowledge into model-based decision-making

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Summary

1. Active engagement with practitioners is a crucial component of model-based decision-making in conservation management; it can assist with data acquisition, improve models and help narrow the 'knowing–doing' gap.

2. We worked with practitioners of one of the worst invasive species in Australia, the cane toad *Rhinella marina*, to revise a model that estimates the effectiveness of landscape barriers to contain spread. The original model predicted that the invasion could be contained by managing artificial watering points on pastoral properties, but was initially met with scepticism by practitioners, in part due to a lack of engagement during model development.

3. We held a workshop with practitioners and experts in cane toad biology. Using structured decision-making, we elicited concerns about the original model, revised its structure, updated relevant input data, added an economic component and found the most cost-effective location for a barrier across a range of fixed budgets and management scenarios. We then conducted scenario analyses to test the sensitivity of management decisions to model revisions.

4. We found that toad spread could be contained for all of the scenarios tested. Our modelling suggests a barrier could cost \$4·5 M (2015 AUD) over 50 years for the most likely landscape scenario. The incorporation of practitioner knowledge into the model was crucial. As well as improving engagement, when we incorporated practitioner concerns (particularly regarding the effects of irrigation and dwellings on toad spread), we found a different location for the optimal barrier compared to a previously published study (Tingley *et al*. 2013).

5. *Synthesis and applications*. Through engagement with practitioners, we turned an academic modelling exercise into a decision-support tool that integrated local information, and considered more realistic scenarios and constraints. Active engagement with practitioners led to productive revisions of a model that estimates the effectiveness of a landscape barrier to contain spread of the invasive cane toad *R. marina*. Benefits also include greater confidence in model predictions, improving our assessment of the cost and feasibility of containing the spread of toads.

Key-words: artificial waterbodies, containment, cost-efficiency, engagement, knowing–doing gap, point process, *Rhinella marina*, spread model, stakeholders, structured decision-making

Introduction

Humans are poor at making unsupported decisions about complex problems (Kahneman & Tversky 1984), particularly when those problems are highly dimensional, probabilistic, stochastic and/or dynamic (Tversky & Kahneman 1974; Sternberg 2003). Conservation decision-making is always complex, involving trade-offs between social, economic and environmental values, each interacting, uncertain and individually complex elements (Ludwig, Mangel & Haddad 2001; Burgman, Lindenmayer & Elith 2005). Given this inherent complexity, humans can be poor at making sensible unsupported decisions around conservation management.

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Quantitative modelling and decision analysis can, however, provide important decision support. These tools help avoid common biases that undermine human judgment, and can explicitly incorporate uncertainty and constraints into decision-making (Akcakaya, McCarthy & Pearce 1995; Burgman 2005). Quantitative models aim to provide predictions about how an environmental system might behave in the future in response to competing management alternatives (Akcakaya, McCarthy & Pearce 1995; Burgman 2005). Models can simulate outcomes of management when on-ground experiments are difficult due to economic, social, ethical or ecological constraints; they can improve transparency, defensibility and repeatability of conservation decisions (Starfield 1997; Burgman & Yemshanov 2013); and they can identify important knowledge gaps for further research.

Advances in computational power, data availability and ecological theory have enabled evermore complex models of ecological systems. Despite this enhanced capacity, an important exercise often neglected by modellers during model development is practitioner engagement (Fulton *et al.* 2013; Wood, Stillman & Goss-Custard 2015). Practitioner engagement can benefit conservation decision-making by: (i) reducing conflicts between modellers and practitioners (Elston *et al.* 2014); (ii) facilitating a collective understanding of management problems, objectives and constraints (Sandker *et al.* 2010; Biggs *et al.* 2011); (iii) improving the representation and conceptualization of the study system (practitioners often have greater knowledge of the system being modelled; Nichols *et al.* 2007); and (iv) providing modellers with access to the most relevant data (practitioners generally have knowledge of unpublished data and literature).

Close collaboration also gives practitioners an increased awareness of, and trust in, model predictions. However, quantitative models remain underutilized by practitioners (Cowling *et al.* 2003; Knight *et al.* 2008), who often rely on unstructured subjective judgment, intuition or personal experience to make conservation decisions (Pullin & Knight 2005; Cook, Hockings & Carter 2010). This 'knowing–doing gap' (Knight *et al.* 2008) is partly the result of practitioners' perceptions of models as expensive, unrealistic, or poorly constructed, parameterized or validated (Wilkerson, Wiles & Bennett 2002; Hajkowicz 2007), or due to lack of communication by modellers during or after model development (Addison *et al.* 2013). As a result, conservation lags behind other fields such as fisheries and marine ecosystem-based management (Fulton *et al.* 2013) in adopting participatory, quantitative decision-making methods.

In this study, we actively engaged with landowners and practitioners to revise an existing model (Tingley *et al.* 2013), which predicted the effectiveness of a landscape barrier to halt the spread of one of Australia's worst invasive species, the cane toad *Rhinella marina*. Cane toads rely on artificial watering points (AWPs) during the dry season to spread across arid regions of Australia (Florance *et al.* 2011). Tingley *et al.* (2013) suggested that managing AWPs to construct a 'waterless barrier' might halt the invasion front and prevent toads from invading an additional 268 000 km^2 of their potential range. However, the model was met with scepticism from some practitioners, in part due to a lack of engagement between modellers and practitioners during model development. Debate centred on whether a barrier would be feasible given the assumptions in the model, undermining support for the best locations identified by Tingley *et al.* (2013).

The aim of this study was to identify and address landowners' and practitioners' concerns relating to the science, assumptions and data underpinning the model, to enable improved, model-based decision support. To achieve this aim, we sought to: (i) actively engage with landowners and practitioners to elicit concerns towards the Tingley *et al.* (2013) model; (ii) update model parameters using more relevant data agreed upon by both modellers and practitioners during engagement; and (iii) use a revised model to identify the most cost-effective barrier location, and assess whether that location is robust to ecological and economic uncertainty. By engaging with practitioners, we sought to improve their understanding of the model and its assumptions, gain feedback and incorporate their expert knowledge, and test the sensitivity of management decisions to this knowledge, while improving our assessment of the cost and feasibility of a cane toad barrier.

Materials and methods

STUDY SYSTEM AND SPECIES

Cane toads are one of Australia's most ecologically destructive invasive species. Since their introduction in 1935, they have spread rapidly across more than 1·2 million km^2 of Australia (Urban *et al.* 2007), causing declines in populations of many native predators (Shine 2010). The toads are predicted to continue spreading throughout coastal regions of tropical and subtropical Australia (Tingley *et al.* 2014), and have now reached the Kimberley region of north-western Australia (Fig. 1). Biophysical and dispersal modelling suggests that toads will continue to spread south into Western Australia (WA; Kearney *et al.* 2008; Florance *et al.* 2011; Tingley *et al.* 2013), threatening numerous endangered and endemic species that are naïve to the toad's toxin.

In the Australian arid zone, cane toad activity during the dry season is restricted to permanent waterbodies such as springs, perennial water courses and AWPs (Florance *et al.* 2011; Letnic *et al.* 2014). AWPs are constructed by pastoralists to make the landscape more suitable for cattle, and include circular dams (~30 m in diameter) and tanks fed by bores. Excluding toads from AWPs by erecting toad-proof fences around their perimeter or by replacing AWPs with toad-proof tank/trough systems may limit the establishment of populations (Florance *et al.* 2011; Letnic *et al.* 2015) and halt further spread of the invasion front if conducted across a large enough area (Tingley *et al.* 2013).

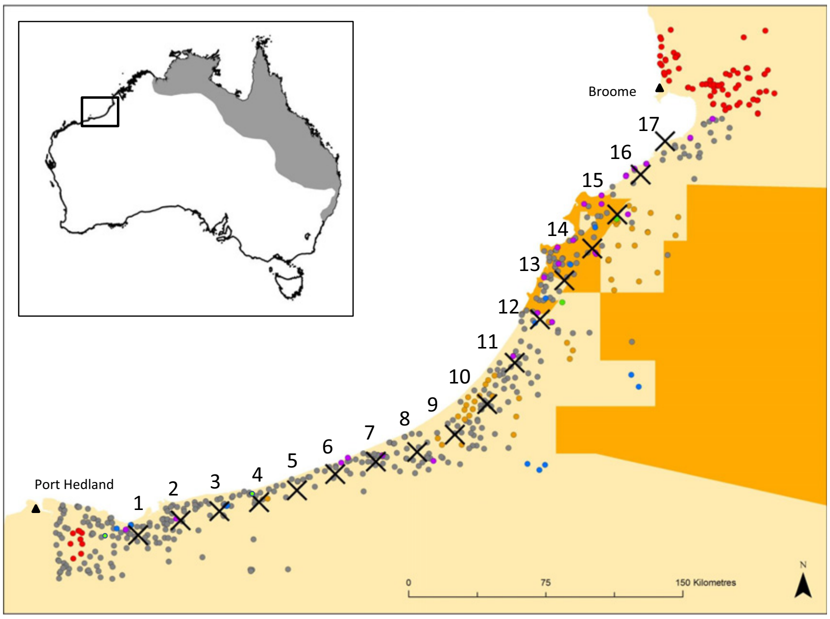

Fig. 1. Locations of dams (orange dots), tanks (grey dots), permanent natural waterbodies (blue dots), dwellings (purple dots) and irrigation (green dots) in the Kimberley–Pilbara corridor in north-western Australia. Waterbodies assumed to be colonized at the start of simulations are shown as red dots in the north of the corridor near Broome. The De Grey River (red dots near Port Hedland in the south) was used as the endpoint of all simulations. The Indigenous Protected Area (IPA) is shown with orange shading, within which AWPs will likely be decommissioned independently of the barrier. Barriers were simulated at 17 equally spaced locations within the corridor (black crosses). Insert map shows the location of the corridor in Australia and the approximate current distribution of toads (grey shading).

MODELLING A TOAD BARRIER

Tingley *et al.* (2013) tested the theoretical feasibility of a 'waterless barrier' to contain the spread of cane toads using a spatial spread model. Their model assumed that toads disperse freely during wet periods when conditions are humid and temporary waterbodies are numerous. Come the dry season, however, toads need to take refuge at permanent waterbodies, or perish. The model simulated the spread of toads using information about the locations of permanent waterbodies and data on the dispersal ability of toads in response to rainfall. The density D of potential colonizing toads at any location m depended on: (i) the toads' rainfall-dependent dispersal kernel $K_i(d_{im})$ and the distance between the location and each occupied waterbody d_{im}; and (ii) the number of potential colonizers emanating from occupied waterbodies C_i, given by:

$$D_m = \sum_{i=1}^{n} C_i K_i(d_{im}) \qquad \text{eqn 1}$$

where n is the total number of occupied waterbodies. Tingley *et al.* (2013) assumed that toads can detect waterbodies within a radius r_d of 100 m; that a waterbody is colonized if two or more toads arrive in a single generation; that the population at a colonized waterbody reaches carrying capacity instantaneously; and that toads disperse from colonized waterbodies the season following colonization.

The total number of days per year that toads could disperse from each waterbody (N) was a function of the number of rainy days at that location, based on the rate at which surface water is likely to evaporate in this landscape:

$$N = x + 3(x)\big(1 - (3(w - w^2) + w^3)\big) \qquad \text{eqn 2}$$

where x is the average number of rainy days (>1 mm between 1961 and 1990) at each waterbody and $w = (x - 1)/364$. To determine the dispersal kernel for toads at each waterbody, data on the movement of 114 radiotracked toads were used to generate a resampled distribution of scalar displacement for days of movement between 1 and 180 days. Dispersal was well described by a two-dimensional t-distribution:

$$K_{ID}(z) = zu^v v\sqrt{\frac{v^v}{(u^2v + z^2)^{(2+v)}}} \qquad \text{eqn 3}$$

where z is absolute displacement and u and v are shape and scale parameters of a t-distribution, respectively.

Using this model, Tingley *et al.* (2013) predicted the effectiveness of a barrier positioned at three locations in an arid region between the Kimberley and the Pilbara in north-western Australia, approximately 650 km ahead of the invasion front where there is a natural 'bottleneck' in the availability of surface water (hereafter referred to as the corridor; Fig. 1). They found that the spread of toads through this area could be contained by managing as few as 110 AWPs. Further details and justifications are described in Tingley *et al.* (2013).

UPTAKE OF THE MODEL

Several NGOs and state and federal government agencies expressed interest in the idea of a barrier, but some practitioners were concerned about the reliability of model predictions. This scepticism impeded any further assessment or implementation of a barrier, and was partly because the model was developed by experts in cane toad biology without consultation with practitioners and land managers at the proposed barrier locations. Below we describe how we actively engaged with local practitioners to elicit and address concerns towards the model, and how we used a revised model to assess the cost–benefit of a proposed barrier scheme.

ELICITING EXPERT AND LOCAL KNOWLEDGE

We held a 1-day workshop in Broome, WA (Fig. 1), to: (i) discuss the feasibility of a toad barrier; (ii) better understand practitioners' concerns towards the model; and (iii) incorporate their knowledge of toad biology and of the corridor into the model.

The workshop was attended by 24 practitioners and experts in cane toad biology from universities, state and federal government agencies, indigenous ranger groups, community groups and NGOs.

We ran the workshop using structured decision-making, which involved systematically evaluating the problem, management objective, alternative actions and sources of uncertainty (Gregory *et al.* 2012). There was widespread agreement that a barrier is the most promising strategy to contain toad spread in the corridor. We presented the model, explaining its capabilities, assumptions and limitations using visual aids. We then elicited all of the concerns towards the model and asked practitioners to identify which three concerns should be addressed to improve predictions (three votes were assigned to the most important concern, two to the second-most important and one to the third-most important). In order of importance, workshop attendees ranked the following concerns:

1. verifying the accuracy of waterbody data and modelling other potential refuges (35 votes);
2. incorporating a cost component, particularly incorporating ongoing costs (14 votes);
3. incorporating more recent rainfall data with temporal and spatial variation (11 votes).

Following the workshop, we updated the original model to address these concerns, described in detail below.

REVISING THE MODEL

Improving the accuracy of waterbody data

Workshop participants were concerned about the accuracy of waterbodies (both artificial and natural) in the original model, collated from a single source (Geoscience Australia mapping; http://www.ga.gov.au/meta/ANZCW0703008969.html). To improve the reliability of waterbody locations, we augmented the original data with data from the Department of Water, WA, and the Department of Agriculture and Food, WA. Data are available upon request from these two agencies. We screened our augmented data set for duplicates and classified each waterbody as a dam (an open man-made reservoir), tank or permanent natural waterbody.

To verify our augmented waterbody data set, we then conducted face-to-face interviews with 10 of the 12 private land managers in the corridor (two were unavailable). We presented each manager with a map of their property and asked them to verify the location, type and status of each waterbody. This process identified 566 waterbodies in the corridor (0·037 per km^2), 44 fewer than identified by Tingley *et al.* (2013).

Workshop attendees and land managers were concerned that toads may seek refuge at locations in the corridor other than permanent waterbodies, such as irrigated areas and dwellings (e.g. homesteads, resorts, roadhouses). We therefore mapped all dwellings (n = 26) and irrigated areas (n = 4) in the corridor after consulting land managers. Irrigated areas were grouped into two categories: horticulture (n = 1) and hay production (n = 3). The detection radius and number of colonists emanating from these points were modified to account for their larger area compared with AWP (see Appendix S1 in Supporting Information).

The workshop also identified AWPs that, although mapped, may not contribute to the future spread of toads. In particular, an Indigenous Protected Area (Karajarri IPA) was recently established in the north of the corridor (Fig. 1). An IPA is a class of protected area formed in agreement with, and managed by, Indigenous Landholders. We consulted the Kimberley Land Council to identify which AWP within the Karajarri IPA will likely be decommissioned and thus not contribute to the future spread of toads.

Incorporating cost

Practitioners viewed cost as a crucial factor influencing the feasibility of a barrier, believing the cost of the barrier to be prohibitive. We therefore added a cost estimation component to the model using information from published reports and local experts (Table 1). Further model assumptions of our revised model included the following:

- Toads could be excluded from AWPs but not from natural waterbodies or dwellings (we call this the 'most likely' scenario, although we tested the sensitivity of these assumptions). To exclude toads from AWPs, we assumed existing dams and tanks would be replaced by leak-proof tanks.
- Toads could be excluded from the single horticultural area by erecting a permanent fence around its perimeter; erecting fences around waterbodies results in toad death within 3–4 days during the dry season (Florance *et al.* 2011; Letnic *et al.* 2015).
- For the three hay production areas, toads could be controlled by foregoing one harvesting cycle each year, preventing toads from accessing water for a period that exceeded their dehydration tolerance.
- The surveillance cost for AWPs is negligible because tanks are already checked by pastoralists every 1–3 days.
- Waterbodies managed as part of a barrier had a small chance of failing in each time step; those that failed were assumed to contribute to one generation of spread before being detected and repaired by the start of the next time step. No information was available on the failure rate of managed AWPs. We therefore chose a conservative failure rate of 5% and conducted a sensitivity analysis on this parameter (Fig. S3).

The cost C (net present value) of managing n waterbodies in the corridor was given by:

$$C = \sum_{i=1}^{n}\left(I + \sum_{t=1}^{T}\left(M + \frac{R}{L}\right)(1-\delta)^{t}\right) \qquad \text{eqn 4}$$

where I is the installation cost, M incorporates ongoing annual maintenance and surveillance costs (visiting AWP to monitor and repair leaks), R is replacement cost, L is the life span of the infrastructure, δ is the rate of time-discounting (set at 2·5%) and t is time. The length of the management programme, T, was set to 50 years. Installation, maintenance and replacement costs were functions of travel costs, labour and materials (Table 1). All costs are given in 2015 Australian dollars.

Refining dispersal data

Tingley *et al.* (2013) assumed that toad dispersal was a function of the average number of rainy days (>1 mm) recorded at waterbodies from 1961 to 1990. Workshop participants were concerned that this did not account for the higher and more variable rainfall experienced in recent years. To account for both temporal and spatial rainfall variability, we extracted the number of rainy days (>1 mm) at each waterbody for each year between 1990 and 2009

Table 1. Summary of cost parameters. All monitoring and maintenance costs are subject to a 2·5% interest rate

Waterbody type	Action	Installation (I) and Replacement (R)	Monitoring and maintenance (M)	Life span (years)	Source
Artificial (AWP)	Install leak-free tank	Travel costs ($1·50/km from Broome or Port Hedland)	Travel costs ($1·50/km from Broome or Port Hedland)	50	Workshop attendees
		Labour (32 h at $100/h) Materials ($8500)	Labour (8 h at $100/h) Materials ($500)		Land managers
Horticulture	Erect fence	Travel costs ($1·50/km from Broome or Port Hedland)	Labour (8 h at $100/h × 26 weeks)	10	Brook, Whitehead & Dingle (2004)
		Labour (32 h/100 m at $100/h) Materials ($3000/100 m × perimeter)	Materials ($100)		Shane Sercombe, Central Outback Contracting (pers. comm.)
Agriculture (Hay production)	Compensation	NA	$1650/ha × area (ha)	NA	Christopher Ham, Department of Agriculture and Food, WA (pers. comm.)

using 5-km gridded rainfall data from the Australian Water Availability Project (AWAP; Raupach *et al.* 2009) and cycled through this 20-year period during simulations (Fig. S1).

The dispersal kernel K_i used in the original model is long-tailed, which allowed toads to disperse infinite distances from colonized waterbodies (albeit with a small probability). Workshop participants identified this assumption as unrealistic, concluding that there is an upper limit to the distance toads can disperse in a given year. We therefore truncated and then renormalized the kernel at a distance of 55 km, the estimated annual advance of the invasion front in the Northern Territory between 2001 and 2006 (Phillips *et al.* 2007). While more accurate, this distance is still likely to overestimate the rate at which toads would spread through the corridor, as it was derived from the toads' advance through tropical Australia where environmental conditions are much more favourable (Tingley *et al.* 2014).

COST-EFFECTIVENESS AND SCENARIO ANALYSES

We first simulated the spread of toads through the corridor assuming no management using the revised model. We assumed that toads had colonized the Kimberley at the start of simulations (Fig. 1). We ran the model for 1000 iterations until either 50 years had elapsed or the De Grey River, located at the southern end of the corridor, had been colonized (Fig. 1).

We then found the most cost-effective location for a barrier across a range of fixed budgets. To do this, we centred a barrier at 17 equally spaced locations along the corridor (~20 km apart; Fig. 1). At each location, we created a barrier by sequentially removing the closest AWPs until a fixed budget was exhausted. Thirty budgets were tested, ranging from $200,000 to $6 M over 50 years. For each budget and barrier location, we assessed two management objectives: (i) minimize the probability that toads reached the De Grey River; and (ii) minimize the number of colonized waterbodies at the end of 50 years.

We ran the simulations described above using what workshop attendees considered the 'most likely' scenario, that is with an active IPA, with spatial and temporal variation in the number of rainy days at each AWP, a dispersal kernel truncation distance of 55 km, a failure rate of 5% and when only AWPs are managed. Workshop attendees agreed that while detection of toads at dwellings will likely be higher than at remote locations such as AWPs, eradication or even restricting their access to water at these locations would be next to impossible (Wingate 2011).

We also ran the model for a range of alternative landscape and management scenarios to test the sensitivity of barrier locations to key model revisions. Specifically, we ran three additional management scenarios: (i) both AWPs and dwellings were managed (although managing dwellings did not incur a cost); (ii) AWPs and irrigation were managed (with a cost for managing irrigation areas); and (iii) both irrigation and dwellings were not included in the data set.

Further sensitivity analyses were also conducted with an inactive IPA, on alternative failure rates (0%, 2·5%, 10%), on the truncation distance of the dispersal kernel and on the number of days that toads could disperse from waterbodies (Figs S2–S4). For example, we tested the robustness of a barrier location to extremes in rainfall by modelling a very dry landscape (toads could disperse from occupied waterbodies for 50 days each year), a very wet landscape (toads could disperse from occupied waterbodies for 180 days each year) and alternative truncation distances (30 and 78 km).

Results

DO NOTHING SCENARIO

Our model predicted that it could take 20·29 years (SD = 1·92) for toads to spread from the Kimberley to the De Grey River in the Pilbara in the absence of a barrier, which is approximately 4 years (16%) faster than predicted by Tingley *et al.* (2013). Toads spread faster in our model because we used updated rainfall data (with spatial and temporal variation) and incorporated dwellings and irrigation in the landscape. More recent rainfall data, in particular, allowed toads to disperse faster through the northern half of the corridor, where it was significantly wetter than assumed in the original model (Fig. S1). Modelling irrigation and dwellings also increased the rate of spread because these points produced more dispersers, were more easily detected by colonists compared with AWP (due to their larger area) and were relatively evenly distributed throughout the corridor. Toads reached the Pilbara in <32 years in the absence of a barrier for all of the scenarios tested (Fig. S4).

THE MOST COST-EFFECTIVE BARRIER LOCATION

The most cost-effective location for a barrier under the 'most likely' landscape scenario (where only AWPs are managed, but not dwellings or irrigation areas) was relatively insensitive to the available budget (Fig. 2a,c). Managers would have to spend ~\$4·5 M over 50 years developing and maintaining a barrier ~80 km wide at location 10 or 11 to reduce the probability of toads reaching the Pilbara to <0·05. A barrier at these locations also minimized the number of waterbodies colonized after 50 years (Fig. 2e). A barrier positioned north of location 12 had little effect at containing the invasion front because toads could still spread via dwellings and/or irrigation.

In the scenario where toads were excluded from *AWPs and dwellings*, location 8 was the most cost-effective at containing the invasion front, followed by locations 7 and 9 (Fig. 3b,d). Again, managers would have to spend ~\$4·5 M over 50 years to reduce the probability of toads colonizing the Pilbara to below 0·05. Barriers positioned north of location 11 or south of location 7 were relatively ineffective for this scenario because toads could still spread using irrigated areas as stepping stones.

When *AWP and irrigated areas* were managed, locations 9, 10 and 11 were most cost-effective, at a cost of, again, ~\$4·5 M over 50 years (Fig. 3a,c). Location 11, followed by locations 10 and 9, minimized the number of waterbodies colonized after 50 years. When *both irrigation and dwellings* were removed from the data set, the most cost-effective location for a barrier was location 17 in the far north of the corridor, followed by locations 16 and 5 (Fig. 2b,d).

Decommissioning AWPs *within the IPA*, changing the number of rainy days at each waterbody and truncating the dispersal kernel had a slight effect on the most cost-effective location for a barrier (Figs S2–S4). However, the absolute cost of a barrier was sensitive to changes in these parameters: a more expensive barrier was required when we assumed a wetter than expected landscape (180 days of movement), or a larger than expected truncation distance (78 km).

Similarly, the most cost-effective barrier location was insensitive to the choice of failure rate, unless management was assumed to be 100% effective (Fig. S3). The overall cost of a barrier did, however, increase with failure rate. For example, the model predicts that managers would need to spend ~\$3·5 M on a barrier if the failure rate is 2·5%, but this amount increased to ~\$9 M if 10% of managed AWPs failed each year.

Discussion

Decisions regarding the optimal location, size and configuration of barriers are complex and entail uncertainties (Bode & Wintle 2010). Our modelling, as a result of extensive practitioner consultation, suggests that toad spread through the Kimberley–Pilbara corridor in north-western Australia can be contained, even for scenarios with extremely high rainfall (180 days of toad movement) or a large truncation distance (78 km). A barrier positioned in the middle of the corridor (locations 10–12) was most cost-effective for scenarios including the revised AWPs, dwellings and irrigation. Our results confirm the importance of practitioner engagement during model development and analysis because local knowledge overlooked in the original incarnation of the model – specifically knowledge about irrigation and dwellings – influenced the best barrier location. Excluding these points from the analysis shifted the most cost-effective barrier location from the middle of the corridor to the far north (locations 16 and 17). The most cost-effective locations for all of our scenarios also differ to those reported by Tingley *et al.* (2013), partly because they tested a barrier at fewer locations, and partly because they did not explicitly incorporate expert knowledge of the corridor into the model.

Our results suggest that for the most likely scenario where only AWPs are managed, an investment of ~\$4·5 M would reduce the probability of toads reaching the Pilbara to < 0·05 over 50 years. This is considerably less than the amount spent on other invasive species management programmes in Australia. For example, the Australian government recently spent \$19 M on feral camels in central Australia over 4 years, and \$35 M on the fox eradication programme in Tasmania over 8 years (Newsome *et al.* 2015). A toad barrier is relatively cost-effective (~\$90,000 per year), because we found that most pastoralists have already converted open dams to tanks (due to aridity and soil drainage conditions), and because they already check their watering infrastructure every 1–3 days. These factors would substantially reduce upfront installation and ongoing maintenance costs. A toad barrier is not only cost-effective, but also has the potential to create a win–win situation for pastoralists and conservationists, because installing leak-proof tanks improves farm productivity, while simultaneously mitigating a key threatening process for biodiversity.

Practitioner engagement not only validated and refuted important data, but also led to more realistic model assumptions. For example, we truncated the dispersal kernel to eliminate long-distance dispersal. Although cane toads occasionally hitchhike on vehicles (White & Shine 2009), the probability of such dispersers establishing viable populations south of the barrier is extremely small because: (i) toads have external fertilization, making it impossible for lone dispersers to establish populations ahead of the invasion front; (ii) if more than one individual jumps ahead of the invasion front, they are likely to be of the same sex because sex ratios are highly skewed in

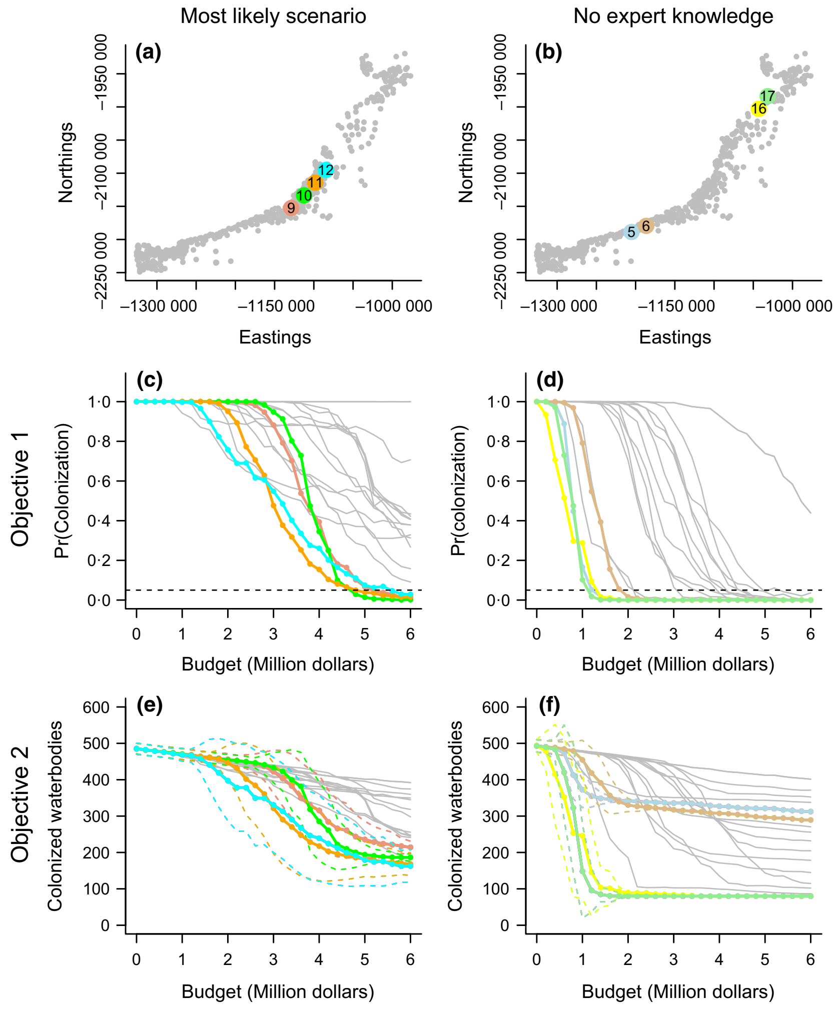

Fig. 2. The most cost-effective locations for a barrier in the Kimberley–Pilbara corridor with a truncation distance of 55 km, our best estimate of the number of rainy days, a 5% failure rate, and assuming only AWPs are managed. The left column (a,c, e) assumes the most likely management scenario with expert knowledge (irrigation and dwellings are modelled but not managed); the right column (b,d,f) ignores expert knowledge (irrigation and dwellings are not included in the waterbody data set). The top row (a,b) shows the locations of the best four barrier locations under objective 1. The probability of toads reaching the Pilbara for each of the 17 potential barrier locations across a range of fixed budgets is shown in the middle row (c,d). The number of waterbodies colonized after 50 years is shown in the bottom row (e,f). In figures (c–f), coloured lines represent the first four locations to fall below a 5% chance of toads colonizing the Pilbara. The corresponding position of these locations is shown in the top row (a, b). Dashed lines (e,f) represent standard errors from 1000 simulations.

space and time; and (iii) dispersal following transportation makes it unlikely that transported toads would find each other to breed. These arguments are backed up by the observation that despite billions of toads being present in Australia for over 80 years, and the relatively common detection of transported toads in densely trafficked parts of the country (i.e. major cities; White & Shine 2009), there have been very few accidentally seeded populations that have successfully established ahead of the front (Lever 2001). Nonetheless, post-barrier surveillance, quarantine and community education would obviously play important roles in minimizing the chance of long-distance dispersal across the barrier.

While there are various ways to engage practitioners, to date, there is little understanding of which approaches achieve and maintain collaboration (Wood, Stillman & Goss-Custard 2015). We adopted a structured decision-making approach, which is advocated in the conservation literature for explicitly acknowledging uncertainty, facilitating relationship building and revealing hidden agendas (Addison *et al.* 2013). There is no doubt that in this case, the engagement process, facilitated by structured decision-making, helped all parties agree on the problem and objective, while improving practitioners' understanding of the model's capabilities and limitations, as well as modellers' understanding of the landscape. The effect of engagement with practitioners on decision-making is often unclear: they may change their mind when provided with relevant information (Walsh, Dicks & Sutherland 2015) or maintain their original belief (McConnachie & Cowling 2013). An avenue of further research, although outside the scope of this study, would be to quantify how engagement influenced trust towards the model and its use as a decision-support tool.

Finally, engaging with practitioners revealed a number of practical considerations that could further clarify the feasibility of a barrier strategy. First, our model relies on the assumption that toads cannot survive between mapped waterbodies during the dry season. Fine-scale on-ground mapping of waterbodies and radiotracking toads at candidate barrier locations would provide useful tests of this assumption. Secondly, the failure rate had little effect on the most cost-effective barrier location unless managed AWPs can be kept completely leak-free. However, the failure rate did influence the overall cost of a barrier. Thus, further research is required to better understand how often managed AWPs leak enough water to sustain at least one toad throughout the dry season. One option to reduce the failure rate, should it be high, is to also erect toad-proof

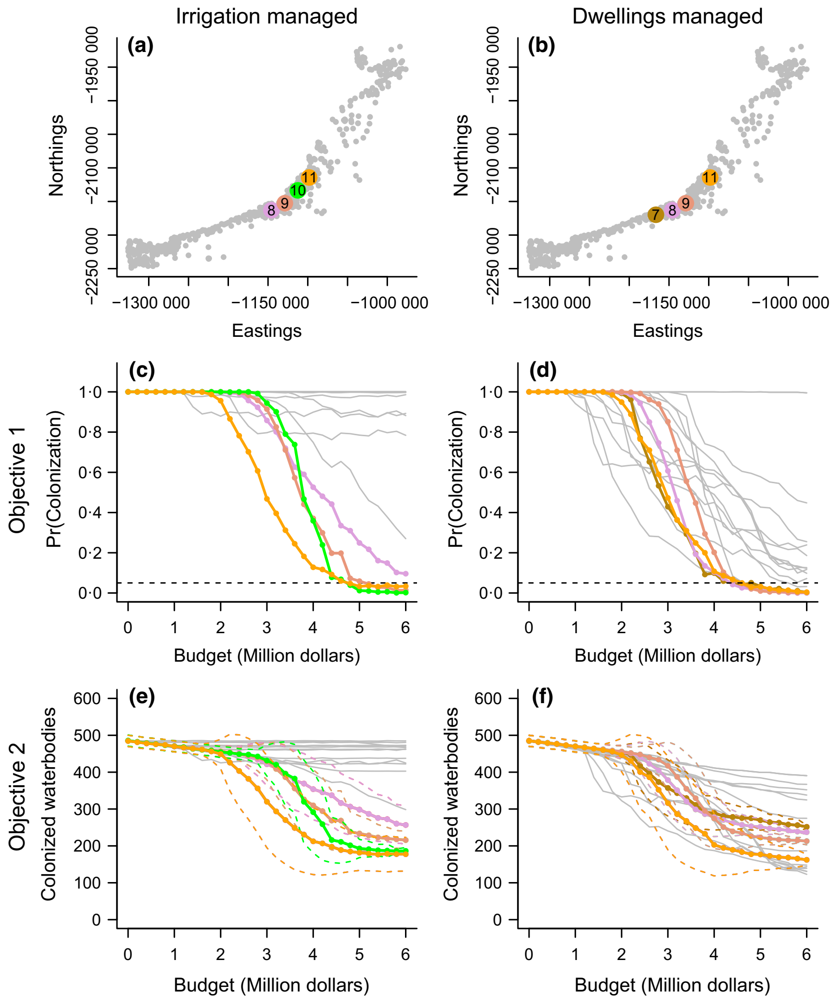

Fig. 3. The most cost-effective locations for a barrier in the Kimberley–Pilbara corridor with a truncation distance of 55 km, our best estimate of the number of rainy days, a 5% failure rate, an active Indigenous Protected Area (IPA), and assuming AWP are managed. The left column (a,c,e) assumes irrigation is managed and that toads cannot be excluded from dwellings. The right column (b,d,f) assumes dwellings are managed and that toads cannot be excluded from irrigation. The top row (a, b) shows the locations of the best four barrier locations under objective 1. The probability of toads reaching the Pilbara for each of the 17 potential barrier locations across a range of fixed budgets is shown in the middle row (c,d). The number of waterbodies colonized after 50 years is shown in the bottom row (e,f). In figures (c–f), coloured lines represent the first four locations to fall below a 5% chance of toads colonizing the Pilbara. The corresponding position of these locations is shown in the top row (a,b). Dashed lines (e,f) represent standard errors from 1000 simulations.

fences around managed AWPs. However, while this additional measure would reduce the chance of toads accessing water, it would substantially increase installation and maintenance costs. Finally, our optimization procedure ignored potential social opportunities or constraints a barrier may present. Further research could parameterize a penalty for barriers that span multiple land tenures, incorporate incentives or include a reward for barriers that present social opportunities such as the involvement of indigenous ranger groups.

We modified a previously published model of cane toad spread across an arid region of north-western Australia to find the most cost-effective location for a barrier through participatory modelling and scenario analysis. Our findings are broadly in agreement with those of Tingley *et al.* (2013): that a barrier can stop toads reaching the Pilbara. However, the results of our refined analysis indicate that the best location is sensitive to local knowledge of the corridor, particularly the locations of dwellings and irrigated areas. By eliciting and addressing concerns with the Tingley *et al.* (2013) model, we involved practitioners in the model-building process. Although this does not guarantee adoption, an ongoing dialogue not only establishes trust, but benefits both modellers and practitioners. As such, ongoing dialogue should be routine in model-based conservation decision-making.

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Data accessibility

Waterbody data are available upon request from Geographic Information Systems at the Department of Agriculture and Food, WA (samantha.vanwyngaarden@agric.wa.gov.au), and the Spatial Data Exchange section of the Department of Water, WA (timothy.fardon@water.wa.gov.au). Rainfall data are available from the Australian Water Availability Project (AWAP) (http://www.csiro.au/awap/).

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Supporting Information

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

Appendix S1. Detection radius for irrigation and dwellings.

Fig. S1. Rainfall variability across space and time.

Fig. S2. Barrier locations with an inactive Indigenous Protected Area (IPA).

Fig. S3. Barrier locations with alternative failure rates.

Fig. S4. Barrier locations with alternative number of rainy days and truncation distance.