Estimating the value of quarantine: eradicating invasive cane toads from tropical islands

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Abstract

Islands are increasingly used to protect endangered populations from the negative impacts of invasive species. Quarantine efforts on islands are typically undervalued, however. Using a field-based removal experiment, we estimate the economic value of quarantine efforts aimed at keeping invasive cane toads (*Rhinella marina*) off Australian islands. We estimate a mean density of 3444 [2744, 4386] individual toads per km^2 and a mean per-night detection probability of 0.1 [0.07 ,0.13]. Using a removal model and estimates of economic costs incurred during toad removal, we estimate that eradicating cane toads would cost $AUD\$96{,}556$ per km^2. Across islands that have been prioritized for conservation benefit across the toads predicted range, we estimate the remaining value of toad quarantine to be more than $1.3 billion. The value of a proposed waterless barrier on the mainland to prevent the spread of toads into the Pilbara was in excess of $26 billion. We conclude that quarantine of toads across Australia provides substantial value in prevented eradication costs.

Keywords: Cane Toad, density, detection probability, eradication, islands, preventative management

Introduction

It is a truth universally acknowledged that an ounce of prevention is worth a pound of cure. Despite this truism, conservation managers rarely ascribe value to preventative management. Without such valuation, we risk falling prey to cognitive biases (e.g., immediacy bias), and so routinely commit substantially more money and effort to tactical, "cure" type approaches, compared to strategic "prevention". Quarantine against invasive species is a case in point; vastly more resources are spent controlling the spread and impact of invaders than are spent on preventing their arrival and establishment.

Quarantine is particularly likely to be undervalued in circumstances in which a failure incurs non-economic costs (e.g., biodiversity loss) (Leung et al. 2002). One way to place a value on such quarantine efforts is to calculate the cost of restoring the system to its former state. In the case of an invasive species with primarily non-economic impacts, we can calculate the ongoing value of quarantine as the expense of a subsequent eradication program. Such a valuation is a lower bound on the value of quarantine for two reasons. First, the same quarantine effort typically protects against many potential invasive species. Second, any impact that the invasive species has before it is eradicated (e.g., local extinction of a native species) must be added to the cost of restoration (Hoffmann & Broadhurst 2016, Jardine & Sanchirico 2018). Thus, the cost of eradication of a single invader is a very conservative estimate of the true value of quarantine efforts.

Islands are important resources for conservation quarantine because they offer a natural barrier to the spread of invasive species. Conservationists routinely exploit this property of islands, not only to protect species that naturally occur on islands, but also to provide refuge for species under threat on the mainland (Thomas 2011). In Australia alone, 47 conservation translocations to islands have been carried out to date (Department of the Environment, Water, Heritage and the Arts, 2009). In these circumstances – where the conservation value of an island has been artificially bolstered – the arrival of invasive species can have a larger impact than they otherwise would.

Typically, island quarantine is used by conservation managers to protect native species from invasive predators (e.g., foxes, cats, weasels, rats). In Australia, however, islands are also used to mitigate the impact of cane toads (*Rhinella marina*) on native predators (Moro *et al.* 2018). Cane toads were introduced to northeastern Australia in the 1930s and, in northern Australia, continue to spread westerly at a rate of ~50 km per year (Phillips et al. 2010). This invasion has had major impacts on populations of native predators, many of which have no resistance to the toad's toxin (Nelson et al. 2010; Greenlees et al. 2010; Llewelyn et al. 2014). In response to declines of multiple predator species (e.g., dasyurids, monitors, snakes) the Australian government implemented the Cane Toad Threat Abatement Plan (2011), which aimed to identify, and where possible reduce, the impact of cane toads on native species (Shanmuganathan et al. 2010). A lack of viable methods for broad-scale control, however, has since led the Australian government to place an increased emphasis on containment (on the mainland) and on quarantine (on offshore islands) to mitigate the biodiversity impacts of cane toads.

While quarantine is currently the best available strategy, it is not a panacea: cane toads have already established on at least 48 islands across northern Australia (McKinney et al. 2018 unpub data), with potential for further natural and anthropogenic introductions. Thus, execution of the strategy outlined in the Cane Toad Threat Abatement Plan requires ongoing quarantine and containment efforts. Here we estimate the monetary value of these ongoing efforts, by quantifying the cost of eradicating cane toads from an island in northern Australia. We approach this problem by estimating the density and detection probability of toads on an island, and use these estimates to calculate the amount of time and money it would take to remove enough toads to ensure eradication.

Methods

Study Area

This study was carried out at Horan Island on Lake Argyle, Western Australia. Lake Argyle is Western Australia's largest man-made reservoir and is located within the East Kimberly region. The study site is comprised of exposed hilltops and savannah woodland. Freshwater is available year-round, with the lake contracting from May–November. Toads are thought to have colonized islands on the lake via a flooding event in 2010/2011.

Field sampling

Cane toad surveys occurred over six nights, denoted, $t = \{0,1,\ldots,5\}$, during November 2017. Surveys commenced at 1830 each evening and lasted 3–5 hours. Temperatures ranged from 26–35°C. The entire island was circumambulated each night by two people using headtorches; one individual focused on the higher part of the shoreline, the other on the lower shoreline. Every toad encountered was collected and humanely killed on site in accordance with The University of Melbourne animal ethics protocol (1714277.1) and State laws regarding handling of non-native species. Each night, we recorded the number of individuals collected, c_t. Only post-metamorphic age classes were encountered during sampling.

Statistical analysis

We assume that we do not encounter every individual on a given night, and so incorporate imperfect detection. We aim to estimate two parameters: N_0, the true number of toads on the island at the commencement of surveys, and p, the mean per-individual detection probability. The number of individuals collected each night, c_t, can be considered a draw from a binomial distribution with:

$$c_t \sim \text{Binom}(N_t, p).$$

Where N_0, the pre-sampling population size, is a latent variable with a mean and variance equal to λ, such that:

$$N_0 \sim \text{Poiss}(\lambda).$$

For $t > 0$:

$$N_t = N_0 - \sum_{0}^{t-1} c_t$$

The model was fit with Markov chain Monte Carlo (MCMC) in JAGS v.4.6.0, run through R v3.4.1 via the package rjags v4.6.0 (Plummer & Martyn 2013). Three model chains were run for 30,000 iterations, with the first 10,000 iterations discarded as a burn-in, which was sufficient for the MCMC chains to converge. Convergence was checked using the Gelman-Rubin diagnostic (Gelman & Rubin 1992); all chains produced potential scale reduction factors $<$ 1.1, indicating convergence of chains. The remaining samples were thinned by a factor of 2, resulting in 10,000 samples per chain for post-processing. Minimally informative prior distributions for p and λ were specified as uniform between 0-1 and 0-10,000, respectively.

We denote a successful eradication to have occurred when only a single toad remains (i.e., no further breeding pairs remain). As we assume that removal efforts take place on consecutive nights until completion, we disregard breeding and immigration.

Cost analysis

We estimate the cost of eradicating toads on Horan Island based on consumable, personnel, and travel costs incurred during toad collection (Table 1). Relative to most islands in northern Australia, Horan Island is readily accessible, thus our travel costs are modest. We assume that eradication is conducted by a fully-equipped organization; hence we do not include vehicle/boat purchase or hire (i.e., set-up costs). Travel costs include travelling to and from Horan Island from Darwin, NT. Removal efforts are carried out on subsequent nights until eradication is reached; therefore, the cost associated with travel to and from our site is incurred only once. Travel costs include a $85/hour consultant rate plus the additional costs of fuel, insurance, and vehicle maintenance (an extra $36/hour based on a per km charge). Thus, total travel costs are $111/hour.

Cost Scenarios

We use our estimate of toad removal on Horan Island to highlight the potential value of quarantine efforts on high priority islands, based on a list of the top 100 islands that the Australian Commonwealth has prioritized for conservation due to their biodiversity value and presence of species listed under the Environment Protection and Biodiversity Conservation Act (Department of the Environment and Energy [DEE], 1999). We refined this list to include only islands that are >2 km from the Australian mainland, and occur within the predicted potential distribution of cane toads (Kearney et al. 2008). All islands were crossed-checked for the presence of cane toads with the 'Feral Animals on Offshore Islands' database (DEE, 2016).

In addition to the islands derived from this report, we explore the value of a potential toad containment strategy outlined in a revised version of the Cane Toad Threat Abatement Plan (unpub data). This strategy aims to develop a 'waterless barrier' on the Australian mainland by excluding cane toads from artificial water bodies on cattle stations between Broome and Port Hedland in Western Australia. If implemented successfully, this strategy could keep toads out of the Pilbara (and subsequent regions) –an effective quarantine of 268,000km^2 of the Australian mainland (see Florance et al. 2011; Tingley et al. 2013; Southwell et al. 2017 for further information).

Results

The number of cane toads removed from Horan Island declined over time (Figure 1). Over the duration of our survey, we captured and removed 1251 cane toads. The estimated probability of detecting an individual toad on a given night was low (mean p [95% credible interval] = 0.1 [0.07, 0.13]; Figure 2). Given our survey effort and estimated detection probability, the number of toads present on Horan Island at the initiation of our surveys (N_0) was estimated to be 2638 [2140, 3421] (Figure 3). Horan Islands is $0.78 km^2$, so this translates to a cane toad density of 3444 per km^2 [2744, 4386].

Using our estimates of p and λ, we examine the total survey effort (in days) required to eradicate toads from Horan Island. Given our best estimate of N_0, leaving a single individual is equivalent to leaving $r_{crit} = \frac{1}{N_0} = 0.000379$ of the original number of individuals. The time to reach this point is given by $\ln r_{crit}/\ln(1-p) = 72$ days. Multiplying this estimate of the number of days required to achieve eradication by our incurred daily removal costs suggests that \$77,670 (2017 AUD) would be required to eradicate toads from Horan island, or \$96,55 per km^2 of toad eradication.

Value of quarantine

Given our estimated per-area cost of cane toad eradication, we can explore the economic value of quarantine efforts across Australian islands. We present the estimated value of island quarantine by State (Table 2), as well as the cost required to eradicate toads from islands they have already colonized. We estimate it would cost \$415,151,032 to remove cane toads from all islands across Australia on which they are currently known to be present. The remaining value of quarantine across all toad-free islands in Australia is estimated at \$1,376,345,130, or a staggering \$26,416,746,616 if the waterless barrier is implemented in Western Australia.

Discussion

Our results demonstrate the immense value of toad quarantine across Northern Australia. Using costs derived from our removal efforts, we conservatively estimate that it costs \$98,569 per km^2 to eradicate cane toads. There is only one instance in which cane toads have been successfully eradicated (Nonsuch Island in Bermuda: Wingate 2010). This effort was the culmination of \$10,000 USD, six years, and countless hours of volunteer effort - all to remove toads from an island roughly 0.065 km^2. Given the high monetary cost of toad eradication, and the susceptibility of Australian fauna to multiple introduced species (e.g., cats, foxes, toads), island quarantine has significant value for protecting declining populations from the detrimental impacts of invasive species (Ringma et al. 2018).

Our analysis of the feasibility and cost of cane toad eradication is timely, given renewed emphasis on Australia's offshore islands as safe-havens to buffer biodiversity against cane toad impacts (Tingley 2017). Sixty-two offshore islands designated as 'high conservation status' fall within the cane toads predicted distribution; 21 of those have already been colonized by toads. Given these numbers, we estimate the remaining value of toad quarantine across toad-free islands in northern Australia to be \$1.37B. This value is conservative for two reasons. First, it is a reasonable expectation that as islands become home to increasing numbers of insurance populations or endangered species, their value (measured as the cost of restoration) will increase. Second, as further islands are colonized by toads, the value we place on remaining islands should increase. These questions are outside the scope of our analysis but require careful consideration.

The vanguard of the cane toad invasion is currently sweeping across Western Australia at ~ 50 km per annum, but, recent research suggests that a waterless barrier between the Kimberley and Pilbara could halt the toad invasion (Florance et al. 2011; Tingley et al. 2013; Southwell et al. 2017). Applying our results to this management strategy revealed that the value of quarantine over such an area ($26.5B) is more than an order of magnitude higher than the value of quarantine across all offshore islands combined ($1.3B). Our results therefore hint at the immense value of such a strategy, though questions surrounding implementation remain (Southwell et al. 2017).

Estimating the feasibility and cost of cane toad eradication enabled us to estimate a per-individual detection probability and a density estimate. Despite substantial community and research effort into toad removal via trapping and hand capture, we are unaware of a published detection estimate for this species. Our detection estimate is, of course, specific to the details of our survey. Nonetheless, it is surprisingly low: individual toads in our closed system had roughly a 10% chance of being seen on any given night. Individual toads are relatively easy to see when they are active, but our results suggest that this gives a misleading impression of detectability.

Our results suggest that cane toads can achieve a density of 3440 individuals per km^2. This estimate is similar to density estimates derived from previous studies of invasive cane toads in the Solomon Islands archipelago (1035 individuals per km^2; Pikacha et al. 2015) and the islands of Papua New Guinea (3000 individuals/km^2; Zugg et al. 1975; Freeland et al. 1986). Studies conducted on the Australian mainland have reported densities as high as 213,400 individuals per km^2, but these higher estimates include metamorph toads, which often occur at very high densities prior to dispersal. Metamorphs are strongly constrained to the edges of water bodies (Child et al. 2008), and typically suffer high mortality from predation and desiccation before reaching maturity (Ward-Fear et al. 2010). It is important to note, however, that our toad density estimate is derived from a population that is not limited by access to freshwater. Cane toads are inherently limited in their ability to persist across the landscape in areas where near-constant hydration is not possible (Florance et al. 2011). Our estimate is likely to be applicable solely to areas in which water bodies persist through the dry season, such as natural catchments or structures engineered to house water year-round (e.g., cattle watering points).

Placing a monetary value on preventative management is critical as conservation actions increasingly rely on offshore islands and fenced areas as cost-effective avenues to protect biodiversity from the impacts of invasive species. Quarantine measures often protect against multiple potential invaders but our results suggest that even when considering a single species, the monetary value of quarantine can be substantial. Prevention, it seems, is worth more than we might naively guess, even with aphorisms to remind us.

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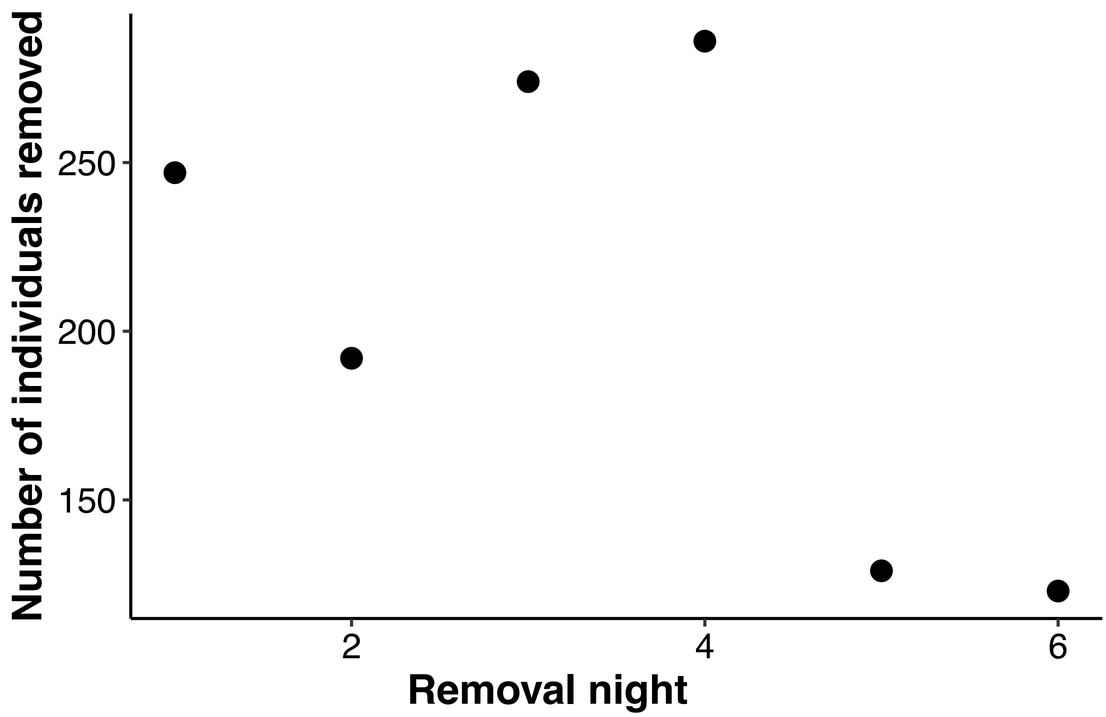

Figure 1. The number of individual cane toads removed from Horan Island, NT over six consecutive collection nights.

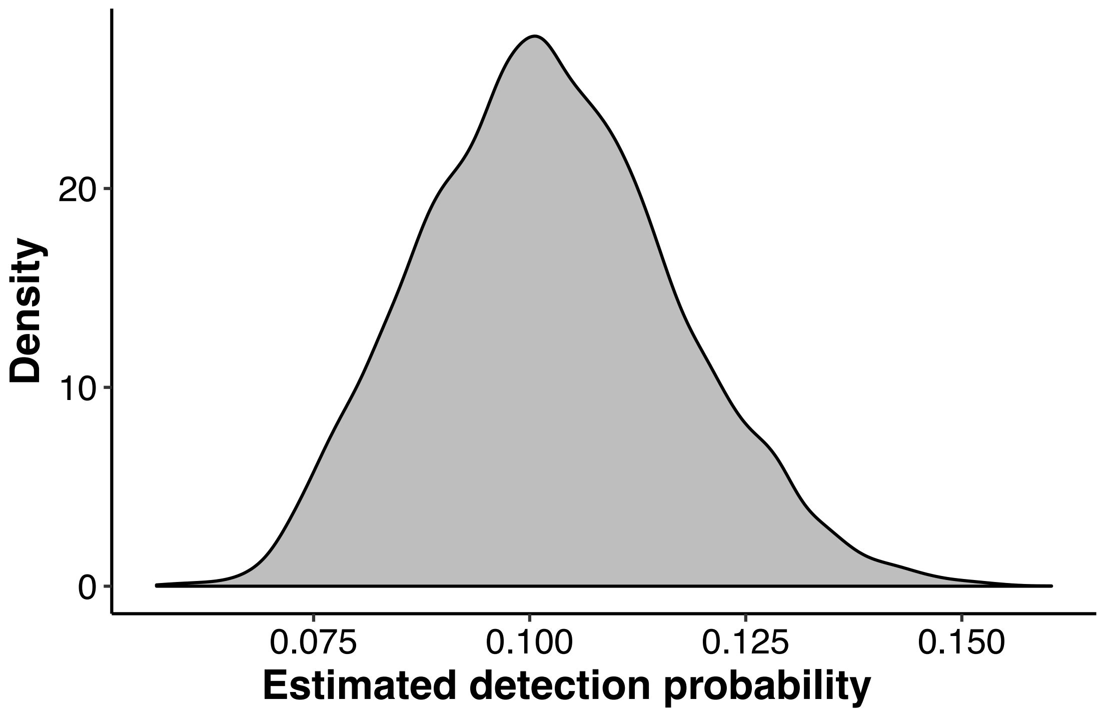

Figure 2. Distribution of estimated detection probability of individual cane toads.

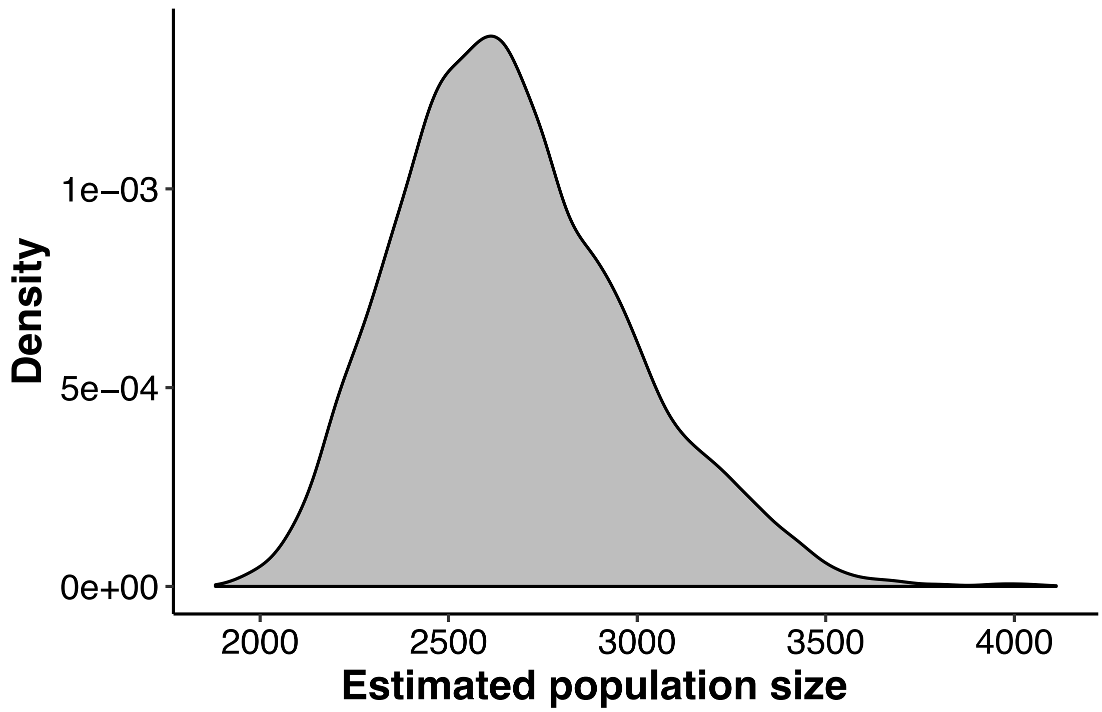

Figure 3. Distribution of cane toad population size on Horan Island, NT.

Table 1: Estimated costs (AUD) of cane toad eradication on Horan Island, NT.

Cost category	**Cost (AU)**
Consumable cost	$5,611
Personnel cost	$61,200
Equipment preparation	$6,120
Survey time	$48,960
Waste disposal	$6,120
Travel cost	$9,768
Travel to site	$1,776
Motorized travel in site	$7,992

Table 2: Estimated cost (AUD) to eradicate cane toads across states and territories in Australia.

Region within Australia	**Cost to eradicate toads**
Cost to eradicate toads per km^2	\$98,569
Horan Island	\$76,579
WA islands (toad free)	\$112,578,720
NT islands (toad present)	\$1,037,843,083
NT islands (toad free)	\$121,443,116
QLD islands (toad present)	\$224,148,083
QLD islands (toad free)	\$293,707,917
Waterless barrier (WA)	\$26,416,748,616

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