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Special Issue Article: Tropical rat eradication

Factors associated with rodent eradication failure

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ABSTRACT

Invasive rodents have an overwhelmingly detrimental impact to native flora and fauna on islands. Rodent eradications from islands have led to valuable biodiversity conservation outcomes. Tropical islands present an additional suite of challenges for rat eradications due to unique characteristics associated with these environments. To date tropical island rat eradications have failed at a higher rate than those undertaken outside the tropics. Critical knowledge gaps exist in our understanding of what drives this outcome. We collated an in-depth dataset of 216 rodenticide based rat eradication operations (33% of all known rodent eradications) in order to determine correlates of eradication failure, including both project implementation factors and target island ecology, geography and climate. We assessed both failed and successful projects, and projects inside and outside the tropics, using random forests, a statistical approach which compensates for high dimensionality within, and correlation among, predictor variables. When assessing all projects, increasing mean annual temperature, particularly above 24 °C, underscored the higher failure rate and greater difficulty of rodent eradications on islands in lower latitudes. We also found clear trends in eradication failure for factors unique to the tropics, including the presence of land crabs – burrowing and hermit crabs, and coconut palms (*Cocos nucifera*). The presence of agriculture was also associated with failure. Aerial operations had a higher success rate than ground-based methods but success with this technique was less likely in the presence of hermit crabs and other non-target bait consumers. Factors associated with failure in ground-based eradication methods suggested limitations to project scaling such as island area and number of staff. Bait station operations were less likely to succeed when using stopping rules based on measures of rodent abundance. Factors influencing rat eradication failure in tropical environments continue to require a deeper understanding of tropical island dynamics to achieve a higher rate of eradication success.

1. Introduction

Invasive rodent species are estimated to have colonized more than 80% of the world's island groups (Atkinson, 1985) where they have been associated with widespread damaging impacts including the extinction or decline of native flora and fauna populations (Campbell and Atkinson, 2002; Jones et al., 2008; Towns et al., 2006) and ecosystem modification (Kurle et al., 2008). Efforts to eradicate invasive rodents from islands have progressed considerably in the past two decades (Howald et al., 2007; Russell et al., 2008; Veitch et al., 2002, 2011), and resulted in demonstrable biodiversity conservation outcomes (Bellingham et al., 2010; Lorvelec and Pascal, 2005). Eradication methods were primarily developed in temperate regions where the majority of rodent eradications have been conducted (Howald et al., 2007). Tropical islands represent an important conservation need given their high biodiversity value (Kricher, 2011; Myers et al., 2000). Tropical island rodent eradications present challenges that contrast with islands in cooler climates, including less temperature aseasonality which provides consistent or rapidly responding food supply to support rodent populations, plus unique biota such as land crabs (Russell and Holmes, 2015; Varnham, 2010; Wegmann et al., 2011). To date the success rate of rat eradications in tropical environments has been lower when compared to non-tropical regions (81 versus 92%, $n = 516$ excluding reinvasions, $\chi^2(1, n = 516) = 11.8$, $p < 0.001$, Russell and Holmes, 2015), and critical knowledge gaps exist in our understanding of what has driven this outcome (Russell and Holmes, 2015; Varnham, 2010). The direct outcome of the higher failure rate in the tropics is that

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populations of those native species identified to benefit from rat eradication remain at risk from invasive species, with indirect implications being a loss of investment – both cost and time to repeat the eradication, biological impacts to native species from the operation, and a potential reduction in confidence in eradication methods.

Central hypotheses for the failure of rodenticide based rodent eradications include inadequate bait availability, low bait palatability, insufficient bait toxicity and toxicant tolerance. These mechanisms represent failed operations whereby rodents survived the operation and repopulated an island and are distinguished from successful operations where rodents subsequently reinvaded and populated an island. Rodent invasion biology and recommendations regarding reinvasion and biosecurity have been reviewed elsewhere (Harris et al., 2012; Russell et al., 2008). Inadequate bait availability implies that some rodents did not have access to sufficient bait due to low application rates, operational deficiencies that resulted in poor bait distribution such as equipment failure, or biological influences such as rodents foraging only in unbaited landscapes (e.g. subterranean features). Low bait palatability suggests that all rodents had access to adequate bait but some individuals did not eat it, or ate an insufficient amount to ingest a lethal dose due to alternative natural or anthropogenic foods that were more desirable or more readily available (Weerakoon and Banks, 2011). Insufficient bait toxicity suggests that all rodents had access to and consumed sufficient bait but not all bait contained a prescribed toxicant concentration for a lethal dose (i.e. bait irregularity) – this is likely a lower risk for eradication projects given there are few bait manufacturers for island eradication purposes and these are subject to rigorous industry standards (e.g. US CFR, 2014). Resistance/tolerance suggests that some rodents accessed and consumed sufficient bait that contained the prescribed concentration of the toxicant but did not die. Resistance is a definition applied to survivors in a population that underwent selection pressure due to chronic exposure to a rodenticide that otherwise would have succumbed to the rodenticide at that dose, and tolerance is typically an *a priori* physiological trait that makes a species less susceptible to a rodenticide – e.g. mice (*Mus* spp.) are more tolerant of anticoagulant rodenticides than rats (MacNicoll, 1993). Resistance has been observed as a genetic adaptation in long-term pest control (Buckle et al., 1994) and should be a lower risk for island eradication projects where prolonged exposure to rodenticides is absent, but is suggested to potentially occur on islands where natural anticoagulants such coumarin occur in plants (Pascal et al., 2008). Bait toxicity and resistance/tolerance are best investigated *a priori* in a laboratory environment. Inadequate bait availability and low bait palatability represent two hypotheses for rodent eradication failure that allow *a posteriori* data collection where relevant operational elements and target island ecology can be investigated.

Determining what causal factors may underlie rodent eradication failure is challenging. As a high cost conservation management intervention there is little scope for experimentally manipulating eradication, c.f. other successful examples of adaptive management in conservation biology (e.g. Whitehead et al., 2008). The number of potential causal factors is also large, multiplicative, and with correlations among them, while the number of rodent eradication failures is comparatively small, potentially making consistent trends hard to detect. Classical statistical analyses of historical efforts can analyse broad trends (e.g. Gregory et al., 2014; MacKay et al., 2007), but will be limited in exploring the breadth or depth of many potential factors. Data-mining methods are suited to such high-dimension data, and have application in diverse fields, especially where users seek to identify important variables from a large pool of candidates (e.g. Cutler and Stevens, 2006; Hochachka et al., 2007). Random forests in particular compensate for correlation among predictor variables (Strobl et al., 2008) and provides a list of predictors ranked by their discriminating power. The identification of variables which have strong correlation with the response then allows the generation of hypotheses of potential causal factors which can be tested in further study, and subsequently used to refine best practice (Keitt et al., 2015).

To date more than 650 eradications of *Rattus rattus*, *Rattus norvegicus* and *Rattus exulans* from more than 527 islands have been attempted globally with outcomes recorded as failed, successful or successful (reinvaded) (DIISE, 2014). When comparing only successful and failed rat eradications using second generation toxicants, aerial operations have a higher success rate (96%, $n = 138$) compared to bait stations (83%, $n = 147$) and hand broadcast (87%, $n = 127$) (DIISE, 2014). While basic information such as target species, method and outcome has been consolidated for each of these projects (DIISE, 2014; Keitt et al., 2011), more detailed operational and environmental data are only available within individual project reports, with varying degrees of detail and availability. Consolidating these data offers an opportunity to quantitatively evaluate rodent eradication operation failures, and particularly what factors are associated with the elevated failure rate in the tropics. We collated data on rat eradication operations, both project implementation factors and target island ecology, geography and climate, in order to determine correlates of eradication success. We used a random forests classification and regression tree (CART) approach (Cutler et al., 2007) which compensates for high dimensionality and correlation among predictor variables (Strobl et al., 2008). This work was motivated by a desire to expand our understanding of the higher failure rate in the tropics by determining the suite of factors that have a consistent relationship with eradication failure throughout the world. We assessed both failed and successful projects, and projects inside and outside the tropics, in order to isolate factors unique to failed tropical *Rattus* eradications.

2. Methods

2.1. Dataset

We used the Database of Islands and Invasive Species Eradications (DIISE, 2014; Keitt et al., 2011) to identify rat eradications undertaken globally. In this database every unique landform from which a rat population was completely and intentionally removed is considered an independent eradication. We selected projects were eradication events were verified either by a primary reference reporting the event, or the event was documented in a peer reviewed summary paper. We excluded islets which we considered functionally part of the principal island on which an eradication took place but do not distinguish 'eradication units' where reinvasion among principal islands in an archipelago is possible (sensu Abdelkrim et al., 2005; Robertson and Gemmell, 2004). We also acknowledge operational dependencies where multiple eradications are conducted under one umbrella of operational planning for logistical efficiency (e.g. shared boat coasts). We selected projects where status could be defined as operational failure (the eradication effort did not eliminate every rodent) or success. We included projects that successfully eliminated every rodent even if the island was subsequently reinvaded but only if reinvasion was robustly confirmed either by genetic analyses (e.g. Russell et al., 2010) or where the time elapsed between the operation and reinvasion excluded operational failure. We selected projects where second generation anti-coagulants (brodifacoum, bromadiolone, difenacoum) were distributed across the entire island during the eradication project and the target species were invasive rats