Improving the efficiency of aerial rodent eradications by means of the numerical estimation of rodenticide density

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Abstract Invasive rodents are present on approximately 80% of the world's islands and constitute one of the most serious threats to island biodiversity and ecosystem functioning. The eradication of rodents is central to island conservation efforts and the aerial broadcast of rodenticide bait is the preferred dispersal method. To improve the efficiency of rodent eradication campaigns, the generation of accurate and real-time bait density maps is required. Creating maps to estimate the spatial dispersion of bait on the ground has been carried out using traditional GIS methodologies, which are based on limiting assumptions and are time intensive. To improve accuracy and expedite the evaluation of aerial operations, we developed an algorithm for the numerical estimation of rodenticide density (NERD). The NERD algorithm performs calculations with increased accuracy, displaying results almost in real-time. NERD describes the relationship between bait density, the mass flow rate of rodenticide through the bait bucket, and helicopter speed and produces maps of bait density on the ground. NERD also facilitates the planning of helicopter flight paths and allows for the instant identification of areas with low or high bait density. During the recent and successful rodent eradication campaign on Banco Chinchorro in Mexico, carried out during 2015, NERD results were used to enable dynamic decision-making in the field and to ensure the efficient use of resources.

Keywords: aerial dispersal, bait density, invasive species, rodenticide

INTRODUCTION

Island ecosystems are vulnerable to the threat posed by invasive species due to the combination of high levels of endemism and isolation, coupled with smaller population sizes (Loope & Mueller-Dombois, 1989; D'Antonio & Dudley, 1995; Reaser, et al., 2007). Invasive rodent species such as *Rattus rattus* are particularly harmful to island ecosystems. Worldwide, invasive rodents are found on more than 80% of the world's islands and their high potential for dispersal indicates that this number is on the rise (Russell, et al., 2008; Harris, et al., 2012). The presence of invasive rodents on islands can lead to rapid population decreases of both flora and fauna and the extirpation of endemic species (Towns, et al., 2006; Medina, et al., 2011) as invasive rodent species begin to dominate communities (Angel, et al., 2009; Towns, et al., 2013). Island biodiversity is not only affected by the presence of invasive rodents; in cases where rodent invasion is severe, key island ecosystem functions and services are often lost (e.g., Towns, et al., 2006). Island ecosystems are unable to recover while rodents are present; as such, the first step to restore ecological functioning and island biodiversity is the eradication of invasive rodent species via the dispersal of rodenticide (Towns & Broome, 2003; Harris, et al., 2012).

The aerial-based dispersal methods of rodenticide bait via helicopter are preferable to ground-based methods in many circumstances (Towns & Broome, 2003; Broome, et al., 2014). Aerial bait dispersal strategies are designed to cover large areas rapidly, reduce the complications associated with complex topography, and target potential refuge sites (Towns & Broome, 2003; Howald, et al., 2007). The evaluation of the effectiveness of aerial rodenticide dispersal is informed by bait density maps that show the spatial variation of bait on the ground (Broome, et al., 2014). Traditionally, bait density maps have been created with *in situ* measurements or from GPS helicopter trajectories although there are challenges associated with both methods. To obtain *in situ* measurements, quadrat bait density sampling is carried out on the ground and requires a substantial investment of both time and human resources. The effectiveness of this method depends on the topography, accessibility, and climate of the island at the time of sampling, in addition to existing time constraints and available manpower. In contrast, the spatial estimation of bait density from recorded GPS helicopter trajectories is time intensive and can be imprecise as it is based on several untested assumptions, the principal one being that the bait density remains constant within the treated polygon.

We have developed a method for the numerical estimation of rodenticide density (NERD) that improves upon the aforementioned methods. NERD creates bait density maps using GPS helicopter trajectories but is not constrained by the assumptions of traditional GIS analysis. NERD does not assume that bait density is constant within the treated polygon nor is it time intensive. Results from NERD are both automatic and instantaneous, allowing for modifications to helicopter flight plans during an ongoing eradication. During helicopter refuelling, GPS data from the helicopter are downloaded into NERD and bait density maps are returned in minutes.

The NERD algorithm combines two models. The first model estimates the mass flow rate as a function of the bait bucket aperture diameter and the second model describes the bait density profile perpendicular to the flight path of the helicopter. By combining the two models, bait density on the ground is estimated as a function of the aperture diameter of the bait bucket and the speed of the helicopter.

In this paper, we present the first field implementation of NERD on the island of Banco Chinchorro, Mexico, a small false atoll in which rodents were most likely introduced during the 19th century (Samaniego, et al., 2017).

METHODS

Study site

Banco Chinchorro is comprised of four flat keys that create a false atoll measuring 0.5–539 ha, located in the Caribbean Sea approximately 35 km off the coast of Quintana Roo, Mexico, and is classified as both a Biosphere Reserve and Ramsar site (CONANP, 2000; 2006; Samaniego, et al., 2017). Banco Chinchorro presents a wet tropical climate and is primarily covered with mangrove vegetation, composed of *Rhizophora mangle*,

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Laguncularia racemosa, *Avicennia germinans*, and *Conocarpus erectus*, and has tropical trees such as *Thrinax radiata*, *Bursera simaruba*, and *Tournefortia gnaphalodes* (Samaniego, et al., 2017). The island provides habitat for a number of crab species, the American crocodile (*Crocodylus acutus*) and the seabird *Fregata magnificens* (Samaniego, et al., 2017). Prior to eradication efforts, the invasive rodent (*Rattus rattus)* occurred at densities from 6.5–47.9 rats/ha on Cayo Centro to 25.3–102.5 rats/ha on Cayo Norte Major (Samaniego, et al., 2017). The extensive mangrove presence on Banco Chinchorro and the presence of the *C. acutus* makes ground-based evaluation methods of bait density both hazardous and ineffectual.

Relationship between density, mass flow rate, and helicopter speed

The combination of the two models comprising NERD is presented. Here, we show that the function $\sigma(x,y)$ used to represent superficial bait density (kg/m^2) complies with the following equation

$$\int_{-\frac{w}{2}}^{+\frac{w}{2}} \sigma(x)dx = \frac{\dot{m}}{s}$$

where $\dot{m}$ is the bait flow (kg/s), s is the speed of the helicopter (m/s) and w is the swath width (m).

We set the origin of a Cartesian coordinate system on the middle point of the bottom side of a rectangle with base w and height δy. This way, the bottom side is found at $y = 0$, the top side at $y = \delta y$, the left side at $x = -\frac{w}{2}$, and the right side at $x = +\frac{w}{2}$. The rectangle represents one dispersion cell.

After the helicopter completes a pass, in each point (x,y) of the dispersion cell, a superficial bait density is obtained $\sigma(x,y)$. In instances where two or more dispersions cells overlap, we simply add the density from each cell to get the total density on the overlap. The definition of the superficial bait density of mass m indicates that $\sigma(x,y) = \frac{dm}{dA}$. Rewriting the superficial density substituting dA by $dydx$ and integrating along the dispersion cell, it follows that

$$\delta m = \int_{-\frac{w}{2}}^{+\frac{w}{2}} \int_0^{\delta y} \sigma(x,y)dydx. \qquad (1)$$

Assuming superficial density is uniform with respect to the helicopter's flight path, represented in Fig. 1, equation (1) becomes

$$\frac{\delta m}{\delta y} = \int_{-\frac{w}{2}}^{+\frac{w}{2}} \sigma(x)dx. \qquad (2)$$

The left-hand side of the equation represents the linear bait density, which is related with the mass flow of bait from the bucket and the speed of the helicopter. A helicopter equipped with a dispersion bucket with a constant mass flow rate,

$$\dot{m} = \frac{\delta m}{\delta t} \qquad (3)$$

flies from the point (0,0) to the point (0,δy) with a speed of

$$s = \frac{\delta y}{\delta t}. \qquad (4)$$

Combining equations (3) and (4), the linear bait density

$$\frac{\delta m}{\delta y} = \frac{\dot{m}}{s} \qquad (5)$$

is obtained.

Finally, setting equations (2) and (5) equal to each other, we obtain

$$\int_{-\frac{w}{2}}^{+\frac{w}{2}} \sigma(x)dx = \frac{\dot{m}}{s}. \qquad (6)$$

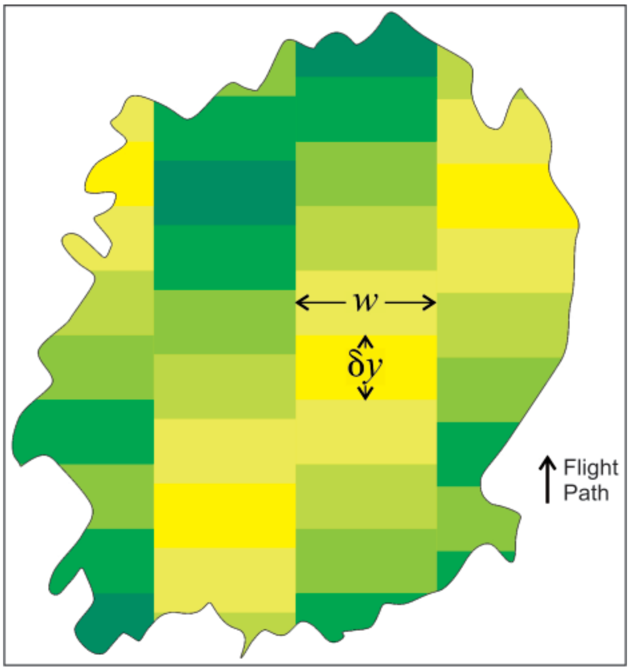

Fig. 1 Hypothetical island with bait swaths. Each vertical band represents one bait swath. Each shaded rectangle represents one dispersion cell. Shade intensity corresponds to bait density, with darker shades indicating higher densities.

Equation (6) relates the bait density on the ground with the mass flow rate and the speed of the helicopter. In order to get an explicit form of σ, a model is fitted to cross-density profiles, such as the ones shown in Fig. 2.

Simplified relationship between density, mass flow rate, and helicopter speed

The required bait density for the successful eradication of an invasive species on an island is determined by evaluating the ecosystems present and the biology of the target species. Once this density has been determined, NERD can be used to estimate the aperture of the bait bucket needed for the eradication operation in question and to plan helicopter flight paths. During the planning phase of an eradication campaign, prior to arriving on the island, a simplified relationship between density, mass flow rate, and helicopter speed is used where bait density is assumed to be constant along and across the flight path of the helicopter.

Assuming density is independent of x, i.e. σ does not change perpendicular to the flight path, equation (6) can be easily solved to obtain

$$\sigma = \frac{\dot{m}}{s \cdot w}. \qquad (7)$$

To write equation (7) as a function of the aperture diameter of the bait bucket, we express the mass flow rate of bait as a function of the aperture diameter, $\dot{m}(d)$. To do this, the bait in the bucket was weighed and the time required to empty the bucket was measured and repeated using several aperture diameters (Fig. 3).

The resulting three-dimensional model,

$$\sigma(d,s) = \frac{\dot{m}(d)}{s \cdot w} \qquad (8)$$

is shown in Fig. 4.

An implementation of this model can be found at <*http://github.com/IslasGECI/nerd*>.

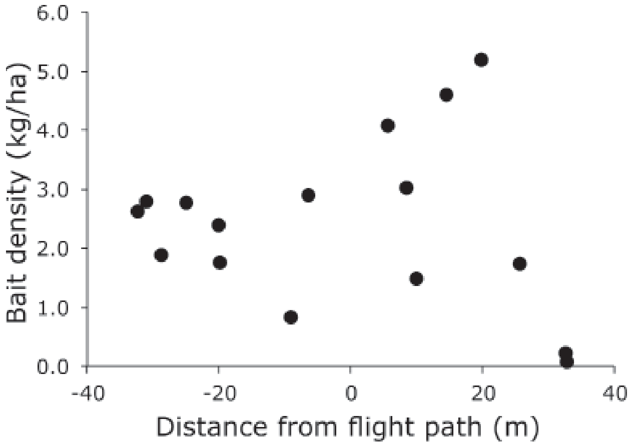

Fig. 2 Bait density profile perpendicular to the flight path of the helicopter during a test flight in Oxnard, CA in 2013. Each black dot shows the bait density measured within a quadrat.

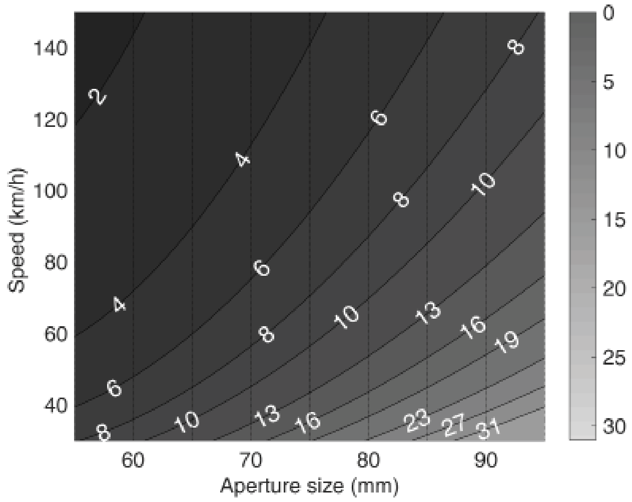

Fig. 4 Surface bait density σ (kg/ha) as a function of aperture diameter d (mm) and speed s (km/hr). The horizontal axis shows the aperture diameter of the bait bucket and the vertical axis shows the speed of the helicopter. The resulting bait density on the ground is shown in white superimposed numbers and in the second vertical grayscale axis.

RESULTS AND DISCUSSION

NERD was used to plan and carry out the 2015 eradication campaign on Cayo Centro of Banco Chinchorro. Given the desired helicopter speed, NERD was used to determine the aperture of the bait bucket and the flight paths of the helicopter required to achieve the desired bait density within the target polygon. The results of the 2015 rodent eradication campaign on Banco Chinchorro are detailed by Samaniego et al. (2017). During the course of the eradication campaign, NERD was operated by two people and generated an updated bait density map multiple times each day providing instantaneous visualisations of the current state of bait application over the island, such as the map shown in Fig. 5. These visualizations provided feedback in real time, allowing for helicopter course corrections and promoting the efficient use of rodenticide bait.

Fig. 5 shows the final bait density map estimated with NERD for the eradication campaign. From this map, it is apparent that all terrestrial areas of Banco Chinchorro were estimated to be covered with at least 60 kg/ha of rodenticide, which was the target bait density for this campaign. The colormap of Fig. 5 indicates bait density on the ground (kg/ha), with warmer colours corresponding to lower bait densities. The large red polygons that appear on the map represent inland lagoons, which were not covered with rodenticide bait excepting a few swaths that correspond to the presence of sandbars within the lagoons. Around these lagoons, manual bait placement was carried out by a team of field operatives. The maps generated by NERD were also used by this team to ensure even bait coverage and avoid excess bait application. Overall, few areas in Fig. 5 show bait densities near 100 kg/ha, indicating that helicopter flight paths were rarely redundant. Furthermore, any small isolated areas of low bait density were always surrounded by areas with target bait densities of at least 60 kg/ha.

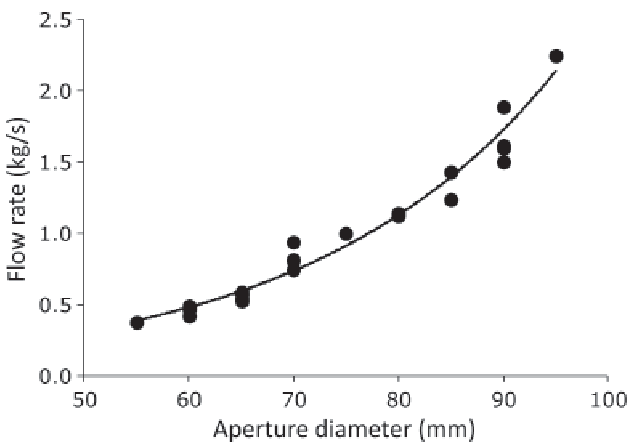

Fig. 3 Mass flow rate (kg/s) as a function of aperture diameter d (mm). Each dot represents a calibration event and the black curve is the quadratic model fitted to the data.

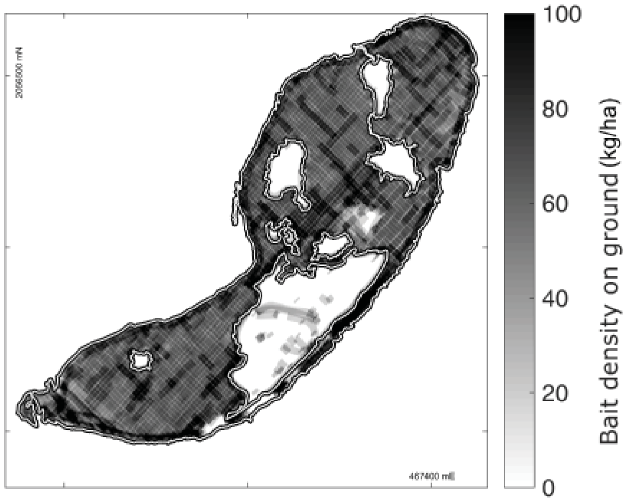

Fig. 5 Estimated bait density (kg/ha) resulting from the aerial operation of the rodent eradication campaign in Banco Chinchorro, Mexico, during 2015.The shade bar on the right indicates predicted bait density on the ground (kg/ha), with lighter shades indicating lower densities. The large white polygons show the location of inland lagoons.

The information provided by NERD was indispensable to the eradication campaign on Banco Chinchorro and allowed for immediate decisions to be made regarding not only the aerial dispersal of rodenticide bait, but also for the manual placement of bait on the ground. Until now, efforts to generate bait density maps have been inefficient and results were often not available until after the end of an eradication campaign. NERD provides information in real time, enabling dynamic decision making in the field and ensuring the efficient use of resources.

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