Considerations and consequences when conducting aerial broadcast applications during rodent eradications

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Abstract Aerial broadcast application is currently one of the most common methods for conducting rodent eradications on islands, particularly islands greater than 100 ha or with complex and difficult topography where access by ground teams is difficult. Overall, aerial broadcast applications have a high success rate, but can be burdened by logistical, regulatory, and environmental challenges. This is particularly true for islands where complex shorelines, sheer terrain, and the interface with the marine environment pose additional risks and concerns. Using data collected during ten eradication projects we investigate the influence that operational realities have on broadcast applications. We tested the association between the amount of bait used and island size, topography, and the desire to reduce bait application into the marine environment and then compared planned bait application to actual bait application quantities. Based on our results, islands of decreasing size and increasing coastal complexity tended to use more bait than anticipated and experienced greater variability in localised bait densities. During operations, we recommend analysing flight data to identify treated areas with localised bait densities that fall below the target application rate. We recommend that areas with low localised bait densities may result in biologically significant gaps that should receive an additional application of bait based on project risk variables such as target home range size, non-target bait competitors, and alternative foods. We also recommend a common language for discussing aerial broadcast applications and where future work can be done to improve operational decision making.

Keywords: bait density, gaps, geographic information systems (GIS), island invasives, operational monitoring

INTRODUCTION

History of aerial broadcast applications

One of the primary principles for rodent eradication is ensuring sufficient bait is distributed to every potential rodent home range, so that every rodent is exposed to bait for long enough to cause mortality (Bomford & O'Brien, 1995; Howald, et al., 2007). The aerial application of rodenticide is one of the most common and effective ways for eradicating rodents from islands (Holmes, et al., 2015). Aerial broadcast techniques were first developed in the 1980s and methodology and principles were developed over several decades as lessons learnt were applied to projects of increasing size and complexity (Towns & Broome, 2003). The first aerial applications relied on the use of modified "monsoon" fire-fighting buckets slung beneath a helicopter and flown by eye or guided by ground personnel. These early projects were often successful in removing rodents, despite difficulty in controlling application rates and the need to use hand spreading to fill gaps (Garden, et. al., 2019). The advent of specialised mechanical spreading buckets to control bait application rates and distribution, and global positioning systems (GPS) to guide pilots along straight flight paths and record bait spread, revolutionised aerial application techniques (Garden, et. al., 2019). These changes allowed rodent bait to be delivered with far greater precision over much larger areas, resulting in the successful removal of rodents from islands larger than 10,000 ha (Campbell 11,300 ha; Macquarie 12,800 ha; and South Georgia 108,700 ha) (Broome, 2009; Russell & Broome, 2016; Martin & Richardson, 2017).

Aerial application principles

It is impossible to predict where all rodent home ranges are and, because rodents are highly tolerant of a wide range of habitat types, the whole island must be assumed to support rodents, and the entire island is ultimately treated. Bait application rates are set to ensure that bait is readily available in all potential rodent home ranges and target bait application rates are often informed by bait availability trials (Pott, et al., 2015) or rates used on similar islands that were previously successful (Broome, et al., 2014). These rates are conservatively selected to ensure enough bait for all the rodents on the islands while accounting for loss and uptake by non-target competitors, like land crabs, that reduce the amount of bait rodents are exposed to (Pott, et al., 2015).

In general, one bait application rate is targeted across an entire island because stratification increases complexity and the risk of gaps in bait coverage (i.e. areas where some rodents may not be exposed to bait), increasing the risk of eradication failure (Keitt, et al., 2015). Subsequently, projects are generally designed to use parallel flight lines with 50% overlap between lines and additional parallel flights along the coast to reduce the risk of gaps. Projects may apply additional bait on steep cliffs because they have a larger surface area (3D) than planar area (2D), resulting in un-even bait distribution from bait falling downslope (Broome, et al., 2014).

Challenges in aerial application

There are technical limitations of helicopters and mechanical bait spreaders in applying bait over an entire island. Operational realities, like wind, flight speed and turning capabilities of the helicopters, steep terrain, and unevenness of bait pellet distribution from the mechanical spreader can impact bait placement on the ground, leading to potential gaps in coverage. To ensure sufficient coverage the pilot must reapply bait over potential gap areas, resulting in locally increased bait densities where this additional application partially overlaps with previous flight lines. Additional complications arise when areas need to be excluded from aerial application, such as human habitation, inland water features or the marine environment. These operational constraints tend to increase the total amount of bait needed because additional overlapping flight lines are required to ensure no gaps in coverage exist along edge boundaries.

When trying to eradicate a rodent population, planning tends to focus on targeting the worst-case scenario,

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ensuring that there are no gaps, meaning that bait overlaps with the smallest known home range. However, it is not well understood if applying less bait could constitute biologically significant gaps where reduced bait availability within a rodent's home range decreases the likelihood of a rodent being exposed to a lethal dose. The potential risks posed by biologically significant gaps may be particularly relevant on tropical islands, which tend to have more non-target bait competitors and alternative food sources (Holmes, et al., 2015), or when targeting multiple rodent species.

These challenges have generally led to an "over-engineering" approach to project design under the perception that more bait increases the likelihood of eradication success (Cromarty, et al., 2002); however, higher bait use has trade-offs, such as increasing risk to non-target species (Parkes, et al., 2011). We sought to improve existing knowledge of what constitutes an 'optimal' bait application rate, and what is a biologically relevant gap in baiting. We examined ten projects to 1) understand factors influencing the difference in bait use between what was planned and what happened on the ground, and 2) characterise localised bait application rates amongst these ten projects to further understand what may constitute a gap. Specifically, we asked:

What are the differences in total bait used between three baiting scenarios and what physical and operational factors are associated with these differences?

How does localised bait application rate vary and how do areas estimated to be below the target application compare to rodent home range size?

METHODS

Aerial application terminology

The *target application rate* is the desired rate of bait deployment, in mass per unit area (e.g. kg/ha), to be applied across the island. The target application rate is usually based on bait availability trials and is set to maintain bait availability for a certain period. The *average application rate* is the total amount of bait distributed over an island divided by the area of the island, in bait mass per unit area, and is generally used for comparing eradication projects.

In general, bait is applied via a modified fertiliser bucket underslung from a helicopter that distributes bait either 360 degrees (*full swath*) or 180 degrees (*half swath* or directional) from the bucket. Each bucket throws bait pellets a certain distance as a function of bait product size and weight and the speed of the distribution spinner. The *swath width* is the effective distance that baits are consistently sown, which is conservatively set during calibration trials and less than the maximum distance the bucket can throw bait.

The *flow rate* is the rate, in mass per unit time (i.e. kg/sec), at which bait is distributed by the bucket. This may be controlled in a variety of ways, depending on the mechanics of a bucket, but is often controlled manually with *aperture discs* that vary in size to restrict how much bait can enter the spinner.

A bucket's *sow rate* is the rate, in mass per unit area (e.g. kg/ha), that bait is distributed from the bucket and is a function of the helicopter's *flight speed* and the bucket's *flow rate.* In general, a faster *flight speed* will decrease the *sow rate* while a larger *aperture disc* will increase the *sow rate.*

Using a GPS unit, bait is generally spread in parallel *flight lines* employing planned *overlap* between flight lines to reduce the possibility of gaps in bait coverage. When using overlap the *sow rate* must be reduced to achieve the desired *target application rate* (i.e. using a planned 50% overlap buckets would require a sow rate of 5 kg/ha if the target application rate was 10 kg/ha). In areas where multiple flight line *swaths overlap* localised *bait densities* achieved on the ground*,* in mass per unit area (e.g. kg/ha), may be higher than the *target application rate,* and where planned *overlap* does not occur *bait densities* may be lower – resulting in *undertreated areas.* The GPS unit assists helicopter pilots during bait application by indicating deviance from the desired flight line and displaying the current flight speed.

Supplemental bait is additional bait needed to fill unplanned *gaps*, *undertreated areas*, or areas that require additional treatment like steep cliffs or preferred habitat. *Contingency bait* is bait held in reserve to replace spoiled bait and is generally intended to be left unused at the end of an operation.

Data from aerial broadcast eradication projects

Between 2008 and 2016 aerial baiting data were collected and analysed across ten different rodent eradication projects representing a variety of different island habitats, sizes, strategies, outcomes, and regulatory environments (Table 1). We used these data for our analyses.

For each operation, an aerial baiting plan was developed to estimate the total amount of bait required to complete the operation. High resolution satellite imagery (<1 metre per pixel) was acquired and used to estimate the island area by digitising along the mean high-water mark at a scale of 1:2,500. Treatment area estimates were generated by calculating the area from hypothetical parallel flight lines over the island with 50% overlap, using an estimated effective swath width, and a single directional coastal boundary swath, at half the estimated effective swath width, along the coastline. For the nine projects with the most conservative regulatory guidelines that restricted bait entry into the marine environment, the start and end of the parallel flight lines were brought in from the coast by half of the estimated effective swath width, and an additional coastal overlap buffer was estimated that overlapped with the ends of the interior flight lines and the coastal swath.

On several operations, areas were identified for supplemental treatment (e.g. steep cliffs) or exclusion from aerial treatment (e.g. inland bodies of water, human habitation) and treatment areas were calculated based on the operational parameters. Steep cliff areas were estimated by acquiring Digital Elevation Models (DEM) with a resolution of 30 metres per pixel or better. Slope estimates were calculated based on the DEM and used to identify areas for additional treatment. Exclusion zones were treated like the coastal edge, with flight line ends starting and stopping at least half the effective swath width from the exclusion boundary and a half swath flown around the exclusion boundary to minimise gaps.

To estimate the total amount of bait required per application treatment, area estimates were multiplied by the sow rates required to achieve the target application rate on the ground.

Aerial bait tracking

During each operation, a tracking worksheet was completed that recorded detailed information about each bucket load including: helicopter departure time, helicopter arrival time, bucket type, disc size, bait placed in the bucket, bait returned in the bucket, and cumulative area treated as recorded by GPS (TracMap Ltd., Otago, New Zealand iOS 1.7.2). For each bucket load the amount

Table 1 Operational data analysed to evaluate factors influencing total bait used.

Project	Country	Year	Block	Habitat	Island type	Max. elev. (m)	Size (ha)	Coastline (km)	No. of flight lines	Supplemental treatment	Coastal overlap buffer	Target rate (kg/ha)	Δuniform.planned	Δplanned.actual	Δuniform.actual
Rabida	EC	2010	Plaza Norte	Tropical	Volcanic	5	8.4	2.1	9	None	FALSE	6.0	0.0	82.5	82.5
Pinzon	EC	2012	Plaza Sur	Tropical	Volcanic	10	14.8	2.7	25	None	FALSE	6.0	31.1	7.2	40.5
Rabida	EC	2010	Bainbridges, Sombrero Chino and Beagles	Tropical	Volcanic	35	72.2	9.2	116	Coast	FALSE	6.0	41.7	70.6	141.8
Acteon-Gambier	FP	2015	Gambier (Manui, Makaroa, Kamaka*)	Tropical	Volcanic	140	88.0	8.1	103	None	FALSE	24.0	34.1	34.1	79.8
Desecheo	US	2012	Desecheo*	Tropical	Volcanic	220	117.1	7.9	85	None	TRUE	20.0	3.2	-6.0	-3.0
Desecheo	US	2016	Desecheo	Tropical	Volcanic	220	117.1	7.9	159	Cliff	TRUE	34.0	36.7	-1.7	34.5
Rabida	EC	2010	Bartolome	Tropical	Volcanic	80	129.3	7.2	68	Coast	TRUE	6.0	47.9	2.0	50.8
Palmyra	US	2011	Palmyra	Tropical	Coral	10	234.9	64.0	664	None	TRUE	80.0	12.2	-6.5	5.0
Acteon-Gambier	FP	2015	Vahanga	Tropical	Coral	10	380.0	25.0	288	None	FALSE	24.0	21.1	6.1	28.5
Acteon-Gambier	FP	2015	Tenarunga	Tropical	Coral	10	425.0	23.5	214	None	FALSE	24.0	16.5	13.5	32.2
Acteon-Gambier	FP	2015	Temoe	Tropical	Coral	5	431.0	36.9	431	None	FALSE	24.0	28.5	13.7	46.1
Rabida	EC	2010	Rabida	Tropical	Volcanic	340	499.0	11.1	117	Coast	TRUE	6.0	19.1	6.5	26.9
Wake	US	2012	Wake+	Tropical	Coral	5	637.0	39.6	776	None	TRUE	15.2	15.6	5.6	22.1
Murchison & Faraday	CA	2013	Murchison and Faraday	Temperate	Volcanic	190	806.0	40.9	607	None	TRUE	16.0	11.8	23.4	38.0
Pinzon	EC	2012	Pinzon	Tropical	Volcanic	430	1,789.6	18.3	408	Cliff	TRUE	6.0	9.2	2.5	12.0
Antipodes	NZ	2015	Antipodes	Temperate	Volcanic	366	2,129.5	33.7	661	Cliff	TRUE	16.0	7.1	20.8	29.3
Hawadax	US	2008	Hawadax	Temperate	Volcanic	340	2,900.0	43.8	1096	Coast	TRUE	6.0	5.3	1.2	6.5

*Project failed to remove invasive rats.
+Project successfully removed one of two species of rats.

of bait used and area treated were calculated and used to estimate the sow rate achieved. The sow rate information was relayed to project management and the pilot to inform decisions about adjusting disc size or flight speed to ensure a consistent sow rate.

Flight line data were downloaded from the GPS unit and treatment polygons (spatial representations of where bait was spread) were estimated by buffering the flight lines based on the effective swath width calculated during operational bucket calibration. Using the helicopter times from the tracking worksheet and the times recorded in the flight line GPS data, the recorded sow rates were assigned to treatment polygons (now spatial representations of where bait was spread and at what rate it was applied). GIS-derived bait density estimates were calculated by dissolving overlapping treatment polygons into new non-overlapping polygons and summing the sow rates of the overlapping parts. Bait density estimates and flight line maps were reviewed to identify gaps or undertreated areas.

Factors associated with difference in planned and actual bait amounts used

To evaluate what factors were associated with the total bait applied during an aerial operation, aerial baiting data from the ten projects, comprising 17 different island blocks, were collated (Table 1). In some cases, an island block comprised of multiple treatment units (i.e. motu or small islets) that were treated collectively. There were three projects where multiple island blocks were treated as independent units. Ten exploratory factors thought to be associated with differences in aerial bait applications were collected for each application (Table 2). Only the first application for each island block was analysed as they were the most comparable because the amount of bait applied during the second application could be influenced by the amount of bait used during the first application, bait availability monitoring data, or the use of supplemental bait.

These ten factors were compared against two response variables, referred to as bait use scenarios: 1) the percent change between the bait amount in a hypothetical uniform scenario, where bait is evenly distributed across an island, and the planned amount of bait to be used (Δuniform.planned); and 2) the percent change between the planned amount of bait and the actual amount of bait used (Δplanned.actual) (Fig. 1). The variable 'Δuniform.planned' represents the change in bait required between a uniform application and what was planned to account for physical island characteristics and strategy decisions such as reducing bait into the marine environment. The variable 'Δplanned.actual' represents the difference between what was planned and what happened on the day due to operational realities, such as unexpected deviations in sow rates and flight path.

We used Spearman's rank correlation to explore relationships between variables we thought may influence planning (Δuniform.planned) and how the reality of the day affects the plan (Δplanned.actual). To minimize the chance of Type I error resulting from multiple pairwise tests, we chose to test four variables (elevation, size, coastline, and flight lines) for correlation with the two bait use scenarios and penalized the p-value by a factor of 8 ($P<0.0006$). The remaining explanatory variables were expressed as boxplots and compared with exploratory statistics.

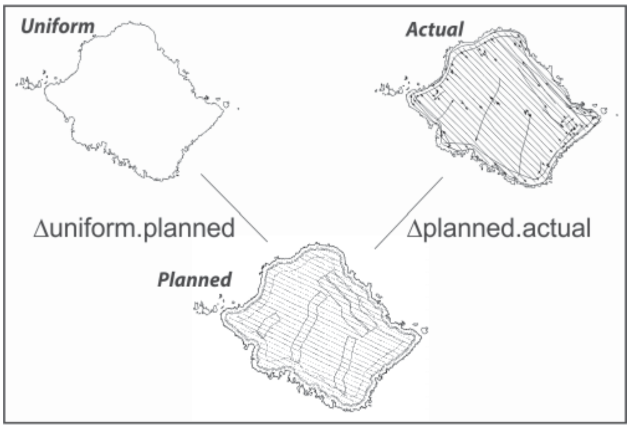

Fig. 1 Examples of bait use scenarios used and normalised percent change, delta, in bait use between scenarios. Uniform represents bait needed in an even distribution of bait across island area, planned represents bait needed based on predicted flights paths and overlap, and actual represents bait used.

Table 2 Explanatory physical and operational characteristics evaluated.

Physical characteristic	**Definition**
Country	Country operation was implemented in
Habitat	Tropical or temperate
Island type	Volcanic or coral atoll
Max. elevation	Maximum elevation in meters as a proxy for steep terrain
Size	Size of area to be treated (km^2)
Coastline	Length of coastline to be treated (km)
Operational characteristic	**Definition**
Target rate	Minimum application rate expected to be achieved on the ground, in some cases the coast and interior had different expected rates. The lowest expected rate was selected
Number of flight lines	The total number of flight lines flown
Supplemental treatment	Cliff, coast, or none to represent areas that received additional treatment above the target application rate
Coastal overlap buffer	True or false if the coastal overlap buffer strategy was employed to reduce bait into the marine environment

Variability in bait densities achieved

To evaluate the distribution of bait densities (kg/ha) we used GIS-derived bait density estimates from the 17 island blocks. For each island block, the area and estimated bait density of each polygon representing the bait density achieved on the ground from overlapping swaths was exported. Polygon areas representing areas smaller than 100 square meters (0.01 ha) were excluded as they were smaller than what is commonly considered a significant gap. For each island block, a bait density distribution was calculated to represent the total amount of island area treated at each bait density rate (e.g. 10 ha at 5 kg/ha) by summing the areas of treatment polygons at each bait density rate. To normalise bait density distributions across island blocks, values were represented as a percentage of the target application rate (e.g. 50% = half, 100% = target rate, 200% = twice target) and areas as a percentage of the total island area treated.

RESULTS

Factors associated with differences in planned and actual bait amounts used

The 10 projects analysed most often occurred in tropical regions (7 projects, 14 of 17 island blocks) and ranged in size from 8–2,900 ha, and 5–430 m in elevation. Target application rates ranged from 6 to 80 kg/ha, supplemental baiting used in seven island blocks, the coastal buffer overlap strategy used in 10 island blocks, and the number of flight lines flown spanned 9–1096.

On average, 20% more bait than the uniform scenario (Δuniform.planned) was planned for, and 16% more bait was used than planned (Δplanned.actual). The variables Δuniform.planned and Δplanned.actual showed no associations with the four factors investigated (elevation, size, coastline length and the number of flight lines) (Table 3). Median results of the 17 island blocks were 380 hectares, 214 flight lines, 80 m in elevation, and an 18 km coastline. Although no statistical correlation was evident among the island blocks and these factors, those blocks below the median showed a mean Δuniform.planned that was two to three times greater than blocks above the median, suggesting that compared to larger islands in our sample, planning on smaller islands typically identified proportionally more bait than a uniform distribution. The same trend is evident for Δplanned.actual with mean values for islands blocks below the median being one and a half times greater than above the median, showing that among our sample, smaller islands used proportionally more bait than planned for, compared to larger islands. Of the 14 tropical island blocks, five were on coral atolls, and these generally had a higher number of flight lines (M = 474.6, SD=215.1), compared to volcanic islands (M=121.1, SD=110.5).

Three island blocks conducted in the United States (Desecheo 2012, 2016, and Palmyra) had a negative Δplanned.actual, putting less bait on the ground than planned. The 10 blocks using the coastal buffer overlap strategy to reduce bait into the marine environment showed, on average, lower Δuniform.planned and Δplanned.actual compared to blocks that did not use this strategy.

Analysis of bait density estimates

On average, 5.1% (SD=3.8) of total island area received less than 50% of the target application rate and 0.8% (SD=1.6) of total island area received more than 400% of target (Fig. 2). The GIS derived bait density estimate polygons representing these areas had an average size of 0.12 ha (SD=0.2) and 0.03 ha (SD=0.04), respectively. Bait density estimates from each island block are shown in Fig. 3. Bait density estimates of less than 75% of the target application rate were visually compared against grids representing conservative minimum (0.01 ha) and average (0.1 ha) rodent habitats on tropical islands based on available literature (Fig. 4).

DISCUSSION

Factors associated with differences between planned and actual bait amounts used

From a statistical perspective, the sample size we used is considered small (n=17), and less than ideal because it was opportunistically collected (and not experimentally collated). From a conservation practitioners perspective, the opportunity to compare 17 different island blocks consistently is rare, and a positive example of collaboratively working to answer questions relevant across the island restoration field. A key result from our investigation is that projects planned to use 20% more bait than the hypothetical uniform application and used 16% more bait than planned, suggesting that simply estimating bait quantities by multiplying island area by target application rate is insufficient to judge how much bait will be needed. On average, the percent change between the planned amount of bait and actual bait used was less than the percent change between the hypothetical uniform

Table 3 Spearman's correlation and p-value of factors thought to influence bait use. Factors were considered associated with changes in bait use if Rho > 0.3 and p-value<0.006. Negative numbers represent a negative association (i.e. as one factor increases the other decreases) and positive numbers a positive association (i.e. as one factor increases so does the other).

Scenario	Factor	Rho	p-value
Δuniform. planned	Max. elevation	-0.193	0.458
	Size	-0.389	0.123
	Coastline	-0.288	0.262
	Flight lines	-0.311	0.224
Δplanned.actual	Max. elevation	-0.252	0.328
	Size	-0.212	0.414
	Coastline	-0.185	0.477
	Flight lines	-0.272	0.291

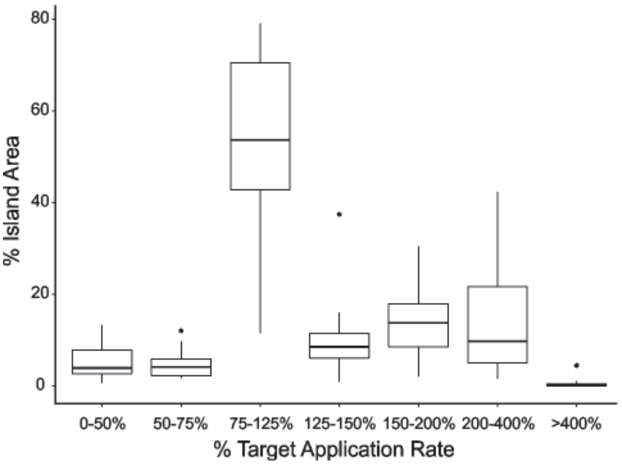

Fig. 2 Box plot of bait densities across projects represented as % of total island area treated vs % of target application rate.

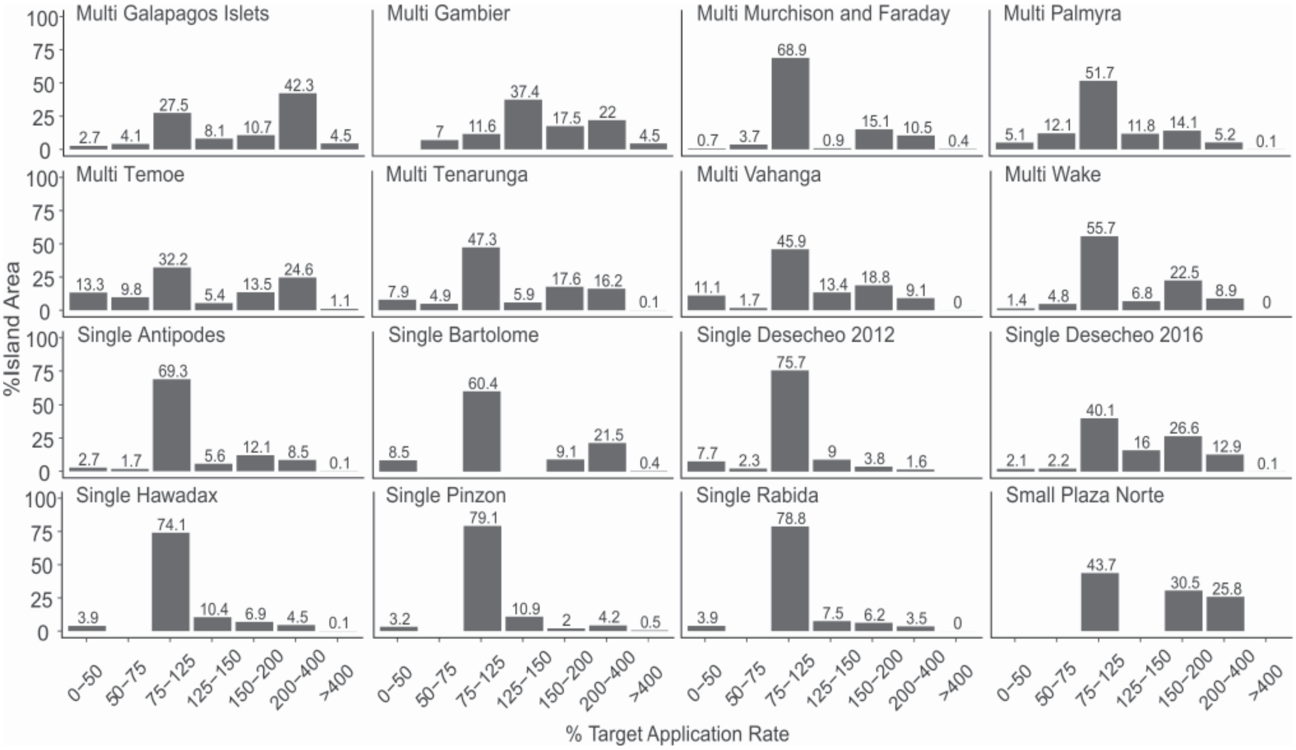

Fig. 3 Estimated bait density distributions per island block as % of total island area treated vs % of target application rate. Projects are grouped into multi (i.e. multiple treatment areas), single (i.e. single continuous treatment area > 100 ha), and small (i.e. < 100 ha).

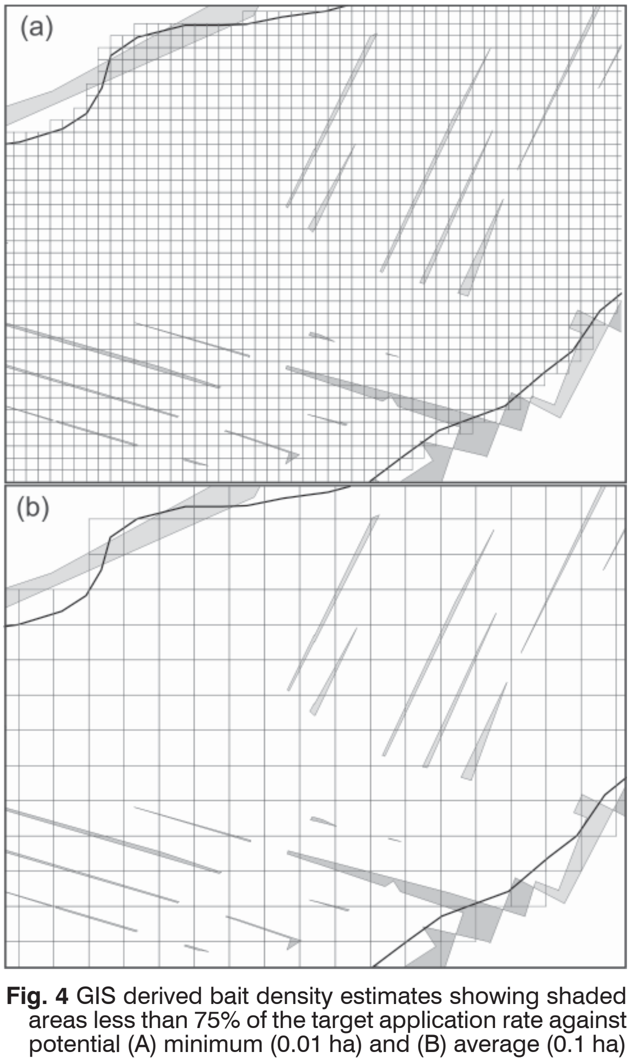

Fig. 4 GIS derived bait density estimates showing shaded areas less than 75% of the target application rate against potential (A) minimum (0.01 ha) and (B) average (0.1 ha) home range sizes from literature review.

amount of bait and actual bait used, suggesting that the aerial bait plans were more accurate at forecasting bait use but still underestimated actual bait required.

In general, smaller islands and islands with shorter coastlines, less elevation, or fewer flight lines planned to use, and actually used, a higher percentage of bait than projects on larger islands or those with more topography or flight lines. This suggests that small islands use proportionally more bait and that projects with fewer flight lines are more complex. While coastline length and maximum elevation were likely not differentiated enough from island size to detect a significant difference, the four-fold increase in the number of flights flown on tropical coral atolls, which have two coastal edges (lagoon and ocean), compared to volcanic tropical blocks suggests coastal complexity needs to be factored into planning. While the number of flight lines is also related to size, projects with fewer flight lines also have less room for error and could experience greater variability in bucket sow rates. Small islands may be able to improve bait applications, and reduce unplanned bait use, by employing strategies to increase the number of flight lines flown such as flying the parallel flight lines twice per application at half the target rate.

Perhaps the most interesting result was that projects implemented in the United States were the only projects, on average, to use less bait than planned. The United States has a complex regulatory environment, and aerial broadcasts are required to stay below permitted application rates. When implementing an eradication, projects in the United States had to balance the desire to achieve the desired target application rate with not exceeding the permitted application rate. Striking this balance resulted in projects using less bait than planned, particularly when the desired target rate was close to the permitted rate. This suggests that regulators should be involved early in the planning process so that regulatory approval can be sought to maximise project success. A single permitted application rate, such as the one designated on the bait product registration in the United States, is not necessarily appropriate for every project and, when appropriate, projects should develop site-specific operational strategies using the best available science. Regulatory bodies should review these strategies and recommended application rates on a case by case basis.

Bait application variability and consequences

It is noteworthy that, on average, 5% of the total island block area had bait density estimates less than half of the target application and 0.4% had bait density estimates greater than four times the target application rate (Fig. 2). This suggests a relatively high degree of precision in balancing the risk of failure (i.e. low localised bait densities) with unintended environmental impacts (i.e. high localised bait densities). Comparing the distributions of bait densities, larger (> 100 ha) single unit island blocks (i.e. those treated as a single contiguous unit: Antipodes, Desecheo, Hawadax, Pinzon, and Rabida) generally tended to have less bait density variability, with more than 60% of total island area near the target application rate, compared to smaller islands (< 100 ha) or island blocks consisting of multiple treatment units (Galapagos Islets, Gambier, Palmyra, Plaza Norte, Temoe, Tenarunga, Vahanga, and Wake) with less than 50% of total island area near the target application rate (Fig. 3). This is logical given that large or single unit island blocks have longer flight lines with which to "settle" into consistent sow rates and a smaller coast to size ratio resulting in fewer overlapping flights. Island blocks with multiple treatment units, particularly tropical coral atolls (Palmyra, Temoe, Tenarunga, and Vahanga), tended to have a higher percentage of total island area with localised bait densities more than twice the target application. These tropical coral atolls have more coastline for their size than other similarly sized islands, and thus the consequences of the flight line overlap necessary to minimise the chance of gaps near the coastline (i.e. higher localised bait densities) are more pronounced. This result underscores the trade-offs of ensuring complete coverage along complex coastlines.

Examinations of the two failed projects (Desecheo in 2012 and Wake) suggested low bait densities as one of the potential reasons contributing to failure (Derek Brown, pers. comm.). The bait density distribution of the failed 2012 Desecheo project shows a larger proportion of the island experienced localised bait densities less than half the target application rate during the first application (7.7%), compared to similar islands. Desecheo had a high abundance of non-target bait competitors (up to 833 crabs/ha) and bait availability plots in one habitat showed bait availability reaching zero within two to three nights (Will, et al., 2019). It seems likely that areas with localised bait densities less than half the target application rate would have experienced even less bait availability. On Wake, the bait density distribution shows a smaller proportion of the island achieved less than half the target application rate (1.4%) compared to similar islands, but bait density maps also show fewer flight lines extending up to the coastal edge and the presence of bait gaps on the beaches between the mean high-water mark and predominant vegetation. These observations may be instructive in improving the quality of future bait applications, suggesting that future applications consider applying additional bait (i.e. reapply) in areas with bait densities identified to be less than the target application rate and consider minimising the amount of untreated coastal edge on tropical coral atolls. These are areas where bait availability may be much less than expected and may not be immediately obvious when inspecting flight line maps. It is impossible to know if these improvements would have resulted in successful eradication attempts on Desecheo in 2012 and on Wake, but they would have removed questions about the quality of bait coverage as a possible contributor to eradication failure.

What is a significant biological gap?

Comparing actual bait densities achieved to the hypothetically smallest potential home range size can be instructive in informing risk tolerance for future operations. Rodent home ranges are highly variable, but amongst *R. rattus* have been recorded ranging from 0.012 to > 10 ha (Shiels, et al., 2016; Harper & Bunbury, 2015). It is in the smaller home ranges, particularly for breeding female rodents, where localised deficiencies in bait density present the highest risk of a rodent not being exposed to a lethal dose of bait (i.e. undertreated areas). We considered any areas that achieved less than 75% of the target application rate to be undertreated, which were generally the result of flight line deviation and were small (<0.1 ha) and irregularly-shaped (hundreds of meters long and <20 m wide). Despite their size and shape, these undertreated areas were still large enough to encompass most, if not all, of an assumed 0.01 ha potential minimum home range, but a minority of an assumed 0.1 ha average home range (Fig. 4). This suggests that, at the extreme, localised deficiencies in bait density could make bait less available than expected in entire potential rodent habitats where rodents have small home ranges.

Whether localised bait density deficiencies (i.e. undertreated areas) constitute biologically significant gaps is largely a consequence of toxicology, rodent biology and island ecology, and is project dependent. Ultimately, projects should anticipate that localised deficiencies in bait density are almost inevitable and determine what risk they pose to project success based on site specific conditions. In the presence of alternative foods and non-target bait competitors, or on islands targeting species with small home range sizes or multiple rodent species, areas that receive less than the target application rate could result in insufficient bait availability and constitute biologically significant gaps that pose a risk to project success. Where biologically significant gaps are a concern, project managers can either choose to increase the target application rate to increase the localised bait density of undertreated areas or set area size and application rate thresholds (i.e. 0.1 ha or larger with a bait density less than half the target application rate) to reapply bait.

Improving aerial application data analysis

Although GIS-derived bait density estimates provide a useful metric for identifying gaps or undertreated areas, they do have limitations and assumptions. A key limitation is they are not a direct measure of bait on the ground, and where possible on-ground measures of bait density, particularly with adequate sample size, can improve these data. Further, GIS-derived bait density estimates assume a) that flight speed is constant along the length of a flight line, b) bait pellet distribution across a swath is even, and c) wind has no impact on bait spread. A novel model called the Numerical Estimation of Rodenticide Dispersal (NERD) models these assumptions to generate a probability density function describing bait density and was successfully implemented on several projects in Mexico (Rojas-Mayoral, pers. comm.; Samaniego-Herrera, et al., 2017). These sorts of novel models are highly appropriate on high risk islands targeting species where smaller rodent home ranges may be anticipated (e.g. tropical islands where breeding may be expected). However, regardless of the analysis method used, managers are advised to trust in the broader rodent eradication principles and exercise caution to avoid overanalysing baiting data.

RECOMMENDATIONS

In summary, we propose the following recommendations to improve the planning and implementation of aerial broadcast applications for eradications.

Use high-resolution satellite imagery to estimate island size. Accurate estimates of operational area will improve estimates of the amount of bait needed and reduce the risk of having insufficient bait or the cost penalties of transporting and disposing of too much bait.

Create predicted flight plans to inform planning and estimate bait requirements. Multiplying island area by target rate is not an accurate estimate of bait needed. Including flight line overlap between parallel swaths and at the coastal boundary will improve accuracy of bait total estimates, reducing the chance of having too little bait. Additionally, predicted flight plans are useful in communicating the desired strategy.

Projects should plan for small islands to use more bait than anticipated and islands with complex coastlines to experience greater variability in bait densities. Coral atolls with lagoons have two coastal edges, which increases complexity, and should plan to use more bait and experience more areas of high localised bait densities. Small, complex projects should plan on ordering additional bait to treat gaps and compensate for areas of unplanned overlap.

Managers of projects on small islands should consider modifying operational strategies to reduce using additional bait. Increasing the number of flight lines by flying the island twice per application (with sowing rates adjusted to achieve the target rate), reducing the amount of bait in the bucket per load to reduce the percentage of island covered per flight, or conducting additional calibration runs to ensure consistency should be considered.

Projects should seek site-specific regulatory approval that maximises project success. A single permitted application rate is not sufficient to maximise success for all projects. Where appropriate, application rates should be tailored to site-specific conditions and be informed by the best available science. Additionally, to ensure clarity, projects should seek site-specific approval to implement predicted flight plans that describe the application rates and strategy needed to maximise project success. This is particularly relevant for projects implemented in the United States.

Use bait density estimates to identify areas treated below the target application rate. Tracking sowing rates achieved per load and assigning them to flight line data improves the understanding of bait coverage and allows managers to identify undertreated areas. Novel or high-risk projects should also consider using more fine scale bait density modelling approaches like NERD (Rojas-Mayoral, pers. comm.).

Projects should set gap size tolerances and application rate thresholds to match project risk variables. Clarify in advance of the project what constitutes a biologically relevant baiting gap based on what is known about the target species, island habitat, topography, and presence of non-target bait competitors. It is highly likely that a broadcast application will result in less than expected bait availability in the smallest potential rodent home ranges. For rodents with small home ranges, or tropical islands with high densities of non-target bait competitors, alternative food sources, or multiple rodent species a smaller gap size or higher application rate threshold may be warranted.

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