Improved design method for biosecurity surveillance and early detection of non-indigenous rats

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Abstract: A recent advance in biosecurity surveillance design aims to benefit island conservation through early and improved detection of incursions by non-indigenous species. The novel aspects of the design are that it achieves a specified power of detection in a cost-managed system, while acknowledging heterogeneity of risk in the study area and stratifying the area to target surveillance deployment. The design also utilises a variety of surveillance system components, such as formal scientific surveys, trapping methods, and incidental sightings by non-biologist observers. These advances in design were applied to black rats (*Rattus rattus*) representing the group of invasive rats including *R. norvegicus*, and *R. exulans*, which are potential threats to Barrow Island, Australia, a high value conservation nature reserve where a proposed liquefied natural gas development is a potential source of incursions. Rats are important to consider as they are prevalent invaders worldwide, difficult to detect early when present in low numbers, and able to spread and establish relatively quickly after arrival. The 'exemplar' design for the black rat is then applied in a manner that enables the detection of a range of non-indigenous species of rat that could potentially be introduced. Many of the design decisions were based on expert opinion as data gaps exist in empirical data. The surveillance system was able to take into account factors such as collateral effects on native species, the availability of limited resources on an offshore island, financial costs, demands on expertise and other logistical constraints. We demonstrate the flexibility and robustness of the surveillance system and discuss how it could be updated as empirical data are collected to supplement expert opinion and provide a basis for adaptive management. Overall, the surveillance system promotes an efficient use of resources while providing defined power to detect early rat incursions, translating to reduced environmental, resourcing and financial costs.

Keywords: Barrow Island; expert elicitation; invasive species; *Rattus;* statistical design

Introduction

Non-indigenous species (otherwise known as invasive, alien, exotic, or introduced species) are a major threat to island biodiversity, as island ecosystems and their native species can be severely impacted when non-indigenous species invade and establish (Case & Bolger 1991; Vitousek et al. 1997). Three species of commensal rats: black rats (*Rattus rattus*), Norway rats (*R. norvegicus*) and Pacific rats (*R. exulans*) are particular problems on islands worldwide. Black rats are listed in the top one-hundred of the world's worst invasive species (Lowe et al. 2000). Rodents are transported on ships and introduced as cargo is unloaded or ships are wrecked (Morris 2002), they can persist in a wide range of habitats and environments (Watts 1995), and are known to have particularly severe effects on native ecosystems (Towns et al. 2006) and species (Wanless et al. 2007; Jones et al. 2008). Despite knowledge of non-indigenous rat impacts on native species and ecosystems, surveillance systems designed to prevent further rat introductions are lacking.

One or more invasive rodents are known to occur on 74 of the 8294 islands around Australia, but have been eradicated from another 39 Australian islands (Commonwealth of Australia 2009a). Australian governments currently plan to eradicate non-indigenous rodents from more of these islands and to increase biosecurity measures to limit invasion or re-invasions and to detect and deal with any breaches. These initiatives have been given impetus by the publication of a national Threat Abatement Plan to manage non-indigenous rodents on Australian islands (Commonwealth of Australia 2009b) under the *Environment Protection and Biodiversity Conservation Act, 1999*.

The biosecurity continuum can include a variety of actions pre-border (e.g. logistic supply chain), in transit (e.g. marine vessel, aircraft, personnel luggage), or by border and post-border actions. The latter can include prophylactic actions such as placement of permanent control devices to intercept any invaders, or reaction to any detected breaches (Dilks & Towns 2002; Russell et al. 2008a). The optimal intervention along this biosecurity continuum depends very much on the species involved, the likelihood of the species reaching the island, and the costs of mitigating any breaches of the system. In the case of invasive rodents, efforts to limit incursions are generally more cost-effective than eradication options. However, surveillance to detect incursions of non-indigenous species early remains a major challenge in biosecurity.

The need for better surveillance design has been identified (Russell et al. 2005; Broome 2007; Department of Conservation 2008). The use of multiple detection methods has been suggested for the detection of rats (Dilks & Towns 2002; Russell et al. 2008a) recognising that usual methods used in eradication of populations (e.g. traps and bait stations) were not successful in detecting the presence of rats when they were in small numbers. Failure in the past to detect rat incursions early using only a few methods, usually trapping and baiting, is likely to be attributed to neophobic (i.e. fear of unfamiliar objects in a familiar environment) or trap-shy behaviours (i.e. due to being previously caught) of rats, as it may take several days or weeks for rats to enter bait stations (Clapperton 2006; Russell et al. 2008a). Newly established populations of rats display extreme neophobia, and if abundant food sources are present then baits are not as attractive, possibly resulting in atypical behaviour (Dilks & Towns 2002; Russell et al. 2005).

Our study area is Barrow Island, a 230 km^2 island located 70 km off the coast of north-western Australia. It has very high conservation values. There are almost 400 species of plants, 13 terrestrial native mammal species (many of them threatened), more than 110 bird species, 44 terrestrial reptile species, at least 1261 species of terrestrial invertebrates, and at least 59 taxa of subterranean fauna. In 1908, Barrow Island was declared a Class A Nature Reserve for the protection of flora and fauna.

Barrow Island's reserve status has been maintained despite being home for over 40 years to Australia's largest onshore oilfield, during which time more than 300 million barrels of oil have been produced. Due to rigorous environmental management the island is currently free of non-indigenous mammals (Bamford Consulting Ecologists et al. 2005). Black rats were present over a small part of the island and eradicated in 1991 (Morris 2002). House mice (*Mus musculus*) have also been detected on the island in the past but were commensal and eradicated before they could establish more widely in the wild (Morris 2002). Barrow Island is the site for Australia's single largest resources project, the Gorgon Project. The Gorgon Project is being pursued by an unincorporated joint venture comprising of Chevron 50%, Shell 25% and ExxonMobil 25%. In 2007 the Gorgon Project received approval from the Commonwealth and State Governments for a 10 million tonne per annum (MTPA) LNG development. In 2008 the Gorgon Project submitted a revised and expanded proposal for a 15 MTPA LNG development and a 300 TJ/d domestic gas plant. The final investment decision on the overall Gorgon Project has recently been announced. The Gorgon Project gas plant will be developed within a 300-ha allocation on Barrow Island (1.3% of total area). As part of the existing approval, the state government has required the proponents to develop a rigorous quarantine management system and meet strict conditions for its implementation.

One element of the quarantine management system is to design and implement a surveillance and detection system that has statistical power (decreased Type II error: falsely declaring a non-indigenous species absent) of 0.8 or greater to detect non-indigenous species when their numbers are very low and early enough to enable eradication without significant environmental consequences (Government of Western Australia 2007). Chevron has developed rigorous pre-border quarantine requirements and risk mitigation based on pathway risk analysis. This should mean very low probabilities of entry and therefore, low probabilities of the presence of non-indigenous species that might establish without an effective surveillance system on the island.

In this paper we apply and extend a new design methodology which was originally developed to meet this statistical power condition for a non-indigenous invertebrate species, the big-headed ant (*Pheidole megacephala*) (Whittle et al. 2008; Barrett et al. 2009), to a non-indigenous vertebrate species, the black rat. Inherent biological differences among the big-headed ant and the black rat result in a different ecological model underpinning the surveillance system for each. For example, the big-headed ant and black rat have different habitat requirements, different introduction mechanisms and pathways, require different methods of detection, have different levels of detectability, and vary in rates of movement and spread. However, the surveillance design methodology can be applied to both with due consideration given to ecological differences. The design methodology stratifies risk spatially over the heterogeneous sampling frame and includes the use of a variety of detection methods applicable to the species. For the big-headed ant this resulted in increased power to detect ant incursions on Barrow Island while minimizing environmental and financial costs (Barrett et al. 2009). We hypothesise that applying the new design methodology to the black rat will likewise result in increased power to detect rat incursion on Barrow Island, while minimizing environmental and financial costs.

Methods

Expert elicitation

A group of six independent vertebrate specialists were consultatively nominated to assist with expert judgment in the design of the surveillance system, particularly when data gaps require advice for the model parameters. The elicitation was held during part of two one-day group workshops in late 2008. There were several steps to the elicitation process roughly following the guidelines set out in Low Choy et al. (2009), where expert judgment provides information for the model, which can be updated as data becomes available. Expert judgments contributed to the model at various stages (indicated on Fig. 1).

Most of the specialists (five of six) had knowledge specific to Barrow Island and the region. Group (consensus) judgments were sought in workshops such that the majority of opinion was captured. Group elicitation has certain advantages over other types of elicitation (see Burgman 2005; O'Hagan et al. 2006). Consideration was given to the various types of uncertainty by involving a variety of specialists in the field and using a group workshop setting (O'Hagan et al. 2006). Herein this group of independent specialists is referred to as the 'experts'.

Selection of an exemplar species

R. rattus was selected for study by the experts due to its threat of introduction to Barrow Island, due to its known invasiveness (previously established on Barrow Island) and its widespread presence on the Australian mainland and many overseas locations where materials might be sourced. In addition, its biology and ecology are relatively well understood and reported and it can be detected by a range of techniques applicable to other rat species. Based on the advice of experts, the surveillance system for *R. rattus* is likely to detect other non-indigenous rats, including *R. norvegicus* and *R. exulans*, i.e. species that

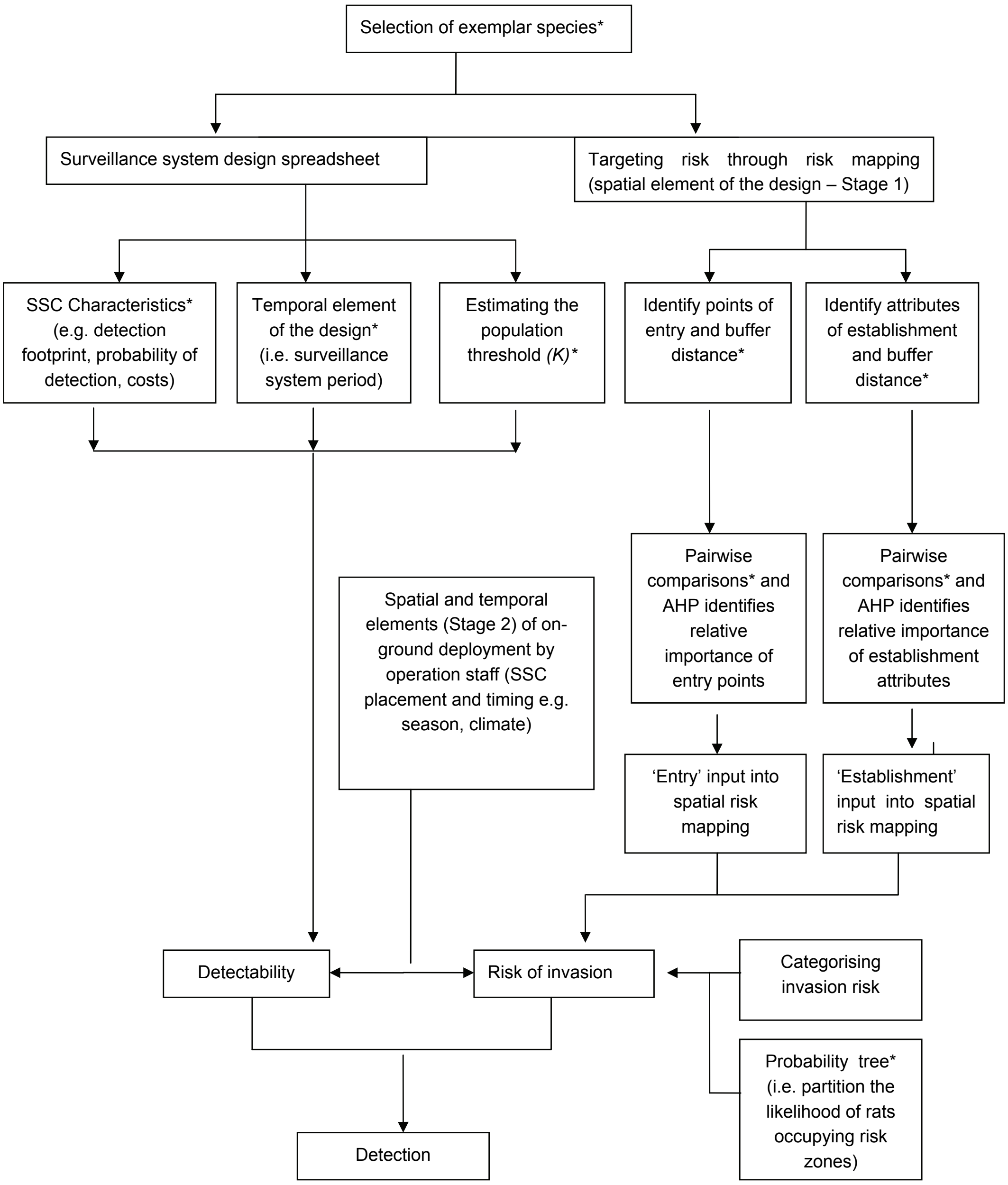

Figure 1. Process flow chart for determining the surveillance system. Surveillance system components (SSCs) consists of traps, surveys and incidental sighting, etc. Expert elicitation contributed at various stages of the model (*). Figure adapted from the Generic Invasion Model in Whittle et al. (2008).

utilise similar habitat and entry pathways and can be detected using the same suite of surveillance system components (SSCs; terminology after Martin et al. 2007).

Conceptual model for detection

As shown in the process flow chart (Fig. 1), detection is determined by the probability that the surveillance system will detect at least one individual of the target species, given it is present in the sampling frame when the population is at a specified threshold (K). K is set to a number of individuals that is large enough to be detected, but small enough to be effectively eradicated without significant environmental consequences and costs. Here, we are concerned only with anthropogenic sources of introduction associated with the Gorgon Project (i.e. not with other sources such as shipwrecks). Detection thus depends on: (a) the ability of the SSCs such as surveys, traps and incidental sightings, to detect a non-indigenous species should it be present in the sampling frame during the deployment time period (i.e. cycle of the entire surveillance system); and (b) risk of invasion - the likely distribution and abundance of the species in the sampling frame, which depends on likelihood of entry to the locality and habitat suitability for the species to establish a breeding population.

Risk mapping to target surveillance effort

In order to efficiently target surveillance, the risk of invasion was mapped across a large and heterogeneous landscape. The first stage involved stratifying the landscape spatially (not

Table 1. Categorisation of invasion risk relative ranges for mapping, using the combined distribution of entry and establishment relative importance weights. Risk decreases from Zone 1 to 4. Invasion risk was calculated by multiplying relative importance weights for entry (see Table 2) and establishment (see Table 3).

Risk zone	Basis for categorisation	Invasion risk relative range
Zone 1	Range from the (maximum entry value × minimum establishment value) to the maximum invasion risk value	0.063– 0.317
Zone 2	Range from the (minimum entry value × maximum establishment value) to the (maximum entry value × minimum establishment value)	0.015 – 0.063
Zone 3	Range from the minimum risk value above zero to the (minimum entry value × maximum establishment value)	0.003 – 0.015
Zone 4	The value for either entry or establishment (or both) is very low, making the product close to zero	<0.003

temporally) according to likelihood of entry and establishment which provides risk of invasion; such that numbers of SSC units can be calculated for each risk zone and locality (see below for a descriptions of risk zone and locality). The second stage involves deployment of SSC units within zones and localities, and over time, using local fine scale spatial knowledge. This second stage of the risk mapping requires the SSC units to be deployed to maximum effect spatially within the zones and temporally, and relies on the skills and training of the operational staff carrying out the surveillance.

Experts identified potential points of entry and habitat attributes for successful establishment of the black rat. Experts compared the relative importance of entry points and establishment attributes in a pair-wise fashion using the Analytic Hierarchy Process (AHP) (Saaty 1987). Pair-wise comparisons were made using a linguistic scale ranging from equal preference (e.g. to both entry points in a pair) to absolute preference (e.g. of one establishment attribute over another), related to a numerical scale of 1-9. Here, the number 3 indicated a 'weak preference', 5 indicated a 'strong preference', 7 indicated a 'demonstrated preference', and numbers 2, 4, 6 and 8 were intermediate values. Demonstrated preference was generally taken to mean 'very strong preference' in the absence of demonstratibility. The pair-wise comparisons are combined to give a numerical weight or priority (Relative Importance Weight; RIW) for each element of the hierarchy (in this case each entry point or establishment attribute).

Entry points and habitat attributes for establishment were assigned to features that could be mapped using spatial layers available in a geographical information system (GIS). The cumulative RIWs for entry and establishment were calculated and assigned to areas mapped as GIS polygons, resulting in maps of likelihood of entry and establishment. Likelihood of entry was multiplied with likelihood of establishment for each GIS polygon (via a GIS overlay), resulting in a map of invasion risk. Entry points were assumed to encompass the entire construction and anthropogenically disturbed area. Each entry point was extended to a larger area using a buffer distance which reflected the approximate home range of a black rat. The vegetation classes were based on Mattiske & Associates (1993) and Mattiske Consulting (1997). GIS services were provided by Chevron Australia.

Invasion risk was categorized into four levels (Table 1) using the combined distribution of entry and establishment RIWs. For instance, the highest risk is in Zone 1, and ranges from the upper threshold of 'maximum invasion risk value' to the lower threshold of 'maximum entry value multiplied by the minimum establishment value'. The lowest risk is in Zone 4 and occurs when the value of entry or establish (or both) is very low, making the product a very small value close to zero. The basis for defining the other two risk categories is shown in Table 1.

Experts were consulted and published data was evaluated to estimate and partition the relative risk (*rr*) of invasion among zones during the early stages of invasion using a likelihood tree. The likelihood tree indicates likelihoods for black rats arriving, dispersing and establishing on Barrow Island. The surveillance system was designed to detect non-indigenous rats not detected on arrival by quarantine measures.

Surveillance system design, components and deployment

A surveillance system consists of a number of SSCs which were selected by experts to address the range of non-indigenous species the system is designed to detect. Each SSC has several characteristics: a detection footprint (detection area of one unit of SSC deployment, m^2), probability of detection (σ) conditional on presence in the sampling frame (i.e. risk zone), and cost (per unit of SSC, summed to hours) (Whittle et al. 2008; Barrett et al. 2009). In the design methodology, cost refers to the time of operation of one SSC unit, each a single performance to normal protocol, and is a flexible parameter that can accommodate a range of factors such as detriment to native species or logistical constraints. Operational details of SSCs were discussed during the workshops and a consensus on the list of SSCs and their characteristics were reached, subject to knowledge gained from other published studies and knowledge gained by implementation and monitoring of survey results.

The surveillance system was designed to achieve 80% power to detect any individual of the target species (with the null hypothesis of species absence). Power in this context is defined as the probability that the surveillance system detects a non-indigenous species, given it is present in the sampling frame.

The theoretical basis for the SS has been presented in Whittle et al. (2008) and Barrett et al. (2009) therefore only a brief description of the statistical design is given here. To calculate N (the number of SSCs required to detect any individual of the target species) the following equation was utilized:

$$n_{SSCi} = \frac{\log(1 - utility_{SSCi})}{K \log(1 - \sigma_{SSCi} F_{SSCi})} \qquad \text{Equation 1}$$

where n is the number of SSCs required to detect the target species; K is the species population size, large enough to be feasibly and sensibly detected but not so large as to pose a threat to the native environment: this tolerable population size is termed K (where $K \geq 1$) and is considered to be a population consisting of groups of individuals where each individual within the group has the same σ; this specification of K accommodates possible dependent behaviour between the species individuals; β is the probability of a type II error; F is the fraction of the sampling frame to be sampled. It is expected that each individual rat is spends equal time in the footprint of an SSC. Further work will include a conditional specification within equation 1 to accommodate dependent behaviour.

In equation 1, cost and risk (rr) are incorporated as follows:

$$Utility_{SSCi} = 1 - (\beta)^{relative\ weight} \qquad \text{Equation 2}$$

where:

$$relative\ weight = \frac{1}{(1 - \sigma_{SSCi} F_{SSCi}) \times cost \times (1/rr)} \qquad \text{Equation 3}$$

Here, 'cost' is hours of labour, but in other applications it may be useful to use cost to represent a dollar amount. It follows that the contribution of each SSC to the overall power of the surveillance system is based on the proportional utility of each SSC:

$$Power = 1 - \prod (1 - utility_{SSCi}) \qquad \text{Equation 4}$$

where i is the number of SSC types not units, i.e. cage traps etc.

Finally, once the numbers of SSCs are calculated they are deployed across the various locations and risk zones based on the relative magnitude of each locality.

The resulting surveillance system has two components required for implementation: (i) the design spreadsheet where the above calculations are performed and the number of SSCs calculated and, (ii) the risk maps which enable deployment across the sampling frame/landscape by field workers. It is expected that the spreadsheet and maps will be updated as new information becomes available.

Results

Risk mapping

Likely entry points for black rats were identified at three vessel and aircraft entry points on Barrow Island (a marine offloading facility, a barge landing site, and the airport) and five additional sites where human and cargo activity occurs (the LNG plant construction area, horizontal direct drilling site on the west coast, Gorgon construction village, existing oilfield construction camp, and existing oilfield base). These localities are shown in Fig. 2 and have been described in more detail by Whittle et al. (2008).

A buffer area at all entry points was set to a distance of 100 m, reflecting an average 1 ha home range selected from a published study (Dowding & Murphy 1994), and judged to be appropriate for Barrow Island by the experts.

Pair-wise comparisons indicated that experts considered the marine offloading facility a relatively more important potential entry point than the barge landing, and both to be relatively more important than the remaining six potential entry points (Table 2). Expert judgments were largely based on amounts and frequencies of material, people, aircraft and vessels arriving at each locality.

Establishment attributes were identified and their relative importance judged by experts: preferred vegetation types; other vegetation types; human inhabited areas; and areas lacking of vegetative cover. There are no sources of free-standing surface water on the island, except in the episodes of extreme rainfall associated with cyclonic depressions resulting in temporary surface water, which would otherwise be considered an important attribute for establishment.

Preferred habitat type included areas of 'coastal complex and dune ecosystem' including adjacent beach to the water line at low tide. The coastal complex and dune ecosystem is the habitat where black rats were known to be present on Barrow Island prior to their eradication in 1991 (Morris 2002). Other less preferred habitat types included areas of seasonal drainage lines, limestone ridges, inland grasslands, escarpments and valley slopes, marine tidal habitats (Mattiske & Associates 1993; Mattiske Consulting 1997). Human inhabited areas referred to locations containing human supplies of food, water or shelter. Areas lacking vegetation cover included disturbed bare ground or rocky, clay or sandy (non-coastal) substrate with no vegetation. The preferred vegetation type was considered relatively more important to the establishment of black rats, compared to other vegetation types, no vegetation, and human inhabited areas (Table 3).

A map of invasion risk is shown in Fig. 2. Areas of high and moderate invasion risk were observed at discrete localities on the island as a result of risk mapping, because risk of invasion must meet both entry and establishment criteria.

Evidence suggests that during the early stages of invasion rats introduced into a new place appear to 'sit tight' for a few days before moving further from the point of introduction (Innes et al. 2007; Russell et al. 2008a). Based on consultation with experts and utilising an invasion likelihood tree to estimate and partition the likelihood of rats occupying Zones 1 to 3 during the early stages of invasion, the ratio of risk across Zones 1 to 3 was set to 55:40:5. An outcome of the likelihood tree was to exclude the lowest risk zone (Zone 4) from the surveillance design because the risk of invasion is so small during the early stages of invasion that it would require an unrealistically large surveillance effort to contribute to the overall power of detection. This small risk of invasion and establishment in Zone 4 is nevertheless addressed by a more conventional ecological monitoring program on Barrow Island.

Surveillance system design, components and deployment

For the detection of non-indigenous rats on Barrow Island the surveillance system incorporates eleven detection methods (SSCs). The combination of these SSCs was considered by experts to provide the best overall strategy to detect the range of non-indigenous rats, and is supported by other studies that use multiple detection methods (Dilks & Towns 2002; Russell et al. 2008a). These studies recognise that usual methods used in eradication of populations (i.e. traps and bait stations) were not successful in detecting the presence of rats when they were in small numbers.

Following consultation with experts, the surveillance system was designed with K selected to be a tolerable population

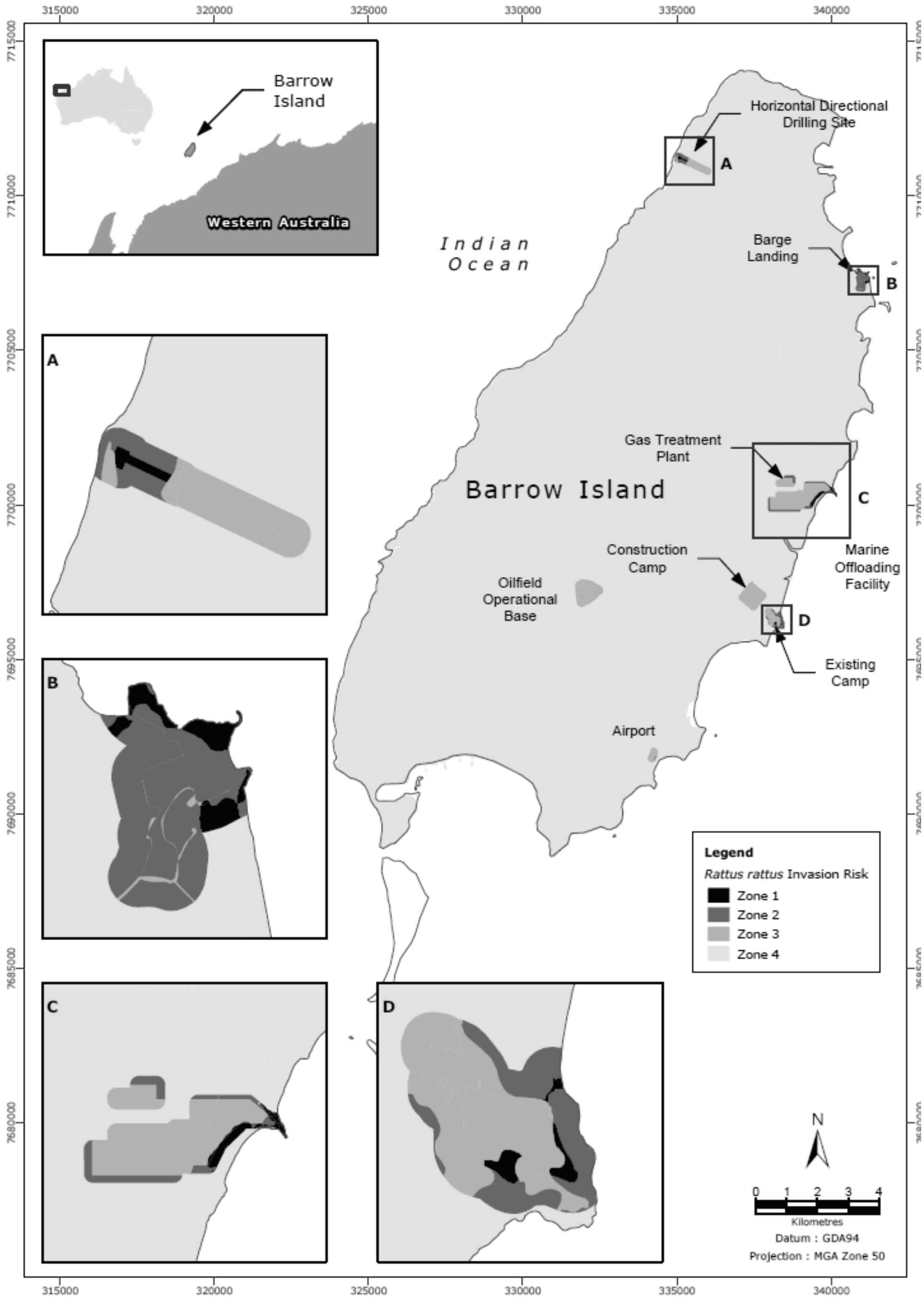

Figure 2. Invasion risk map for *Rattus rattus* on Barrow Island.

Invasion risk was calculated by multiplying Relative Importance Weights for entry points and establishment attributes to give invasion risk values (refer to Table 1). Zone 1 indicates a higher risk compared to Zone 2, etc.

size of 10 for the black rat, because $K > 10$ was considered by experts to be detectable, enable effective eradication and not have significant environmental consequences. It is noted that as K increases the total number of SSCs required decreases because it requires less units of SSCs to detect a larger number of rats if power is held constant (Fig. 3). The surveillance system cycles over a one year period. This was judged to be the likely timeframe for the number of rats to reach 10, under the constraints of a very low likelihood of entry, seasonality and periodicity (e.g. volumes of materials etc.).

The surveillance system relies on inputs (i.e. detection footprints, detection probabilities, etc.) that have been supported by data in the literature where possible, but usually required expert judgments for data gaps. A description of the costs estimates indicate that structured biologist survey's have the highest cost per single performance to normal protocol (3 hours), and cameras have the lowest cost (15 minutes) (Table 4). Logistical and practical constraints of each SSC are discussed in Table 4. The remaining characters of each SSC; a detection footprint (m^2) and probability of detection (σ) are described in Table 5. Table 5 is based on the design spreadsheet and shows allocation of SSC units to localities.

The resulting surveillance system consists of a number of SSCs including cage traps, unbaited ink pads, baited ink pads, structured (or formal) surveys by biologists, chew cards, hair traps along tunnels, remote cameras, Scentinel traps®, and incidental sightings by both biologists (250, 60, 21, 20, 23, 22, 26, 26, 38, across zones 1 to 3) and non-biologist staff

Table 2. Pair-wise comparisons and Relative Importance Weights (RIWs) for entry points for *Rattus rattus* on Barrow Island.
RIWs were calculated using the Analytic Hierarchy Process. Pair-wise comparisons were based on expert judgments, using a scale of 1 (equal preference) to 9 (absolute preference). Points of entry include the Marine Offloading Facility (MOF), the Horizontal Direct Drilling site (HDD), and the Liquefied Natural Gas (LNG) plant.

	Elicited pair-wise comparisons								
Points of entry	MOF	Airport	HDD	Barge landing	LNG plant	Construction camp	Existing camp	Oilfield base	RIWs
MOF	1	5	7	1	3	7	7	7	0.25
Airport		1	1	1	1	7	0.2	0.2	0.08
HDD			1	1	1	7	0.2	0.2	0.08
Barge landing				1	7	7	6	6	0.22
LNG plant					1	7	6	6	0.14
Construction camp						1	8	5	0.08
Existing camp							1	1	0.08
Oilfield base								1	0.08
Total									1

Table 3. Pair-wise comparisons and Relative Importance Weights (RIWs) for habitat attributes for establishment of *Rattus rattus* on Barrow Island.
RIWs were calculated using the Analytic Hierarchy Process. Pair-wise comparisons were based on expert judgments, using a scale of 1 (equal preference) to 9 (absolute preference). Attributes of establishment are described in Results section.

	Elicited pair-wise comparisons				
Attributes of Establishment	Preferred vegetation type	Other vegetation types	No vegetation	Human inhabited areas	RIWs
Preferred vegetation type	1	9	9	9	0.73
Other vegetation types		1	7	3	0.17
No vegetation			1	0.5	0.04
Human inhabited areas				1	0.06
Total					1

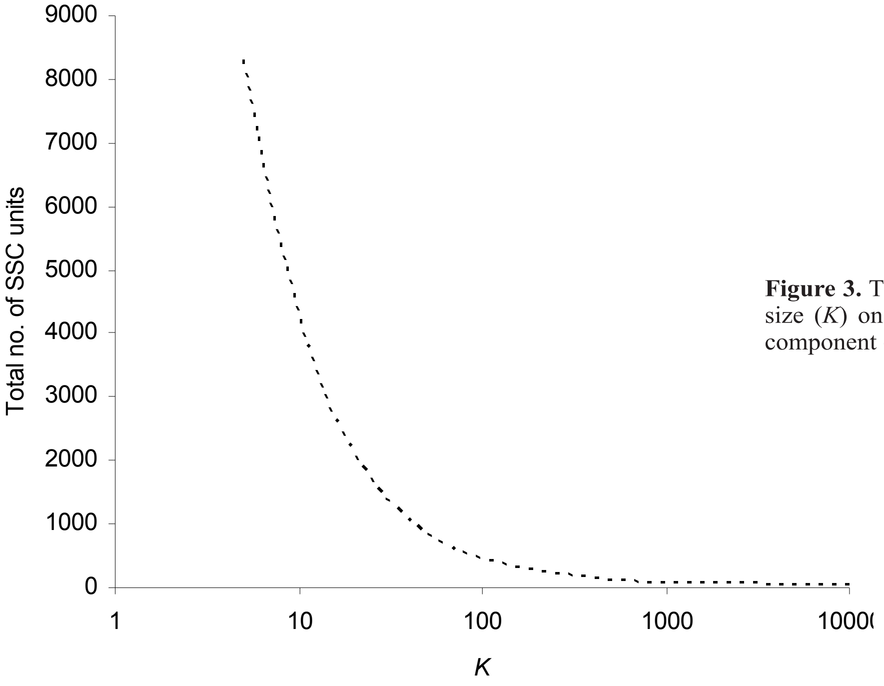

Figure 3. The effect of changing the tolerable population size (*K*) on the number of required surveillance system component (SSC) units for *Rattus rattus*, power of 0.8.

Table 4. Time-based cost estimates of surveillance system components (SSCs) for *Rattus rattus* based on discussions with experts.
Costs refer to 1 unit (a single performance to normal protocol) and represent resources associated with an operational surveillance system accounting for constraints, while excluding time associated with initial set-up and commissioning.

SSC	Time to operate and screen	Logistical/practical constraints and environmental issues	Costs (hr)
Cage trap baited	Approx. 12 minutes per trap in a trapping grid to check and re-set trap	Main constraint is saturation by non-target species. Trapping of non-target species results in stress on trapped individuals	1
Ink pad unbaited	Approx. 12 minutes per trap in a multi-pad layout to check and re-lay pad	Main constraint is saturation by non-target species (Russell et al. 2009a). An environmental cost of placing device over small areas of vegetation	1
Ink pad baited	Approx. 12 minutes per trap in a multi-pad layout check and re-lay pad, plus an extra 6 minutes to prepare bait per trap	Main constraint is saturation by non-target species (Russell et al. 2009a). An environmental cost of placing device over small areas of vegetation	1
Biologist structured survey	Standard survey time of 3 hours on wet sandy substrates (i.e. beaches) where tracks can be distinguished from tracks of other species present	More likely to be constrained by the number of available biologists compared to other SSCs, given the time it takes to conduct a survey of this type	3
Chew cards baited	Approx. 30 minutes per card in a multi-card layout, plus an extra 90 minutes for biologist to screen chew marks	More likely to be constrained by the number of available biologists compared to other SSCs, given the time it takes to conduct a survey of this type	2
Hair traps along tunnels baited	Approx. 30 minutes per trap in a multi-trap layout, including time for biologist to screen hair		0.5
Remote cameras baited	Approx. 30 minutes per camera per time period for biologist to check images	Reduced labour resources	0.25
Scentinel traps®	Approx. 30 minutes per camera per time period for biologist to check images	Reduced labour resources	0.25
Biologist unstructured survey	Incidental sightings made by biologist over a 3 week period (i.e. one standard employee rotation)		2
Engaged worker	Incidental sightings made by non-biologist trained employees over a 3 week period	Workers spend the majority of their time in Zone 1	2
Passive worker	Incidental sightings made by non-biologist untrained employees over a 3 week period	Workers spend the majority of their time in Zone 1	1

(engaged workers and passive workers, 12 and 3378 units, respectively, in Zone 1).

The Gorgon construction workforce will be large and some will be trained in awareness of non-indigenous species and will contribute to the power of the surveillance effort (designated 'engaged workers'). The vast majority of workers will be assumed as not interested in non-indigenous species ('passive workers') and therefore have a low probability of detection and small detection footprint. The numbers of passive workers is high compared to the other SSCs, however, this is not problematic because there are likely to be around 2500 workers on Barrow Island during construction activities, and each passive worker observation period is limited to three weeks (one standard employee rotation). Hence, in reality there will be over 43 000 passive worker units per year (2500 workers × 52/3 weeks).

The probability of detection given presence in the sampling frame (σ) for SSCs ranged from a minimum of 0.01 (cage traps) to a maximum of 0.9 (biologist structured survey). Biologist structured surveys, remote cameras and Scentinel traps® were judged by the experts to have comparatively high σ. Baited ink pads and chew cards have an estimated σ of 0.5, and the remaining SSCs, less than 0.2. Cage traps in particular where thought to have low σ because they are likely to be saturated with native species and rendered less effective. Nevertheless, cage traps are included in the surveillance system to provide the variety of SSCs most effective in trapping rats, and their efficiency can be determined over time as data is collected. Passive workers were assessed to detect the presence of rats in their living quarters (10 m^2) with σ of 0.05.

The detection footprint for a cage trap reflects the distances between traps in a trapping grid of 50 m (MacKay & Russell 2005; Russell et al. 2009b), which equates to a circular area of approximately 2000 m^2 (radius ≈ 25 m) for each trap. This formed the basis of detection footprint size for other detection devices (ink pads, chew cards, etc). Biologist structured survey reflected a three hour walking transect of 10 000 m^2, and the biologist unstructured survey reflected the area they are likely to cover over a three week period (1000 m^2). An engaged worker has an estimated footprint of 1000 m^2 over a three week rotation because they are more likely to observe a rat throughout their daily activities, compared to a passive worker whose detection capacity is limited to their living quarters where they are directly impacted on by the rat's presence.

Table 5. Determination of a surveillance system for *Rattus rattus* with K=10 individuals and detection power ≥ 0.8, using appropriate surveillance system components (SSCs) with characteristics assessed by experts.

The detection capability of the SSC unit is indicated by detection probability given presence (σ); F is the sampling fraction covered by one SSC unit; utility of SSC is defined as a function of the relative costs, σ, the sampling fraction and the relative risk of the zone in which the SSC is situated (Whittle et al. 2008; Barrett et al. 2009). Deployment is across localities including; construction camp (Const. camp), Liquefied Natural Gas (LNG) plant, Horizontal Direct Drilling site (HDD) and the Marine Offloading Facility (MOF). Zones 1 to 3 are indicated by Z1, Z2 and Z3. Engaged worker consists of incidental sightings made by trained workers, passive worker refers to incidental sightings made by untrained workers; workers spend the majority of their time in Zone 1. Shaded area indicates total power of the surveillance system.

SSC unit	Detection footprint (m^2)	F (%)	σ	Utility of SSC	SSC units (N)	Const. camp	Airport	LNG plant	HDD	MOF	Barge landing	Existing camp	Oilfield base	Total SSC units (N)	Final utility of SSC unit	Total costs	Total relative costs
Cage trap baited, Z1	2,000[A]	0.012	0.01	0.05	47	-	1	21	6	7	11	5	-	51	0.06	51	0.01
Cage trap baited, Z2	2,000	0.003	0.01	0.04	123	-	1	49	17	3	39	18	-	127	0.04	127	0.03
Cage trap baited, Z3	2,000	0.001	0.01	0.01	67	13	3	28	6	1	1	5	15	72	0.01	72	0.02
Ink pad unbaited, Z1	2,000	0.012	0.05	0.05	10	-	1	5	2	2	3	1	-	14	0.08	14	0.00
Ink pad unbaited, Z2	2,000	0.003	0.05	0.04	25	-	1	10	4	1	8	4	-	28	0.05	28	0.01
Ink pad unbaited, Z3	2,000	0.001	0.05	0.01	14	3	1	6	2	1	1	1	3	18	0.01	18	0.00
Ink pad baited, Z1	2,000	0.012	0.5	0.05	1	-	1	1	1	1	1	1	-	6	0.30	6	0.00
Ink pad baited, Z2	2,000	0.003	0.5	0.04	3	-	1	2	1	1	1	1	-	7	0.11	7	0.00
Ink pad baited, Z3	2,000	0.001	0.5	0.01	2	1	1	1	1	1	1	1	1	8	0.03	8	0.00
Biologist structured survey, Z1	10,000	0.060	0.9	0.02	1	-	1	1	1	1	1	1	-	6	0.96	18	0.00
Biologist structured survey, Z2	10,000	0.016	0.9	0.01	1	-	1	1	1	1	1	1	-	6	0.59	18	0.00
Biologist structured survey, Z3	10,000	0.004	0.9	0.00	1	1	1	1	1	1	1	1	1	8	0.24	24	0.01
Chew cards, Z1	2,000	0.012	0.5	0.11	2	-	1	1	1	1	1	1	-	6	0.30	3	0.00
Chew cards, Z2	2,000	0.003	0.5	0.08	5	-	1	2	1	1	2	1	-	8	0.12	4	0.00
Chew cards, Z3	2,000	0.001	0.5	0.01	3	1	1	2	1	1	1	1	1	9	0.03	5	0.00
Hair traps along tunnels baited, Z1	2,000	0.012	0.2	0.03	2	-	1	1	1	1	1	1	-	6	0.13	12	0.00
Hair traps along tunnels baited, Z2	2,000	0.003	0.2	0.02	4	-	1	2	1	1	2	1	-	8	0.05	16	0.00
Hair traps along tunnels baited, Z3	2,000	0.001	0.2	0.00	2	1	1	1	1	1	1	1	1	8	0.01	16	0.00
Remote camera baited, Z1	2,000	0.012	0.8	0.20	3	-	1	2	1	1	1	1	-	7	0.49	2	0.00
Remote camera baited, Z2	2,000	0.003	0.8	0.15	7	-	1	3	1	1	3	1	-	10	0.23	3	0.00
Remote camera baited, Z3	2,000	0.001	0.8	0.02	4	1	1	2	1	1	1	1	1	9	0.05	2	0.00
Scentinel traps®, Z1	2,000	0.012	0.8	0.20	3	-	1	2	1	1	1	1	-	7	0.49	2	0.00
Scentinel traps®, Z2	2,000	0.003	0.8	0.15	7	-	1	3	1	1	3	1	-	10	0.23	3	0.00
Scentinel traps®, Z3	2,000	0.001	0.8	0.02	4	1	1	2	1	1	1	1	1	9	0.05	2	0.00
Biologist unstructured survey, Z1	1,000	0.006	0.1	0.03	5	-	1	3	1	1	2	1	-	9	0.05	18	0.00
Biologist unstructured survey, Z2	1,000	0.002	0.1	0.02	13	-	1	6	2	1	5	2	-	17	0.03	34	0.01
Biologist unstructured survey, Z3	1,000	0.000	0.1	0.00	7	2	1	3	1	1	1	1	2	12	0.00	24	0.01
Engaged Worker, Z1	1,000	0.006	0.1	0.05	9	-	1	4	2	2	2	1	-	12	0.07	24	0.01
Passive Worker, Z1	10	0.000	0.05	0.10	3376	-	8	1461	404	475	734	296	-	3378	0.10	3378	0.86
Total		-	-	0.80	3751									3876	0.9997	3938	1.00

[A] The footprint for a cage trap is reflects the distances between traps in a trapping grid of 50 meters (MacKay & Russell 2005; Russell et al. 2009b), which equates to a circular area of approximately 2 000m^2 (radius = 25m) for each trap. This formed the basis detection footprints for other detection devices.

Through the process of deployment in zones, the calculated numbers of SSC units were often increased above the power requirement. For example, one unit of ink pads was required in Zone 1, divided over eight localities, each locality receiving 0.125 of a unit. These fractions were rounded up to whole units at each locality for practicality, such that eight ink pads were specified in the surveillance system, rather than one ink pad. Therefore, the implementation of the surveillance system has higher power than was required by the design (≥ 0.8) – calculated to be 0.9997 after rounding-up fractions of SSC units at each locality.

Discussion

Recent advances have been made by Whittle et al. (2008) and Barrett et al. (2009) in the statistical design of biosecurity surveillance systems, by extending the approach of Barclay & Hargrove (2005) to incorporate considerations of risk, power and system optimisation. The surveillance design methodology in Whittle et al. (2008) and Barrett et al. (2009) has many advantages over those proposed by Barclay & Hargrove (2005) and others (e.g. McArdle 1990; Green & Young 1993; Kéry 2002) including the ability to cover multiple surveillance targets in the one surveillance design, stratify for risk (including likelihood of entry and establishment), incorporate multiple sources of surveillance data, and manage for costs. However, the method is equally applicable to single-target surveillance objectives. Whittle et al. (2008) and Barrett et al. (2009) are the first to report a method for designing complex biosecurity surveillance systems that include all the features mentioned above.

Several authors have identified the need for better surveillance design for rodents (Russell et al. 2005; Broome 2007; Department of Conservation 2008), and here we provide an ecologically based and statistically powerful surveillance systems for invasive rats. Invasive rats have been able to expand their range globally, partly due to a lack of adequate quarantine measures. Active surveillance is generally lacking and surveillance responses to incursions have been reactive – established once an incursion is detected and consist mainly of trapping and baiting programs aimed primarily at eradication.

Recent studies show greater success of detecting rat incursions (where in some cases they were deliberately released) on small islands by using a variety of detection methods (Russell et al. 2007; Russell et al. 2008a; Russell et al. 2008b). The use of multiple detection methods in the surveillance system design reflects recommendations of another study (Dilks & Towns 2002; Russell et al. 2008a) where usual methods used in eradication of populations (e.g. traps and bait stations) were not successful in detecting the presence of rats when they were in small numbers.

The use of multiple SSCs has the further benefit of broadening the potential for detecting non-indigenous species of rat other than the black rat. For this to be effective, the surveillance system relies on the similarities between the exemplar and the species it is designed to represent, such that the design for each would need to be very similar for the same level of power of detection to apply to both. As there are slight differences among species behavior, detectability and preferred habitat, it is possible that the overall power to detect *R. norvegicus* and *R. exulans* will be different to the required power of the surveillance system to detect *R. rattus*. The allocation of SSCs in this surveillance system for the black rat results in a higher overall power (calculated to be 0.9997), which makes the surveillance system robust for similar target species. The higher overall power for implementing the SSCs to detect the exemplar species gives confidence that the power of detection for the exemplified species is above the required design power of 0.8.

Additional exemplar species can be selected if the variety of target species cannot be adequately represented by a single exemplar. Expert advice was sought to select and determine exemplar species for the objectives of the surveillance system. Such analysis of multiple exemplar species to design an integrated surveillance system is the subject of further study (including, for example, the house mouse).

The deployment process in this paper builds on methods previously used, which generally do not formally stratify risk (stage one of the two stage process). Stage one resulted in increased efficiency of detection by targeting areas according to entry points and suitable habitat. It is not practical nor is it environmentally sensible to cover the entire island with surveillance, which would overwhelm resources and cause unjustifiable ecological disturbance.

The surveillance system is an instruction on the number of units of each SSC that must be deployed in each locality in one deployment time period (i.e. cycle of the surveillance systems, e.g. 1 year). The appropriate cycle time is uncertain, because it must consider the likelihood of entry which is assumed to be very low but is unknown, and will depend upon seasonality and periodicity (e.g. volumes of materials etc.). The SSC units then need to be deployed to maximum effect spatially within certain areas, and temporally (e.g. related to breeding cycles, rainfall, etc). This second stage relies on the skills and training of the operational staff carrying out the surveillance. They need to have knowledge of the baseline studies of the survey area, the local landscape, potential invaders, and detection methods. A strength of the design is that ecological information can be incorporated at each level of the design. SSCs may have varying probabilities of detection across the landscape within zones, and operational staff must optimise the probability of detection of each trap by appropriate SSC placement in time and space.

The surveillance design allows for the incorporation of incidental sightings by non-biologists working on the island on three week rotations, a method of detection that is not fully utilized in traditional surveillance designs. Incorporating the contribution of various sources of surveillance data has been previously studied (Martin et al. 2007). However the power of incidental sightings has not been calculated and used in a design before, even though incidental sightings have been recognized as a common way introductions, including in agricultural and environmental biosecurity, were first detected (Froud et al. 2008). Even if the vast majority of workers have no interest in non-indigenous species and therefore have a low probability of detection and small detection footprint, their collective numbers create a substantial power contribution that can be included using this design.

The surveillance design enables flexibility in relation to logistical or practical constraints that are particularly relevant to remote islands. The numbers of SSCs can be capped at a maximum, or specified at a particular value, and the model readjusts numbers of remaining SSCs to accommodate the change. For example, if the optimum number of units of chew cards (23, see Table 5) is not available or no chew cards are available, the surveillance design can accommodate this 'constraint' by increasing numbers of the remaining SSCs and maintaining overall power. Likewise, if 50 remote cameras are available, 24 more than the surveillance design calculates as optimal, then the number of cameras can be specified as 50, and the surveillance design can accommodate this constraint by decreasing numbers of the remaining SSC. Perhaps in this case the number of Scentinel traps®, which are similar devices to remote cameras in terms of detection footprint, detection probability and cost, could be reduced so as to maintain the optimised suite of SSCs. Capping and specifying SSCs should be considered within the overall aims of the surveillance system, i.e. while maintaining the ability to detect all the species that are exemplified by black rats by including a range of SSCs. The numbers of SSCs recommended by the surveillance system have been found to be reasonable in terms of required resources and labour to implement the surveillance system, compared to the potential cost of eradication if an incursion were to happen and go undetected (as suggested by Howald et al. 2007). Early detection of invasive rats is generally accepted to be far more cost-effective than reactionary response and eradication.

The surveillance design relies on inputs (i.e. detection footprints, detection probabilities, etc; Tables 4 and 5) that have been supported by some data from the literature and expert judgments where data gaps existed. The characteristics of inputs represent the opinion of the group of experts from which the data was elicited in the facilitated workshops. The group of experts selected was considered appropriate by virtue of consultation and inclusion of highly qualified vertebrate specialists, and provided the best available estimates in the absence of empirical data. Future research should be directed to refine probabilities of detection, footprints and costs, and to better understand the behaviour of colonizing rats, to supplement expert opinion.

The specified population threshold for the minimum detectable population size (K) cannot be experimentally verified, and in the case of black rats, the total number of SSCs required appears to be sensitive when $K<100$. The number of SSCs required to detect a smaller number of black rats is substantially greater than the numbers required to detect a larger number of black rats. For $K = 10$, the total number of SSC units required is 4166, substantially more than required if $K = 100$ (434 SSCs), and substantially less than if $K = 5$ (8317 SSCs). Once K is greater than around 200, very little benefit is gained by adding more SSC units (Fig. 4) because the sampling frame is saturated.

O' Hagan et al. (2006) reports that experts tend to be conservative in their probabilistic assessments, assigning high probability to 'typical' events while having difficulty estimating probabilities of rare events. In this study the latter issue is partly addressed in risk mapping methods by eliciting relative probabilities via pair-wise comparisons. The consequence of changing the value of a detection probability (or a footprint, or a cost) would likely result in a different combination of SSCs, depending on the magnitude of the change. For instance, if detection probabilities were 10% more conservative (smaller), additional numbers of SSCs would be required to maintain overall power: 14 more cage trap units; five more ink pad units; two more chew card units; 27 more units of biologist unstructured survey; two more engaged worker units; and 377 more passive worker units. Nevertheless these numbers of SSCs remain achievable and illustrate how the optimal allocation by the system changes, SSCs that cost less increase in number, compared to SSCs that cost more. Preliminary sensitivity analysis indicates the design is robust to changes such as this, and future work is planned to further investigate robustness of the design with surveillance system implementation and further research.

Importantly, the model is designed for continuous improvement, an overarching requirement of the Gorgon Project quarantine management system. SSC characteristics should be reviewed and updated over time, as new information becomes available and as data is collected through surveillance, or possibly, verified through data simulation or experimentation.

In summary, better surveillance systems for non-indigenous rats are needed if their arrival to new locations (or re-invasion) is to be detected and invasion prevented. Early detection is critical and there is increasing emphasis on power and differential special risk in surveillance design. Success in detecting rats is unlikely to be perfect or without risk, because SSC units cannot detect rats with 100% certainty, nor can they cover the entire island. Nevertheless, the surveillance system presented here offers advantages over current surveillance designs being used to detect rats. The surveillance system has been developed using statistical methods to ensure that it meets a desired power to detect multiple non-indigenous species of rat by stratifying risk spatially and using a variety of detection methods. Further work will test the robustness of the surveillance system to uncertainty in expert assessments through implementation of the surveillance system and further research. Being able to update SSCs and their characteristics is a feature that not only allows for verification of the SSCs, but could also accommodate longer-term changes, such as altered conditions under climate change. The surveillance design for rats has the potential to be integrated with surveillance designs for other exemplar species to become a comprehensive biosecurity surveillance design for vertebrates.

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