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Biosecurity threats: the design of surveillance systems, based on power and risk

Susan Barrett · Peter Whittle · Kerrie Mengersen · Richard Stoklosa

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Abstract We consider the problem of designing a surveillance system to detect a broad range of invasive species across a heterogeneous sampling frame. We present a model to detect a range of invertebrate invasives whilst addressing the challenges of multiple data sources, stratifying for differential risk, managing labour costs and providing sufficient power of detection. We determine the number of detection devices required and their allocation across the landscape within limiting resource constraints. The resulting plan will lead to reduced financial and ecological costs and an optimal surveillance system.

Keywords Biosecurity · Surveillance system · Power · Differential risk

1 Introduction

Relatively little attention has been given to the statistical design of biosecurity surveillance systems (SSs) to detect incursions of non-indigenous species (NIS) across national borders or to offshore island systems (Marsh and Trenham 2008). Design challenges include using data from multiple sources (such as a combination of scientific visual surveys, farmer/consultant observations and a formal trapping grid), stratifying for risk of entry and establishment due to spatial and temporal heterogeneity, and cost-optimisation of the different SS components. There is also the potential need to

S. Barrett (✉) · P. Whittle · K. Mengersen
School of Mathematical Sciences, Queensland University of Technology, Brisbane, QLD, Australia
e-mail: susan.barrett@qut.edu.au

S. Barrett · P. Whittle · K. Mengersen
Cooperative Research Centre for National Plant Biosecurity, LPO Box 5012, Bruce, ACT 2617, Australia

R. Stoklosa
Chevron Australia Pty Ltd, Perth, WA, Australia

account for multiple NIS targets within the design. Explicit inclusion of these factors in the design of a SS is intended to lead to more efficient allocation of resources, whilst at the same time providing sufficient power to detect the NIS.

In the context of biosecurity surveillance design, one could consider a null hypothesis of species absence with power defined as the ability of the system to detect a NIS if it is present (where ‘presence’ is defined as the establishment of a specified population size of the organism). Hence an increase in the power of a surveillance system is brought about by a decrease in the type II error (the probability of falsely declaring the NIS to be absent). The other inferential mistake, notably a type I error in which the NIS is falsely declared to be present, is less common in such systems but may be inconvenient due to unnecessary detection and response activities.

Type I and type II errors have been addressed to some extent in related designs for detection of rare species. For example both Green and Young (1993) and Zonneveld et al. (2003) used Poisson distributions to detect low density species with a power of 0.95; in the case of Green and Young to detect a range of unionid mollusc species in Tennessee, and Zonneveld et al the rare Quino checkerspot butterfly (*Euphydryas editha quino*) in southern California. To demonstrate extinction, Reed (1996) used a probability model based on McArdle (1990) to calculate the number of visits needed to determine the status of a theoretical species based on presence/absence data: the number of sightings (successes), the probability of detection and the desired type I error. Influences upon the probability of detection, from a species’ geographic range and habitat usage, were accounted for in the calculation of this probability and the balance between type I and type II errors was discussed. Kéry (2002) also used McArdle (1990) method to confirm the absence of three snake species in Europe (*Vipera aspis, Coronella austriaca* and *Natrix natrix*) with the addition of logistic regression to incorporate factors that influenced the probability of detection and an emphases on both type I and type II errors. The same probability model was utilised by Barclay and Hargrove (2005) to determine when an area can be declared ‘pest-free’, focussing on the tsetse fly (*Glossina* spp.). They recognised that the detectability of the insect will be reduced by the fraction of the area sampled and included this in their model. Issues of multiple data sources, differential spatial risk and cost were largely ignored in the above studies.

In this paper, the approach by Barclay and Hargrove (2005) is extended to a surveillance design that addresses not only power, but also combines data from multiple sources, stratifies for risk across the sampling frame and optimises cost. The paper is organised as follows: Sect. 2 describes the surveillance design; Sect. 3 presents a surveillance plan for an exemplar invertebrate and Sect. 4 discusses the implications and limitations of the proposed approach.

2 Model

Consider a NIS that has entered a target area. To achieve a reasonable probability of detecting such an incursion, a number of parameters need to be estimated at the design stage. For example, it is likely that the landscape will not be uniform; there may be areas more conducive to NIS establishment than others, due to competition, micro climate, food resources etc. Thus, there will be zones of varying risk of establishment within the target area, which need to be identified and quantified. A heterogeneous landscape will most likely result in at least two risk zones (low and high risk) within a background of minimal risk. Defining the target area into different risk zones enables the allocation of limited resources to those areas where there is a greater likelihood of detecting the NIS. This identification of risk zones is accomplished by risk mapping, achieved by combining geographic information system (GIS) data with the ecological and environmental requirements of the NIS (the latter obtained from experts). The probability of NIS establishment in the various risk zones can then be determined.

It also seems reasonable that detection of the NIS in the target area should occur as early as possible following the incursion. However, whilst the NIS population must be large enough to be detected it should not become so large that eradication processes cause significant environmental damage to native flora and fauna. Hence, to calculate the number of surveillance system components (SSCs) required to have a realistic chance of detecting at least one individual (presence/absence), this minimum population number needs to be estimated (with input from appropriate experts such as entomologists, biologists etc.).

Also required are the detection probabilities of the SSCs, selected to detect the NIS. These probabilities are based on the NIS being present within the footprint or area of attraction of the SSC. There may be many SSCs which are appropriate to detect a particular NIS, for example pitfall traps, baits, litter extraction and vacuuming, site inspections by biologists, observations by ground workers/wildlife staff and observations by non-scientists are all appropriate to detect many invertebrates. The detection probability of each of the selected SSCs needs to be estimated by expert elicitation, taking into consideration the technical parameters of each SSC.

Another consideration is the fraction of the target area surveyed (since it is unlikely that resources will allow the total target area to be utilised). This sampling fraction is utilised as the proportion of the target area covered by the area of attraction or footprint of each SSC (footprint/total target area). The *effective* detectability of each SSC is then the product of this sampling fraction and its probability of detecting the NIS. As the total sampling fraction increases, the number of SSCs required to detect the NIS reduces accordingly. If the sampling fraction is not considered, then the SS will be more conservative and more costly than necessary.

The final consideration is the efficacy of the SSCs and this is usually measured on a cost basis, as a limiting resource. Costs may be estimated by experts and include such factors as the labour time taken (hours) per SSC unit (for set up, retrieval of specimens and diagnostic processing).

2.1 Number of SSC units

The number of SSC units required to provide a given power of detection of a NIS (with a null hypothesis of NIS absence) depends on the detection capability of the SSC, the fraction of the sampling frame that is covered by each SSC unit and the minimum size of the NIS population that is to be detected. Obviously, as these three factors increase, the number of required SSC units decreases. For this reason, although the statistical approach is generic, the calculation of SSC units depends on assumptions relevant to each NIS.

As per Barclay and Hargrove (2005), the probability of detecting the ith individual of the NIS in a single SSC unit, given the detection capability of the SSC, is termed σ_i; the probability of non-detection is therefore $(1-\sigma_i)$. It is recognised that the population of NIS may increase to a 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 $K \geq 1$). Thus, assuming that all SSC units have the same detection capability, the probability of detecting no individuals in n SSC units is:

$$\left(\prod_{i=1}^{k}(1-\sigma_i)\right)^{n} \tag{1}$$

The allowance of different σ_i, $i = 1, \ldots, K$, accommodates possible dependent behaviour between the NIS individuals. A conservative bound on Eq. 1 can be obtained by using $\sigma_{\max} = \max(\sigma_i)$ in which case, Eq. 1 reduces to $(1-\sigma_{\max})^{Kn}$. An alternative approach adopted here is to consider K as representing the number of individual NIS equivalent to the tolerable population size, so that each NIS individual has the same detection probability σ; in this case Eq. 1 reduces to $(1-\sigma)^{Kn}$. Although the inflation (or reduction) factor required to achieve this equivalence is typically unknown, it was readily estimated by experts familiar with the NIS of interest. Moreover, it was found to be easier to estimate this factor than determining $\sigma_{\max}$ or σ_i, $i = 1, \ldots, K$.

Under this formulation, if the aim of the SS is to provide a specified power, denoted by $(1-\beta)$, to detect the NIS, then the probability of a type II error is β and the SS must ensure that $(1-\sigma)^{Kn} < \beta$. Taking the logarithms and isolating n provides the following equation:

$$n = \frac{\log \beta}{K \log(1-\sigma)} \tag{2}$$

This equation, or the analogous version induced by using Eq. 1 for the probability of detecting no individuals in n SSC units, does not explicitly account for the amount of time (T) lapsed since the NIS incursion occurred. Indeed, the power of detection may increase with the passage of time and if known, can be included in Eq. 2. In the majority of cases, however, T will be unknown and N is evaluated at a presumed period of time which is described implicitly by K and σ.

Figure 1 illustrates the steep decline in the required SSC units (n) as σ increases, for $K = 100$ individuals and different values of the power$(1-\beta)$. Clearly, maximising detection probabilities, by including information from all sources pertaining to this detection, will dramatically reduce the number of SSC units required.

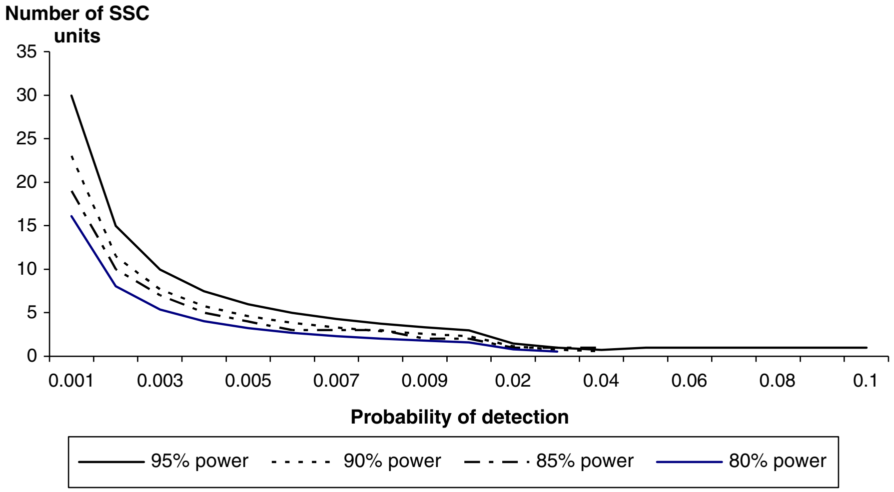

Fig. 1 Number of required units of a surveillance system component (SSC) for $K = 100$ individuals and varying power

2.1.1 Sampling fraction

The second factor to be considered when calculating the number of SSC units is the fraction of the sampling frame to be sampled. In a typical SS the sampling fraction (F) is less than 100% of the sampling frame, usually due to time, personnel, financial or logistical constraints. F is calculated as if each individual member of the species is expected to spend the same amount of time in the footprint of a SSC, Eq. 2 is modified as follows (with a similar modification for Eq. 1):

$$n = \frac{\log \beta}{K \log(1 - \sigma F)} \quad (3)$$

For $K = 100$ individuals and a power of 0.8, Fig. 2 demonstrates the differences in the number of SSC units required for increasing detection probabilities. As the sampling fraction reduces, the number of SSC units required for a power of 0.8 increases accordingly.

2.1.2 Resource costs

One of the limiting factors on the efficacy and success of a SS is the financial cost of its implementation along with constraints on the resources available for implementation, and the potential ecological consequences of over-sampling a sensitive environment. In practical terms, whilst a SS must be designed to provide sufficient power to detect a NIS, the costs involved in achieving this power must be considered. A plan that has sufficient power but is very costly (in financial, resource or ecological terms) may well be rejected in favour of one that has less power but which has lower costs.

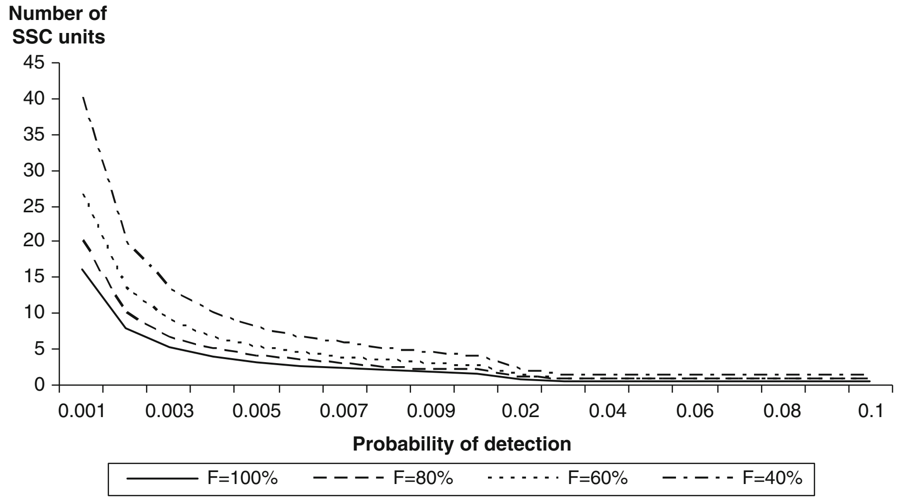

Fig. 2 Number of required units of a surveillance system component (SSC) for $K = 100$ individuals, power of 0.8 and differing sampling fractions

Costs are included in the calculation of the utility of each SSC, with utility defined as:

$$\text{utility}_{\text{SSC}i} = 1 - (\beta)^{(1-\sigma_{\text{SSC}i})\times \text{cost}_{\text{SSC}i}\times \text{rr}_{\text{SSC}i}} \tag{4}$$

where rr is the relative risk for a particular SSC and incorporated in Eq. 3 as follows, with a similar modification for Eq. 1:

$$n_{\text{SSC}i} = \frac{\log(1 - \text{utility}_{\text{SSC}i})}{k \log(1 - \sigma_{\text{SSC}i} F_{\text{SSC}i})} \tag{5}$$

where $1 - \text{utility}_{\text{SSC}i}$ was represented by β in Eqs. 1–4.

The contribution of each SSC to the total power of the SS is then based on the proportional utility of each SSC:

$$\text{Power} = 1 - \prod (1 - \text{utility}_{\text{SSC}i}) \tag{6}$$

where i is the number of SSC types not units, i.e. pitfall traps, litter extraction, etc.

3 Application of model: background

Barrow Island in Western Australia, a Class A Nature Reserve, is the site of Australia's oldest operating oilfield, established in the 1960s, and has produced over 300 million barrels of oil. Currently, the existing operations employ extensive quarantine measures focussing on mainland departures and arrivals of both employees and materials on the island.

Chevron and its Joint Venture Partners (ExxonMobil and Shell Australia) have proposed the construction and operation of a 15 million tonne per annum (MTPA) liquefied natural gas (LNG) and domestic gas plant on Barrow Island. The construction site, accommodation village and other land disturbance associated with the Gorgon Project is limited to 300 hectares of the 26,000 ha island and will involve the importation of 3.5 million freight tonnes of material to the island along with a peak construction workforce of around 2,500 persons. Western Australian State Government approval has been granted for a two-train, 10 MTPA development, conditional upon rigorous biosecurity measures and a revised three-train, 15 MTPA project is currently being assessed. The Revised Proposal is not expected to pose any significant new or additional risks to the Barrow Island environment, in comparison to the already approved development. The conditions of approval include sufficient power ($\geq$0.80) for detecting terrestrial NIS (invertebrates, vertebrates and vascular plants). Detection must be early enough to enable eradication without significant environmental consequences to native flora and fauna.

3.1 Model configuration

An essential early step in the design was to establish baseline profiles of all species on the island. At the commencement of operations, these profiles enable species detected in the SS to be identified as part of the baseline assemblage of species present on the island, or a new NIS. Initial SS design has focused on detecting all invertebrate NIS; ongoing work involves the addition of vertebrates and vascular plants to the SS. To this end, six exemplar invertebrate species were selected by experts, providing a range of species that is representative of all invertebrates for the purpose of SS design.

Pheidole megacephala, the big-headed ant was selected as one of the invertebrate exemplar species due to its known invasiveness and its proximity to the Island on the Australian mainland, as well as in many other locations in the world from where materials could be imported to the Island. The Australian Department of the Environment and Heritage[1] (Commonwealth of Australia 2006) has identified *P. megacephala* as one of six invasive species that may have a negative impact on Australian biodiversity (the other five are *Solenopsis invicta*, *S. geminata, Wasmannia auropunctata*, *Anoplolepis gracilipes*, and *Linepithema humile*).

3.1.1 Risk of long-distance dispersal and entry of P. megacephala

P. megacephala is one of about 150 ant species known as ‘tramp ants’, that have become widely distributed in the world due to human activity, with seven species of tramp ants being invasive worldwide (Holway et al. 2002). It is one of the world’s most invasive species, having achieved a global distribution in a wide range of habitats. It spreads readily in general freight and household movements and displaces most native invertebrate fauna directly through aggression. As such, *P. megacephala* is a serious threat to biodiversity (CSIRO 2003).

[1] Now known as the Department of the Environment, Water, Heritage and the Arts.

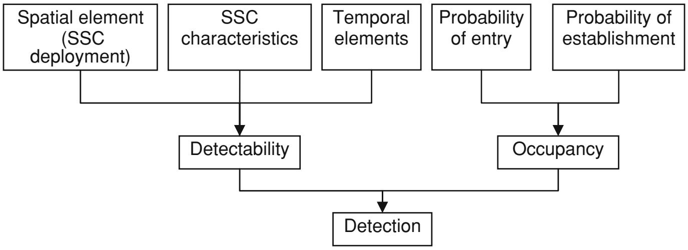

Fig. 3 Generic invasive model. SSC = 'surveillance system component' (e.g. pitfall trap, biologist survey, etc.); risk zones are defined by the heterogeneous nature of the sampling frame

3.1.2 Risk mapping

The process of risk mapping utilised the analytical hierarchy process (AHP: Saaty 1987) which involved combining the generalised detection model (Fig. 3) with the geographical information system (GIS) for Barrow Island (which has extensive data on landforms and vegetation on the island). For each of the factors which may influence entry, dispersal and establishment of *P. megacephala*, a set of criteria was defined and under AHP relative importance weightings were determined for each of these factors by a process of pairwise comparisons by experts. Values were then calculated for each polygon (mapped units of land) based on data and relative importance weightings for the paired comparisons. Likely entry points for *P. megacephala* on Barrow Island are (see Fig. 4):

- *Marine Offloading Facility* (MOF)—where the majority of construction materials arrive on Barrow Island.
- *Barge landing*—where a large quantity of materials and shipments arrive on the island early in the construction program, before the MOF is built.
- *Airport*—primarily the area where aircraft unloading and disembarkation occur.
- *Horizontal Directional Drilling* (HDD) *site* —including the materials that are brought in for installation of an underground pipeline shore crossing, the construction of the feed gas pipeline to the liquefied natural gas plant, and the movement of people and vehicles.
- *Liquefied natural gas plant*—where construction of the gas plant and operational activities occur. It will be contiguous with the MOF and will be the primary point of entry to the island from materials unloaded from marine vessels at the MOF.
- *Accommodation camp*—human ingress and activity and the built environment providing suitable habitat.

For habitat suitability, factors influencing distribution and establishment of *P. megacephala* were water, food, disturbance, sheltered microhabitat, construction activities and vegetation. Values for these factors were estimated by experts, combined to obtain a risk of occupancy and ranked to create three risk zones. The highest level of risk (zone 1) was allocated to the areas containing either the initial entry points to the island or the areas of most disturbance/construction. A lower level of risk (zone 2) was associated with buffer zones surrounding all areas of high risk. It

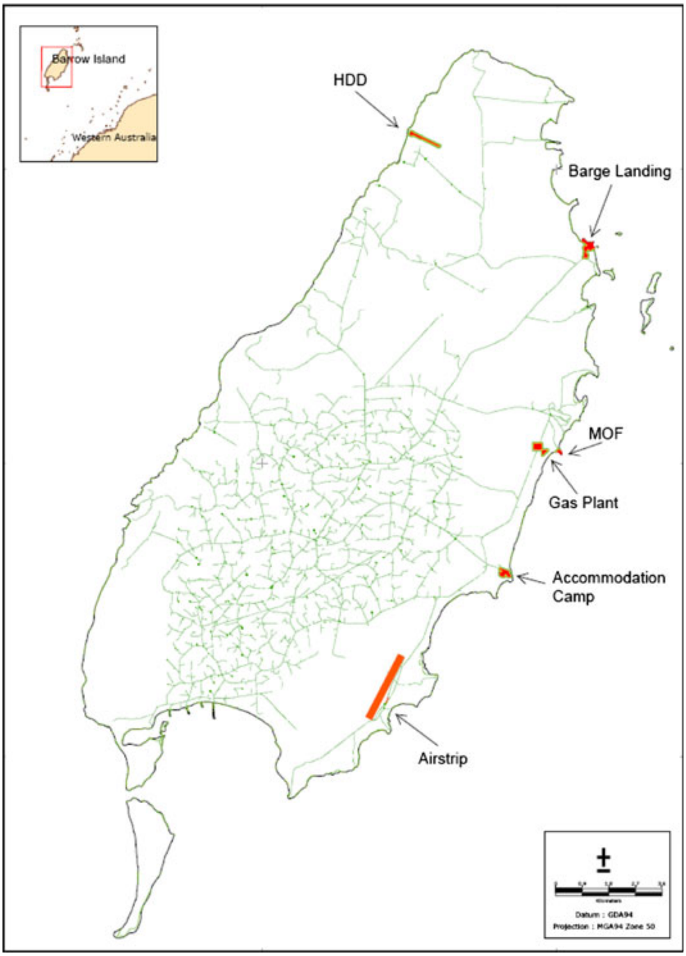

Fig. 4 Potential entry points for *Pheidole megacephala* on Barrow Island. HDD = horizontal directional drilling site, MOF = marine offloading facility

was anticipated that, due to extensive quarantine operations on arrival, the risk of entry, dispersal and establishment of *P. megacephala* in these high risk areas was very small, yet much greater than for the buffer areas. Experts estimated the relative probability of entry and establishment for zone 1 compared to zone 2 as 9 to 1. Zone 3 refers to the remainder of the Island which was considered to pose negligible risk to the dispersal of *P. megacephala* from zones 1 and 2, given the objective of the SS to detect *P. megacephala* early enough to eradicate before such dispersion occurs.

In light of this, the formal SS was designed around zones 1 and 2, as the only areas on the island where surveillance could be practically implemented to detect *P. megacephala*. Long-term ecological monitoring of zone 3 by biologists was not quantified as part of the statistical power assessment of the SS.

3.1.3 Costs

In this instance, the primary concern was not the dollar cost of the SS but the constraints of skilled labour resources (measured in hours) available on the Island for surveillance, sample processing and diagnostics. Changes to costs can easily be incorporated into the design and N recalculated as necessary.

3.1.4 SSC units

Five different mechanical SSCs were selected for consideration by experts to detect *P. megacephala*: pitfall traps, baits, vacuuming of shrubs and litter collection methods are common techniques used by biologists to detect many invertebrate species. The combination of these five methods was considered by the experts to provide the best overall strategy to detect a wide range of invertebrate NIS. In addition, it was proposed that structured surveys would be performed by biologists, augmented by on-site construction and operations workers trained to recognise a range of NIS. The anticipation is that a number of trained and motivated employees will be alert for NIS and report incursions during their daily duties or when off-duty in their personal space (engaged workers). Some employees may also detect invasives but may be less motivated than engaged employees and therefore have the capacity to observe NIS in a much smaller observation footprint area such as their own personal accommodation space (passive workers). Off-duty biologists may also detect NIS simply by virtue of being present on the island for extended periods, or taking the initiative to explore for NIS beyond their planned survey duties (unstructured surveys).

The number of SSC units can be determined using Eq. 4 with $K = 100$ individuals. The value of K was selected by experts to be the minimum number of *P. megacephala* individuals that can be practically detected and which can be eradicated without significant environmental consequences to native fauna. Allocation across the six entry localities then occurs based on the relative magnitude of each locality as follows:

$$\text{Allocation} = \frac{N_{\text{SSC}} A_{\text{locality}}}{A_{\text{total}}} \tag{7}$$

where N_{SSC} = number of traps per trap type, A_{locality} = area of locality (m^2), A_{total} = total area of all localities (m^2).

Allocation of the SSCs across the six locations and two risk zones is presented in Table 1, along with F and σ required in the calculation of N. In addition, the utility for each of the SSCs is shown both before and after allocation. This is because, on allocation, the number of SSC units calculated using Eq. 6 for a minimum statistical power of 0.80, is rounded up to the next highest value. In cases where $N = 1$, this rounding occurs at all localities and zones and results in at least one SSC unit allocated to each area. For example, in the case of structured surveys by biologists in zones 1 and 2, one SSC unit needs to be allocated across six locations and this would result in a fraction of each survey occurring at each of the six localities. Instead, each allocated fraction is rounded up to one and yields a total of six units.

Table 1 Determination of a surveillance system for *Pheidole megacephala* with $K = 100$ individuals and detection power ≥ 0.80, using appropriate surveillance system components (SSCs) with characteristics estimated by experts

SSC unit	F (%)	σ[a]	Cost (hours)	Utility of SSC	SSC units (N)	Accommodation camp		Airstrip		LNG plant		HDD		MOF		Barge landing		Total SSC units (N)	Final utility of SSC unit
						Z1	Z2	Z1	Z2	Z1	Z2	Z1	Z2	Z1	Z2	Z1	Z2		
Pitfall trap, Z1	0.015	0.4	1.5	0.16	29	3	–	2	–	17	–	3	–	1	–	7	–	33	0.18
Pitfall trap, Z2	0.010	0.4	1.5	0.02	5	–	1	–	1	–	5	–	1		1	–	1	10	0.04
Barrier pitfall trap, Z1	0.008	0.5	2.5	0.10	28	2	–	2	–	16	–	3	–	1	–	7	–	31	0.11
Barrier pitfall trap, Z2	0.005	0.5	2.5	0.01	5	–	1	–	1	–	5	–	1	–	1	–	1	10	0.02
Baits/lures, Z1	0.019	0.7	1.0	0.23	20	2	–	1	–	12	–	2	–	1	–	5	–	23	0.26
Baits/lures, Z2	0.012	0.7	1.0	0.03	4	–	1	–	1	–	4	–	1	–	1	–	1	9	0.07
Vacuuming shrubs, Z2	0.015	0.9	10.0	0.03	3	–	1	–	1	–	3	–	1	–	1	–	1	8	0.10
Litter extraction, Z1	0.001	1.0	9.5	0.03	29	3	–	2	–	17	–	3	–	1	–	7	–	33	0.03
Litter extraction, Z2	0.001	1.0	9.5	0.00	5	–	1	–	1	–	5	–	1	–	1		1	10	0.01
Biologist structured survey, Z1	0.950	0.7	3.0	0.08	1	1	–	1	–	1	–	1	–	1	–	1	–	6	0.98
Biologist structured survey, Z2	0.605	0.1	3.0	0.01	1	–	1	–	1	–	1	–	1	–	1	–	1	6	0.30

Table 1 continued

SSC unit	F (%)	σ[a]	Cost (hours)	Utility of SSC	SSC units (N)	Accommodation camp		Airstrip		LNG plant		HDD		MOF		Barge landing		Total SSC units (N)	Final utility of SSC unit
						Z1	Z2	Z1	Z2	Z1	Z2	Z1	Z2	Z1	Z2	Z1	Z2		
Biologist unstructured survey, Z1	0.190	0.3	1.0	0.23	5	2	–	1	–	3	–	1	–	1	–	2	–	9	0.40
Biologist unstructured survey, Z2	0.121	0.3	1.0	0.03	1	–	−1	–	1	–	1	–	1	–	1	–	1	6	0.20
Engaged worker, Z1	0.190	0.2	1.0	0.25	8	1	–	1	–	5	–	1	–	1	–	2	–	11	0.34
Passive worker, Z1	0.002	0.1	1.0	0.25	1511	1511	–	–	–	–	–	–	–	–	–	–	–	1511	0.25
Total	–	–	49.0	0.80	1655	1524	7	10	7	71	24	14	7	7	7	31	7	1716	1.00

[a] Indicates the detection capability of the SSC unit obtained by expert elicitation; F is the sampling fraction covered by one SSC unit; the utility of SSC is defined as a function of the relative cost of each SSC, the probability that the SSC will detect the NIS, the sampling fraction attributed to the SSC, and the relative risk of the zone in which the SSC is situated. *HDD* is the Horizontal Direct Drilling site; *MOF* is the Marine Offloading Facility; $Z1$ and $Z2$ indicate zone 1 and zone 2, respectively; engaged worker consists of visual observations made by trained employees, passive worker refers to untrained employees. Shaded cell indicates total power of SS before and after allocation across sites

Once the number of SSC units has been determined, the SSCs are allocated to specified localities based on their relative areas. This placement is optimised with respect to both spatial and temporal factors that affect the probability of detection, and is best determined by detailed observation and expert judgement of on-site risk factors at a local level. Spatial factors may include any disturbance of the site, the location of suitable habitats, detection of signs of animal activity by observers, and so on. Temporal factors may be seasonal temperatures and day length, prevailing wind direction and cyclones, and significant rainfall events etc. These judgements may be made by experienced personnel, using operational guidelines to facilitate a systematic approach for the allocation of SSC units.

An important observation of accounting for non-scientists in the SS is the number of engaged (8) and passive (1,511) workers which make a significant contribution to the power of 0.80 for the overall SS. It becomes obvious that if environmental awareness and training programs resulted in more workers becoming 'engaged' that the power of the SS would increase. Of course, the cost of passive workers can be penalised in the calculations, if necessary, to shift the allocation of effort to other SSCs while preserving the desired statistical power of the SS.

It is anticipated that providing educational training to develop engaged workers through awareness campaigns and other initiatives would be a cost effective way to increase the power of the SS. It is anticipated that at least 2,500 employees will undergo awareness training before commencing work on Barrow Island.

3.1.5 Power of the surveillance plan

The surveillance plan was designed to deliver sufficient power (≥ 0.80) to detect *P. megacephala*, based on explicit assumptions concerning the probability of detection, sampling fraction, independence, cost and risk. In fact, the additional SSC units allocated as described above result in an overall power that is considerably greater than 0.80. These additional SSC units explain the increases observed in utility which contributes to the overall power of the SS.

Power was also calculated as a decision tree representing the dispersion of the invasive species in the target area. The tree, displayed in Fig. 5, was quantified by the same experts who provided the inputs to the SS as described above. In its simplest form, this tree presents probabilities for *P. megacephala* arriving, dispersing and establishing on the Island as well as probabilities associated with being detected or not, at these three stages. In addition, risk profiling is incorporated by providing these probabilities for both zone 1 and zone 2. The SS was designed to detect the 20% of *P. megacephala* that is not detected on arrival at the Island, by existing quarantine measures.

This decision tree allows the researcher to interpret the power of the SS to detect *P. megacephala* in three different ways. First, the probabilities indicated in the tree represent the probability of detecting (or not detecting) *P. megacephala* along specific pathways. For example, if *P. megacephala* arrives on the Island, the probability is 0.80 that quarantine measures at the point of entry will successfully detect it. If *P. megacephala* is not detected on arrival, the probability of remaining in zone 1 (the high risk zone) is 0.90, the probability of subsequent establishment in this zone is 0.80 and the

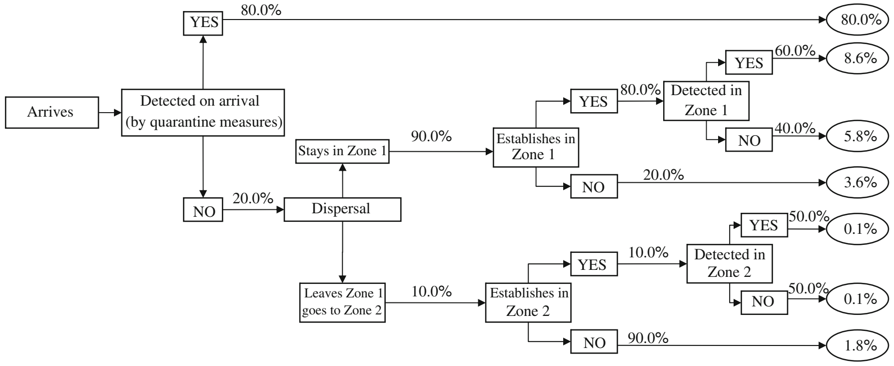

Fig. 5 Decision tree of *Pheidole megacephala* distribution and dispersion in target area. Zone 1 refers to the higher risk zones where the initial introduction occurs; zone 2 refers to a lower risk area, surrounding zone 1, to which the non-indigenous species may escape

probability that *P. megacephala* will be detected by the SS is 0.60. The joint probability of detecting *P. megacephala* along this pathway is 0.086 ($0.20 \times 0.90 \times 0.80 \times 0.60$). Alternatively, the probability of *P. megacephala* not being detected on entry to the Island, remaining and establishing in the high risk zone, and still not being detected in this zone is 0.058 ($0.20 \times 0.90 \times 0.80 \times 0.40$). For zone 2, this last probability is 0.001. Proportional stratification based on the relative magnitude of these probabilities suggests that 86% of the SSC units should be deployed in zone 1 with the remainder in zone 2, which aligns well with the risk of entry and establishment for *P. megacephala* in zone 1 (0.90) and zone 2 (0.10) discussed earlier.

The second interpretation of these decision tree probabilities is the power of the SS to detect *P. megacephala* according to the risk profile of the landscape. For example, the power to detect *P. megacephala* in zone 1 (regardless of whether a viable population is established or not) is 0.942 ($1 - 0.058$); for zone 2, this power increases to 0.999 ($1 - 0.001$); both of which are larger than the minimum required power of 0.80.

Finally, the third interpretation is the power of the SS to detect *P. megacephala*, regardless of the pathway or zone. This calculation involves the probabilities calculated using the risk profiles above and the percentage of *P. megacephala* that remains in each zone (90% in zone 1 and 10% in zone 2) as follows: $(0.90 \times 0.942) + (0.10 \times 0.999) = 0.95$, which exceeds the minimum power of 0.80 required of the SS.

4 Conclusions and recommendations

There is increasing pressure to design SSs to detect NIS with explicit emphasis on power and differential spatial risk. Power is a fundamental component of a well designed SS, as it provides a formal way of assessing the utility of the plan to detect the target species across a heterogeneous sampling frame and can assist with optimal deployment of the SSC units. The resulting plan will lead to reduced financial and ecological costs and an optimal system.

All of the calculations performed here can easily be included in the design of a SS for any invasive or low density species. All that is required is an estimate for the probability of detection and the fraction of the sampling frame covered by the SSC, along with any limiting resource costs. It is suggested that the additional cost in time to incorporate power and risk into a SS will be offset by the confidence that the system will achieve its design goals, both ecological and financial. Additionally, if resource costs change or new data emerge about SSC characteristics or risk, then the SS can be easily updated.

Invasion risk mapping was facilitated by a GIS model, using spatial data to identify areas meeting attributes of entry and habitat suitability. The GIS model enables rapid updates of risk zones based on changing circumstances or improved knowledge of the attributes used.

We have presented a SS designed specifically to deliver sufficient power ($\geq$0.80) to detect a particular NIS, the exemplar *P. megacephala*, given that it is present within the sampling frame. It is acknowledged explicitly that many of the values utilised in the calculations were based on expert advice. Clearly, large changes to any of the component estimates may well produce quite different design outcomes. However, in the absence of more firm estimates based on empirical data, expert judgment is the best available source of information to incorporate into the SS; further comfort is taken from the fact that the estimates were obtained by agreement among a panel of such experts based on the available information.

To investigate the reliability of the estimates provided by expert elicitation, in the case study described in Sect. 3 a reasonable error (σ) was determined to be $\pm$10%. It was found that an increase of 10% in σ only affected the engaged and passive workers by reducing N by 1 SSC; reducing σ by 10% increased N by one for both types of pitfall traps and by two for both the engaged and passive workers. Errors in estimating σ therefore, unless they are considerable, will not reduce confidence in the utility of the SS.

A second choice which may be considered arbitrary was the choice of $K = 100$ individuals. This decision was made following consultation with expert entomologists who declared that the number of individuals, defined as being ‘a specified group of individual members, large enough to be detected, but small enough to be effectively eradicated without any significant environmental consequences’ for *P. megacephala* was far more likely to be 100 than 10, 1000 or 10,000. Figure 6 indicates that as K increases the number of required SSC units decreases accordingly, and also that when $K = 100$ this number becomes fairly stable suggesting that $K = 100$ was a reasonable choice.

Whilst we have presented a method to detect one NIS, in many practical situations multiple NIS need to be detected. This can be achieved by designing the SS to detect a number of carefully selected exemplars using a diverse set of SSCs, many of which will detect more than one NIS. These individual designs can then be amalgamated to create a comprehensive SS designed to detect a wide range of taxa, and is the subject of ongoing work. This methodology can also be adapted to suit any geographic area or situation, such as ports, where there exists a risk of incursion by one or more potential NIS.

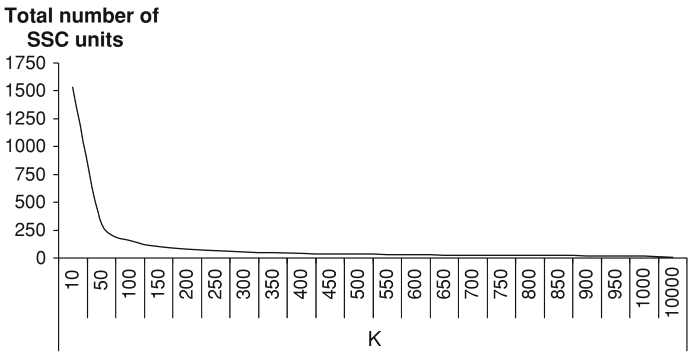

Fig. 6 The effect of changing the number of individuals (K) on the number of required SSC units for *P. megacephala*

Finally, we acknowledge the potential for a dependency between the individuals of some NIS and the influence this may have on the determination of N. A full discussion of this issue, however, is outside the scope of the current work but it does motivate further extensions of the proposed model. In particular, it would be interesting to consider cases in which the detection of only one individual invokes a responsive action by management (leading to possible eradication measures) compared with a situation where a minimum number of individuals need to be detected before such a policy is actioned.

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Author Biographies

Susan Barrett is a Research Fellow in the School of Mathematical Sciences at Queensland University of Technology, Brisbane, Australia and received her PhD at Griffith University in 2007. She has a broad range of experience in statistical consulting and applied statistics.

Peter Whittle is a Principal Research Fellow at Queensland University of Technology, Brisbane, Australia having previously worked in Biosecurity Queensland and BSES. He received his PhD in 1993 in agricultural science and holds an MBA. He has wide interests and experience in biosecurity research and applications.

Kerrie Mengersen is a statistician with expertise in fundamental statistical research, applied statistics and statistical consulting. She is Professor of Statistics in the School of Mathematical Sciences and Director of the Collaborative Centre for Data Analysis, Modelling and Computation at QUT, Brisbane, Australia.

Richard Stoklosa earned degrees in Bioengineering and an MSc in Chemical Engineering from the University of California, and is a long-term consultant to Chevron Australia. His company, E-Systems Pty Limited, specializes in ecological risk assessment, and has innovated the use of engineering techniques for quantitative and qualitative analysis, eliciting expert judgment and public consultation. Richard's interests include biosecurity, fisheries sustainability and environmental management of major resource projects.