# Strategies to detect and manage incursions of exotic species on Mexican islands

*Isla Isabel*

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# Contents

# SUMMARY

The Global Environment Facility (GEF) has funded a program to enhance Mexico's capacity to manage invasive alien species (IAS) on islands. Kurahaupo Consulting was commissioned to:

- To discuss the general principles of Early Detection-Rapid Response (EDRR) (surveillance and detection, rapid diagnosis, and rapid response) with emphasis on IAS that pose risks to islands.
- To discuss how these principles may be applied to six Mexican islands (with different risk and response profiles) selected for the GEF program.

**Main points**

1. Detection and rapid response systems cannot be simply applied to all IAS on all islands with a single recipe. EDRR has to be planned within the wider biosecurity risk chain where intervention at potential sources of the IAS, on the different pathways and vectors by which IAS may reach the island, and/or post-establishment might be more appropriate (in some cases) than planning EDRR actions at the point of introduction.

2. Detecting incursions by new species requires three management components:

- An appropriate surveillance system - where to search, what with, and how often? Surveillance systems can be active where some agency has responsibility to search the risk areas under some plan, or passive where individuals or groups (usually working on the island for some other reason) 'keep an eye out' for IAS. Some element of skill or training is implied.
- The ability to interpret lack of evidence (detection probabilities) so one does not respond inappropriately.
- The technical capacity to identify any plants or animals detected as IAS.

3. For the six demonstration islands known IAS present at likely source places and those already present on the island are listed, and the likely arrival sites on the islands are identified. Potential passive or active players that might conduct surveillance and subsequent responses are identified for each island.

**Main recommendations**

- The lists of risk IAS at source ports needs to be refined to survey just those found at the places where most boats (or planes) and most cargo they carry originate.

- Key species found at such sources could be managed (removed or controlled) at the source or flagged for management on pathways and vectors departing for the islands.
- The footprint sites on all the islands are small (relative to the size of the island in most cases) and EDRR is tractable for these footprint sites – assuming the capacity to conduct the surveillance.
- Longer-term such active surveillance cannot hope to meet all the ‘early detection’ needs and people living at high-risk sites will need to be involved in detection (and sometime early response for some IAS). They will need resources (photographs and descriptions of any high-risk IAS identified by the analysis above), training and motivation to use it.
- Five of the six islands have Navy bases which present both a risk that the boats or aircraft servicing these bases will carry IAS, and an opportunity to use Navy personnel to conduct surveillance and perhaps response. The problem with military personnel is they change with each deployment on the island. The solution is to include biosecurity Standard Operating Procedures in the military chain of command. Someone in each deployment is made responsible for biosecurity and surveillance/reporting and provided with a manual (with some basic training) of what to do (usually passive surveillance) and who to report to if something is found.
- Five of the six islands also have semi-permanent fishing communities. Those on Guadalupe and San Benito are organised cooperatives and may be prepared to conduct passive surveillance and report (or act) on any IAS they discover.
- Scientific expeditions are sent to all six islands from time to time. Scientists are marginally more likely to report IAS than other people, much more if the IAS is in their taxonomic range. However, it is best if active surveillance is conducted by suitable experts. I recommend conducting baseline surveys of all footprint sites to list IAS that are NOT widespread on the island. This would useful for two reasons (a) to build capacity to detect and manage such IAS in preparation for future EDRR processes, and (b) to refine the risk analyses implied in Table 7 – which new IAS to keep under review.
- On rodent-free islands with high risks of invasion (ships visiting from source sites and unloading cargo) many managers deploy permanent bait stations at the footprints sites. This is not possible on the islands with rodents (or other native mammals) as it would simply feed the mice. If the risk of a rodent incursion was high (and it does not appear to be so for Mexican islands) the only proactive way to manage the risk is to have a response ability in place at the footprint ready to deploy at the first sign of a new rodent in an attempt to intercept the incursion – with a high risk of failure. Management at sources and on vectors is the best appropriate way to reduce the risk from such species.
- Rapid response options are also generic on all six islands but depend very much on the IAS and particulars of its discovery.

# 1 Introduction

The Global Environment Facility (GEF) through the United Nations Development Program and the Mexican National Commission for Knowledge and Use of Biodiversity (CONABIO) is funding a program to enhance national capacities to manage invasive alien species (IAS) by implementing the Mexican National Strategy for IAS. As part of this program *Kurahaupo Consulting* has been commissioned to contribute to issues around 'Early Detection/Rapid Response' (EDRR), and, as part of this, to review the principles of EDRR as they relate to managing IAS incursions on islands in general and in particular to six Mexican islands nominated as demonstration sites for the national program. This component of work will also inform a wider project on IAS management on Mexican islands being conducted by Grupo Ecología y Conservación de Islas (GECI).

# 2 Objectives

- To discuss the general principles of EDRR (surveillance and detection, rapid diagnosis, and rapid response) with emphasis on IAS that pose risks to islands.
- To discuss how these principles may be applied to six Mexican islands (with different risk and response profiles) selected for the GEF program.

# 3 Background

Mexico has about 300[1] islands in the Pacific Ocean, the Gulf of California and the Gulf of Mexico and Caribbean Sea (Table 1). The total area of the islands is 512,700 ha (Aguirre-Muñoz et al. 2011), or only 0.26% of the land area of Mexico. However, as elsewhere in the world this small area contains a disproportionate amount of Mexican biodiversity with high levels of insular endemism. For example, the islands in the Gulf of California have 28 species of endemic mammals (Álvarez-Casteñada & Ortega-Rubio (2003), while the remote oceanic islands in the Revillagigedo Archipelago have almost 30% of their biota found nowhere else (Ortega et al. 1992).

[1] The number of islands in Mexico is rather unclear. Álvarez-Casteñada & Ortega-Rubio (2003) claim over 900, Aguirre-Muñoz et al. (2011) claim 600 plus islands in the Pacific and Gulf of California. Presumably these tallies include many small islets and rocks. Many islands have several names and many current lists do not give coordinates for islands so it is difficult to provide a definitive database.

**Table 1.** Number of islands by geographic region in Mexico (after Case et al. 2002 and J. Parkes (unpubl. data).

| **Region** | **No. of islands** | **Islands nominated for the GEF project** | **Area (ha)** | **Status** |
|---|---|---|---|---|
| Pacific Ocean (coastal) | 48 | San Benito (3 islands) | 390 | Biosphere Reserve |
| Pacific Ocean (offshore) | 22 | Guadalupe (+ 5 islets);<br>Socorro | 24171, 13200 | Biosphere Reserve<br>Biosphere Reserve |
| Gulf of California | 206 | Espíritu Santo (2 main and 7 islets) | 9625 | Area for Protection of Flora and Fauna |
| Gulf of Mexico | 6 | Arrecife Alcaranes | 53 | National Park |
| Caribbean Sea | 20 | Banco Chinchorra (3 cays) | 581 | Biosphere Reserve |

The Mexican National Strategy on invasive species (Anon 2010, Koleff et al. 2010) notes the importance of island biodiversity both nationally and internationally, and while few are pristine with respect to IAS, an active program to eradicate those present has been underway over the last two decades (Aguirre-Muñoz et al. 2011). Stopping or intercepting IAS is thus an investment in maintaining the values on these islands and defending the progress made to date.

# 4 General principles of EDRR

## 4.1 Some definitions

*Biosecurity:* the exclusion, eradication or effective management of risks posed by invasive alien species (IAS) - exotic pests, weeds and diseases - to the economy, environment and human health. This may be achieved by actions pre-border, along the pathways and vectors bringing the unwanted organisms, at the border or post-border.

Early detection rapid response (EDRR): in essence requires a putative new IAS is detected and managed before it establishes in a new range. This report focuses on IAS arriving on islands but the principles can be applied anywhere at risk of invasion by IAS. The EDRR process requires any putative new species is detected, that the find is quickly confirmed as a new species, that any planning or regulatory requirements for action are streamlined so that the appropriate response (usually the removal of the IAS population) is in time to intercept establishment and spread (e.g. see NISC 2003). Clearly, the timeframes for this process will always depend on the ability of people to work through this process, but it is also clear that the biological timeframe between arrival and establishment will depend on the life history of the IAS – some must be dealt with very quickly while others will be slow to establish and spread so we can be 'less rapid' in our response.

*Eradication:* the permanent removal of all individuals capable of breeding.

*Extirpation:* the removal of all individuals capable of breeding but on-going regular management of new immigrants required to maintain zero density.

*Pathways and vectors:* A pathway is the process by which an IAS reaches the island while a vector is the physical or biological means by which it does so. Thus a pathway might be the pet, horticultural trade or a cargo system, while the vector is the ship that carries the pet, plant or container.

*Incursion:* arrival of one or more individuals of a species on an island. Fortunately many incursions fail either because the individuals fail to survive or fail to reproduce. Note: the literature on the deliberate introduction of animal species suggests that even for species that eventually established (i.e. the habitat was suitable) several attempts were often required (e.g. Forsyth & Duncan 2001).

*Invasion:* an incursion that establishes a reproducing, self-sustaining population of the IAS on the island.

*Invasive Alien Species:* an alien species (the UNEP definition) is one occurring in an area outside of its historically known natural range as a result of intentional or accidental dispersal by human activity (also known as an exotic or introduced species). An alien species becomes an Invasive Alien Species (IUCN definition) when it becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity.

There is some debate about these formal definitions to cover alien species that damage productive or agricultural values, and, particularly for islands, to include species that are alien and/or invasive at sources but disperse naturally to the island without direct human activity.

*Rapid response:* action against an IAS that has recently arrived in a new area but before the incursion can be classed as an invasion, i.e. a timeframe based on the biology of the IAS is implied. The action would ideally entail removal of the individuals in the incursion, but could also include actions to ensure none reproduce, or none spread and establish more widely. Removal of the incursion may be identical strategically and tactically to eradication or extirpation, but generally rapid response follows a different regulatory, funding and accountability process than projects that attempt to eradicate an established population of IAS. Deciding when an incursion becomes an invasion is a key decision point in biosecurity management.

## 4.2 Risk and management matrix

Detection and rapid response systems (e.g. Worrall 2002, Crall et al. 2012) cannot be simply applied to all IAS on all islands with a single recipe. First, EDRR has to be planned within the wider biosecurity risk chain where intervention at potential sources of the IAS, on the different pathways and vectors by which IAS may reach the island, and/or post-establishment might be more appropriate (in some cases) than planning EDRR actions at the point of introduction. Similarly even within an EDRR strategy the mix of risk and potential management factors (Table 2) need to be considered to ensure appropriate surveillance and detection procedures and any subsequent responses are deployed so that rational decisions on intervention can be planned. As a simple example, the presence of a permanent human population on an island adds risks that new species will be introduced both accidentally and deliberately, but also provides opportunities for surveillance and thus rapid detection of and response to any IAS that do arrive – compared with uninhabited or rarely visited islands.

Before addressing the issues of EDRR on islands a few words on biosecurity before an incursion eventuates will put EDRR on the island in context.

**Table 2.** The matrix of potentially interacting factors that affect EDRR strategies for islands.

| Physical characters | Human influences | Biological characters | Management options |
|---|---|---|---|
| Island size | Permanent residents | Habitat complexity and types | Detection methods for risk species |
| Distance from sources | Temporary residents | Native species diversity | Detection probabilities known |
| Topography and access | Military base | Exotic species diversity | Feasibility of eradication |
| | Wharf | Risk species types, e.g.<br>Vertebrates<br>Invertebrates<br>Weeds | Capacity to detect<br>Presence<br>Diagnosis<br>Training |
| | Airfield | Native coloniser or exotic invader? | Capacity to react<br>Legal<br>Funding |
| | Types of vectors<br>Ships<br>Aircraft<br>People | Island pristine or modified | Consequence of inaction |
| | | Rates of increase and rates of spread | Frequency and scale of surveillance |

### *Management at sources*

IAS may come from anywhere in the world. However, it is clearly more likely that IAS risks will be proportional to the volume of 'baggage' taken to the island and more likely that IAS living at the sources of such ‘baggage’ might be transported to the island, especially when these sources have similar environments to the island. The question is whether any action against the IAS populations found at these focal departure points is feasible and will reduce the risk?

Perhaps the main threat that could be managed at sources, i.e. to stop them getting on to ships, would be from *Rattus rattus*. This rat is present on Cedros Island (Aguirre-Muñoz et al. 2013) and probably on all the mainland source ports and could stowaway on ships especially when they are moored at wharfs. Other countries attempt to keep wharf areas free of rats by setting bait stations or traps (e.g. see Parkes et al. 2004), ensuring mooring ropes have rat-guards and keeping gangways in bright lights at night to discourage the rats.

***Management on pathways***

The process by which IAS can be transported to an island might be thought of as pathways, and these can be either intentional or accidental. Some common pathways relevant to Mexican islands include personal baggage of inhabitants and visitors, military and civilian cargo and packaging material, construction materials, mail, pets, horticultural material for food gardens, aquaculture, fresh food, fishing equipment, etc. It is outside the scope of this report to analyse which IAS might be transported by what pathways but those interested might review the extensive analysis done for the USA island of Guam which attempts to list and rank risks by many pathways relevant to that island (USDA 2012).

For example, the Mexican Navy inspects passengers’ luggage at the Ensenada airport for flights to Guadalupe Island. Including IAS biosecurity risk items in the search procedures would be useful with some training of the officers. It would be interesting to find out what IAS risk items, if any, these officers note.

The general principle for biosecurity around cargo is to develop a process that allows assumed contaminated cargo to be cleaned before it is loaded on the ship – dirty in clean out (Fig. 1).

**Figure 1.** (Left) Quarantine room, Puerto Ayora, Santa Cruz, Galapagos where fresh food is inspected and cleaned before taken to other islands (left). Some quarantine systems are even

stricter and allow no fresh food to be taken – even for the year-long visits of the meteorological staff of Gough Island. (Right) A clean room for checking passengers and cargo before departure to the limited access Takaporewa (Stephens) Island in New Zealand. Note: footwear is inspected and dipped in disinfectant (pathogens for endemic frogs). In both systems packs and personal baggage are emptied, repacked and kept overnight in a freezer to kill any invertebrates.

Larger-scale cargo biosecurity systems can require fumigation of bulk cargo or containers before they are sealed (Fig. 2) and/or specific workflow buildings where cargo is packed in clean spaces.  Some systems simply require cargo to be stored in such a way that limit IAS access, e.g. containers are stored at the source wharf raised above the ground to limit the ability in ants or other insects to gain access.

***Management on vectors***

IAS, particularly animals such as invertebrates and rodents, can live on ships especially if transit times from source to island are short.  Basic hygiene on board the ship to make it less attractive for animals is the first step in any management, but if evidence is found of IAS on board the ability to react (set traps right through to fumigating a hold) should be options.

As an example, the biosecurity officer on the rodent-free Pribilof Islands (Alaska) may deny access to their harbour for any fishing vessel showing evidence that rodents are present.


**Figure 2.** Bags of rodent bait on pallets (background) being enclosed in wooden crates which are fumigated and sealed before transport from Hobart, Tasmania to Macquarie Island.

## 4.3 Early detection on islands

Detecting incursions by new species requires three management components:

- An appropriate surveillance system - where to search, what with, and how often? Surveillance systems can be active where some agency has responsibility to search the risk areas under some plan, or passive where individuals or groups (usually working on the island for some other reason) 'keep an eye out' for IAS. Some element of skill or training is implied.
- The ability to interpret lack of evidence (detection probabilities) so one does not respond inappropriately.
- The technical capacity to identify any plants or animals detected as IAS.

How to respond when an IAS is detected is discussed in section 4.4.

The first two of these components (surveillance and detection probabilities) are based on the simple fact that to be 100% certain that no IAS is present in an area (the island in this case) the whole island must be searched everywhere with a system that has perfect detection. Neither total search coverage nor perfect detection is usually possible so the questions managers must answer are:

(a) What is the probability, given realistic surveillance strategies and imperfect detection devices, that no IAS of interest is actually present when none were found?
(b) If this probability is low and the cost of failing to detect an incursion in time to respond effectively or efficiently is high, how much more surveillance should be applied to increase the detection probability commensurate with the risk?

***Surveillance strategies***

A surveillance strategy needs to set (and adapt) a plan on where to search, when to search, how often to search, who should search, what risk IAS should be flagged for the search, who should identify any suspected IAS found, how should data and other information collected be stored and made accessible, and what technical tools should be used given these other aspects?

(a) Where to search?

Ideally the whole island should be searched for IAS. When resources to do this are finite the search effort might be stratified so that more effort is expended in parts of the island where IAS are most likely to arrive or establish. Resources are almost always limiting so at least for large islands and for most species only these risk areas are searched in any formal surveillance strategy. Note: vectors for IAS such as ships or aircraft may also be searched but this quarantine process is arguably outside the 'early detection' objectives of this report. However, actions to detect and deal with IAS on vectors obviously merge into EDRR strategies as, for example, risk cargo is unloaded on the island.

On mainland areas, where the aim is to monitor the potential spread of IAS, such sites are often called 'sentinel sites' (e.g. see those set up to monitor the spread of the cactus moth

(*Cactoblastis cactorum*) Westbrooks et al. (2006)). Similarly, animal or plant disease managers often monitor sentinel herds or populations in an attempt to identify new outbreaks (e.g. Racloz et al. 2006, Adell et al. 2010). The equivalent on islands, where early detection of incursions is the aim has been called 'detection footprints' (Jarrad et al. 2011).

On Barrow Island in Western Australia an oil company wanting to develop infrastructure over a small part of the 23,000-ha island was required by government to be 80% certain that any new species arriving on the island would be detected in time to intercept its establishment and spread. Eradicating an established, widespread IAS would be very difficult given the presence of a large and diverse native fauna, thus the emphasis on EDRR. A surveillance system was designed based on stratifying risk that species are more likely to arrive at some places on an island (e.g. at the wharf, airport, or where people live) than others. Understanding the detection probabilities of devices (e.g. traps, people searching) at these risk sites then allowed a system to be designed to meet the 80% rule - given the constraints on search extent, constraints on detection devices (presence of many native species meant lethal detection devices were not practical), and costs of the detection systems. The strengths of this approach are in the careful design of the surveillance footprint and the attempt to meet pre-determined risk standards. The weakness is (as with many systems) the paucity of data on detection probabilities for many of the devices and arrays used to try and find any IAS that arrives.

There is a subtle difference between sentinel sites and detection footprints that has relevance for some IAS on islands. If the detection probability for an incursion is low, the species' rate of spread is likely to be rapid (i.e. the IAS is unlikely to stay at the point of entry on the island), and the whole island is suitable habitat for the IAS, then a system of sentinel sites over the whole island might be justified. However, if the IAS is likely to have a low capacity to disperse quickly from its introduction site then the footprint surveillance system is clearly the most efficient. For example, experiments with rats released on rat-free islands or in fenced exclosures in New Zealand suggest the animals stay close to their introduction point for only a few days before they disperse and explore their new home (Russell et al. 2008; Innes et al. 2007). An EDRR strategy based on the footprint model would require a high probability of detecting the incursion and a response deployed on the footprint and the rats removed in these few days. (Note: see section 4.4.2 for a discussion on the benefits and constraints of having a detection device that kills the IAS). If this capacity was not likely, the sentinel model would be best with a consequence being that an island-wide response would have to be implemented if a rat was detected.

In practice, decisions on where to search under the footprint model can be made by mapping the relative likelihoods that different IAS types will arrive at, for example, wharfs, airfields, human habitation sites, beaches nearest to source populations, or restricted habitats for some IAS. Jarrad et al. (2011) describe a system based on expert knowledge (Low Choy et al. 2009, Saaty1987) to rank the relative importance of such sites for each type of IAS so that surveillance effort can be stratified and/or a given level of certainty can be determined to reduce the chance of declaring the IAS absent when it was in fact present.

Statistical advice should be sought to design the search methods within the footprint sites. Adaptive and unequal probability survey designs (Thompson 1990, Brown et al. 2011) are often used for monitoring rare or clustered objects and, depending on the IAS and circumstance might be suitable (see also section 4.4.3 on delimiting the response area).

(b) When to search?

There are obvious times when an incursion is most likely – when cargo or stores are being landed on the island, after a shipwreck, when people arrive – and so obvious times when surveillance is most required.

Apart from these risky times, there are also times of the year when an IAS might be most detectable. Weeds, for example, are likely to be easiest to detect (and certainly identify) when they are flowering and so information on the reproductive ecology of target IAS should be part of any plan.

Occasionally it is not the IAS but its impact that is detected. For example, incursions by disease-causing microorganisms are not usually detectable until they infect some local organism and symptoms (or bodies) become visible. Similarly, evidence of predation on birds might be the first sign of an incursion by a predator and so instigate a search to identify the culprit.

(c) How often to search?

Search 'devices' (some described in (f) below) can search almost continuously (e.g. automatic cameras) through to flexible longer frequencies (e.g. surveys by people). Early detection of course favours search frequencies towards the continuous end of the spectrum, while rapid response decisions depend on the behaviour of the IAS predicted over the times between incursion – detection and diagnosis – first response. Sometimes the window of opportunity to respond to the IAS is short, so the lag between incursion and detection must be short, and so the island (or more usually the footprint/sentinel area) must be searched frequently. To illustrate this point we can consider two plant species taken to the island as say garden or amenity species. A long-lived tree such as a eucalypt may take many years to reach an age where it can produce seed and potentially establish and spread as a population of weeds. Rapid response to detection is thus not essential. In contrast, an annual, wind-dispersed plant such as a composite may flower and seed within a short period after arrival (e.g. as a house pot plant) so it should be removed as soon as it is detected (actually it should not be introduced in the first place).

Surveillance can be planned at a set frequency, ad hoc as people visit the island, or ad hoc by island residents, but the frequency needs to be considered in light of the predicted risk that particular IAS will arrive and the costs of the surveillance relative to the costs required to manage IAS not detected at an early time. Sometimes it is best not to spend money on surveillance if the incursion can be effectively eradicated cheaply at some later date, e.g. a plant species that takes many years to reproduce and has a low rate of spread.

(d) Who should conduct the surveillance and report potential IAS?

Permanent island residents are best if they have the motivation and training to detect, identify and report or respond to incursions because they are present all the time and likely to be familiar with the biota already present around their homes. Training is required to identify high-risk species that are not immediately recognisable to non-experts – a chart with photographs of high risk species such as weeds and invertebrates.

Reporting an incursion to someone who has the responsibility and capacity to respond is important. On islands where local residents are trained to look out for IAS it is important that they have the means (email or a telephone hotline) to report any suspicious animal or plant. Equally, it is important that the responding agency or person reports back to the original observer to ensure that person's on-going interest.

Surveillance is a task in perpetuity and so people who do it and are accountable will change over time. System memory of what was done, when and what was or was not found is essential and so a system to keep good records that are accessible and interpretable by future staff must be developed.

(e) Should some potential IAS be flagged as targets for surveillance?

To answer this question we must link EDRR strategies with an analysis of the source – vector components of a biosecurity system. What risky species are present in places from which vectors (ships, aircraft) are departing for the island? Most biosecurity systems try to identify particular species that are likely to arrive at the border but are representative of a wider range of IAS, i.e. surveillance system(s) for these exemplar species will also detect a wide range of other known risk species and those unpredictable species we have not even thought about. I will discuss some possible exemplars in the case studies in section 4.5.

I note that management at the source or on the pathway/vector may be a better option than EDRR on the island and will comment on this in the case studies in section 4.5.

Typical animals that stowaway on ships and in cargo elsewhere in the world include some mammals such as rats (*Rattus* spp.), mice (*Mus musculus*), small Indian mongoose (*Herpestes javanicus*) which is present in the Caribbean), some birds (Indian house crows (*Corvus splendens*), common and jungle mynas (*Acridotheres tristis* and *A. fuscus*) which are spreading through the Pacific, some reptiles (brown tree snakes (*Boiga irregularis*), house geckos (*Hemidactylus frenatus*), amphibians (cane toads (*Rhinella marina*)), many ants, and some molluscs (e.g. African snails (*Achitina fulca*)). Their presence or that of similar species already known to be in Mexico, and particularly at source ports, would increase the risk that they may be on the vectors travelling to the islands.

Most invasive plants on islands have been introduced on purpose so the best strategy is to manage the importation process (by education and regulation) and rely on an EDRR strategy to manage breaches – hopefully zero. However, some plants (usually seeds) can be introduced accidentally with people or cargo (e.g. Cooper et al. 2011) and islands within wind or bird range of seed sources may receive IAS by these means.

A database on plants in Mexico records 618 exotic species (as well as 3000+ native plants classed as weeds) (Koleff et al. 2010 and see Vibrans (2010) in www.malezasdemexico.net). Medellin Legorreta (2000) recorded 2 amphibians, 12 reptiles, 24 birds and 68 mammals as exotic species in Mexico. Not all of these will be invasive on islands, but many will be (e.g. Table 3) and they and those from other taxa (fish, invertebrates, fungi and diseases) for which I have seen to tallies present but the intra-Mexican risk to the islands.

This table is obviously not complete but it does illustrate the process to identify risky species for islands. There must be a realistic pathway for the species to get to the island from a plausible source, and suitable habitat to establish and spread if it does reach the island.

Therefore on the list in Table 3 we might discount flagging the freshwater aquatic species as major threats to most islands because they usually require deliberate transport by people, and many Mexican islands have no or few suitable freshwater habitats.

New incursions of individuals of species already present on the island are less of a problem unless (a) the species is to be targeted for eradication in which case re-invasion risks need to be managed or (b) additions of new genetic material may make the population more of a problem. On this latter point recent reports show that a genetic variant in fire ants (*Solenopsis invicta*) allows colonies to harbour multiple queens rather than just one queen with potential consequences of larger and more damaging colonies (Wang et al. 2013).

**Table 3.** Some likely risk IAS present in mainland Mexico that might establish on some islands. Those marked * are considered to have highest potential impact in the National Strategy on Invasive Species in Mexico

| **Risk species** | **Locations in Mexico** |
|---|---|
| Ship or black rat (*Rattus rattus*)* | Widespread and already on some islands |
| House mouse (*Mus musculus*) | Widespread and already on some islands |
| Feral cat (*Felis catus*)* | Widespread and already on some islands |
| Feral pigeon (*Columbia livia*)* | Widespread commensal species |
| Cattle egret (*Bubulcus ibis*)* | Widespread |
| House sparrow (*Passer domesticus*)* | Widespread mostly commensal |
| Monk parakeet (*Myiopsitta monachus*) | Widespread escapees |
| Gecko (*Hemidactylus turcius*) | Gulf of Mexico and Caribbean |
| Red-eared slider (*Trachemys scripta elegans*)* | Native to northern Mexico (Nuevo Leon and Tamaulipas) and reported as invasive in Cuatrociénegas |
| American bullfrog (*Lithobates catesbeianus*) | Escaped populations |
| Cane toad (*Rhinella marina*)* | Widespread |
| Common carp (*Cyprinus carpio*)* | Widespread |
| Nile tilapia (*Oreochromis niloticus*)* | Widespread |
| Mozambique tilapia (*Oreochromis mossambicus*)* | Widespread |
| Red fire fish (*Pterois miles*)* | Caribbean and parts of the Gulf of Mexico |
| Lion fish (*Pterois volitans*)* | Caribbean and parts of the Gulf of Mexico |
| Armored catfish (Loricariidae) | Widespread |
| Cactus moth (*Cactoblastis cactorum*) | Introduced biocontrol in USA (Florida, Texas, Louisiana); Present in Cuba; Eradicated on Mujeres and Contoy islands in Mexico |
| Bumble bee (*Bombus impatiens*) | Introduced to fertilize glasshouse crops |
| Red fire ant (*Solenopsis invicta*) | Northern Mexico |
| Giant reed (*Arundo donax*)* | Northern Mexico |
| Buffelgrass (*Pennisetum ciliare*)* | Widespread |
| Bermuda grass (*Cynodon dactylon*)* | Widespread |
| Crowfoot grass (*Dactyloctenium aegyptium*)* | Widespread |
| Water hyacinth (*Eichhornia crassipes*)* | Widespread |
| Beach sheoak (*Casuarina equisitifolia*)* | Widespread as ornamental particularly in urban areas. Some wild populations in protected areas |
| Tamarisk (*Tamarix ramosissima*)* | Northern Mexico |
| *Eucalyptus* spp. | Widespread |

### *Detection devices, probabilities and analyses*

The only 'device' that can detect all (or most macroscopic) IAS is the human eye. Thus observation by people is probably the most important single surveillance system. How people search of course varies from casual and ad hoc as might be done by alert island residents (called passive) to formal surveys as might be done by botanists assessing plant composition and distribution (called active).

However, in this section I want to note a few specialised survey devices used to detect some key classes of animals IAS (Table 4).

**Table 4.** Characteristics of devices used to detect some key IAS – as exemplars of rodents, reptiles or predator scats in general.

$G_0$ is the probability that one device will detect (catch, kill, locate) an animal when the device is set near the centre of the animal's home range (see Ball et al. 2005). G(%) is the proportion of times the target animal was detected over many attempts (see Savidge et al. 2011 for the brown tree snake and Parkes & Anderson (2011) for red fox scats).

| Exemplar IAS | Detection device | Detection probability | Parameter | Reference |
|---|---|---|---|---|
| *Rattus rattus* | Live trap | 0.020 – 0.106<br>0.023 – 0.041 | $G_0$<br>$G_0$ | Parkes & Byrom (2009)<br>Wilson et al. (2007) |
| | Wax tags | 0.169 ± 0.22 | $G_0$ | Samaniego-Herrera et al. (in press) |
| *Rattus norvegicus* | Dogs | 0.87 | G(%) in 360 minutes over 32 ha | Gsell et al. (2010) |
| *Mus musculus* | Dogs | 0.80 | G(%) in 360 minutes over 32 ha | Gsell et al. (2010) |
| *Boiga irregularis* | Dogs | 0.26 – 0.44 | G(%) in 60 minutes over 0.16 ha | Savidge et al. (2011) |
| | | | | |
| *Vulpes vulpes* faecal scats | Dogs | 0.10 – 0.40 | G(%) in 30 minutes over 100 ha | Parkes & Anderson (2011) after Ramsey (unpubl. data) |
| | People | < 0.10 | G(%) in 30 minutes over 100 ha | Parkes & Anderson (2011) after Ramsey (unpubl. data) |
| | | | | |
| *Solenopsis invicta* | Baited traps | 0.8 | | Stringer et al. (undated) |

Dogs trained to detect particular species are increasingly being used in pest control and eradication projects and to check islands and sanctuaries' pest-free status (Gsell et al. 2010). For example, a dog found 4 of 5 Norway rats (*Rattus norvegicus*) known to be present (4 in cages and one free but radio-telemetered) on the 60-ha Browns Island in New Zealand (e.g. Shapira et al. 2011). Dogs have also been used to detect fire ants in Taiwan (Lin et al. (2011).

Ants are always a major threat as invasive species, although it is not clear if Mexican islands, with their own native ant fauna, are as susceptible to invasion as other island systems. Boulton & Ward (2002) note a single exotic ant (*Paratrechina longicornis*) as being present in the Gulf of California islands, but species known to be invasive are present in mainland Mexico, e.g. the red imported fire ant (*Solenopsis invicta*) and Argentine ant (*Linepithema humile*).

Between 1955 and 2005 over 4,300 interceptions of 115 species were made at the New Zealand border. Interestingly, of those that came with a known commodity, most came with fresh produce (Table 5), possible indicating likely risk pathways and footprint sites for Mexican islands especially if the invasion of fire ants from the USA continues (Sánchez-Peña et al. (2005).

**Table 5.** Interceptions of exotic ants at the border of New Zealand (from Ward et al. 2006).

| Commodity inspected | No. of ant interceptions | % of all ant interceptions | No. of species |
|---|---|---|---|
| Fresh produce | 156 | 46.7 | 26 |
| Containers (air and sea) | 75 | 22.4 | 18 |
| Personal baggage | 53 | 15.8 | 17 |
| Vehicles | 37 | 11.1 | 15 |
| Timber | 13 | 3.9 | 11 |

Ant invasions on islands is an issue (although which ant is often unclear – see section 4.3.3), but early detection is not so simple. The usual ways are to regularly inspect footprint areas for ants, or to deploy a grid of traps at high risk sites. Stringer et al. (undated) have developed a model that measures the detection probabilities of various trap types set at different grid spacings and set over different times to detect red imported fire ants. For example, baited vial traps (see the design in Stringer et al. 2010) shows detection probabilities ($G_0$) fell to near zero once the traps were more than a few meters apart but when set for longer the detection probabilities exceeded 0.5 even when the trap spacing was about 50 m.

Given a surveillance system with known footprint and detection probabilities, the next step is to determine how any data (or more usually lack of data) will be analysed and interpreted to (a) determine presence/absence of IASs and (b) optimise surveillance effort.

There are several analytical approaches to answer this question, some using classical statistical methods and other Bayesian approaches. There are several studies using both classical (e.g. Choquenot et al. 2001, Rout et al. 2009, Cacho et al. 2006, Regan et al. 2006) or Bayesian methods (Solow 1993) that use the decline of sightings over time (during eradication or as a population declines towards zero) or with distance from the searcher (Anderson et al. 2004) to infer absence.

However, I think the question of early detection is ideally suited to Bayesian analysis. The strength of the Bayesian approach to answer this question is that it allows an answer to the question ‘if searching or sampling does not find anything, what then is the probability that none were, in fact, present to be found?’ Classical statistics cannot answer this question because it estimates the probability that all samples were negative given the object was in fact present.

The theory of search and detection was developed for military purposes (submarine and mine warfare) in the 1940s (Koopman 1980) using Bayes' theorem. This Bayesian approach is used in some modern search and rescue systems (Frost & Stone (2001), and is increasingly used to validate the success of eradication projects (Ramsey et al. 2009, 2011; Samaniego et al. in press). These three examples set different questions. Is there a foreign submarine present in the Gulf of California? Where is the lost yacht that set out from La Paz and is overdue in Tahiti? Are there any feral sheep left on Socorro? The questions in EDRR are more akin to the submarine example (uncertainty that there were ever any present) than to the lost boat (there is one but can we find it), or the sheep (there were some but are there any left); but the analytical principles are the same (Appendix 1).

### *Diagnostic capacity*

Reliable identification of a potential incursion is essential to direct the appropriate response.

- Is the animal or plant a native species? New native and even endemic species are still commonly found on islands and obviously protection and not eradication is the desired management.
- Is it a native to nearby islands or the mainland and has arrived on the island naturally. The appropriate management response is more complex as the incursion can be seen as a desirable natural part of island biogeography, or (if the new species is likely to adversely affect some valued island resident species) seen as undesirable and treated as an IAS.
- Is it an alien incursion? Treatment as an IAS is the management choice.

Some IAS (most vertebrates) are obvious as invasives and identification is relatively simple using available descriptions. However, even among vertebrates there may be identity issues. For example, the common invasive rodents can be distinguished one from another by morphological characters (Table 6) and certainly by DNA if there is doubt. However, the presence of 20 or so North American rodents (*Peromyscus, Chaetodipus, Neotoma, Dipodomys, Reithrodontomys*) amongst the Mexican islands (Lawlor et al. 2002, Samaniego-Herrera et al. 2007), may complicate diagnosis in Mexico if one is found on a rodent-free island.

Invertebrates and plants are more difficult to identify and expert taxonomic advice may have to be sought. From whom is not clear although I note the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad and their network of taxonomic experts might be the primary source.

**Table 6.** Morphological characters of common IAS rodents.

| | ***Rattus rattus*** | ***R. norvegicus*** | ***R. exulans*** | ***Mus musculus*** |
|---|---|---|---|---|
| Body Wt (g) | 95 – 340 | 200 – 400 | 30 – 100 | 10 – 25 |
| Ears | Large and cover eyes when pulled forward | Do not cover eyes when pulled forward | Smaller than *R. rattus* but also cover eyes when pulled forward | Smaller than for the rats |
| Belly fur (characteristic for *R. exulans*) | | | White-tipped with grey underneath | |
| Tail | Much longer than head/body length. Uniformly dark | Clearly shorter than head/body length. Thick with pale underside | Similar to head/body length. Thin and uniformly dark | Similar to head/body length. Uniformly grey-brown |
| Tail length (mm) | 185 – 245 | 150 – 215 | 125 – 135 | 75 – 95 |
| No. of nipples | 10 – 12 (usually 10) | 12 | 8 | 10 |

# 5 EDRR on six Mexican islands

If we return to the matrix in Table 2 we can see how many of the components interact to inform how EDRR systems would need to be deployed (in general) on islands with different constraints and opportunities. We have used the six islands nominated for the GEF program in Table 1. The general approach for each island is to compare data on:

(a) Which risk IAS species are present at likely source places on the mainland. It is assumed that IAS present at points where vectors depart for the island will have the highest probability of reaching the island, followed by IAS present elsewhere in the region, Mexico, adjacent countries and then the world. In the discussion on each island I have used the exotic species listed as present in the region around source ports in a CONABIO database. A better assessment of the risk species would require a more focussed survey of actual departure sites.

(b) Whether these species have possible pathways or vectors to reach the island?

(c) Which IAS are already present on the island, and thus not of immediate concern for an EDRR process?

(d) Which of the IAS in (b) are currently restricted to high-risk entry places (footprints) and might be used as test cases for EDRR training?

(e) Which risk IAS are most easily detectable and manageable, and how might these species be used as exemplars for a range of other known and unknown IAS that may arrive. What sort of IAS would you find if you focussed on a few risky species?

(f) Who should do what, where and when to detect, validate and respond to any IAS arriving on each island? Biosecurity for remote islands with restricted access is easier than biosecurity for islands where public access is not so restricted. Relatively few trained, accountable individuals (or agencies) can be targeted to manage and regulate the human pathways to detect IAS breaches – compared with open-access, frequently visited islands. In the latter islands a change in attitudes and behaviour of all users are required (as well as the key individual/agency approach) for effective biosecurity.

There are no current plans that enable EDRR on Mexican islands (Aguirre-Muñoz et al. 2013) but there is a manual (Manual de campo para la detección oportuna y monitero de mamiferos invasores (roedores y gatos) aplicables a ecosistemas insulares) to assist island managers detect reinvasion by rodents and cats on islands from which they have been eradicated. This manual could form a template for a wider EDRR manual for the islands and for both agencies and the Navy.

The following data on IAS distribution in sources and on each island (Tables 7 to 9) are probably too broad-brushed to answer the questions (a) and (d). If such focussed data does not exist some simple surveys should be conducted at the main sources and particularly at main entry points on the islands.

## 5.1 Guadalupe Island

Guadalupe is a large (24171 ha), remote (250 km off mainland Baja California in the Pacific Ocean), high (1290 m asl) island, with three small adjacent islets. The island has a diverse series of habitat types depending on the substrate, rainfall, altitude, aspect, past fire events, and past human activities and is a Biosphere Reserve.

It is under active restoration with the removal or eradication of feral goats, donkeys, horses, rabbits and dogs between 1996 and 2007 (Aguirre-Muñoz et al. 2011) and plans to eradicate the feral cats (Luna-Mendoza et al. 2011). If this succeeds the only introduced mammal present will be the house mouse. Passive restoration will also be achieved as areas are reforested with the endemic pines, cypress and palms that shade out many IAS grasses and shrubs.

***Risk profile***

Guadalupe has been much modified by human activities with many IAS (particularly grasses) dominating the vegetation (Leon de la Luz et al. (2003) (Table 7) and reduced numbers of native species (Luna-Mendoza et al. 2011). When the fishing village is occupied the population of the island is about 100 people. Permission is needed to visit the island.

*(a) Source sites, pathways and species*

Most people who visit the island come via ship or fixed-wing aircraft from Ensenada. The Navy boat sails monthly and sometimes calls in to Cedros Island before arriving at Guadalupe Island. Scientific visitors arrive regularly by both aircraft and on the Navy boats. Recreational boats (fishing and shark watching) visit the island's waters but although they are generally not permitted to land the tour operators sometimes provide gifts or supplies to the fishing community – and thus may present a risk.

The known IAS present in the mainland of northern Baja California (Table 7) include a large number of weed species. Some plants not present on the island that stand out as potential problems include *Bidens pilosa*, all the grasses adapted to semi-arid habitats and the brassicas. The native deermouse and exotic ship rats should be flagged as mammals of concern, while the absence of reptiles on Guadalupe suggests the two *Hemidactylus* geckos might spread past their usual commensal habitats if they established. Note: I have no data on what invertebrate IAS (exotic ants may be a significant risk) are present at source ports or on the island.

*(b) Arrival sites*

The island has a small permanent base for the Mexican Navy (footprint = c. 11 ha), and a permanent village (footprint = c. 6 ha) occupied for most of the year by an abalone and lobster fishing community. It also has two permanent scientific base camps (footprint = c. 1 ha) used by GECI and CONANP staff. There is an airstrip with no associated buildings, but no permanent wharf although small boats can berth temporarily near the Navy base and near the fishing village.

**Table 7.** Known IAS in northern Baja California (including Cedros Island) and on Guadalupe Island.

[1] From a list provided by Conabio. The data on IAS at source regions comes from formal records in herbaria or other collections and certainly will underestimate the actual IAS in each region.

[2] From Table 5 in Aguirre-Muñoz et al. (2013). Note 61 exotic plant species (but only 8 listed[4]) were extant on Guadalupe Island in 2000 (Leon de la Luz et al. (2003).

[3] Species not currently on Guadalupe Island, present on the mainland, with likely pathways and vectors to the island, capable of establishing if they arrived, and where rapid response is feasible (i.e. most marine species could not be effectively managed if they arrived).

| Alien species recorded in northern Baja California[1]<br>*=native to other parts of Mexico | Risk IAS for Guadalupe Island[3] | Alien species recorded on both northern Baja California and Guadalupe Island[2] | Alien species recorded on Guadalupe Island but not noted in the northern Baja California list[2]<br>*= probably native to mainland Mexico |
|---|---|---|---|
| Terrestrial plants | | | |
| *Amaranthus albus** | + | | *Agave spp.** |
| *Amaranthus palmeri** | + | | *Atriplex suberecta* |
| *Ambrosia artemisiifolia** | + | | *Avena barbata* |
| *Anthemis cotula* | + | | *Bromus hordeaceus* |
| *Atriplex semibaccata* | | *Atriplex semibaccata* | *Bromus trinii* |
| *Avena fatua* | + | | *Cerastium glomeratum* |
| *Bambusa vulgaris* | 0 (too arid) | | *Erodium brachycarpum* |
| *Beta vulgaris* | + | | *Erodium moschatum* |
| *Bidens pilosa* | + | | *Galium aparine* |
| *Brassica napa* | + | | *Herniaria hirsute* |
| *Brassica nigra* | + | | *Hypochaeris glabra* |
| *Brassica tournefortii* | + | | *Lactuca serriola* |
| *Bromus diandrus* | | *Bromus diandrus* | *Lamarckia aurea* |
| *Bromus madritensis* | | *Bromus madritensis rubens* | *Malva parviflora* |
| *Bromus rigidus* | + | | *Melilotis indicus* |
| *Bromus rubens* | + | | *Mentha citrata* |
| *Bromus tectorum* | + | | *Mesembryanthemum nodiflorum* |
| *Capsella bursa-pastoris* | | *Capsella bursa-pastoris* | *Nerium oleander* |
| *Casuarina equistifolia* | + | | *Nicotiana glauca** |
| *Centaurea melitensis* | | *Centaurea melitensis* | *Pennisetum setaceum* |
| *Chenopodium album* | + | | *Raphanus sativus* |

| Alien species recorded in northern Baja California[1]<br>*=native to other parts of Mexico | Risk IAS for Guadalupe Island[3] | Alien species recorded on both northern Baja California and Guadalupe Island[2] | Alien species recorded on Guadalupe Island but not noted in the northern Baja California list[2]<br>*= probably native to mainland Mexico |
|---|---|---|---|
| *Chenopodium murale* | | *Chenopodium murale* | *Ruta chalepensis* |
| *Chrysanthemum coronarium* | + | | *Schimus barbatus* |
| *Cirsium vulgare* | + | | *Silene gallica* |
| *Conyza canadensis** | + | | *Sisymbrium irio* |
| *Cotula coronopifolia* | 0(too arid) | | *Sisymbrium orientale*[4] |
| *Cynodon dactylon* | + | | *Solanum americanum** |
| *Cyperus odoratus** | 0(too arid) | | *Sonchus tenerrimus* |
| *Digitaria ciliaris** | + | | *Spergularia bocconei* |
| *Erodium cicutarium* | | *Erodium cicutarium* | *Vulpia myuros var. hirsuta* |
| *Hirschfeldia incana* | + | | |
| *Eucalyptus spp.* | | *Eucalyptus spp.* | |
| *Hordeum murinum* | | *Hordeum murinum leporinum* | |
| *Lobularia maritime* | + | | |
| *Lolium temulentum* | + | | |
| *Marrubium vulgare* | + | | |
| *Medicago polymorpha* | | *Medicago polymorpha* | |
| *Melilotus alba* | + | | |
| *Phalaris minor* | | *Phalaris minor* | |
| *Plantago major* | + | | |
| *Poa annua* | | *Poa annua* | |
| *Poa pratensis** | + | | |
| *Polygonium lapathifolia** | + | | |
| *Polypogon monspeliensis* | | *Polypogon monspeliensis* | |
| *Ricinus communis* | 0(too arid) | | |
| *Rumex crispus* | + | | |
| *Rumex pulcher* | + | | |
| *Salosa kali* | | *Salosa kali* | |
| *Sambucus mexicana** | + | | |
| *Senecio vulgaris** | + | | |
| *Setaria verticillata* | + | | |
| *Sisymbrium irio* | + | | |
| *Sonchus asper* | + | | |

| Alien species recorded in northern Baja California[1] *=native to other parts of Mexico | Risk IAS for Guadalupe Island[3] | Alien species recorded on both northern Baja California and Guadalupe Island[2] | Alien species recorded on Guadalupe Island but not noted in the northern Baja California list[2] *= probably native to mainland Mexico |
|---|---|---|---|
| *Sonchus oleraceus* | | *Sonchus oleraceus* | |
| *Sorghum halepense* | + | | |
| *Stellaria media* | + | | |
| *Stenotaphrum secundatum** | + | | |
| *Tamarix aphylla* | + | | |
| *Taraxicum officinale** | + | | |
| *Tecoma stans** | + | | |
| *Vulpia bromoides* | + | | |
| *Xanthium strumarium** | + | | |
| *Xanthium spinosum* | + | | |
| Freshwater plants | | | |
| *Echinochloa crus-galli* | 0(no habitat) | | |
| *Pistia stratiotes* | 0(no habitat) | | |
| *Typha latifolia* | 0(no habitat) | | |
| Marine plants | | | |
| *Pseudo-nitzschia australis* | 0 | | |
| *Pseudo-nitzschia multiseries* | 0 | | |
| *Pseudo-nitzschia pungens* | 0 | | |
| *Pseudo-nitzschia seriata* | 0 | | |
| *P.-nitzschia delicatissima* | 0 | | |
| *Dinophysis fortii* | 0 | | |
| *Dinophysis acuminate* | 0 | | |
| *Dinophysis acuta* | 0 | | |
| *Dinophysis sacculus* | 0 | | |
| *Protoperidinium spp.* | 0 | | |
| *Sargassum mutica* | 0 | | |
| Crustacea | | | |
| *Procambarus clarkia** | 0(no habitat) | | |
| *Paracerceis sculpta* | 0(no habitat) | | |

| Alien species recorded in northern Baja California[1]<br>*=native to other parts of Mexico | Risk IAS for Guadalupe Island[3] | Alien species recorded on both northern Baja California and Guadalupe Island[2] | Alien species recorded on Guadalupe Island but not noted in the northern Baja California list[2]<br>*= probably native to mainland Mexico |
|---|---|---|---|
| Amphibians | | | |
| *Rana catesbeiana* | 0(too arid) | | |
| Reptiles | | | |
| *Hemidactylus turcicus* | + | | |
| *Hemidactylus frenatus* | + | | |
| Marine fish | | | |
| *Acanthogobius flavimanus* | 0 | | |
| Freshwater fish | | | |
| *Lepomis macrochirus* | 0(no habitat) | | |
| *Micropterus salmoides* | 0(no habitat) | | |
| Birds | | | |
| *Bubulcus ibis* | 0(no habitat) | | |
| *Columba livia* | + | *Columba livia* | *Molothrus ater** |
| *Passer domesticus* | + | *Passer domesticus* | *Streptopelia decaocto* |
| *Sturnus vulgaris* | + | *Sturnus vulgaris* | |
| Mammals | | | |
| *Ammospermophilus leucurus** | + | | |
| *Mus musculus* | | *Mus musculus* | |
| *Felis catus* | | *Felis catus* | |
| *Peromyscus eremicus cedrosensis** | | | |
| *Rattus rattus* | + | | |

***Surveillance and response options***

Passive surveillance at the footprint sites will require the cooperation of the Mexican Navy staff based on the island and the fishing families resident on the island. Getting the interest and cooperation of at least some of these individuals is likely to require both agreements with their 'agencies' – the Mexican Navy and the Sociedad Cooperativa de Produccción Pesquera de Participación Estatal Abulones y Langosteros. Since the navy and fishing communities (either or both) are present on all six islands I leave discussion to section 6.

GECI and other research and conservation groups have ongoing projects on Guadalupe and are best suited to conduct any active surveillance required. First, they too can conduct passive surveillance for any possible IAS as they go about their projects across the island. However, I would recommend such groups also conduct a program of more active surveillance at the footprint sites noted above. This should include a baseline survey to record what IAS are already present at the footprint sites (i) those present but widespread elsewhere on the island and (ii) those apparently only present at the footprints, then an annual (or as required by some pathway/vector arrival event) survey for new IAS. How to conduct such surveys and identify any species found is again a generic issue and is discussed in section 4 and later in section 6.

## 5.2 San Benito Oeste Island

San Benito Oeste (364 ha) is one of three small islands in the San Benito group 25 km off Cedros Island and 70 km off Baja California. It is inhabited by abalone fishing community (Fig. 1). Rabbits, feral goats and donkeys were eradicated between 1998 and 2005. Only nine exotic plants and one vertebrate have been recorded on the island (Table 8), with the exotic ice plants (*Mesembryanthemum* spp. dominating much of the vegetation (Junak & Philbrick 2000).

**Figure 1.** Fishing village on San Benito Oeste Island.

### *5.2.1 Risk profile*

*(a) Source sites, pathways and species*

Boats servicing the fishing community arrive from Ensenada and Cedros Island. Cedros Island has both a wharf and airfield. The risk species from sources are probably similar to those from northern Baja California listed in Table 7.

*(b) Arrival sites*

The fishing village covers about 2 ha in a bay on the south of the island while there are lighthouses in the north of the island.

### *5.2.2 Surveillance and response options*

The best response option is to ensure no unwanted IAS are present on the supply ships leaving Ensenada or Cedros Island. Whether management at the source ports could stop IAS getting on board the ships or whether actions on the ships is possible should be explored. At least some education program among the fishing community to make them aware of the risks of IAS (e.g. household plants or pet animals) would be a logical first step.

Passive surveillance at the village might be possible (see section 6) but again any active surveillance is likely to require the periodic presence of biologists.

**Table 8.** Known IAS in northern Baja California (including Cedros Island) and on San Benito Oeste Island.

[1] From a list provided by Conabio.

[2] From Junak & Philbeck (2000).

[3] Species not currently on San Benito, present on the mainland, with likely pathways and vectors to the island, capable of establishing if they arrived, and where rapid response is feasible (i.e. most marine species could not be effectively managed if they arrived).

| Alien species recorded in northern Baja California[1] *=native to other parts of Mexico | Risk IAS for San Benito Island[3] | Alien species recorded on northern Baja California or Cedros Island and on San Benito Island[2] | Alien species recorded on San Benito but not noted in the northern Baja California list[2] *= probably native to mainland Mexico |
|---|---|---|---|
| Terrestrial plants | | | |
| See Table 7 | See Table 7 | | *Cakile maritime* |
| | | *Chenopodium murale* | *Datura discolour* |
| | | | *Erodium moschata* |
| | | | *Malva parviflora* |
| | | | *Melilotus indicus* |
| | | | *Mesembryanthemum crystallinium* |
| | | | *Mesembryanthemum nodiflorum* |
| | | | *Sonchus tenarrimus* |
| *Birds* | | *Columba livia* | |
| | | *Molothrus ater** | |
| | | *Passer domesticus* | |
| | | *Streptopelia decaocto* | |
| Mammals | | | |
| | | | *Peromyscus eremicus cedrosensis** |

## 5.3 Espíritu Santo Island

Espíritu Santo Island (7991 ha) is 6 km off Baja California in the Gulf of California. The management unit consist of two main islands (Espíritu Santo and Isla Partida at 1634 ha, and seven islets). It is an Area for Protection of Flora and Fauna. It has fewer major habitat types than Guadalupe and is less modified by human activities with fewer weeds. Unlike Guadalupe, Espíritu Santo has a diverse native fauna of endemic mammals, and reptiles – along with the IAS goats and feral cats.

***Risk profile***

The island has no permanent human settlement but does have many temporary fishing camps and is regularly visited by people for recreational purposes and no formal permit to visit is required.

*(a) Source sites, pathways and species*

Recreational boats (and there are many from simple pangas to large luxury tour boats) originate from the city of La Paz. The IAS recorded from around La Paz as the most likely source for the island are listed in Table 9. Fortunately the arid and hot islands in the Gulf of California make it difficult for many IAS to establish.

*(b) Arrival sites*

There are many potential arrival places on Espíritu Santo Islands as boats can and do land on numerous beaches. However, the main footprints are the fishing huts at the sand spits between the two main islands (c. 5 ha on Partida and < 1 ha on the main island), and at a popular camping ground in a bay on the northwest of the main island (footprint = c. 3 ha).

**Table 9.** Known IAS in southern Baja California and on Espíritu Santo Island.

[1] From a list provided by Conabio.

[2] From Table 9 in Aguirre-Muñoz et al. (2013). Argentine ants have been recorded in southern Baja California.

[3] Species not currently on Espíritu Santo Island, present on the mainland, with likely pathways and vectors to the island, capable of establishing if they arrived, and where rapid response is feasible (i.e. most marine species could not be effectively managed if they arrived).

| Alien species recorded in southern Baja California[1] *=native to other parts of Mexico | Risk IAS for Espíritu Santo Island[3] | Alien species recorded on both southern Baja California and on Espíritu Santo Island[2] | Alien species recorded on Espíritu Santo Island but not noted in the southern Baja California list[2] *= probably native to mainland Mexico |
|---|---|---|---|
| Terrestrial plants | | | |
| *Amaranthus palmeri** | + | | *Datura stramonium* |
| *Brassica nigra* | + | | *Gossypium sp.* |
| *Cajanus cajan* | | | *Phoenix dactylifera* |
| *Cenchrus ciliaris* | | *Cenchrus ciliaris* | *Tamarix ramosissima* |
| *Chenopodium murale* | | | |
| *Coronopus didymus* | | | |
| *Cryptostegia grandiflora* | | | |
| *Cucumis dipsaceus* | | | |
| *Cynodon dactylon* | + | | |
| *Cyperus esculentus* | 0 (too arid) | | |

| | | | |
|---|---|---|---|
| *Cyperus odoratus** | 0 (too arid) | | |
| *Cyperus rotundus* | 0 (too arid) | | |
| *Cyperus involucratus* | 0 (too arid) | | |
| *Dactyloctenium aegyptium* | | | |
| *Digitaria ciliaris** | + | | |
| *Digitaria sanguinalis* | | | |
| *Echninochloa colona* | | | |
| *Eleusine indica* | | | |
| *Mollugo verticillata** | | | |
| *Momordica charantia* | | | |
| *Pennisetum ciliare* | | | |
| *Poa annua* | | | |
| *Ricinus communis* | 0 (too arid) | | |
| *Rumex pulcher* | + | | |
| *Salsosa kali* | | | |
| *Sonchus asper* | + | | |
| *Sonchus oleraceus* | | | |
| *Tamarix aphylla* | + | | |
| *Tecoma stans** | + | | |
| Marine plants | | | |
| *Pseudo-nitzshia seriata* | 0 | | |
| Marine animals | | | |
| *Crassostrea gigas* | | | |
| Insects | | | |
| *Digitonthophagus gazelle* | + | | |
| *Linepithema humile* | + | | |
| Reptiles | | | |
| *Hemidactylus frenatus* | + | | |
| Birds | | | |
| *Bubulcus ibis* | | | |
| *Columba livia* | + | | |
| *Passer domesticus* | + | | |
| *Sturnus vulgaris* | + | | |
| Mammals | | | |
| *Felis catus* | | *Felis catus* | |
| *Capra hircus* | | *Capra hircus* | |

### *Surveillance and response options*

Regular tour operators might be encouraged to keep IAS off their boats or even to check sites they regularly land but given the number of casual visitors (and the many places they can land) it is probably best if surveillance is conducted actively by scientific visitors. Targeting the casual visitors by general public education about the IAS risks posed by their activities would be a long-term objective but I doubt it would reduce the risks without some form of active inspection by government agents.

## 5.4 Socorro Island

Socorro Island (13033 ha) in the Revillagigedo Archipelago is the most remote of the demonstration islands being some 480 km south-west of Baja California. It is a Biosphere Reserve with many endemic species. Feral sheep were probably eradicated in 2011 but feral cats and mice remain. There is a small commensal ant present at the Navy base – possible an invasive?

### *Risk profile*

Socorro Island is only visited by Navy personnel and visiting scientists. The island is too far off mainland Mexico to attract fishermen or tourists.

*(a) Source sites, pathways and species*

The Navy ships depart from Manzanillo in Colima region and there is a small wharf on the island. The airfield is large enough to let large aircraft land and so they can depart from many airports in Mexico or elsewhere in America. Exotic species known from near the mainland port and on the island are noted in Table 9.

**Table 9.** Known IAS in the Manzanillo region and on Socorro Island.

[1] From a list provided by Conabio.

[2] From Table 11 in Aguirre-Muñoz et al. (2013).

[3] Species not currently on Socorro Island, present on the mainland, with likely pathways and vectors to the island, capable of establishing if they arrived, and where rapid response is feasible (i.e. most marine species could not be effectively managed if they arrived).

| Alien species recorded in Manzanillo[1]<br>*=native to other parts of Mexico | Risk IAS for Socorro Island[3] | Alien species recorded both near Manzanillo and on Socorro Island[2] | Alien species recorded on Socorro Island but not noted in the Manzanillo list[2]<br>*= probably native to mainland Mexico |
|---|---|---|---|
| Terrestrial plants | | | |
| *Anoda cristata* | + | *Anoda cristata* | *Acacia farnesiana* |
| *Arundo donax* | + | | *Annona muricata* |
| *Clitoria ternatea* | + | | *Argemone ochroleuca* |
| *Cyperus iria* | | | *Boerhavia coccinea* |
| *Cyperus rotundus* | | | *Canavalia rosea* |
| *Dactyloctenium aegyptium* | + | | *Cenchrus ciliaris* |
| *Digitaria sanguinalis* | + | | *Cenchrus echinatus* |
| *Echninochloa colona* | + | | *Chamaecrista nicitans* |
| *Eleisine indica* | + | | *Citrellus vulgaris* |
| *Euphorbia hirta* | | *Euphorbia hirta* | *Citrus limon* |
| *Momordica charantia* | + | | *Citrus sinensis* |
| *Uruchloa mutica* | + | | *Cleome viscosa* |
| | | | *Cocos nucifera* |
| | | | *Codiaeum variagatum* |
| | | | *Cordia cylindrostachia* |
| | | | *Crotalaria incana* |
| | | | *Delonix regia* |
| | | | *Desmodium acorpuinus* |
| | | | *Echinopepon sp.* |
| | | | *Hibiscus pernambucensis* |
| | | | *Hyptis mutabilis* |
| | | | *Ipomoea fistulosa* |
| | | | *Lagenaria vulgaris* |
| | | | *Luffa cilindrica* |
| | | | *Macadamia integrifolia* |

| Alien species recorded in Manzanillo[1] *=native to other parts of Mexico | Risk IAS for Socorro Island[3] | Alien species recorded both near Manzanillo and on Socorro Island[2] | Alien species recorded on Socorro Island but not noted in the Manzanillo list[2] *= probably native to mainland Mexico |
|---|---|---|---|
| | | | *Malvastrum americanum* |
| | | | *Malvastrum coromandeliaum* |
| | | | *Mangifera indica* |
| | | | *Mitracarpus hirtus* |
| | | | *Passiflora edulis* |
| | | | *Pithecellobium dulce* |
| | | | *Prosopis chilensis* |
| | | | *Prunus capuli* |
| | | | *Psidium guajava* |
| | | | *Salvia sp.* |
| | | | *Senna obtusifolia* |
| | | | *Sesbania herbacea* |
| | | | *Skrankia intonsa* |
| | | | *Solanum torvum* |
| | | | *Sonchus sp.* |
| | | | *Tamarindus indica* |
| | | | *Terminalia cattapa* |
| | | | *Thevetia peruviana* |
| | | | *Tournefortia hartwegiana* |
| | | | *Vinca major* |
| Freshwater plants | | | |
| *Eichhornia crassipes* | 0 | | |
| *Phragmites australis* | 0 | | |
| *Pistia stratiotes* | 0 | | |
| Marine plants | | | |
| *Dinophysis fortii* | | | |
| *Gymnodinium catenatus* | | | |
| *Phalocroma mitra* | | | |
| *Protoperidinium mite* | | | |
| *Pseudo-nitzschia pungens* | | | |
| Crustacea | | | |
| *Litopenaeus vannamei* | | | |
| Amphibians | | | |

| Alien species recorded in Manzanillo[1] *=native to other parts of Mexico | Risk IAS for Socorro Island[3] | Alien species recorded both near Manzanillo and on Socorro Island[2] | Alien species recorded on Socorro Island but not noted in the Manzanillo list[2] *= probably native to mainland Mexico |
|---|---|---|---|
| *Bufo marinus* | 0 | | |
| Reptiles | | | |
| *Hemidactylus frenatus* | + | *Hemidactylus frenatus* | |
| *Hemidactylus mabouia* | + | | |
| Marine fish | | | |
| *Oreochromis mossambicus* | | | |
| Birds | | | |
| | | | *Bubulus ibis* |
| *Columba livia* | | *Columba livia* | *Molothrus ater** |
| *Passer domesticus* | | *Passer domesticus* | *Sturnus vulgaris* |
| Mammals | | | |
| *Felis catus* | | *Felis catus* | |
| *Mus musculus* | | *Mus musculus* | |

### *(b) Arrival sites*

The airfield is 1300 m long but the hanger area where people and cargo disembark is less than 1 ha. The Navy base has a wharf area (footprint = 1 ha) and nearby base (footprint = c. 22 ha) that represent the high risk arrival sites on the island. If the feral cat eradication project proceeds (Parkes et al. 2012) the necessary establishment of temporary basecamps may also present risks as materials are imported to build them.

### ***Surveillance and response options***

The Navy has a permanent presence on Socorro and could conduct at least passive surveillance at sites they use. Again, the Navy needs to develop a protocol to ensure their ships are not vectors of IAS by including good practices at their departure ports and on-board inspections. The Navy has also already planted several exotic plants at their base (for fruit or shade). Those that might be invasive should be checked to see if they are in fact reproducing and, if so, their removal or control should be considered.

More general and active surveillance over the whole island would require specific effort by trained personnel.

## 5.5 Arrecife Alacranes

Alacranes Reef consists of five islets within an atoll. Mice were present on two (Muertos and Pájaros) and ship rats are (or were) on Pérez but confirmation of an eradication attempt by GECI in 2011 is awaited.

***Risk profile***

The Alacranes (Scorpion) Reef Gulf of Mexico about 140 km off the Yucatan Peninsula. Only the largest islet, Pérez at 17 ha is inhabited with a lighthouse and field base used by government agencies such as CONANP. The exotic plants appear to be mostly species planted by people for food or shade (Table 10).

The presence of *Casuarina equisitifolia* on the beaches of islands where marine turtles nest can present a problem for the reptiles, e.g. see www.conservationindia.org/case-studies/freeing-sea-turtle-nesting-beaches-from-casuarina-plantations.

*(a) Source sites, pathways and species*

The nearest port is at Progreso which is where I assume most visiting boats originate.

*(b) Arrival sites*

There are two places where boats can land on Pérez but the total footprint area is probably < 1 ha.

***Surveillance and response options***

Visiting divers and tourists seem unpromising candidates for passive surveillance so active surveillance by government agency staff (CONANP) or other scientists seems the only practical option for surveillance on the atolls of the reef.

**Table 10.** Known IAS at Progreso and on Arrecife Alacranes
[1] From a list provided by Conabio.
[2] From Table 13 in Aguirre-Muñoz et al. (2013).

| Alien species recorded near Progreso[1]<br>*=native to other parts of Mexico | Risk IAS for Arrecife Alacranes[3] | Alien species recorded both near Progreso and on Arrecife Alacranes[2] | Alien species recorded on Arrecife Alacranes but not noted in the Progreso list[2]<br>*= probably native to mainland Mexico |
|---|---|---|---|
| Terrestrial plants | | | |
| *Bidens pilosa* | + | | *Cenchrus echinatus* |
| *Calotropis procera* | + | | *Cocos nucifera* |
| *Casuarina equisitifolia* | | *Casuarina equisitifolia* | *Opuntia cochenillifera** |
| *Cryptostegia grandiflora* | | | *Opuntia dilleni** |
| *Cyperus odoratus** | | | |
| *Dactyloctenium aegyptium* | | | |
| *Euphorbia heterophylla* | | | |
| *Euphorbia hirta* | | | |
| *Nerium oleander* | + | | |
| *Ricinus communis* | | | |
| *Sesbania grandiflora* | | | |
| *Sonchus oleraceus* | + | | |
| *Sorghum halapense* | + | | |
| Marine plants | | | |
| *Ulva fasciata* | | | |
| Crustacea | | | |
| *Balanus Amphitrite* | | | |
| Reptiles | | | |
| *Anolis sagrei* | + | | |
| *Hemidactylus turcicus* | + | | |
| Freshwater fish | | | |
| *Astyanax fasciatus* | | | |
| *Heterandria bimaculata** | | | |
| *Poecilia spenops** | | | |
| *Poecila velifera** | | | |
| *Thoricthys meeki** | | | |
| Birds | | | |
| | | | *Bubulcus ibis* |

## 5.6 Banco Chinchorro

Banco Chinchorro is a large atoll in the Caribbean consisting of four narrow cays and large areas of mangrove. It has a diverse native fauna including reptiles and birds but only bats as native mammals. Ship rats have been eradicated from two cays but are still present, along with feral cats, on Cayo Centro.

***Risk profile***

*(a) Source sites, pathways and species*

Boats depart from the ports at Mahahual and perhaps Chetumal on the mainland. The Cayo Centro is used by local fishermen and scientists, while the Mexican navy uses Cayo Norte Mayor (see Aguirre-Muñoz et al. 2013 for details). Some risk species from the mainland are noted in Table 11.

*(b) Arrival sites*

The Navy base on Cayo Norte Mayor and three sites on Cayo Centro have a combined footprint of a few hectares.

***Surveillance and response options***

The main risk sites are on the inhabited cays, at least from terrestrial IAS. As with other island used by fishermen, the navy and scientists a mix of passive surveillance by the permanent inhabitants and active by the specialists is the best option on the island. Although outside the EDRR process, management at source ports to stop IAS getting on ships and surveillance and action on the ships requires development – see the generic recommendations for these actions for all islands.

**Table 11.** Known IAS at Mahahual and Chetumal on the mainland and on Banco Chinchorro
[1] From a list provided by Conabio.
[2] From Table 15 in Aguirre-Muñoz et al. (2013).

| Alien species recorded in Mahahual and Chetumal[1]<br>*=native to other parts of Mexico | Risk IAS for Banco Chinchorro[3] | Alien species recorded both in the Yucatan area and on Banco Chinchorro[2] | Alien species recorded on Banco Chinchorro but not noted in the Mahahual/Chetumal list[2]<br>*= probably native to mainland Mexico |
|---|---|---|---|
| Terrestrial plants | | | |
| *Arundo donax* | | | *Casuarina equisitifolia* |
| | | | *Cenchrus echinatus** |
| | | | *Cocos nucifera* |
| | | | *Eustachys petraea** |
| | | | *Urochloa(Panicum) maxima* |
| Marine plants | | | |

| | | | |
|---|---|---|---|
| | | | *Halodule beaudettei** |
| Reptiles | | | |
| | | | *Hemidactylus turcicus* |
| *Fish* | | | |
| *Petenia splendid** | | | |
| *Thorichthys meeki** | | | |
| Birds | | | |
| | | *Bubulcus ibis* | |
| | | *Streptopelia decaocto* | |
| Mammals | | | |
| *Felis catus* | | *Felis catus* | |
| *Odocoileus virginianus* | | | |
| *Rattus rattus* | | *Rattus rattus* | |

# 6 General conclusions and recommendations

- The lists of risk IAS at source ports needs to be refined. The 'source' areas around ports, for example, need to be delineated and the area surveyed to see what exotic species are present and which have plausible pathways to the nearest islands and are likely to establish and spread if they arrive. Perhaps a job for a student at each source place.
- Key species found at such sources could be managed (removed or controlled) at the source or flagged for management on pathways and vectors departing for the islands.
- Management on the vectors (usually ships) going to the islands will require the active participation and compliance of the ships' owners, crew and passengers, which will require some development. The practicality of this is likely to depend on the type of vector. Organised shipping such as Navy ships, those servicing the government or NGO agencies using the islands, or servicing the organised fishing communities might be targeted with a set of agreed protocols or standard operating procedures. Individual boat of casual visitors would have to rely on more generic public awareness campaigns, which may be of limited worth.
- The footprint sites on all the islands are small (relative to the size of the island in most cases) and EDRR is tractable for these footprint sites – assuming the capacity to conduct the surveillance.
- Longer-term such active surveillance cannot hope to meet all the 'early detection' needs and people living at high-risk sites will need to be involved in detection (and sometime early response for some IAS). They will need resources (photographs and descriptions of any high-risk IAS identified by the analysis above), training and motivation to use it.
- Five of the six islands have Navy bases which present both a risk that the boats or aircraft servicing these bases will carry IAS, and an opportunity to use Navy

personnel to conduct surveillance and perhaps response. The problem with military personnel is they change with each deployment on the island. The solution is to include biosecurity Standard Operating Procedures in the military chain of command. Someone in each deployment is made responsible for biosecurity and surveillance/reporting and provided with a manual (with some basic training) of what to do (usually passive surveillance) and who to report to if something is found.

- Five of the six islands also have semi-permanent fishing communities. Those on Guadalupe, San Benito and Banco Chinchorro are organised cooperatives and may be prepared to conduct passive surveillance and report (or act) on any IAS they discover.
- Scientific expeditions are sent to all six islands from time to time. Scientists are marginally more likely to report IAS than other people, much more if the IAS is in their taxonomic range. However, it is best if active surveillance is conducted by suitable experts. I recommend conducting baseline surveys of all footprint sites to list IAS that are NOT widespread on the island. This would useful for two reasons (a) to build capacity to detect and manage such IAS in preparation for future EDRR processes, and (b) to refine the risk analyses implied in Table 7 – which new IAS to keep under review.
- On rodent-free islands with high risks of invasion (ships visiting from source sites and unloading cargo) many managers deploy permanent bait stations at the footprints sites. This is not possible on the islands with rodents (or other native mammals) as it would simply feed the mice. If the risk of a rodent incursion was high (and it does not appear to be so for Mexican islands) the only proactive way to manage the risk is to have a response ability in place at the footprint ready to deploy at the first sign of a new rodent in an attempt to intercept the incursion – with a high risk of failure. Management at sources and on vectors is the best appropriate way to reduce the risk from such species.
- Rapid response options are also generic on all six islands but depend very much on the IAS and particulars of its discovery. Responses can range from:
    - The person finding a definite IAS (e.g. ants found in cargo, a resident importing and planting a gum tree) dealing with the event on the spot.
    - The person finding a possible IAS (a strange plant appears at the footprint or a gecko is seen in a building) takes a sample and has it checked by an expert before acting to remove it.
    - A major incursion is identified and an appropriate response is not immediately clear but requires some advice from experts on delimitation surveys and how to manage it.
- The planning documents et required are (a) a set of generic protocols on IAS management on vectors and EDRR activities, developed by government (CONABIO?) in consultation with the three main groups of island users – the Mexican Navy, the fishing cooperatives and major science and NGO users, and (b) a biosecurity plan for each island that develops the EDRR timetable and accountabilities for detection and response. It is important that these plans be developed in consultation with those groups expected to implement them to ensure

they are practical. Residual risks, i.e. those that the groups cannot resolve will require additional management response from the Mexican government agencies responsible for managing the islands.

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## Appendix 1: A statistical framework for estimating the probability of absence

There are two complementary hypotheses ($H$), either the target IAS is not present ($H_1$) or it is present in the search area ($H_2 = 1-H_1$). Note: to 'prove' that none are present (i.e. $P(H_1) = 1$) requires that monitoring be undertaken over the entire island using a detection method that is infallible. Meeting this condition is likely to be impossible or extremely unlikely. Hence the weight of evidence for either hypothesis is normally expressed in the form of a probability statement (e.g. the probability of $H_1$ is 0.95 or $H_2 = 0.05$).

A natural framework for handling multiple data sources and uncertainties is provided using a Bayesian approach. Under this approach the quantity of interest that we wish to estimate is the conditional probability that the IAS is present in the search area (or whole island):

$$\mathrm{P}(H_2 \mid -ve\ survey), \tag{1}$$

where the | sign signifies a conditional probability and −*ve survey* indicates the condition where surveys have not detected the presence of the IAS. Thus, this conditional probability reads as 'the probability that the IAS is present, given that they have not been detected'.

We might have some belief or prediction that IAS is not present (or its complement that it is present) in each search area. This can be based on 'intuition' perhaps informed by past experience for the island or other islands. This information can be used to formulate a subjective prior belief in the probability that the IAS is present ($P(H_2)$). It does not matter too much for our purposes whether this probability is accurate and in fact a conservative belief would be that the probability is near zero for most island cases. For some IAS we could estimate this prior belief by using the known frequencies of invasion averaged over islands or types of island, e.g. Russell et al. (2008) for rats. We can also make some judgement on risks by looking at the proportion of islands of different sorts that already have different classes of IAS. For example, islands with wharfs have a higher probability of having exotic rodents than those that do not (Atkinson ?).

We can update this prior probability using survey information (evidence) to estimate an objective prior probability of IAS presence (eqn 1) using Bayes' Theorem:

$$P(H_2 \mid -ve\,survey) = \frac{P(H_2)\,P(-ve\,survey \mid H_2)}{P(-ve\,survey)}, \tag{2}$$

where $P(H_2 \mid -ve\ survey)$ is our posterior (revised) probability of IAS presence, given none were detected (eqn. 1), $P(H_2)$ is our prior probability or belief of IAS presence, and $P(-ve\ survey \mid H_2)$ is the evidence or likelihood of detecting the IAS, given that they are present, obtained from monitoring data and $P(-ve\ survey)$ is the probability of detecting no IAS under all permissible hypotheses. Note: these analyses can be done starting with the first area searched, and thus if the belief that the IAS is not in this search area is correct, the prior belief for the next search area increases – and vice versa.

Following any rapid response, a certification phase is required. This consists of additional monitoring be carried out to confirm that no IAS remain. Thus, the certification phase is designed to provide 'weight of evidence' for the statement that the IAS have been eradicated. During the certification phase, a series of surveys would need to be carried out in each block. If an IAS is detected, then eradication is deemed to have failed and the probability of eradication is zero (P($H_1$) = 0; P($H_2$) = 1)). However, we are concerned with the more likely outcome of monitoring where IAS have not been detected. In this instance we require a statistical framework for evaluating repeated surveys that detect no evidence of IAS to make inference about the probability of eradication. In addition, surveys may use markedly different detection techniques, some of which may have inherently low detection power. Thus, any statistical framework should have the flexibility to incorporate multiple sources of survey information as well as handle the uncertainties posed by surveys of variable (or unknown) detection power.

The application of Bayes' Theorem to estimate the 'degree of belief' that at least one IAS persists is illustrated in the following example.

Let us assume that the control phase has been completed for a given block. Following the monitoring phase we might suspect that there is about a 30% chance that at least one IAS still persists in that sector. Thus $P(H_2) = 0.3$, which is the prior probability that an IAS persists in the sector following the putative end of the response phase. Here we need to have some estimate of the detection probability of the search device or system and this is usually collected during the operation or experimentally determined from places where the IAS is more common. Assume a high detection probability of 0.8 (e.g. see the ant example in Table 4). Hence $P(-ve\ survey \mid H_2) = 0.2$. The survey was then undertaken, and returned no evidence of an IAS. Applying Bayes' Theorem gives:

$$P(H_2 \mid -ve\,survey) = \frac{P(H_2)\,P(-ve\,survey \mid H_2)}{P(H_2)P(-ve\,survey \mid H_2) + P(H_1)P(-ve\,survey \mid H_1)} \quad . \tag{3}$$

Substituting the known probabilities and/or their complements gives

$$P(H_2 \mid -ve\,survey) = \frac{(0.3)(0.2)}{(0.3)(0.2) + (0.7)(1)} = 0.079\,. \tag{4}$$

Note that we assume that the probability of obtaining a negative survey, given an IAS is *not* present, is equal to 1 (i.e. there are no false-positive IAS identifications). This assumption can be relaxed if false-positive identifications are a potential issue.

Thus the revised probability that at least one IAS persists in the sector has been modified from 0.3 to 0.079 based on the results of survey information. The process can sum multiple survey techniques and can use the results of consecutive surveys, with the posterior probability calculated from the results of the previous survey used as the prior probability to calculate the posterior from results of subsequent surveys, i.e. we can include the proposed 'certification' monitoring.

Additionally, we can incorporate uncertainty in our estimates of the prior probability and/or survey detection probabilities to calculate a posterior probability distribution (compared with the point estimate calculated previously) using a continuous version of Bayes' Theorem:

$$f(\theta \mid -ve\,survey) = \frac{f(\theta)\, f(-ve\,survey \mid \theta)}{\int_{\theta} f(\tau)\, f(-ve\,survey \mid \tau)\, d\tau} \tag{5}$$

where $f(\theta)$ and $f(\tau)$ now refer to probability density distributions. Continuing with the above example, assume that there is uncertainty associated with the prior information such that it can be modelled using an independent probability distribution such as a beta distribution. (e.g. $\theta \sim \mathrm{Beta}(a_\theta, b_\theta)$). The form of the prior probability distribution would then reflect the degree of uncertainty associated with the expert information (e.g. Fig. 1). A uniform probability distribution would reflect a high degree of uncertainty associated with the prior (Fig. 1a), while a sharply peaked probability distribution would reflect a relatively high degree of certainty associated with the prior (Fig. 1d). Numerical estimation techniques can then be used to approximate the posterior probability distribution. For example, assuming a prior probability distribution equivalent to Fig. 1c with a mean probability of IAS persistence of 0.3, and then conducting a survey on the population that had a 80% chance of detecting a one gives an estimate of the posterior probability with a mean as above of 0.08 and with a 95% confidence (credible) interval of 0.03–0.16 (Fig. 2). This highlights the need to design surveys that have a high probability of detecting an animal.

Where monitoring surveys are undertaken over a portion of the management area of interest, the coverage is incomplete and this must be taken into account when calculating the probability of persistence. The Bayesian procedure illustrated above can be generalised across space by assuming that detection techniques can be characterised by a two-dimensional detection function (Fig. 3). A detection function assumes that the probability of detection declines with increasing distance away from the detection device. Different detection methods would be parameterised by different detection functions. For example, helicopter monitoring may have a large width of detection, but low probability of detection on the line of travel (Fig. 3, solid line). Alternatively, ground monitoring may have a high probability of detection on the line of travel, but have a narrow width of detection (Fig. 3, dashed line). This two-dimensional detection probability can be used in conjunction with the above Bayesian formulation to produce a spatially explicit map of the posterior probability of wallaby persistence. Prior probabilities can also be made spatially explicit by assuming that wallaby persistence is influenced by habitat features, such as degree of vegetative cover such that habitat features on the island would have differing prior probabilities of wallabies persisting following control efforts. The advantages of a spatial approach to map the posterior probability of wallaby persistence is that it gives a convenient spatial representation of the degree of monitoring coverage so that managers can visually identify areas where monitoring coverage is inadequate.